A System Modelling Approach to Assessment of Hybrid Water Supply Solutions in eThekwini Municipality

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Declaration

I, Danica McKune, know the meaning of plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own.

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Abstract

Water security in South Africa is a major concern, particularly in the context of urbanisation, the concomitant increases in water demand, and the potential for climate change to aggravate water shortages. Provision of basic services remains a significant challenge. Improving economic and social equity, vitally supported by adequate water supply and water quality, while ensuring environmental sustainability (maintaining water resources requires healthy ecosystems) is the dual challenge facing South Africa.

There is growing recognition of the need for alternative approaches to water management, such as Sustainable Urban Water Management (SUWM). Decentralisation and integration to allow consideration of the total water cycle are fundamental themes of the SUWM paradigm. There is theoretical and experiential evidence that the current infrastructure archetype (of conveying a particular water stream from origin to destination by the most efficient means) could benefit from inclusion of such principles. SUWM is purported to have three core benefits: (1) A more natural water cycle, (2) Improved water security through diversification of sources, and (3) Resource efficiency.

A complete transition to alternative water provision models is neither economical nor practically feasible in already developed areas, necessitating innovations in new areas and as retrofits to existing systems; systems where the water services configuration is evolving in this way are termed hybrid systems. Alternative water provision models bring dynamic changes to existing systems which may not be intuitive: the complexity of urban water systems and the resulting uncertainty means an intervention may achieve one SUWM objective yet undermine another. Thorough evaluations of alternative water provision models are therefore essential, while recognising that less learned experience on the performance of innovative solutions means uncertainty remains part of the evaluation.

This research therefore aims to contribute to the theoretical body of knowledge on the net system effects of integrated management of the water cycle where alternative and decentralised solutions are introduced to existing systems. The overarching research objective was therefore application of an assessment framework, which was underpinned by the development of a systems dynamics model in GoldSim software.

The systems dynamics model has been tailored for application to the selected case study area – eThekwini Municipality in South Africa. Akin to most South African cities, this region is home to a diverse range of consumers (fully serviced urban suburbs, informal settlements, peri-urban settlements, and rural areas), is experiencing urbanisation and growth in demand, and is supplied by catchments whose water resources are fully developed and are at risk of becoming significantly stressed. This is set against a backdrop of challenges in service delivery, environmental concerns as a result of water practices, potential impacts of climate change in the future, and ultimately sustainability of service provision.

The developed systems dynamics model is a macro-scale integrated flow model, capable of assessing implementation of water servicing scenarios (specifically any combination of Water Conservation and Water Demand Management, rainwater harvesting, stormwater harvesting, groundwater use, greywater reuse, wastewater recycling, and desalination) at a regional level.

Monte Carlo analyses were carried out to test system sensitivity to uncertainty in particular parameters.

Of the possible interventions, five scenario paths were assessed: (1) Baseline, or “business as usual”, (2) WCWDM, (3) rainwater harvesting and real loss reduction, (4) greywater reuse and WCWDM, and (5) wastewater recycling and real loss reduction. Considered against the three core benefits of SUWM, each of the intervention scenarios yielded positive results. The developed model proved valuable in the scoping of SUWM interventions, and understanding the system-wide effects SUWM interventions may have on the water cycle. Such systems modelling approaches may therefore be considered to provide the framework and parameters within which further detailed and project-specific hydraulic and contaminant transport analysis could take place.

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Abbreviations / Acronyms / Definitions

AWBM	Australian Water Balance Model
BMC	Billed Metered Consumption
CARL	Current Annual Real Loss
CBA	Cost Benefit Analysis
COD	Chemical Oxygen Demand
CSCM	Coastal Engineering Stormwater Catchment Management
DEWATS	Decentralised Wastewater System
DWS	Department of Water and Sanitation
ELL	Economic Level of Leakage
EWR	Environmental Water Requirement
EWS	eThekwini Water & Sanitation
FBW	Free Basic Water
FOG	Fats, Oils and Grease
GIS	Geographic Information System
GRA2	Groundwater Resource Assessment Phase II
IA	Integrated Assessment
IDP	Integrated Development Plan
IUWM	Integrated Urban Water Management
KZN	Kwa-Zulu Natal
MMTS	Mooi-Mgeni Transfer Scheme
NRW	Non-Revenue Water
RWH	Rainwater Harvesting
SIP	Strategic Integrated Projects
SIV	System Input Volume
SuDS	Sustainable Urban Drainage Systems

SUWM	Sustainable Urban Water Management
TBL	Triple Bottom Line
TKN	Total Kjeldahl Nitgrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UARL	Unavoidable Annual Real Loss
UD	Urine Diversion
UEIP	uMngeni Ecological Infrastructure Partnership
uWMP	uMkhomazi Water Project
UW	Umgeni Water
VIP	Ventilated Improved Pit
WCWDM	Water Conservation and Water Demand Management
WR2012	Water Resources of South Africa 2012 Study
WRSM	Water Resources Simulation Model
WRSS	Water Reconciliation Strategy Study
WSA	Water Service Authority
WSDP	Water Services Development Plan
WSS	Water Supply System
WTP	Water Treatment Plant
WWTW	Wastewater Treatment Works

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1 Introduction

1.1 Background

According to the United Nations World Water Development Report (2019), worldwide water use has been increasing by 1% per annum since the 1980s, as a result of the cumulative effects of population growth, socio-economic development and changing consumption patterns. Rising demand in industrial and domestic sectors is predicted to drive the same trend in increasing consumption until 2050, though it is expected that the agricultural sector will remain the largest consumer. A large number of people live in countries experiencing high water stress. Furthermore, there remain significant inequities in access to safe drinking water and hygienic sanitation systems. The situation in South Africa largely echoes the global challenge. In the Department of Water and Sanitation's (DWS) National Water and Sanitation Masterplan (NWSMP) (2018), it is stated that South Africa's current water crisis is a result of *"insufficient water infrastructure maintenance and investment, recurrent droughts driven by climatic variation, inequities in access to water and sanitation, deteriorating water quality, and a lack of skilled water engineers"*.

The current infrastructure archetype, particularly relating to water services, is based on the most efficient means of conveying a particular water stream (i.e. water, wastewater, or stormwater) from origin to destination (Armitage *et al*., 2014) and generally takes the form of large-scale centralised infrastructure. The current infrastructure archetype and the oftentimes concomitant inefficient use of energy and other resources is now being regarded as an impediment to achieving sustainable development (*ibid*). Effective water management is also recognised as crucial moving forward, with various institutions identifying the need for alternative approaches to water management and transitioning from "water-wasteful" to "water-sensitive" human settlements (*ibid*). Armitage *et al*. (2014) state *"alternative, systems-based approaches to conventional water management of water supply and modes of ensuring water quality are required. New models of water capture, provision, treatment and governance need to be explored and developed to improve and enhance the effectiveness of interaction between the multiple actors who determine water use"*. There is thus a need to change urban metabolism patterns from linear (i.e. where a resource is delivered, metabolised and outputted as waste) to more cyclical where re-use of resources occurs. Environmental considerations in planning processes are also being seen as a necessity (Armitage *et al*., 2014). These concepts applied to the water space are encapsulated by Wong (2006): "*The words 'Water Sensitive' define a new paradigm in integrated urban water cycle management that integrates the various disciplines of engineering and environmental sciences associated with the provision of water services including the protection of aquatic environments in urban areas*".

The above principles may be implemented through simultaneous consideration of all infrastructure elements of the water cycle, where solutions such as sustainable urban drainage systems, wastewater recycling, improved wastewater effluent quality, managed aquifer recharge, groundwater use, rainwater harvesting, stormwater harvesting, and Water Conservation and Water Demand Management (WC/WDM) could be considered. (Armitage *et al*., 2014). In developed urban areas, alternative approaches to water management and the associated solutions are generally implemented in conjunction with existing (centralised) separate water servicing streams; such systems may be termed hybrid water supply systems

(Sapkota *et al*., 2015). For purposes of this research, a hybrid water supply system should be taken to mean that alternative water sources are widely incorporated into an existing (generally large-scale, centralised) system to supplement water supply. Depending on the type of alternative water source, the scale may vary from individual households to entire regions. These hybrid systems represent a shift towards integrated management of the water cycle and therefore the principles of Sustainable Urban Water Management (SUWM). Approaches to water management are further discussed in Chapter 2.

1.2 Problem Statement

Despite the potential benefits of integrated management of the water cycle and resulting diversification of water supply sources, the implementation of such has been slow (Marlow *et al*., 2013; Sapkota *et al*., 2015). One of the key impediments to implementation appear to be the “unknowns” (after Sapkota *et al*. (2015), such as “*changes to flow, nutrient and sediment regimes, energy use, greenhouse gas emission, and the impacts on rivers, aquifers and estuaries*”) around the performance of alternative solutions and technologies and the effects on existing (centralised) systems. This research therefore aims to contribute to a greater understanding of the net system effects of integrated management of the water cycle where hybrid water supply systems are formed (i.e. alternative sources and decentralised solutions are introduced to existing systems) in a South African context. The research aim was achieved by developing and testing a number of water servicing options for a selected case study area.

1.3 Research Objectives and Questions

In support of the research aim, the overarching objective of this research was to develop a means of assessing the potential performance of the identified hybrid water supply system options and scenarios, which required:

i. Ascertaining through literature review, the theoretical way in which hybrid water supply systems may function.
ii. Identification of a case study area in South Africa and determining appropriate context-specific scenarios to test the performance of hybrid water supply system options.
iii. Development of an assessment framework – within which the development of a modelling approach is central – for application to the case study area.

Research questions were determined to address the research objectives:

i. Water management:
  - What are the alternative approaches to the current water management paradigm?
  - What are the theoretical and experienced benefits and shortfalls of alternative water management paradigms?
  - What solutions could be considered, and what lessons learnt from other studies?

ii. Case study area:
  - What is the national and local context within which water services exist?
  - What are the challenges faced, and what opportunities are there for moving towards water sensitive settlements?

iii. Assessment framework:
  - How are water servicing options assessed in the water sector?
  - What frameworks and tools could be used to assess alternatives and compare or rank alternatives?

1.4 Document Structure

This thesis comprises seven chapters (including the introductory chapter):

- Chapter 2: The **Literature Review** presents research on alternative water servicing options, methods utilised in assessment of water servicing options; and the framework within which water services exist in South Africa.
- Chapter 3: The **Research Approach** is presented, including the selection of the case study area and an outline of the assessment framework.
- Chapter 4: The particularities of the **Case Study Area (eThekwini Municipality)** are presented, with the aim of developing the context and framework for the system model.
- Chapter 5: The **System Modelling** presents the model inputs and an explanation of the model construction.
- Chapter 6: The **Results and Discussion** presents the outcomes of the system model and selected scenarios.
- Chapter 7: The **Conclusions** revisits the research objectives and the findings of this study, including an assessment of the function of the modelling tool developed. The **Recommendations** identify possible improvements to the study and potential future research endeavours.

2 Literature Review

This chapter presents the key differences between conventional centralised systems and alternative water management paradigms such as Sustainable Urban Water Management (SUWM), following which the benefits and drawbacks of SUWM approaches are detailed. A brief synopsis of the regulatory and developmental environment of water services in South Africa is presented to provide the context within which potential solutions exist. Finally, this chapter focuses on literature detailing the frameworks and tools utilised to assess water servicing options.

2.1 Global and Local Water Challenges

According to the United Nations World Water Development Report (2019), globally in excess of 2 billion people live in countries experiencing high water stress; the aggregated results of water stress across countries do not, however, take into account potentially extreme differences in water resource availability between river basins. Seasonal variability also has significant impact: it is estimated that about 4 billion people (approximately half the global population) are subjected to severe water scarcity for at least one month per annum. Finally, the reported figures do not consider unavailability of water infrastructure for the resource to reach the end-user; i.e. the water stress may be significantly greater in certain regions where water resource development has lagged behind the need. Increasing water demand and intensified climate change effects will exacerbate the water scarcity challenge. Additionally, from 1995 to 2015, floods accounted for 43% of all documented natural disasters, with some 2.3 billion people being affected by these events. Climate change is expected to increase the frequency and magnitude of flooding events (UN, 2019). In terms of access to water supply and sanitation, three out of ten people do not have access to safe drinking water, half of whom reside in Sub-Saharan Africa; and six out of ten people do not have access to hygienic and well-managed sanitation systems. Water quality remains a challenge in both developed and developing countries; asides from environmental degradation, communities without safe drinking water are vulnerable to contaminants in surface water bodies. Again, there are significant inequalities between and within regions (of varying scale) which are masked by these global figures. Notably, the number of people affected or killed by inadequate drinking water and sanitation services far exceeds the number of people affected or killed by floods, droughts, or conflicts (UN, 2019).

The above statistics and trends are indicative of the breadth and complexity of water-related issues currently facing society. Specific to the local conditions in South Africa, the following challenges reported by DWS (2013; 2018) are pertinent:

- South Africa has relatively low rainfall, along with high variability and high levels of evaporation, making it the 30th driest country in the world. In many water management areas, the ecological reserve has not been implemented (while specific to each river system, on average 25% of the Mean Annual Runoff should remain in rivers) (DWS, 2013).

- Almost all of the financially viable freshwater resources have been harnessed; i.e. the building of new dams or increasing the capacity of existing dams will not be an adequate solution. Where additional resources are available for development of further yield, these areas are far from existing urban centres (i.e. areas where water requirements are concentrated). Substantial inter-basin transfers already occur and are costly where water is pumped long distances (DWS, 2013).

- Water quality issues are a result of mining, urban development, industries, and agriculture. Untreated or poorly treated wastewater has significant impacts in many areas (DWS, 2013). About 56% of the 1150 municipal wastewater treatment works (WWTWs) and approximately 44% of the 962 water treatment works (WTWs) in the country are in a poor or critical condition and in need of urgent rehabilitation and skilled operators. About 11% of the aforementioned infrastructure is completely dysfunctional (DWS, 2018).

- Natural flow regimes have been altered through the harnessing of surface water resources (e.g. construction of dams) and high return flows in urban areas. 60% and 65 % of river ecosystems and wetland ecosystems (respectively) have been identified as threatened (DWS, 2013). The extent of main rivers being classified as having poor ecological condition increased by 500% between 1999 and 2011, with some deemed beyond the point of recovery. 50% of wetlands have been lost, and one third of those remaining are in poor condition (DWS, 2018).

- In terms of service provision, 14.1 million people (i.e. 24% of the total population) still use sanitation facilities below the Reconstruction and Development Programme (RDP) standard (flush toilets connected to septic tanks or sewer network, or ventilated improved pit latrines), and only 64% of households have access to reliable water supply (DWS, 2018).

- Provision of water services is currently not financially sustainable due to under-pricing and poor cost recovery: 41% of municipal water does not generate revenue, of which 35% is lost through leakage (DWS, 2018).

- At a national level, a 17% water deficit by 2030 is forecasted (DWS, 2018); i.e. the total yield of water sources will be exceeded by the total water requirements.

Provision of basic services is a significant challenge, particularly in rapidly growing urban areas where it is expected that 70% of the national population will reside by 2030. In the context of urbanisation and with the potential for climate change to aggravate water shortages, water security is a major concern (Armitage *et al*., 2014). Furthermore, the Second National Water Resource Strategy (NWRS2) DWS (2013) acknowledges the developmental challenge where there is pressure to grow the resource-driven economy and so develop the country, with the resulting over-utilisation of water resources and habitat destruction.

2.2 Approaches to Water Management

2.2.1 Conventional Approaches to Water Management

Generally, urban water services comprise surface water resources, water treatment works, potable water networks, sewer networks (sometimes combined with stormwater drainage), wastewater treatment works, and stormwater drainage networks. In the conventional management of water, potable water networks are typically used by residents and industries for all water needs, including activities which may not necessarily require potable water. Sewer networks typically involve the removal of all generated wastewater from residents and industries and conveyance to a treatment facility. Stormwater drainage networks are typically focussed on flood protection through the most efficient removal of generated runoff. In a conventional system, these water systems are typically compartmentalised such that each system performs a specific and focused function.

The current configuration of urban water services has developed through a number of phases – namely water supply, sewage removal, and drainage – in response to a particular driver for change, many of which relate to public health (Marlow *et al*., 2013). Domenech (2011) states that political control and capital accumulation also contributed to centralisation of water infrastructure. Furthermore, increasing growth in cities resulted in greater water demands; in response, large-scale infrastructure was built and controlled by the public sphere to harness and convey water, meanwhile local sources (e.g. groundwater and rainwater) were abandoned (Domenech, 2011). Urban water infrastructure is therefore predominantly configured as large-scale and centrally managed systems out of the need to deliver cheap and reliable services and overcome the cost, operational complexity and resource intensiveness associated with service provision (Marlow *et al*., 2013).

Benefits of centralised water management includes reliable water supply, flood control, food production, and hydroelectricity generation (Domenech, 2011). Leigh & Lee (2019) note the efficiency of centralised systems in areas of concentrated population and economic activity. The sustainability of conventional urban water management and centralised systems has, of recent times, been called into question. There are inefficiencies in design, cost, energy, natural resources, and management (Leigh & Lee, 2019). Due to their nature, centralised systems rely on significant networks of pipelines to convey a particular water stream from origin to destination. Marlow *et al*. (2013) state that the pipelines for all water services typically comprise 50-75% of a water service provider’s capital and operational costs. Aging centralised systems have severe cost implications for operation and replacement or refurbishment (Leigh & Lee, 2019). Inefficient energy usage is frequently attributed to centralised systems (conveyance of water streams and large-scale treatment works) (Leigh & Lee, 2019). Conveyance of wastewater from origin to destination is associated with the loss of potentially useful resources, such as water, nutrients, and energy (Marlow *et al*., 2013; Leigh & Lee, 2019). Similarly, stormwater drainage for the sole purpose of flood protection is seen as loss of a potentially useful source of water (Marlow *et al*., 2013). Large-scale impoundment of water for subsequent treatment as well as discharge of stormwater alters the natural hydrological function of a system and have unforeseen environmental impacts (Marlow *et al*., 2013; Leigh & Lee, 2019). A small percentage of potable water is utilised for potable purposes; therefore, there exist opportunities to reduce the volume of potable water required (Marlow *et al*., 2013). Finally, given that centralised systems generally rely on a limited number of water sources and are frequently configured in a hierarchal form, these systems can be particularly vulnerable to changes in climate which may result in unexpected floods or droughts (Leigh & Lee, 2019).

2.2.2 Sustainable Urban Water Management

The multifarious challenges around water management and the ideal of alternative water management paradigms are not new: For example, Armitage *et al*. (2014) note the concept of Water Sensitive Urban Design (WSUD) first emerged in the early 1990s following water quantity, quality and drainage challenges in Western Australia. All of the aforementioned shortcomings of conventional water systems has driven the development of a more sustainable way forward; hence the emergence of the SUWM paradigm (Leigh & Lee, 2019). Marlow *et al*. (2013) state the concept of SUWM should be viewed as the next step in the development of water management paradigms and is driven by ideals of community wellbeing, ecological health, and sustainable development, instead of a specific focus on the standard of living and public health which is afforded by adequate provision of water services.

Given the substantial cost of constructing and operating extensive pipe networks, if dependency on these networks is decreased (i.e. through decentralisation), theoretically there could be cost savings which could be refocussed on treatment of water, wastewater and stormwater (Marlow *et al*., 2013). Decentralisation is thus a fundamental theme in the SUWM literature (Marlow *et al*., 2013; Leigh & Lee, 2019). Concomitant with decentralised systems, integration is also a key theme of SUWM through interlinking of water flows which in a conventional system would generally be kept separate.

Decentralised water infrastructure generally includes small to medium-sized water infrastructure which makes use of locally available sources (such as groundwater, harvested rainwater, harvested stormwater, reused greywater, and recycled wastewater). Decentralised water infrastructure lends itself towards operating independently or being integrated with an existing centralised system (Leigh & Lee, 2019). Alternative water schemes have been implemented at different scales, including single households, clusters of dwellings, developments, and distributed schemes to larger areas (West, Kenway & Yuan, 2015). The overarching SUWM paradigm has since seen the development of a range of concepts which exist in this space, including Integrated Urban Water Management (IUWM), Total Water Cycle Management (TWCM), and Water Sensitive Urban Design (WSUD) (Marlow *et al*., 2013). Armitage *et al*. (2014) summarise the activities which may be considered as part of the WSUD approach to urban water management in South Africa.

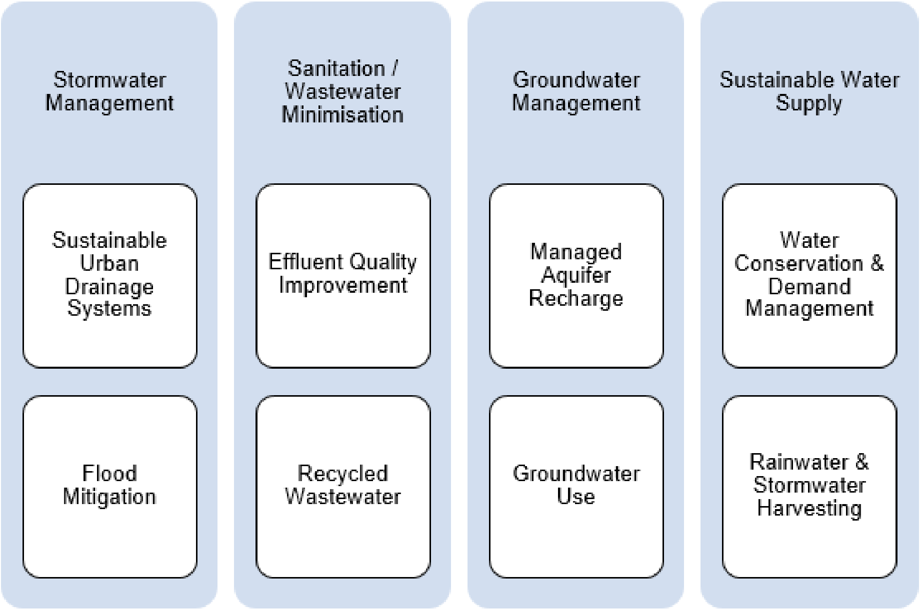


Figure 2-1: SUWM / WSUD Activities [Adapted from Armitage *et al*., 2014]

Figure 2-2 illustrates the flow paths associated with centralised and decentralised water systems and importantly, the integration of flow paths.

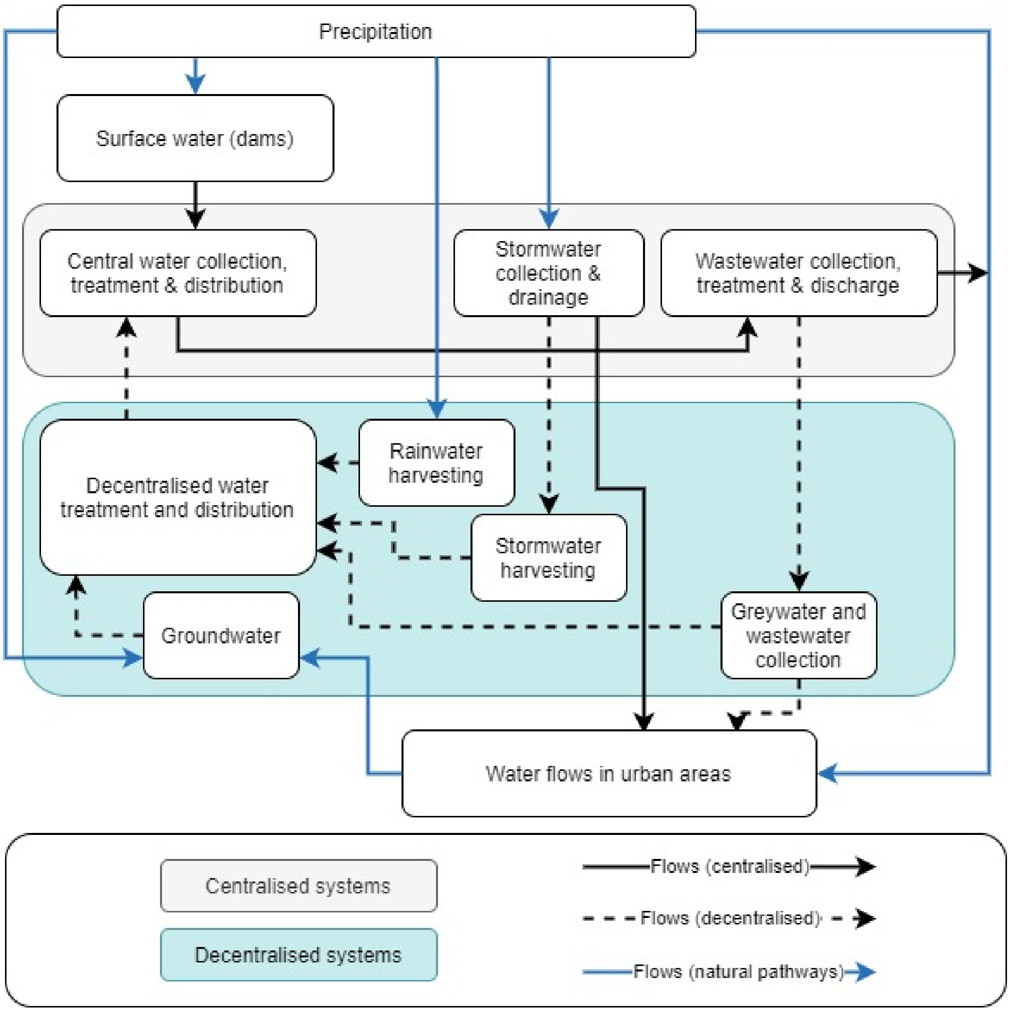


Figure 2-2: Centralized and decentralized components and pathways in urban water management [Adapted from Leigh & Lee, 2019]

Regardless of the term used to describe a more integrated approach to water management, Marlow *et al*. (2013) classify the benefits over conventional approaches into three core areas:

i. A more natural water cycle: Implementation of sustainable urban drainage systems (which is the stormwater-focussed component of SUWM/WSUD) where flow regimes are closer to that which is natural in quantity, frequency of flow, and quality of runoff, in addition to providing flood protection (Marlow et al., 2013).

ii. Improved water security through diversification of sources: Increased system sustainability and resilience is theoretically supported by diversification of water supply sources where the best fit-for-purpose water source within the water cycle is used to supply the appropriate end-use; for example, industrial applications and landscape irrigation requirements could be met with non-potable water. This reduces demand on surface water resources and enables maintenance of healthy environmental flows (Marlow et al., 2013).

iii. Resource efficiency: While resource efficiency is common to any water management authority (regardless of the predominant water management paradigm), SUWM advocates claim that further resource efficiencies can be realised through integrated management of the total water cycle. Reclamation of waste stream components to reduce the ecological impact of urban water systems is encouraged through SUWM (Marlow et al., 2013).

There are a number of impediments to the implementation of SUWM which has seen slow uptake of perceivably more sustainable solutions. Marlow *et al*. (2013) classify these into four key areas:

i. Difficulties in predicting the system effects of innovative solutions: Innovative solutions and the dynamic changes affected on an existing system may not be intuitive. The uncertainty around these matters may also result in the meeting of one SUWM objective undermining another. Such challenges highlight the need for thorough evaluations of alternative water servicing options against multiple criteria. Even if supported by rigorous decision support methods, less evidence and learned experience on the performance of innovative solutions means uncertainty remains. Experimentation, pilot studies, and trials are therefore recommended to build an empirical foundation and so encourage change. The difficulty in predicting system effects is a focus area of this research (Marlow et al., 2013). Further research pertaining to same is discussed in Section 2.2.3.

ii. Practical challenges in managing innovations in technologies and service provision strategies: Requirements of new solutions may not be clear at the outset; institutional capacity is therefore required to be adaptive, which has implications on staffing, management, and skill requirements. Community acceptance of alternative water solutions (especially for water supply) is also a complex issue. On-going engagement with communities following implementation is important to identify and rectify unintended consequences (Marlow et al., 2013). West, Kenway & Yuan (2015) note political and governance aspects may help or hinder implementation and on-going success of SUWM-type solutions.

iii. Financial considerations: Consumers are frequently billed on volume-based consumption. Use of alternative water sources or implementation of water conservation may reduce revenue for water service providers. Where consumers pay flat rates to remain connected to centralised systems, they would likely not realise cost savings, regardless of level of reliance on centralised systems. Financial concerns are exacerbated where centralised systems are still required for times when decentralised systems fail or for fire-fighting requirements, and there is therefore no reduction in the size or extent of the centralised system. Appropriate tariff setting requires valuation of external benefits such that community values are reflected (Marlow et al., 2013).

iv. The effect of bias and advocacy on the promotion of technologies and management paradigms: bias towards particular solutions is a side-effect of accumulated knowledge and experience, and has been observed in supporters of centralised solutions (Marlow et al., 2013).

Where water infrastructure is already in place, a complete transition to alternative water provision models is neither economical nor practically feasible, especially where past system decisions are irreversible. Innovations tend to occur at a local level and as additions or retrofits to existing systems, while aging centralised infrastructure is refurbished or replaced incrementally as is needed and/or is most economical (Marlow *et al*., 2013). Well-established socio-technological regimes favour centralised systems and so result in inertia in the water space (Sapkota *et al*., 2015). Consideration of SUWM solutions often occurs when the capacity of existing infrastructure needs to be increased, but would be prohibitively expensive or technologically difficult (Marlow *et al*., 2013); SUWM solutions involving alternative water supply here aim to meet the additional demand such that capacity increases to centralised systems are reduced or mitigated (Sapkota *et al*., 2015). Other than well-established socio-technical regimes around centralised systems, economies of scale and technical considerations such as catering for peak demands and ensuring water quality for public health are typical drivers for centralised systems (Sapkota *et al*., 2015). Systems in which the process of evolution of the water services configuration occurs are termed hybrid systems (Marlow *et al*., 2013, Sapkota *et al*., 2015).

There are positive drivers for both centralised and decentralised systems; there is, however, both theoretical and experiential evidence that the current infrastructure archetype could benefit from inclusion of decentralised systems and a more integrated approach to the management of the water cycle. Successful implementation of such requires understanding the potential impacts of SUWM initiatives; the subsequent section presents a brief review of typical SUWM initiatives and their impact on the broader water servicing system.

2.2.3 SUWM Options and Impacts

Table 2-1 summarises key details of each activity which may form part of a total suite of SUWM options.

Table 2-1: Summary of SUWM Options

SUWM Option	Details and Configuration	Benefits	Disadvantages
Rainwater Harvesting	The process of diverting, collecting and storing rainwater. Typically, runoff from a roof area is stored in a tank and services a single or cluster of households. System configuration may vary depending on size and position relative to usage points: demand driven pumps deliver water from a tank to end-use; rainwater is pumped from storage to a header tank from which water gravitates to end-use; or the storage tank is located above all points of use and no pumping is required. (West, Kenway & Yuan, 2015)	When used for non-potable uses, case studies have shown 25% reductions in potable water demand. Provides some contingency during variable climatic conditions. May defer investment in increasing surface water supply. Assists in reducing peak flood discharge and reduce quantity of pollutants reaching stormwater systems. Potential for increasing consumers' awareness of the water cycle. (West, Kenway & Yuan, 2015)	Rainwater tank yield is dependent on timing and volume of runoff. Studies have shown rainwater tanks are relatively expensive compared to other water sources. Can be energy intensive, depending on scheme configuration. Although risk of contamination is low, typically poor maintenance or tanks and roof areas by home owners mean rainwater for potable uses is discouraged. (West, Kenway & Yuan, 2015)
Stormwater Harvesting	Scheme configuration depends on the location and end-use, but typically comprises collection, storage, treatment, and distribution infrastructure. Some schemes have also been combined with aquifer storage and recovery. Schemes may vary in scale from cluster to whole catchments. End-uses requiring low levels of treatment may comprise treatment systems such as constructed wetlands, ponds, sand filters, gross pollutant traps, swales or bio-retention systems. End-uses requiring higher levels of treatment may include UV radiation, chlorination or ozonation. (West, Kenway & Yuan, 2015)	Potable water savings are highly variable depending on scheme storage capacity and climatic conditions of the catchment. Reduction of the impacts of urbanisation on aquatic ecosystems. Pollutants and nutrients reaching waterways reduced. Some flood management for low return period floods. Aesthetic value of water bodies. (West, Kenway & Yuan, 2015)	Variable water quality depending on land use changes and climatic conditions; if water quality results in harvested stormwater being unusable for intended end-use, water savings may be lower than planned. Variable cost depending on scale of scheme. Wetlands and such may attract increased bird life, resulting in increased treatment requirements. Accumulation of rubbish around shorelines if not maintained. (West, Kenway & Yuan, 2015)

SUWM Option	Details and Configuration	Benefits	Disadvantages
Greywater Recycling	Greywater reuse involves diversion and/or treatment of wastewater which does not include toilet waste. Greywater reuse may typically be done at household to development level. Schemes may comprise diversion and direct reuse, physical and chemical treatment, or biological treatment. (West, Kenway & Yuan, 2015)	Savings in potable water vary based on scheme configuration, but a study has shown a 10% saving. Diversion devices are relatively inexpensive. Reduces the amount of wastewater to be treated at WWTWs as well as the amount of treated effluent to be released back into the environment. (West, Kenway & Yuan, 2015)	Poor performance and high running costs has seen decommissioning of schemes. Failed treatment components in some schemes has resulted in decommissioning of same. Long-term irrigation with greywater may result in build-up of pollutants, affecting plant health, soil properties and groundwater quality. Increased risk of sewer blockages and corrosion due to reduced flow and increased pollutant loadings. Incorrect management of systems by consumers resulting in undesirable circumstances (odours, mosquito breeding). (West, Kenway & Yuan, 2015) Public health issues as a consequence of variations in levels of service across settlements, which is especially relevant in South Africa (Carden *et al*., 2017).
Wastewater Recycling	Recycled wastewater is distributed to consumers, typically via dual pipe systems. Scale of schemes varies from localised schemes (wastewater is treated and distributed in the vicinity of sewerage generation) to semi-centralised schemes (treated wastewater is distributed to multiple areas) (West, Kenway & Yuan, 2015)	Reduces the demand on surface water resources. Defer expansions to potable water systems. Reduction of nutrient rich discharges of treated effluent to receiving water bodies. Supply of wastewater is not seasonally dependent. (West, Kenway & Yuan, 2015)	Savings depends on nature and end-use of scheme. Cost of schemes is a major barrier to implementation and has resulted in decommissioning of schemes. Unanticipated technical issues may increase operating costs further. Communities may expect to pay less than for potable water, despite higher operating costs for water utilities. Treatment is more energy intensive than conventional water treatment and supply. Potential for cross-connections between potable water and recycled wastewater pipelines and concomitant health risks. (West, Kenway & Yuan, 2015)

SUWM Option	Details and Configuration	Benefits	Disadvantages
Groundwater Management	Potable water, stormwater and wastewater all interact with groundwater; WSUD activities thus require understanding of the relationships. Managed Aquifer Recharge (MAR) is a form of groundwater management and is the intentional recharge for the purpose of future recovery or for environmental benefit. Aquifer recharge may be via infiltration or direct recharge with stormwater, rainwater, or treated wastewater. (Armitage *et al*., 2014)	Groundwater discharge contributes to stream flow in the form of base flow, and surface water resources contribute to the recharge of groundwater. Groundwater therefore plays an important role in ecosystem goods and services. Groundwater is a valuable water resource, particularly in its storage value. MAR can fulfil WSUD objectives such as stormwater management, stormwater re-use, wastewater re-use, and reducing potable water demand through provision of a water source that can be used for 'fit for purpose' applications. (Armitage *et al*., 2014)	Potential for over-abstraction and pollutant ingress, or saline ingress in coastal areas, if groundwater use is not well managed. (Armitage *et al*., 2014) Poor water quality and failure of abstraction systems have resulted in numerous borehole schemes being decommissioned in rural parts of South Africa.
Water Conservation and Demand Management	Variety of interventions which target reducing consumption and reducing losses at different points and scales in the water infrastructure system; interventions may be technical, institutional, financial, or behavioural in nature. Real loss reduction measures may include pressure management, leak repair programmes, pipe replacement programmes. Apparent loss reduction measures may include management of metering and illegal connections. At a consumer level, education and awareness are important to encourage reduction of wastage at point of use. Asides from physical work done on systems, monitoring and management to understand system behaviour are critical to implementing any WCWDM programme (Armitage *et al*., 2014; McKenzie & Lambert, 2002). It should, however, be noted that WCWDM is inextricably linked to sustainable development and WSUD: water conservation focuses on ecologically sustainable development (specifically relating to water resource), and water demand management encompasses sustainable water supply which effectively relates to all streams of the urban water cycle (Armitage *et al*., 2014).	Reduces the demand on surface water resources. Defer expansions to potable water systems.	Requires continuous investment to maintain achieved levels of losses (though effort to do so is off-set by the saving in total demand) as a result of the effects of system attrition. (Umgeni Water, 2019)

Further research on the (oftentimes unintended) consequences of SUWM initiatives is presented below; some of these findings informed the problem structuring and modelling undertaken in this study.

While SUWM is thought to be more efficient in terms of resource utilisation (e.g. potable water use per capita), Tjandraatmadja et al. (2012) found that, in the case of rainwater harvesting for example, the per unit energy requirements of pumping associated with rainwater tanks exceeds that of centralised water system pumping. Of course, this is largely dependent on a specific system's parameters. Recycled water and desalination are generally also highly energy intensive processes (Marlow *et al*., 2013). Related to resource utilisation, the extent of stormwater harvesting requires a careful balance to prevent stream flows dropping below critical environmental flow requirements (Sapkota *et al*., 2015).

The effectiveness of SUWM initiatives can be highly context dependent and care should be taken not to over-estimate benefits. For example, mandatory building provisions in South East Queensland of Australia specified an annual potable water reduction of 70 kL per dwelling where rainwater tanks were installed; in reality, less than 70% of the goal reduction was achieved (West, Kenway & Yuan, 2015). Poor analysis of systems also has a negative impact on the feasibility of alternative water schemes: a combined rainwater and greywater recycling scheme in a UK office unexpectedly presented an increase (8.5 to 10%) in potable water use; this was due to the quantity of collected rainwater and greywater being exceeded by the volume required for system filter backwashing, and potable water was required to make up the difference (West, Kenway & Yuan, 2015). Consumer behaviour, also linked to a number of factors, can be unpredictable. West, Kenway & Yuan (2015) state there are some instances where providing an alternative source of water has seen an unexpected increase in potable water consumption due consumers' perceived security of having two water sources.

Financial challenges have been the primary reason for decommissioning non-potable water schemes (West, Kenway & Yuan, 2015). While the establishment of decentralised systems may generally require less capital outlay compared to a large centralised network, Sapkota *et al*. (2015) note that if wastewater is recycled for non-potable household uses, establishing a second system for each dwelling is likely to be costly, as are the energy requirements to convey both potable and non-potable water. Sapkota *et al*. (2015) state there are many cases of residential non-potable water supply schemes having unit costs (i.e. per unit of water produced) higher than that of conventional water and wastewater services. Economic sustainability from the point of view of water service provider is further complicated: Sapkota *et al*. (2015) note the challenge around pricing of non-potable water supply schemes where it is difficult to quantify all the benefits of such a scheme.

West, Kenway & Yuan (2015) found a major impact on the viability of alternative water supply schemes occurs when there is a discrepancy between planned and actual system demand (which is in turn influenced by a number of factors). Demands much lower than an alternative water supply system's capacity have negative impacts on treatment, storage, and distribution infrastructure; the resulting technical challenges often have subsequent increased operational costs. The Pimpama Coomera recycled wastewater plant – which was planned to supply 65 000 dwellings – is one such example where the plant was decommissioned after a number of challenges arose, many of which were related to the actual demand being much lower than planned demand (*ibid*). Related to treatment challenges, variance in incoming water quality for stormwater or wastewater recycling schemes as a result of changes to the catchment characteristics (due to, for example, land use changes, climatic variability, pollutant discharges, or water user behaviour) may prove problematic where less robust treatment systems have been adopted (*ibid*).

Marlow *et al*. (2013) note wastewater recycling may lead to the presence of trace contaminants in potable water. Cross-connections between potable and non-potable systems also pose a health risk (Sapkota *et al*., 2015). In line with these concerns, microbial and chemical hazards have been a focal point of risk assessments for alternative water source systems, though few public health impacts have been reported to date (West, Kenway & Yuan, 2015). There is, however, increasing focus on emerging contaminants such as microplastics; Sol *et al*. (2020) noting the presence of microplastics in the environment, with wastewater treatment works being a key contributor if effective processes are not employed to remove such. Greywater which is used for irrigation instead of conveyed to a wastewater treatment plant may result in pollutants reaching receiving water (Sapkota *et al*., 2015), though it should be noted wastewater treatment plants which do not treat effluent adequately contribute to pollution too.

Reduced water consumption, or rather less water sent to sewers, may have downstream consequences of sedimentation and corrosion in sewers and impacts on wastewater treatment process efficiencies (Marlow *et al*., 2013). Internationally, research in this area was conducted in California during the drought experienced there in the 1970s. Locally, Bonthuys (2018) reported on the impact of the drought in the Western Cape and the subsequent reduction in wastewater flows on the wastewater conveyance and treatment systems. Five years' worth of data from nine WWTWs in the Cape Metropole area was studied; the findings are summarised below:

- Severe water restrictions resulted in flow reductions between 17% to 52% in the period from July 2016 to July 2017.
- Concentration of influent wastewater parameters – particularly chemical oxygen demand and suspended solids – increased in most cases.
- Where the plant loading in terms of COD and suspended solids decreased, there was no evidence of solids settling or organic matter degradation in sewers, likely attributable to the sewers being predominantly pumped systems (large gravity systems, on the other hand, would be vulnerable to solids build up). Reduced industrial discharge in the midst of water restrictions was seen as the cause of lower plant loading cases.
- Internationally, plants under low flow conditions performed better in terms of compliance; locally, many of the plants were still hydraulically overloaded after the flow reductions, thereby negating any potential benefits in this regard.
- Smaller plants and those with biofilter treatment units were most affected by higher organic loading; on the other hand, plants with activated sludge treatment units proved more robust. This was true of international studies and the Cape Metropole.
- Plants with flexibility (for example, treated effluent being recycled to increase the hydraulic loading or ability to bypass settling tanks) were more capable of withstanding low flow conditions.
- In drought conditions which cause low flows in river systems, the discharged treated wastewater is then a larger portion of the total surface water flow, resulting in more concentrated contaminants (Bonthuys, 2018).

While the above study by Bonthuys (2018) was conducted as a result of the drought, reducing wastewater flows through water conservation and demand management or through reuse of greywater could be expected to have a similar impact. Randall & Ebrahim (2019) found the use of greywater (specifically shower water) for flushing toilets resulted in precipitation of urine constituents, with the subsequent effect of increased solids loadings in sewer networks. While noted as unlikely affecting sewer networks, the immediate toilet and piping could be subjected to blockages. One of the possible mitigating measures included addition of disinfectant or bleach after flushing. Also related to impacts on sewer systems, Sapkota *et al*. (2015) state water from rainwater tanks has higher levels of metal content, which when reaching sewer systems may form metal sulphide precipitates, thereby aggravating corrosion problems in sewer networks.

Reductions of potable water demand also has an impact on potable water networks: Sapkota *et al*. (2015) note a high water age in potable water networks may follow, and bring with it water quality issues as stagnation occurs. Careful analysis and management of complex water distribution systems would be required to ensure the free chlorine concentration does not drop below the minimum disinfection requirement.

Stormwater, wastewater and water supply in an urban environment all impact on the quantity and quality of groundwater: Groundwater can be a source of water and provide water storage functionality; groundwater is a receptor of urban drainage; over-abstraction can result in saline intrusions and land subsidence, while excessive groundwater recharge can cause structural damage or flooding of underground structures; sewer and water pipeline leaks and surface water infiltration can recharge groundwater; sewer pipeline leaks and the use of on-site sanitation solutions can impact urban groundwater quality; while stormwater or treated wastewater can be infiltrated or injected and stored for later use the quality of such must be considered, appropriate treatment and/or infiltration devices could therefore be utilised; SUWM (and similar concepts) therefore require an appreciation and understanding of the relationship between groundwater and urban infrastructure to achieve and preserve adequate groundwater quantity and quality (Armitage *et al*., 2014).

It is clear that SUWM solutions are not without risk; as per West, Kenway & Yuan (2015), increasing changes to the configuration of urban water services will increase the scope of risks associated with service provision. Management of these risks is essential for the potential benefits of SUWM solutions to be realised. Unfortunately, performance data on operational alternative water schemes is lacking, with the result that the fundamental information required for design, construction and operation of optimally functioning schemes is deficient. Overdesign or preference for traditional approaches is then perpetuated. Due consideration for variability and uncertainty in demand forecasts (amongst other system parameters) would improve the performance of alternative water supply schemes (West, Kenway & Yuan, 2015). The very nature of SUWM approaches is likely to increase the complexity of urban water systems; Sapkota *et al*. (2015) note water collection and circulation at multiple scales (household, development, and city) could lead to greater complexity and see new patterns of order evolving. Institutional capacity is essential for effective management of such systems.

Sapkota *et al*. (2015) state previous assessment studies have compared centralised systems to decentralised systems without considering options of combined (hybrid) systems, and therefore in subsequent studies (Sapkota *et al*., 2015; Sapkota *et al*., 2018) a methodology to assess the performance of a hybrid system was developed and applied to a case study area, namely the Northern Growth Area of Melbourne. For hybrid water servicing scenarios, findings included potable water savings of 17%; a reduction in the variability of potable water demand; a reduction in wastewater flows of 25%; and increased pollutant concentrations in wastewater of 32%.

The above literature indicates the type of results which may be expected in the assessment of SUWM solutions, but requires validation through system modelling. Not all modelling approaches will be able to sufficiently cover and consider all of the aforementioned aspects; the modelling approach should suit the problem and the nature of the results which the modeller hopes to ascertain. Considerations of such nature are outlined in Section 2.4.2.

2.3 Water Services in South Africa

As described by The Neighbourhood Planning and Design Guide by the Department of Human Settlements (DHS) (2019), below is a summary of the regulatory environment and some of the key documents which guide water service provision in South Africa:

- DWS is the custodian of South Africa’s water resources, and is mandated to protect, manage, use, develop, conserve and control water resources through regulation and support of the delivery of effective water supply (DHS, 2019).
- The National Water Act (NWA) of 1998 regulates the use of water to ensure equitable allocation, serving the interest of the public, and promoting environmental values (DHS, 2019).
- The National Water Services Act (NWSA),1997 governs the provision of water services to users, a cornerstone being “everyone has a right of access to basic water supply and sanitation” (DHS, 2019).
- The Second National Water Resource Strategy (NWRS-2) of 2013 provides a framework for control of water resources, and adopts a position of developmental water management (DHS, 2019). As noted by Armitage *et al*. (2014), the three objectives of the NWRS-2 are: (1) Water supports development and elimination of poverty and inequality; (2) Water contributes to the economy and job creation; and (3) Water is protected, used, developed, conserved, managed and controlled sustainably and equitably.
- The National Water and Sanitation Master Plan (NWSMP) (DWS, 2019) is part of a suite of initiatives led by the DWS to aim for a water-secure future and is the implementation mechanism for the NWRS-2 and any future iterations of such (DHS, 2019).
- The National Water Security Framework (NWSF) (National Planning Commission, 2019) aims to respond to the water security in South Africa coming under increasing threat, and outlines a pathway to water security such that the imperatives of the National Development Plan may be supported.
- In terms of the NWSA, a Water Service Authority (WSA) is required to prepare a Water Services Development Plan (WSDP) such that each WSA is able to move towards achieving the objectives of the NWSA (DHS, 2019).

The NWSMP (DWS, 2018) states the national water deficit could reach between 2.7-3.8 billion cubic metres (or 17% of available water resources) by 2030, should there be no interventions and should the current demand projections hold. The NWSMP (DWS, 2018) states achieving water security requires a “*paradigm shift that (1) recognises the limitations of water availability;*

(2) addresses the real value of water; (3) ensures equitable access to limited water resources; (4) delivers reliable water and sanitation services to all; (5) focuses on demand management and alternative sources of water; (6) considers the impacts of climate change; and (7) addresses declining raw water quality". To achieve this, there are twelve elements which are clustered under the key themes of water and sanitation management, and an enabling environment (*ibid*).

Within the theme of water and sanitation management, the sub-theme of reducing demand and increasing supply includes optimising the mix of water resources, with the NWSMP (2018) including conventional and increased use of unconventional water sources in the medium and long-term projections. Alternative water sources include groundwater use, desalination, re-use, acid mine drainage. There are specific priorities outlined for desalination, re-use, acid mine drainage, reallocation of water, rainwater harvesting, and WC/WDM. It is, however, noted the water resource development funnel (from feasibility through completion) currently includes limited alternative water schemes. It thus appears implied that solutions involving alternative water sources are to be adopted and driven by municipalities and WSAs to suit their particular needs, and accordingly supported by policies and by-laws in their respective areas of authority and operation. Armitage *et al*. (2014) state while the NWRS-2 highlights the need for alternative water sources to be included in the water supply mix, it nonetheless takes a traditional approach to water resource management and does not provide an adequately comprehensive approach to management of the total water cycle. In this regard, it would appear the NWSMP (2018) sees no change to the approach to integrated management of the water cycle.

The Neighbourhood Planning and Design Guide (DHS, 2019) notes the water sector as endeavouring to establish water sensitive settlements where there is universal access to water and sanitation services, comprising regenerative water services, water sensitive neighbourhoods, communities aware of the value of water, and integrated urban water management. Integrated Water Resource Management, Water Conservation and Water Demand Management, and Water Sensitive Design are included as means of achieving the aforementioned objectives. The Neighbourhood Planning and Design Guide (DHS, 2019) includes planning and design guidelines on the use of groundwater, rainwater, greywater, wastewater recycling, SuDS, stormwater harvesting, and desalination (though the detailed design of any such system would require additional guidance). The inclusion of such concepts and alternative supply methods in this document is notable as it implies encouragement for more widespread uptake in such solutions – planners and engineers frequently adopt the guidelines therein when determining servicing requirements for settlements, and could prove especially useful when authorities themselves have limited or no comprehensive approach to implementation of SUWM initiatives.

At this point, it is pertinent to note that working definitions of sustainability in South Africa must take into account context-specific issues such as social and institutional issues, otherwise SUWM is unlikely to be accepted and encouraged by politicians (Armitage *et al*. 2014). Marlow *et al*. (2013) note the context to consider SUWM is one in which urban communities are already provided with reliable water services. On the other hand, in developing countries it is difficult to drive SUWM agendas when the standard of living and public health requirement (which precedes sustainability on the evolutionary timeline of water services) has not yet been fulfilled by access to water, sanitation, and drainage systems.

As noted by Armitage *et al*. (2014), in terms of water services, a large portion of the population in South Africa do not yet have access to basic services, and only a minority are fully serviced to a level equivalent to other developed countries. Access to water services is one of many instances of inequality in South Africa, and is a lasting consequence of the Apartheid system (*ibid*). Improving economic and social equity while ensuring environmental sustainability is a challenge. The dual challenge is acknowledged by the NWRS2 (DWS, 2013) which recognises the important linkages between adequate water supply and quality to economic and social development as well as the requirement for water ecosystems to be healthy to maintain water resources: "*This indivisibility of water is a cornerstone of the National Water Policy, to the extent that water ecosystems are not seen as users of water in competition with other users, but as the base from which the resource is derived, without which, growth and development cannot be sustainable*" (DWS, 2013).

After Armitage *et al*. (2014), transitioning to Water Sensitive Settlements in South Africa therefore requires consideration of both developed areas and informal and/or un-serviced settlements. Figure 2-3 summarises the pathways for the aforementioned areas with vastly different characteristics merging into a water sensitive future.

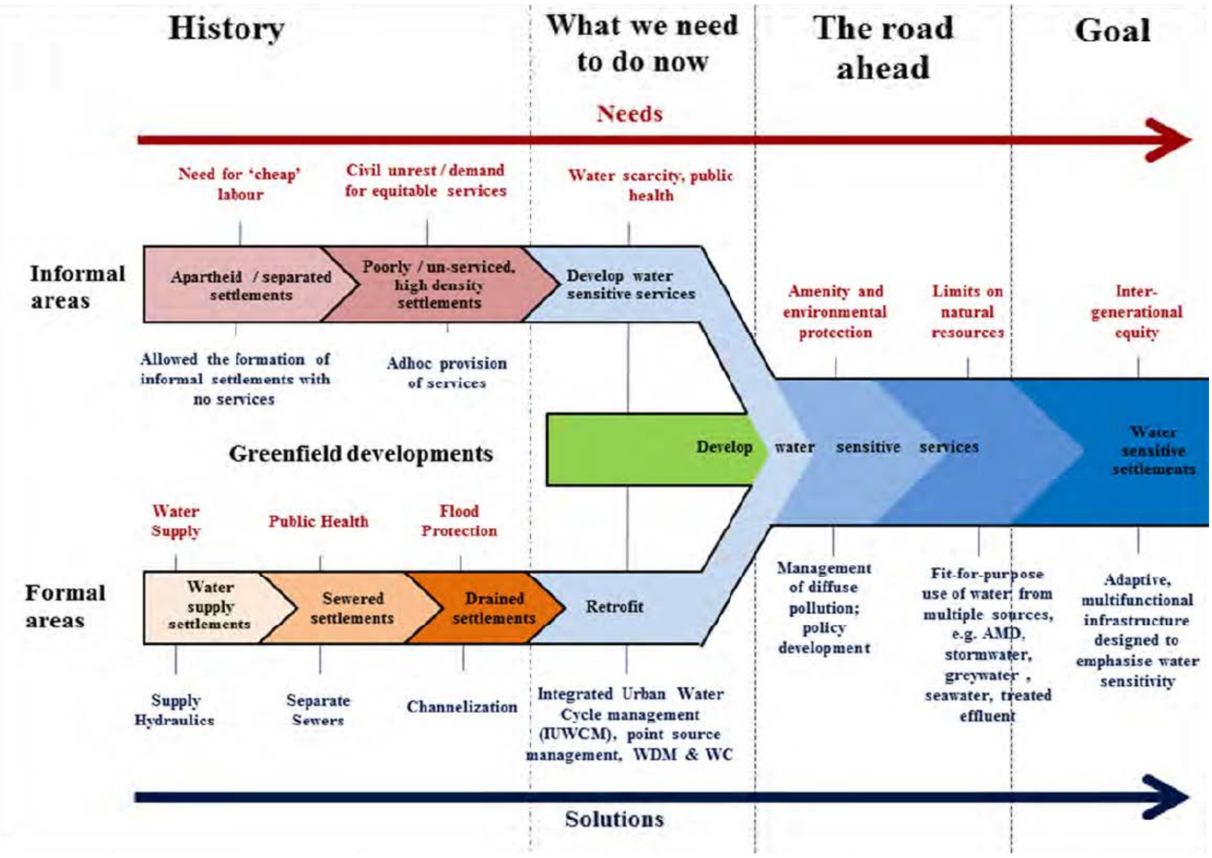


Figure 2-3: Framework for Water Sensitive Settlements in RSA, "Two histories, one future" (adapted from Brown *et al*., 2009) [Source: Armitage *et al*., 2014]

Any solutions for transitioning to water sensitive settlements requires consideration of the context of the area in which water sensitive servicing options are planned such that appropriate solutions are developed. Chapter 4 details alternative water supply options under consideration (by the municipality and bulk water provider) in the case study area, though implementation between suburbs and areas may need to be nuanced.

2.4 Sustainability Assessment of Water Supply Systems

2.4.1 Problem Structuring

In response to the complex and numerous issues around water resources, studies have attempted to apply sustainability principles to water resource management, with the expectation of responsible use of available water resources (Juwana, Muttil & Perera, 2012).

Assessing sustainability is, however, a challenge: the definition is vague and is comprised of multiple dimensions; value judgements are involved; and quantitative approaches have limitations due to the complexity and inherent fuzziness in the concept itself (Lai, Lundie & Ashbolt, 2008). Nonetheless, the water industry has made contributions to furthering integrated sustainability assessments, especially in the development of sustainability criteria. The concept of sustainability is made more operational and practical by use of criteria to assess the contribution of a particular option to achieve sustainability objectives (*ibid*). Lai, Lundie & Ashbolt (2008) summarise the hierarchy within which criteria exist as follows:

i. Principles are the normative definitions and/or goals of sustainability.
ii. Criteria are the factors against which the sustainability of an option may be assessed.
iii. Indicators are the measures of the values of specific criteria (after Juwana, Muttil & Perera (2012), an indicator may also be comprised (if it cannot be explained by a single indicator) of a number of sub-indicators).

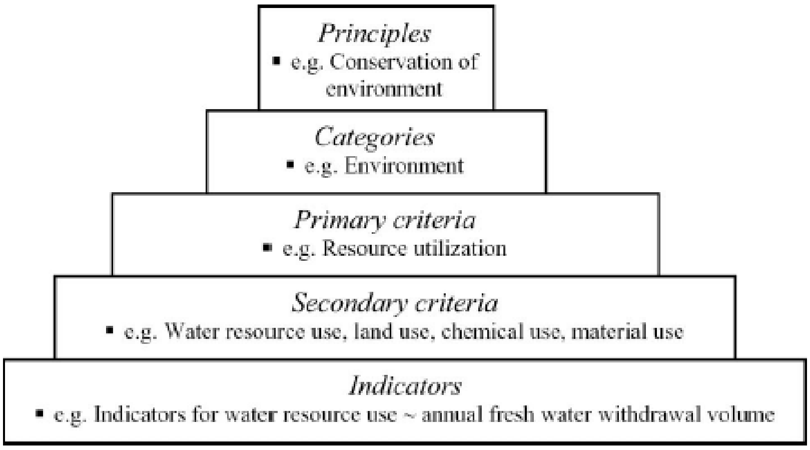


Figure 2-4: Hierarchy of Sustainability Criteria [Source: Lai, Lundie & Ashbolt, 2008]

Returning to the challenge of assessing sustainability, if indicators are observed regularly, changes may be observed and tracked (Juwana, Muttil & Perera, 2012), therefore providing useful information for water institutions. For example, Carden (2013) developed a composite sustainability index for integrated urban water management for application in South Africa, where inputs included information that is regularly updated – such as the regulatory performance measures as used by DWS for water and sanitation service provision. This index could facilitate tracking performance, enable goal-setting, and inform improvement of water services.

Different approaches are available to structure the hierarchy of sustainability criteria. Lai, Lundie & Ashbolt (2008) state the four most commonly used integrative approaches for assessment of the sustainability of urban water systems are: Cost-benefit analysis (CBA); Triple bottom line (TBL); Integrated Assessment (IA); and Multi-Criteria Analysis (MCA).

A CBA comprises the conversion of all costs and benefits (environmental and socio-economic) associated with an option into monetary terms and discounting values over the project life cycle. CBA has been adopted in many water engineering problems due to its ability to be applied as a pragmatic tool which provides a single aggregated result and clarifies the costs and benefits of alternative options. One of the challenges with this method is the monetisation of certain impacts which cannot be priced according to market prices. Stakeholder engagement is not essential to a CBA, but elicitation of certain values may require participation (Lai, Lundie & Ashbolt, 2008).

Due to its nature of reporting on the three separate pillars (economic, social and environmental), a TBL assessment does not provide a holistic result, but if applied as a framework, guides selection of indicators, thereby providing the initial problem structure for further integration. TBL reporting is increasingly used by water service providers in Australia as both a reporting tool and as a planning framework for sustainability assessments (Lai, Lundie & Ashbolt, 2008).

IA is a relatively new discipline which emphasises using knowledge from different scientific disciplines and/or stakeholders representative of the problem at hand to provide decision makers with integrated insights. Diverse methods may be used which are not limited to technical modelling. Some of the approaches include system dynamics, bayesian networks, agent-based model and expert systems. IA is becoming more popular with integrated management of catchments and water resource allocation (Lai, Lundie & Ashbolt, 2008).

MCA is a structured approach with a set of procedures to follow to aid decision making where there are multiple and often conflicting criteria to consider, whereby the relative importance of each criterion is determined by the decision makers. Considerable cognitive effort is demanded of decision makers to make judgements. In that it provides a structured approach to dealing with complex problems (such as water management problems), provides accountability and transparency to decision making, aids conflict resolution, encourages stakeholder participation, and uses decision theory to inform choice, MCDA is frequently used for water policy evaluation, strategic planning and infrastructure selection (Lai, Lundie & Ashbolt, 2008).

Lai, Lundie & Ashbolt (2008) note the flexibility of these four approaches to be applied at different levels, may vary in extent of application as either a tool, framework, or concept. Rathnayaka, Malano & Arora (2016) reviewed studies (conducted from 2000 through 2016, and restricted to those studies which assessed at least three water supply options and included a number of sustainability criteria) which evaluate the sustainability of water supply options. In this period, a large number of studies have been conducted to support water planning decisions; many of these studies are decision support frameworks which include modelling of the water system. The evaluations are frequently supported by MCA, CBA, life cycle assessments, and optimisation processes. While the studies are considerably different, there are three key commonalities to the sustainability evaluation frameworks and studies: water supply and/or demand management options; scenario paths (introduced to assess performance through a range of system variables); and evaluation criteria (used to assess performance and prioritise options) (*ibid*).

In terms of assessment methods, Rathnayaka, Malano & Arora (2016) found that most studies considered sustainability of water supply and demand management options through embedding selected options in the total urban water cycle and then implementing a modelling approach, some of which included: systems analysis, spatial analytical model, system dynamics models, mathematical optimisation models, multi-criteria assessments, life-cycle assessments, goal programming optimisation techniques, material flow analysis, water balance models, contaminant balance models, integrated systems approaches. Many of the reviewed studies evaluated centralised and decentralised options, though limited studies considered both water supply and water demand management options simultaneously, both of which are essential for long-term planning. Rathnayaka, Malano & Arora (2016) note uncertainty and system variability were generally considered or modelled through application of different scenarios; for example, scenarios were defined for climate change, population growth, economic growth (Coombes *et al*. 2012), water shortages, behavioural changes, availability of economic resources (Hellström *et al*., 2000). Mukheibir and Mitchell (2011) defined uncertainty in terms of gradual changes in the system (water demand), shocks to the system (energy price increases), and extreme variability (floods and droughts).

2.4.2 System Modelling

A variety of modelling approaches exist which may be considered for assessment of water supply systems; as outlined below, the capabilities of systems dynamics models are well suited to the nature of the problem explored in this study.

The value of developing mathematical models of real world systems is based on the ability to test behaviour of such systems in a synthetic environment. Dynamic simulations allow observation of systems over time an in reaction to changes within or external to the system, and thus facilitate predicting future conditions (Winz & Brierley, 2007). System dynamics is a means of simulating complex systems, typically comprising: defined boundaries; system structure which is described by positive and negative feedback loops and relationships between variables; stocks and flows (stocks are determined by flows) to describe the overall system states; and system archetypes (Winz & Brierley, 2007; Mashaly & Fernald, 2020). Systems may be sub-divided into subsystems which vary spatially and temporally. The underlying premise of system dynamics methodologies is that system structure results in system behaviour, such that future states may then be observed and predicted (Winz & Brierley, 2007).

Winz & Brierley (2007) summarise the key strengths of systems dynamics models as having the capability to integrate qualitative and quantitative information as well as meaningfully integrate a variety of input parameters (examples given by Mashaly & Fernald (2020)) include hydrological, scientific, ecological, economic, political, and social) such that interactions and feedbacks are captured; recognition and modelling of varying forms of uncertainty; and appreciating that the direction of change is fundamental to guide adaptive responses to system behaviour. Winz & Brierley (2007) further note stakeholder participation may be facilitated through the modelling process as systems dynamic models require user input to define parameter values or conditions.

In that problems in the water management space are inherently complex, Winz & Brierley (2007) note the application of dynamic simulation models to such problems have been used for at least 40 years. Since 1996, no less than 119 studies have applied systems dynamics methodologies to water resources management problems (Mashaly & Fernald, 2020). Winz & Brierley (2007) note focus areas may generally be classed into regional analysis and river basin planning, urban water, flooding, irrigation, and pure process models. As described by Winz & Brierley (2007), system dynamics methods have limitations which ultimately inform suitability for a given problem. In consideration of uncertainties embedded in complex systems, systems dynamic models will not yield precise answers, and are therefore limited in usefulness when dealing with well-defined problems. The infrequent occurrence of pure process systems dynamics models as evidenced in the literature is indicative of this particular limitation. On the other hand, where uncertainty exists, detailed models would not hold value. A model's level of detail should suit the problem and be able to address the complete problem. While the definition of the model boundary can be difficult, only variables which influence system behaviour should be included (Winz & Brierley, 2007).

Uncertainty exists in planning and management of water resource systems as a result of factors affecting the system performance being unknown or not known with certainty. Each component of a system is subject to meteorological, demographic, economic, social, technical, and political conditions in the future, all of which have environmental, social, and economic impacts. Water availability is affected by meteorological processes such as evaporation, rainfall and temperature, all of which are stochastic in nature. Water requirements are affected by populations, water usage rates, and priorities for water use, all of which are subject to uncertainty (Loucks & Van Beek, 2005).

One of the simpler means of dealing with uncertainty is to utilise average, medium, or critical values for those quantities which are uncertain, and follow a deterministic approach, and the importance of uncertainty can be assessed by a sensitivity analysis. Such would be suitable if the uncertainty is small and does not affect system performance, though would unacceptably affect project evaluation if critical parameters are highly variable (Loucks & Van Beek, 2005). Similarly, West, Kenway & Yuan (2015) note urban water schemes are frequently tested on limited scenarios; this is problematic in that infrastructure planning and design relies heavily on projections of parameters such as climate, population growth, and water demand. A wide range of scenarios and uncertainty should be tested to enable a probabilistic analysis of scheme performance. West, Kenway & Yuan (2015) note that in addition to scenario analysis when precise estimates are not possible, threshold analysis is useful to identify the scheme conditions which are required for justification of a particular decision.

Stochastic processes are a powerful means of modelling uncertainty: stochastic processes involve variables whose values change through time according to probabilistic laws. A single realisation of a stochastic process would be an observed time series (for example, a record of stream flows at a particular location). For this reason, future sequences are highly unlikely to match the historical record; use of only historical records thus does not adequately allow for testing alternative designs against future sequences. The important information in the historical record can be used by generating sequences of which are statistically similar to said record, thus providing a more comprehensive range of inputs for modelling alternative designs to produce a range of possible system performance. This should allow more robust system design (Loucks & Van Beek, 2005).

It is important to distinguish between the two fundamental causes of uncertainty: that which is inherently variable over time such that behaviour can only be described statistically (also called aleatory uncertainty), and that which stems from a lack of knowledge or understanding to be able to specify values with certainty (also called epistemic uncertainty). Theoretically, epistemic uncertainty may be reduced through further study of the parameter or system in question. Aleatory uncertainty is inherently irreducible. In some cases, model parameters may encompass both types of uncertainty; for example, flow rate in a river is temporally variable, and some of the statistical measures describing this may be uncertain. In other cases, combining uncertainty may not be appropriate; for example, uncertainty may differ across groups of items, and it would be unsuitable to define a single probability distribution representing the uncertainty across groups of items. Definition of the probability distribution would be problematic, and meaningful interpretation of the modelled results would be difficult (GoldSim, 2018).

Specific to the application in this study, as noted by Sapkota *et al*. (2015), in terms of physical impacts, decentralised solutions change the flow regimes as well as contaminant compositions in water, stormwater, and wastewater streams. Being able to assess these changes is critical for determining the performance of the total water cycle. As described by Rodrigo *et al*. (2012), traditionally, individual hydraulic models or water quality models are used for detailed modelling of each component of the water cycle. On the other hand, the concept of integrated urban water management requires a holistic view of the urban water cycle, therefore in modelling the total urban water cycle, the interconnectedness and relationships between components of the system is emphasised instead of the details of the individual models or system components. A systems model which simulates the entire system simultaneously is well suited to such applications. Water at different stages are not seen as independent types of water, and pollutants are not attributes of specific types of water; instead, the above are resources which travel through a cycle. It should be noted, however, that systems models do not replace more detailed models, but are used in combination with same. Systems models are capable of simulating variables over time, thereby enabling testing the impact of alternatives and testing of potential future conditions. Applied to the urban water cycle, decisions around management of the urban water cycle may have impacts across a number of areas of the system, which can be appropriately quantified. A key advantage of a systems model is the ability to monitor a number of relationships and generate a comprehensive list of outputs tailored to the need of decision makers (Rodrigo *et al*., 2012).

Modelling methods require support through modelling tools and/or software. Rodrigo *et al*. (2012) discuss generic simulation software which can be used to build custom systems models of any kind (from business processes to ecosystems). A few examples of such software include STELLA, PowerSim, Vensim, ExtendSim, and GoldSim. These software tools are useful in that dynamic system responses to actions can be observed, are comprised of object-oriented programming, provide visual representations of results, and can run Monte Carlo simulations; applied to modelling the urban water cycle, these tools are useful for observing mass balance and contaminant transport through the system. While the ability to construct completely custom models is useful, they need to be constructed from the ground up and is therefore time-intensive. Systems models software specific to water resources and have water resource elements built-in are available; Water Evaluation and Planning (WEAP) developed by Stockholm Environmental Institute (SEI) is one such example which can model the total water cycle. WEAP has been used world-wide for various water resources planning studies. While model creation in WEAP is quicker than in generic simulation software, outputs from WEAP are limited and further analysis outside of the platform may be required, and Monte Carlo simulations cannot be executed (Rodrigo *et al*., 2012).

2.4.3 Synthesising Results of Models

Comparing alternatives generally requires synthesising all the information generated in the analysis process (Rodrigo *et al*., 2012). MCA is one method of synthesis, and in consideration of the benefits outlined prior, is preferred for application to this study.

Lai, Lundie & Ashbolt (2008) state that Decision Support Methodologies (DSM) are at the heart of MCDA: this is the means by which preferences are modelled and alternatives compared through aggregation. A vast number of DSMs have been developed and applied to problems of varying nature: Mardani *et al*. (2015) reviewed 393 articles published from 2000 through 2014 where MCDM approaches have been applied. The reviewed articles covered a broad range of applications, including sustainability. The authors found the Analytical Hierarchy Process (AHP) to be most frequently used (33% of all reviewed articles), with hybrid approaches following second (16% of all reviewed articles). Also frequently applied were Elimination and choice expressing reality (ELECTRE), Preference ranking organisation method for enrichment evaluation (PROMETHEE), TOPSIS, ANP, and aggregation methods. In the field of water planning and management, in review of recent literature, Cole *et al*. (2018) found the most commonly used DSMs were (in order of most frequent use): Compromise programming, AHP, PROMETHEE, ELECTRE, and Weighted sum method (WSM).

In that there is no strict relationship between types of problems and appropriate DSM, selection of a DSM a challenge in itself (Lai, Lundie & Ashbolt, 2008). Watrobski *et al*. (2018) reiterate the same difficulty, stating the selection of an appropriate DSM is a matter which has been paid relatively limited attention. Poor selection of a DSM is problematic: *"improper application decreases the quality of recommendations, as different MCDA methods deliver inconsistent results".* Watrobski *et al*. (2018) therefore developed a framework to assist with selection of an appropriate method given the nature of the decision problem (though independent of the field of application); the framework is available as an online tool (open source). On the other hand, Cole *et al*. (2018) noted a number of recent studies have compared the outcomes of different MCDA techniques being applied to the same problem(s); these studies found that regardless of the applied technique, the resulting alternative ranking varied slightly and the top ranked alternative rarely differing. Hajkowicz & Higgins (2006) did, however, find different ranking results were more marked in analyses containing both quantitative and qualitative performance data (instead of purely quantitative data).

Hajkowicz & Higgins (2006) found in many applications there is no overriding methodological reason to adopt one DSM over another. Instead, the deciding factor may be the ease of understanding the MCA technique: if the decision-making process is seen as a "black box" approach, it is unlikely to be used. Hajkowicz & Higgins (2006) cite Beynon & Rasmequan (2002) as stating this being a significant impediment to adoption of decision support tools. Lai, Lundie & Ashbolt (2008) found use of simpler MCDA methods appears to be emphasised in the water space: decision-makers at strategic levels tend not to be experts in the use of MCDA, and lack of transparency tends to prevent non-experts making linkages between the output and the assessment. Cole *et al*. (2018) also emphasise the need for methods which are easy for stakeholders to understand and therefore avoids confusion, enables user acceptance, and buy-in into the decision-making process. Cole *et al*. (2018) therefore selected one of the simpler methods (weighted sum method), and later used PROMETHEE II to confirm the result of the initial decision-making process. There are differing opinions of the AHP: Cole *et al*. (2018) note that it is more complex and less transparent to stakeholders; on the other hand, Amorocho-Daza (2019) commented on the ability of the inherent pairwise comparison method to help stakeholders develop a structured perspective of the problem.

Hajkowicz & Higgins (2006) conclude the selection of the DSM is typically less important than initial structuring of the decision problem – i.e. selection of criteria; selection of decision options; weighting of criteria; and obtaining performance measures for the selected criteria. Hajkowicz & Higgins (2006) cite Janssen (2001): *"The main methodological challenge is not in the development of more sophisticated MCA methods. Simple methods, such as weighted summation, perform well in most cases. More important is the support of problem definition and design"*. Cole *et al*. (2018) also note one of the criticisms of MCDA being poor problem structuring which omits important criteria or alternatives. Some of the other potential challenges with MCDA in sustainability assessments are detailed below.

In that water systems are complex systems comprising numerous factors, Lai, Lundie & Ashbolt (2008) note it is not always possible to assess the effects of system interventions in advance. There is, therefore, preference interdependency where preference for a particular criterion is dependent on another (an example is the preference for water resource use being deemed less important if water availability is high). The basic approach in MCA is therefore to assume preferential independency, though it is recognised this assumption does not always hold. Where the weighting approach is used, double counting and undercounting occur when selected criteria are redundant and key criteria are not included (respectively). Redundant criteria mean impacts of an alternative will be over-stated in certain aspects. Double counting or undercounting occurs where no distinction is made between fundamental criteria (which are fundamentally important because they are valued by decision makers, for example, minimising use of surface water) and means-end criteria (which are important because they have impacts on other criteria, for example, volume of recycled water used) (Lai, Lundie & Ashbolt, 2008). It is worth noting all of the above challenges relate to issues with problem structuring.

3 Research Approach

Figure 3-1 summarises the overarching research process undertaken in this study.

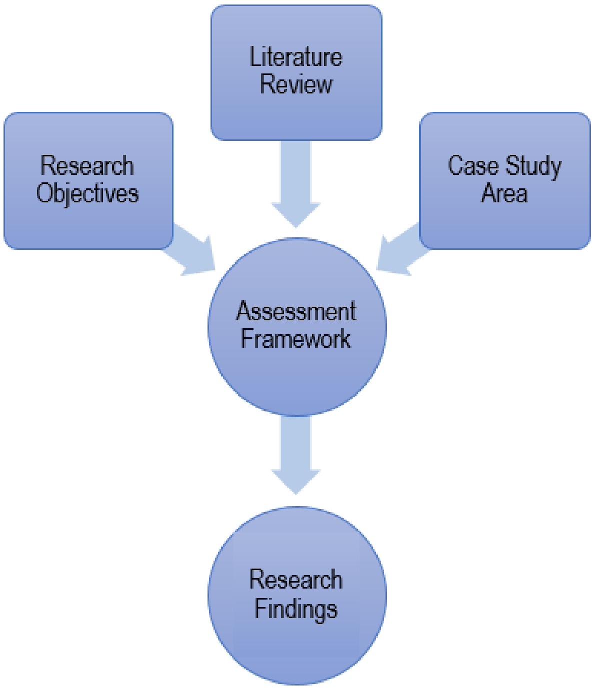


Figure 3-1: Summarised Research Process

Assessing the performance of a water servicing option lends itself well to quantitative research methods; this research therefore used quantitative research methods.

3.1 Case Study Area Selection Process

eThekwini Municipality has been selected as the case study area: this region has a diverse range of consumers to service (fully serviced urban suburbs, informal settlements, peri-urban settlements, and rural areas) and is therefore largely representative of South African cities; the water and sanitation service delivery unit is renowned for continuous investment in research and development and piloting of new technologies; and the region is supplied by a number of integrated surface water resources, but is not without water stresses in some catchments. The whole municipal area has been included in the system modelling; while there are clear distinctions between different water supply systems in the municipal area, these systems and their associated planning and operation are closely linked, it is thus problematic to consider interventions in one area without taking cognisance of the availability of water resources in another area. Furthermore, this research aims to contribute to the broader understanding of the net effects of various interventions; understanding the impact on upstream water resources is therefore useful for future planning and decision making. Information on and relating to water service infrastructure in eThekwini municipality is contained in Chapter 4.

3.2 Assessment Framework Approach

The United States Environmental Protection Agency present a generic method for assessing Total Water Management (i.e. SUWM) systems (Rodrigo *et al*., 2012), which follows many steps ordinarily applied to water services planning and management. The process is recreated below, and is the framework applied to this study.

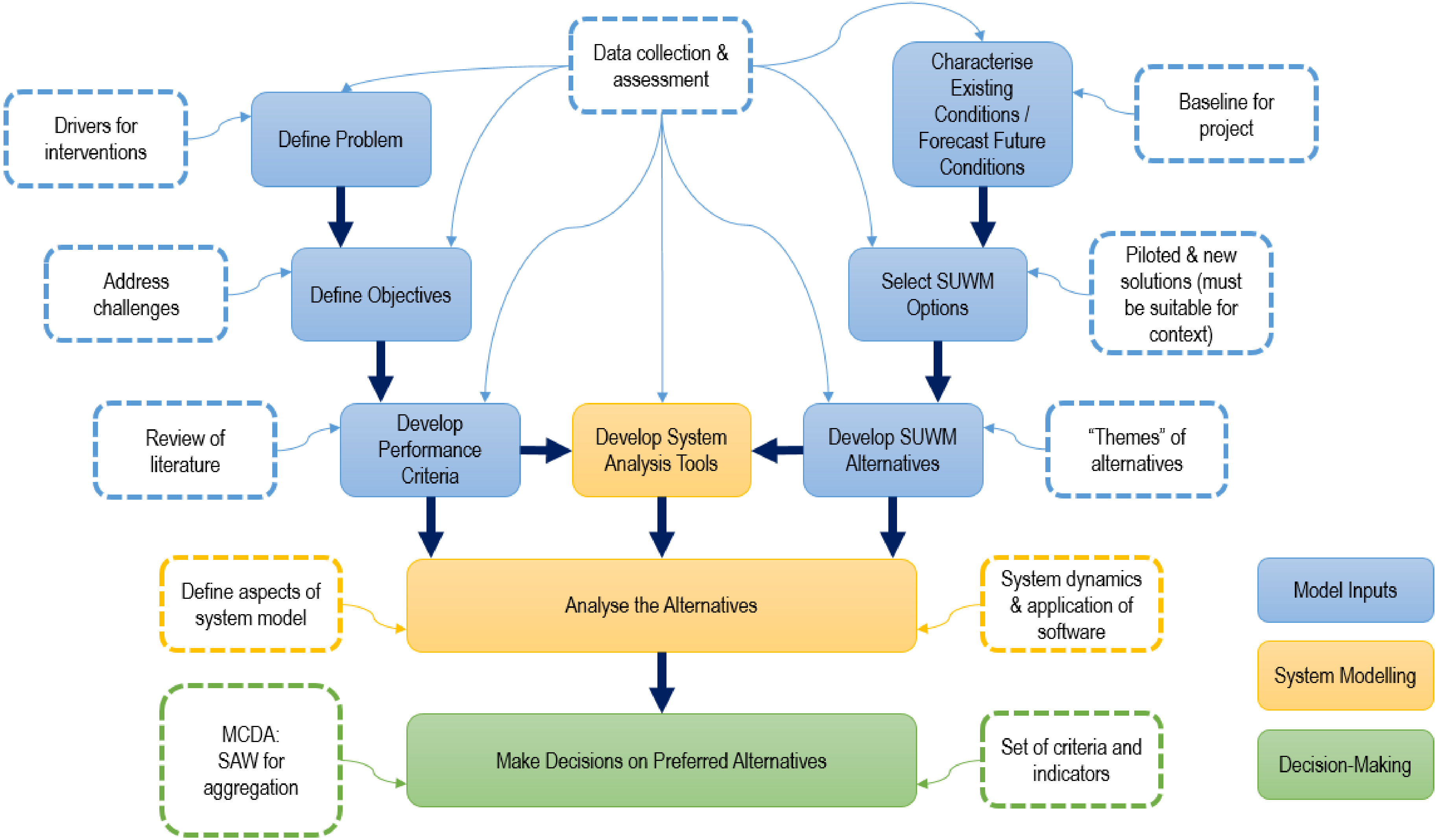


Figure 3-2: Framework for Assessment of Total Water Cycle and Specific Actions Defined for Study [Adapted from Rodrigo et al., 2012]

Problem definition is the initial step in the process where drivers for a particular project are identified. This step can also involve identification of and consultation with stakeholders (Rodrigo *et al*., 2012). Objectives define the goals of a particular project (Rodrigo *et al*., 2012). Typical broad objectives may include meeting water supply and demand, quantity and quality of wastewater and stormwater discharges (Sapkota *et al*., 2015). Both the literature review and analysis of information collected on the case study area (as is presented in Chapter 4) informed the problem definition and objective definition.

Performance criteria are a means of measuring the performance of alternatives against the objectives and therefore need to be mapped accordingly (Rodrigo *et al*., 2012). This study intended to conduct a number of interviews with water sector experts to determine performance criteria deemed most useful and the relative importance thereof; only a handful of interviewees were, however, available. Engagements were therefore rather focussed on general discussions about the provision of water services, challenges faced in South Africa, and possibilities of introducing SUWM measures. Appendix F: Letters and Permissions includes typical interview questions. As an alternative course of action, review of literature enabled development of a preliminary list of criteria: A key output of the Rathnayaka, Malano & Arora (2016) reviewed paper is a comprehensive and generic set of evaluation criteria which is intended to be a guideline for the evaluation of sustainability and is broad enough to cover a wide range of contexts; it is, however, acknowledged the entire set of criteria may not be applicable to every potential study. The evaluation criteria put forward by Rathnayaka, Malano & Arora (2016) are categorised into environmental, social, economic, technical, and functional criteria. In that this set of evaluation criteria draws on a number of previous studies, it formed the basis of the initial set of evaluation criteria used in this study. Farooqui, Renouf & Kenway (2016) applied the concept of an urban water metabolism evaluation framework (which is based on a water mass balance) by extending the methods described by Kenway, Gregory, & McMahon (2011) to evaluate the impact of alternative water sources (specifically stormwater and rainwater harvesting, wastewater recycling, and greywater recycling) within a selected case study area. One of the components of the adopted framework is the application of a set of indicators (describing resource efficiency and hydrological performance) to illustrate impacts in terms of the urban water metabolism. A key feature of the urban water metabolism approach is the consideration of the urban system as an integrated entity and the assessment of all urban water flows. Some of the indicators developed by Farooqui, Renouf & Kenway (2016) were considered for incorporation. The criteria relevant to this study and reasonably quantifiable with the available data were then short-listed, and are presented in Chapter 5.

Characterising the existing conditions and forecasting the future conditions establishes the baseline for the project (Rodrigo *et al*., 2012). As per Sapkota *et al*. (2015), the problem definition and objectives should aim to address the challenges or limitations within the current system and are therefore closely linked to understanding the local conditions. Understanding of the local conditions was achieved through review of relevant data (data sources are summarised in Chapter 5), literature, and interviews with industry experts (refer to Appendix F: Letters & Permissions), providing insight into the following:

- Water resource drivers, such as: climate; population; development patterns; water use trends; water quality; and water resources
- Water resource strategies (both current and potential solutions)
- Water-related challenges and opportunities.

Given the diversity in the range of objectives in water planning, it is unlikely a single option could meet all objectives; scenarios comprising a number of options are therefore often required. Furthermore, any one option may not perform well in isolation, but when considered within an alternative may perform well due to the interactions and integration associated with SUWM (Rodrigo *et al*., 2012). In that a multitude of alternatives are possible, it is useful to use planning objectives to develop a set of alternatives based on themes. Examples of themes may include balanced impacts, balanced benefits, low cost, low risk, high reliability, high sustainability, high adaptability (*ibid*). Scenarios within the suite of potential SUWM solutions were identified; these scenarios were in part informed by the intentions set out by the municipality and bulk water provider.

Development of a systems model requires defining the objectives of the modelling step to help address the problem statement, followed by defining the model scope, including: geographic space (catchment, city, neighbourhood), sectors (water, stormwater, wastewater), analysis layers (costs, flows and volumes, water quality), and time scale (annual, monthly, daily). The above information can then inform the selection of a suitable modelling tool. Following programming of the model, testing and validation is required (Rodrigo *et al*., 2012). As applied to this study, a “top-down” modelling approach was adopted, where the focus was on development of a macro-scale integrated flow model, capable of assessing implementation of water servicing scenarios (specifically any combination of Water Conservation and Water Demand Management, rainwater harvesting, stormwater harvesting, groundwater use, greywater reuse, wastewater recycling, and desalination) at a regional level. Such was deemed the most appropriate means of determining, first and foremost, which SUWM solutions could be most beneficial in the study area (the performance of such in the study area is otherwise unknown), with the intent that more detailed hydraulic and water quality models could investigate some of the finer issues highlighted in the literature review (refer to Section 2.2.3). Furthermore, the system model does not include for modelling of social, institutional, governance, public health, and comprehensive financial matters.

Due to its generic nature (and therefore customisability), GoldSim was selected for developing the system model in this study. Other benefits of using this software, as outlined in the GoldSim User Guide (2018) are summarised below:

- Simulations may be static or dynamic. Systems do not change with time for static simulations, whereas dynamic simulations represent a system changing and evolving over time. The objective of such simulations is to predict the future states of the system and if there are interventions which can be introduced to influence same. GoldSim is capable of running either type of simulation, though for this study, dynamic modelling is most appropriate. In addition to continuous modelling of a system, GoldSim is capable of superimposing discrete events onto continuously varying systems.

- Building and running multiple scenarios within the same model is possible, which is useful for simultaneously comparing system performance.

- In many real-world systems, elements of uncertainty often exist in parameters, processes, and events. When inputs to a system model are uncertain, the prediction of future performance and states of the system is uncertain. GoldSim has built-in functionality to quantitatively assess uncertainty which may be present through probabilistic simulation (refer to Section 2.4.2 for a discussion of uncertainty in water systems, and to Section 0 for an overview of how this has been applied and modelled in this study).

- GoldSim is an object-oriented system model, where the connections and relationships between elements in a system are easy to follow and understand. As part of the model development process, dashboards can be created as a user-interface, where input information may be edited, simulations run, and results viewed. The model is itself documented in GoldSim, which may be viewed and run using the freeware GoldSim Player.

The details of the system model and its development are contained in Chapter 5.

The evaluation of scenarios against the defined performance criteria is usually a quantitative process (Rodrigo *et al*., 2012). In addition to definition of performance criteria, it is important to determine how the criteria are measured and reported. For example, whether the performance is to be measured over a selected horizon or for a specific point in time, and whether the results are presented as a probability distribution or as a single estimate (*ibid*).

The system model and its outputs are central to this study. The application of DSM in this study, on the other hand, is limited to synthesising and summarising the outputs of the system model for demonstrative purposes. Being a simplistic method which performs adequately in achieving the aforementioned purpose, the weighted sum method is applied to this study. Further details on data normalisation, weighting, and aggregation are contained in Chapter 5.

4 *Case Study Area: eThekwini Municipality*

This chapter presents an overview of eThekwini Municipality and the water infrastructure in the region, including insights into service delivery, ecological considerations, climate change, and current and future interventions to improve water security in the region.

4.1 General Overview

eThekwini Municipality is located within the Province of KwaZulu-Natal (KZN) on the east coast of South Africa. As described by the Integrated Development Plan (IDP) (EM, 2019), the municipality covers an area of approximately 2555 km^2 and as at 2016, was home to an estimated 3.6 million people. It is a diverse society which faces various social, economic, environmental and governance challenges. The municipality is divided into four planning regions – namely North, Central, Outer West, and South (EM, 2019). Figure 4-1 summarises the population distribution between the four regions.

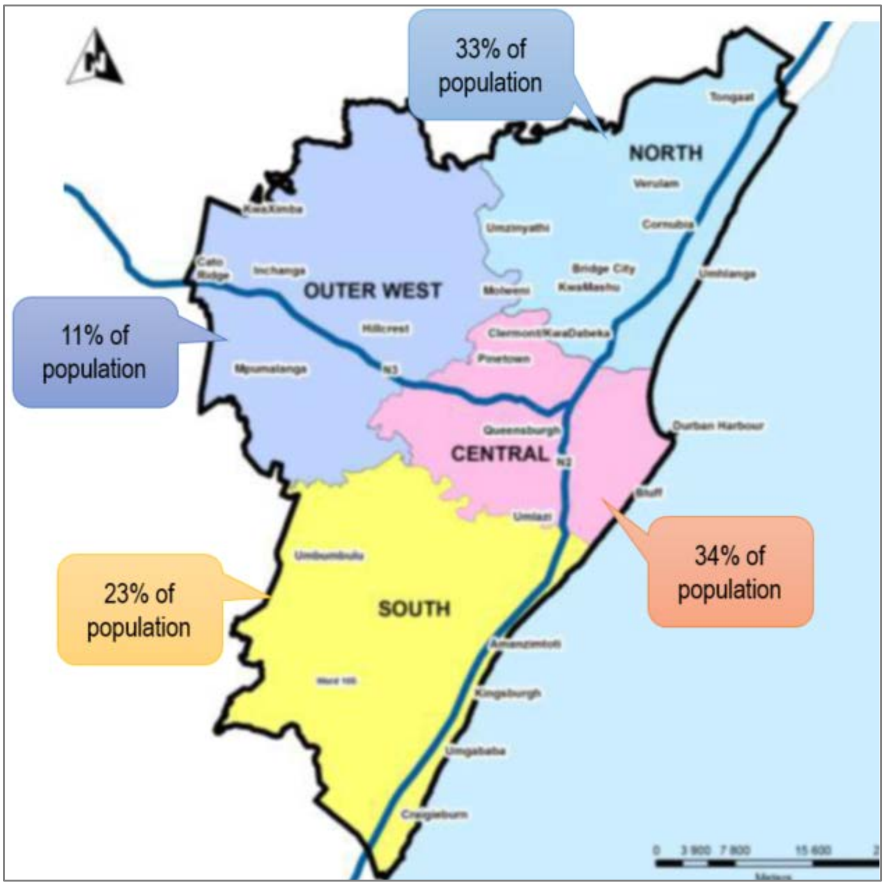


Figure 4-1: Population Distribution in eThekwini [Adapted from EM, 2019]

As described in the IDP (EM, 2019), approximately 68% of the municipal area is considered rural, comprising commercial farms, metropolitan open space, dispersed settlements, and pockets of dense settlement. Hilly, rugged terrain is the dominant geospatial feature. About 90% of the rural area comprises traditional dwellings and communal land holdings under the Ingonyama Trust. This is an institutional arrangement unique to eThekwini Municipality, which presents a number of challenges around land, planning and urban management (see Section 4.3 for further detail). The remaining 32% of the municipal area is urban, comprising residential, commercial, and industrial land uses. Economic land uses are generally located in close proximity to the N2 and N3, are unevenly distributed throughout the Municipality, and are located away from higher density residential areas. There is a large number of informal settlements scattered across the city, with many in peripheral locations and/or located in areas at risk of erosion and flood damage (*ibid*).

As detailed in the Umgeni Water (UW) Masterplan (UW, 2019), the Provincial Growth and Development Strategy (KZN Provincial Planning Commission, 2018) identified eThekwini Municipality as the only Primary Node within KZN (defined as an urban centre with very high existing economic growth, potential for expansion, and of national and provincial economic importance). Secondary nodes are defined as an urban centre with good existing economic development and the potential for growth and services to the regional economy. Pietermaritzburg, Richards Bay, and Port Shepstone have been classed as such. The corridors between these nodes and Durban – forming a T-shaped region – are of economic importance and are expected to experience further development in the future and constitute the KZN portion of the Strategic Integrated Projects (SIP) (*ibid*).

4.2 Institutional Arrangements

As per the National Water Services Act No. 108, the management of water is a local government responsibility. eThekwini Municipality is the Water Service Authority (WSA) and eThekwini Water and Sanitation Unit (EWS) is the Water Services Provider (WSP) for the municipal area. eThekwini municipality has a centralised, formalised public sector system (Pollution Research Group, 2016).

eThekwini Water and Sanitation performs all water and sanitation functions. Roads and Stormwater Maintenance and Coastal Engineering, Stormwater and Catchment Management departments within the Engineering Unit perform all stormwater functions. All of the aforementioned units fall under the major municipal subdivision of Procurement and Infrastructure. Sustainable Development and City Enterprises is responsible for environmental and planning functions, and fall under the major municipal subdivision of Development Planning, Environment and Management (EWS, 2011). Armitage *et al*. (2014) notes environmentally-focused activities have, nonetheless, been undertaken by the aforementioned core water service functions in eThekwini.

Umgeni Water was established in 1974 and has grown into the second largest water utility in South Africa, supplying some 410 million cubic metres of bulk potable water annually to what used to be six WSAs within KZN (UW, 2019). As gazetted by the Department of Water and Sanitation in December 2015, Umgeni Water's operational area includes all WSA's within KZN. Bulk supply agreements with WSAs do not, however, mandate Umgeni Water to supply bulk water across an entire WSA. The economic nodes and corridors (forming the T-shaped region) described prior fall largely within Umgeni Water's current area of operation (*ibid*). eThekwini Municipality is Umgeni Water's largest bulk water user (by volume), though eThekwini Municipality also owns and operates a handful of small capacity water treatment works.

4.3 Service Delivery

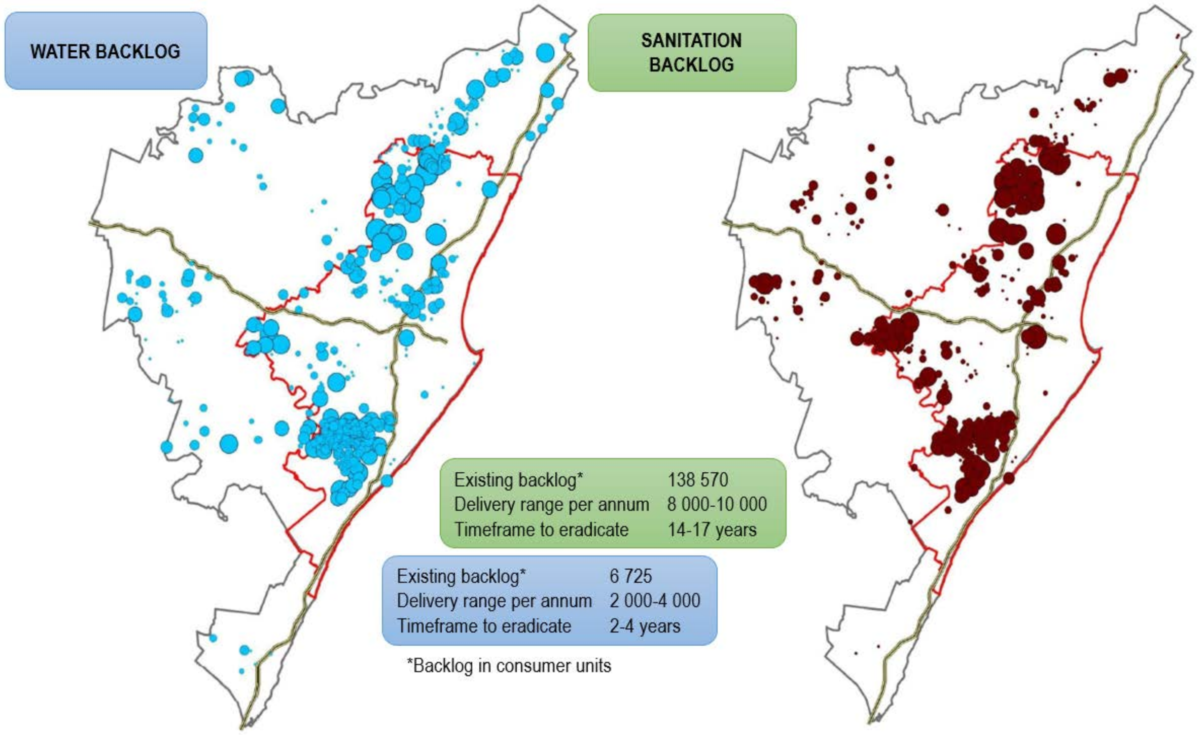
As is the case in other South African cities, the legacy of Apartheid in Durban yielded an unequal distribution of resources and services which had to be rectified through provision of equitable access to water and sanitation (Roma *et al*., 2013). Furthermore, in 2001, the eThekwini municipal boundaries were expanded to include rural and peri-urban areas, of which at the time, 80% (75 000 households) had no access to water or sanitation. A cholera epidemic (occurring August 2000 to July 2001 and affecting some 105 389 people) made adequate service provision a matter of urgency (Roma *et al*., 2013). Substantial effort has been invested in eradication of service backlogs.

The IDP (EM, 2019) describes the spatial backdrop to service provision in urban areas: certain engineering services and most social services are in excess in the central areas of the municipality. On the other and, the outskirts of the municipality have experienced more developments, and it is in these same areas there is limited bulk infrastructure and services. In particular, road and sewer infrastructure in the northern and western regions have been placed under pressure, which has in turn slowed development growth. Development beyond the existing “infrastructure/services edge” is associated with higher infrastructure cost and therefore is outstripping current infrastructure capacity budgets. This tends to cause delays in development. Provision of low cost housing has, over the years, tended to be based on the availability and cost of land rather than infrastructure costs, with the result that these developments have been located in generally inaccessible and peripheral locations removed from the existing infrastructure services edge, and therefore associated with high infrastructure costs. Developing within the bounds of the existing infrastructure services edge (and within the urban core) would promote financial sustainability and densification in accessible areas (EM, 2019). The PRG (2016) describes service delivery complexity particular to the rural areas of the municipality: The Ingonyama Trust was established in 1994 to take ownership of the land previously owned by the KZN Government. Land under the jurisdiction of the Ingonyama Trust is not mandated to follow land ownership regulations as is applicable to metropolitan land, but the municipality is responsible for service provision. The result is that development can progress unchecked – mass “urbanisation” has been experienced in some of these areas – and in some cases in contradiction to water service development planning. Maintenance of services and provision of new services to these rapidly growing areas is therefore more complex. The political and sensitive nature of these land agreements means this is a difficult challenge to address (*ibid*).

In terms of enabling affordability of services, eThekwini provides a range of water and sanitation servicing options: 9 kilolitres of Free Basic Water (FBW) per month is allocated to indigent consumers. A rising block tariff is thereafter applied. The same tariff structure applies to wastewater disposal charges. In urban areas, flow limiting devices may be installed where it is necessary to limit consumption to the FBW volume. In rural areas, groundwater tanks or yard taps fitted with flow limiting devices allocate the FBW volume in rural areas. Where informal settlements are to be upgraded but likely have a long lead-time, standpipes and communal ablution blocks (within 200m of all consumers or serving 75 households) are transitory means of service delivery (EWS, 2011).

There are a range of sanitation options, including connection to the sewer network, septic tanks, conservancy tanks, or urine diversion (UD) toilets where connection to waterborne sanitation is difficult. Ventilated improved pit (VIP) latrines were installed in various settlements by previous local authorities. Though acceptable as a basic level of service, VIP latrines are no longer prescribed unless absolutely necessary; urine diversion toilets are specified as the minimum level of service for sanitation (EWS, 2011). Roma *et al*. (2013) conducted a study on user perceptions of UD toilets, and found low levels of satisfaction, likely as a result of previously marginalised consumers hoping to have higher levels of service. Emphasis on economic returns obtainable from reusing the UD toilet by-products for agricultural purposes was recommended. This is an example of the importance of public perception on provision of services, which has implications for acceptance of diversified water sources.

Service backlogs are defined by the number of consumer units without access to the minimum prescribed level of service (EWS, 2011). Backlogs for water and sanitation as at end December 2017 are summarised in Figure 4-2:



Existing backlog*	138 570
Delivery range per annum	8 000-10 000
Timeframe to eradicate	14-17 years

Existing backlog*	6 725
Delivery range per annum	2 000-4 000
Timeframe to eradicate	2-4 years

*Backlog in consumer units

Figure 4-2: Water and Sanitation Backlogs in eThekwini Municipality [Adapted from EWS, 2011]

Note: a consumer unit is defined as an entity or delivery point which receives water / sanitation services.

It is important to note that the sanitation backlog is only related to disposal of blackwater, and does not account for safe means of disposing of greywater. As stated by Carden *et al*. (2017), there are no comprehensive health regulations or guidelines for the disposal of greywater in settlements without waterborne sanitation in South Africa, though eThekwini has included greywater disposal in the business plan (EM, 2003) which sets out sanitation service delivery for the municipality. Stormwater backlogs are undefined, but lack of drainage in un-serviced settlements is problematic: for example, if informal settlements are unable to safely dispose of greywater, stormwater runoff from these areas results in pollution of the environment and may pose a health risk to inhabitants.

The IDP (EM, 2019) summarises the key Issues around infrastructure delivery:

- Limited funding available for backlogs
- Non-payment for basic services (high levels of poverty and unemployment)
- Illegal water and electricity connections
- High water losses within the municipality
- Ageing infrastructure and maintenance needs which requires adequate budget allocation
- Hilly typography and areas difficult to reach from existing service boundary
- Fragmented spatial patterns which do not support efficient delivery of bulk services
- Dual governance system affects the delivery of service to areas under Ingonyama Trust Board.

4.4 Water Services Infrastructure

4.4.1 Potable Water Supply

(a) Municipal Water Services

In the 2016-2017 financial year, EWS supplied 817 Ml/d of potable water to consumers in the municipal area. There are 268 potable water storage reservoirs, some 13 000 km of pipelines, and 504 000 water connections to the network (EM, 2019). Asides from the Umgeni Water owned and operated water treatment works providing potable water within the municipal area (Durban Heights, Wiggins, and Hazelmere) and those outside the municipal area (Midmar, D.V. Harris), EWS owns and operates four smaller water treatment works ranging in output from 0.5 Ml/d to 13.5 Ml/d (EWS, 2011). Figure 4-3 is illustrative of the extent of water supply services in eThekwini.

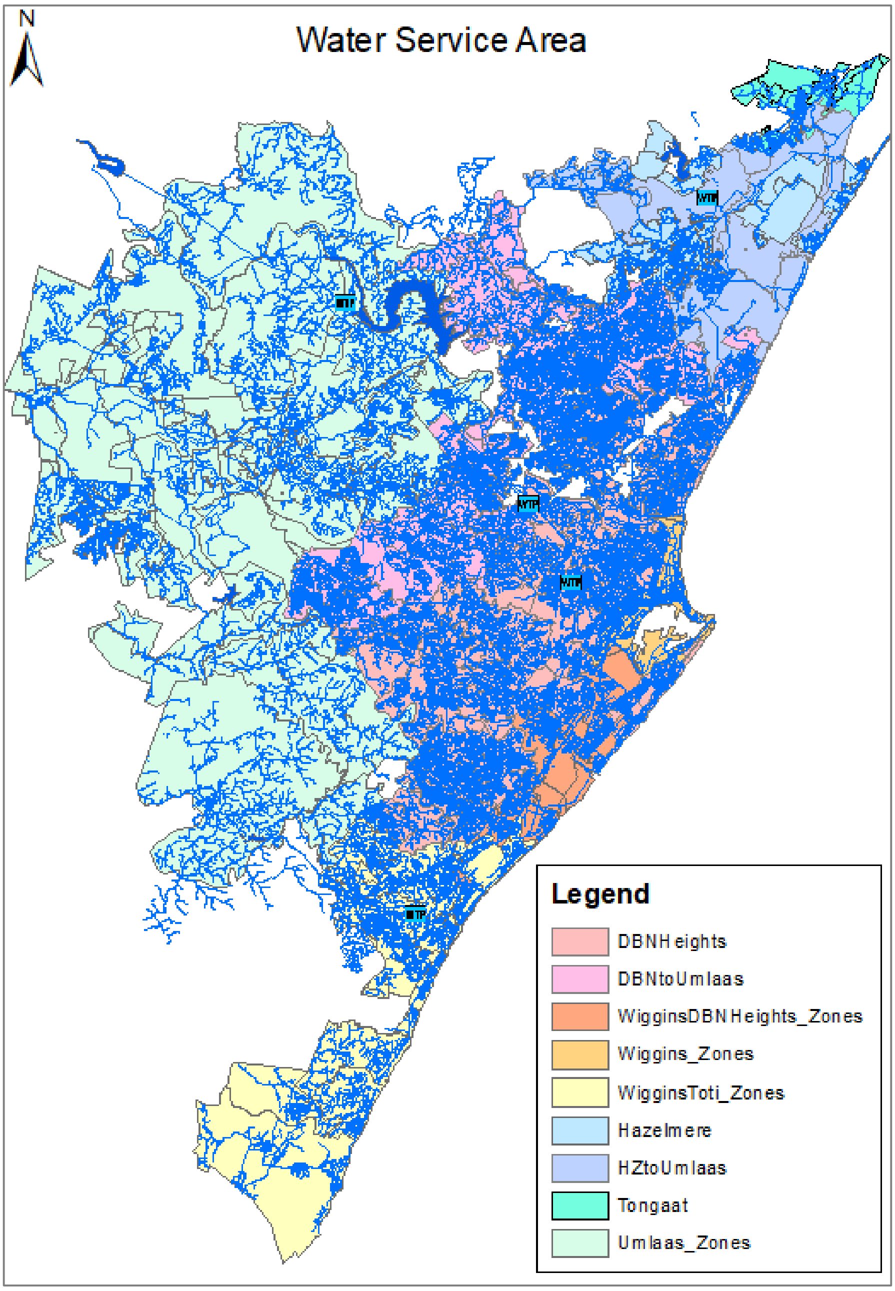


Figure 4-3: Water Services Coverage

Figure 4-4 illustrates the total average daily sales to eThekwini Municipality from November 2013 through to November 2018. As described by UW (2019): the downward trend from the end of 2015 through to the end of 2017 is due to restrictions being enforced during the drought over this period. Subsequently, the 2017/2018 financial year sees a year-on-year growth in sales increase by 4.78%, which is attributed to restrictions within the Mgeni System being lifted during the first half of 2018. Demand projections include increases as a result of drought curtailments being lifted, observed consumer behaviour over the previous quarter, and proposed development demands which have seen consultation between eThekwini and Umgeni Water. Demand is predicted to grow by 1% (per annum) up until June 2020, decreasing to 0.5% (per annum) until June 2022 to account for Water Conservation and Water Demand Management initiatives currently underway. It was estimated that total sales (i.e. System Input Volume (SIV)) will reach pre-drought levels by mid-2020 (*ibid*).

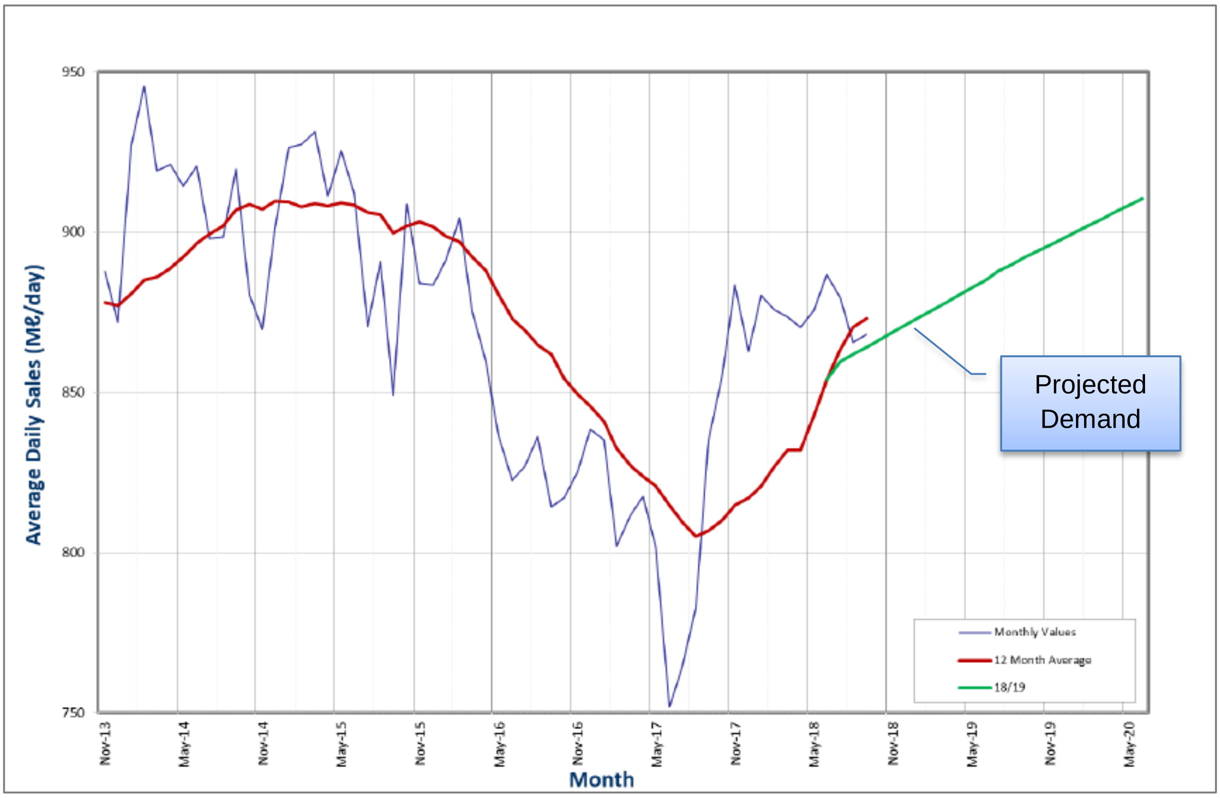


Figure 4-4: Total Average Daily Sales to eThekwini [Source: UW, 2019]

(b) Bulk Water Services

Umgeni Water's area of operation is sub-divided into water supply schemes (WSS); those relevant to this study include the Mgeni WSS, North Coast WSS, and South Coast WSS, each of which are described below.

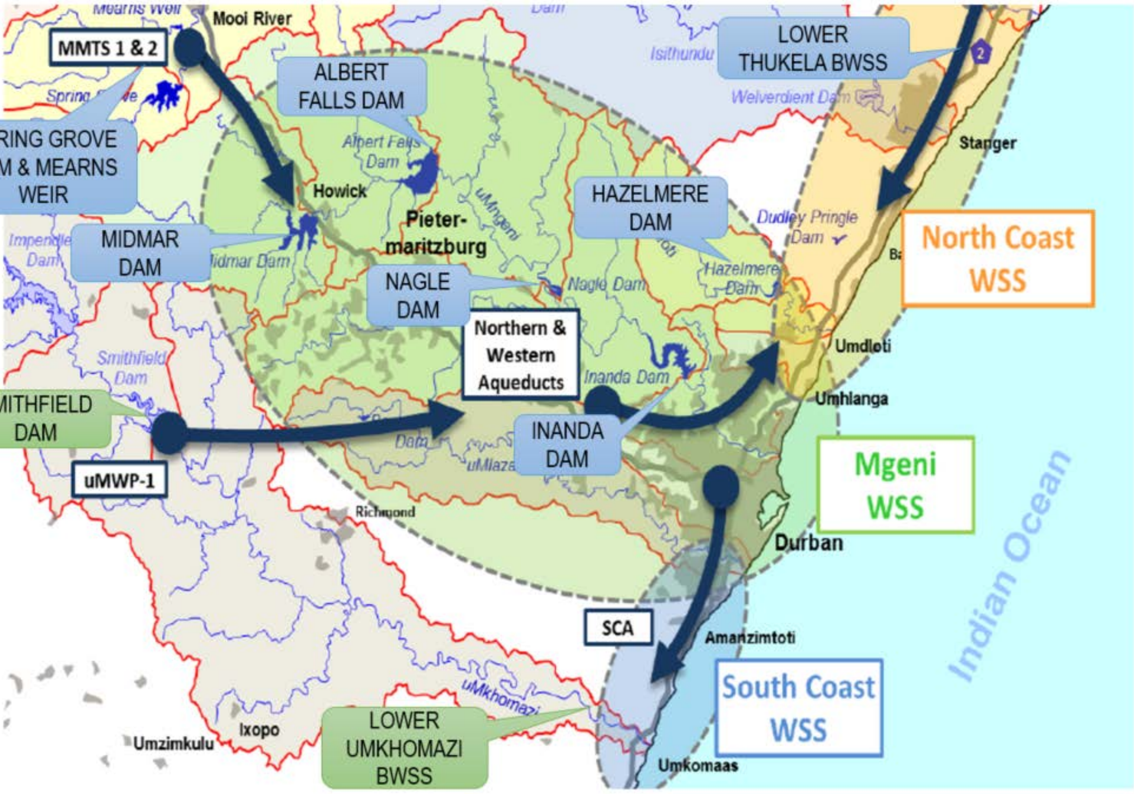


Figure 4-5: Bulk Water Supply Schemes Affecting Study Area [Adapted from DWS, 2017]

(i) Mgeni WSS

The Durban-Pietermaritzburg region is largely supplied by the Mgeni WSS, comprising six storage dams in the Mooi/Mgeni catchments, forming an integrated water resource system in which resources are highly inter-dependant. The Mgeni WSS is subdivided into:

- The Upper Mgeni System which supplies uMgungundlovu District Municipality, Msunduzi Municipality and the Outer West area of eThekwini Municipality, and extends from Howick, Mpophomeni, and Vulindlela in the west; to Wartburg, New Hanover, and Dalton in the east; to Cato Ridge and Mpumulanga in the south; and to Eston and Umbumbulu in the south west.
- The Lower Mgeni System which supplies the coastal areas and hinterland of eThekwini Municipality, from lower Pinetown and KwaDabeka in the west; to Phoenix, Inanda, and Verulam in the north; to the Durban seaboard in the east; and to Amanzimtoti and KwaMakuta in the south. This WSS also supplies the northern coastal areas of Ugu District Municipality via the South Coast Augmentation Pipeline system (UW, 2019).

The Upper Mgeni System derives its water resource from the Upper Mgeni River, with storage at Midmar Dam, and augmentation by the Mooi-Mgeni Transfer Scheme (MMTS). Raw water is treated at Midmar WTW (located in Howick) and the D.V. Harris WTW (located in Pietermaritzburg) (UW, 2019). The MMTS transfers water from the Mooi River to the Mgeni River, with the purpose of increasing the yield of the Mgeni System at Midmar Dam. The MMTS can either transfer 4.5 m^3/s continually from Spring Grove Dam, or 3.2 m^3/s from Mearns Weir and the balance from Spring Grove Dam, the operation of which depends on the storage in each of the aforementioned water resources. Midmar Dam’s yield has been maximised with the completion of the MMTS; all future bulk distribution infrastructure upgrades within the Upper Mgeni System (Midmar WTW to Umlaas Road) should therefore be limited to that which Midmar Dam can support, including contributions to water resource requirements downstream of Midmar Dam (*ibid*).

The Lower Mgeni System derives its water resources from the Lower uMngeni River, with storage at Nagle and Inanda Dams, which are in turn supported by Albert Falls Dam, Midmar Dam and the MMTS upstream. Durban Heights WTW is primarily gravity-fed with raw water from Nagle Dam via a series of aqueducts. Raw water supply is supplemented by Inanda dam via the Inanda Pump Station which draw water from the aqueduct between Inanda Dam and Wiggins WTW. Raw water is treated at Durban Heights WTW (located in Westville), Wiggins WTW (located in Cato Manor) and Maphephethwa WTW (located in the Inanda Dam area). Umgeni Water sells water to eThekwini Municipality at the boundary of each of these WTWs and thus does not own nor operate the bulk distribution pipelines downstream of these WTWs (*ibid*).

The MMTS maximises the benefit which can be obtained from the Mooi River to support the Mgeni WSS, and the Mgeni River is considered fully developed. In that the Mgeni and Mooi catchments have been fully developed, augmentation of this system to support growing demands is to be achieved by transferring water from the uMkhomazi catchment to the Mgeni catchment, and is known as the uMkhomazi Water Project (uMWP). The need for augmentation of the Mgeni WSS via the uMWP is discussed further in Section 4.4.1 (c) (*ibid*).

There has been continuous effort and collaboration between Umgeni Water and eThekwini Municipality to optimise the overall efficiency of the distribution system to better share the demand between the two large WTWs. Examples include the transfer of demand from Durban Heights WTW onto Wiggins WTW (which has already been completed) and the transfer of demand from Durban Heights WTW and Hazelmere WTW onto the Umlaas Road (Upper Mgeni) sub-system (as yet not complete). The latter is known as the Western Aqueduct project, comprising new large-diameter pipelines connecting the Umlaas Road sub-system to key supply points within the eThekwini water supply network. In future, the supply to the areas served by the Western Aqueduct will be augmented by the implementation of the uMkhomazi Water Project, without which, the full load shift requirement of the Western Aqueduct cannot be accommodated. This is due to the yield of Midmar Dam being unable to support the full load for a significant amount of time, as well as hydraulic constraints in the Umlaas Road sub-system which would require significant infrastructure investments to overcome. The available water for eThekwini Municipality at this supply point will decrease as the demands upstream increase over time (*ibid*).

(ii) South Coast WSS

As described by the UW Masterplan (2019), the South Coast WSS is sub-divided into three sub-systems:

- The Upper South Coast, extending from Amanzimtoti southwards to the uMkhomazi River, within the bounds of eThekwini municipality.

- The Middle South Coast, extending from the uMkhomazi River southwards to the Mtwalume River; the southern-most portion of eThekwini municipality and the northern parts of Ugu District Municipality are supplied by this system.
- The Lower South Coast, extending from the Mtwalume River southwards to the Mtamvuna River (in the vicinity of Port Edward).

Umgeni Water currently only supplies water to the Upper and Middle South Coast sub-systems, with bulk water infrastructure located largely within the coastal strip, and pipeline off-takes extending inland to adjacent rural areas. The portion of the South Coast WSS relevant to this study is currently largely supplied by the Lower Mgeni system via Wiggins WTW and Amanzimtoti WTW which is supplied with raw water from the Nungwane Dam, all connected via the South Coast Augmentation (SCA) pipeline. In future, the supply to the SCA pipeline will be augmented by the Lower uMkhomazi Bulk Water Supply Scheme (*ibid*).

(iii) North Coast WSS

As described by the UW Masterplan (2019), the North Coast WSS is sub-divided into:

- The Mdloti Supply System which supplies Phoenix, Verulam and La Mercy in northern eThekwini, a portion of rural Ndwedwe Local Municipality, coastal towns along the Dolphin Coast, and low cost housing areas, namely Etete and Groutville.
- The Lower Thukela Supply System which supplies the towns of Darnall, Zinkwazi, Blythedale and KwaDukuza, amongst other developments between the uThukela River and KwaDukuza.
- The Maphumulo Bulk Water Supply Scheme which is limited to supplying Maphumulo Local Municipality.

The Mdloti Supply System derives its water resource from the Hazelmere Dam. Raw water from Hazelmere Dam is treated at the Hazelmere WTW. DWS recently completed the raising of the Hazelmere Dam wall by 7m, thereby increasing the system yield (98% assurance of supply) by 20 Ml/d. There is a river abstraction on the uThongathi River which provides raw water for the Tongaat WTW. The yield of the river abstraction is lower than the demands; in dry periods the supply is therefore supplemented by the Hazelmere supply system. The Lower Thukela Supply System derives its water resource from a large river abstraction on the Thukela River and raw water is treated at the Lower Thukela WTW (*ibid*).

The Mdloti and Lower Thukela Systems have been integrated to allow for water resource interdependencies and infrastructure integration that is required to supply bulk potable water along the coastal strip of the North Coast Region. The North Coast Pipeline extends from Ballito to KwaDukuza Town, and the Lower Thukela Pipeline extends from KwaDukuza Town to the Lower Thukela WTP. Both pipelines being bidirectional, the aforementioned areas can be supplied from either resource depending on water resource availability, though at present, Hazelmere supplies from Phoenix/Verulam to Groutville and Lower Thukela supplies southwards to KwaDukuza Town. It is expected that as demand in the north of eThekwini and Ballito and surrounds grows, Hazelmere will only supply north as far as Ballito (*ibid*).

The area of Verulam (specifically that supplied by Grange Reservoir) can be supplied from either of or both the Hazelmere WTW and the Mgeni System via Durban Heights WTW: during periods of drought, the supply to this area is dependent on which system has the greater resource availability (*ibid*).

(c) Water Balances

The Umgeni Water Masterplan (UW, 2019) includes a 30-year long-term sales forecast for its supply area, which takes into consideration reduced sales following the recent drought, new supply to the uThukela District Municipality, anticipated natural growth in demand on the existing supply system, and sales from new infrastructure which would extend the area of operation, ultimately resulting in a compounded 1.5% per annum growth rate until 2048/2049. The major water users in the region have agreed to the growth rate. Furthermore, the Umgeni Water forecast closely matches the forecast as derived in the Water Reconciliation Strategy Study for the KZN Coastal Metropolitan Areas undertaken by DWS, in which demands were forecasted based on population projections.

The latest iteration of the Reconciliation Strategy (DWS, 2017) built on the original water requirements from the First Stage Reconciliation Strategy (DWS, 2008), which was based on a demographic study and population projections, applied to a water requirements and return flows database model. In the most recent update (DWS, 2017), the water requirements projections incorporated additional data and studies which became available:

i. The means by which WCWDM impacts were accounted for was a significant revision: instead of assuming the current real losses would hold constant and loss reduction measures imposed on this, the new upper envelope of projected water requirements is constructed by imposing system attrition (increasing water losses as a result of deteriorating infrastructure) on the current losses. The lower envelope of water requirements is then obtained by deducting the impact of WCWDM measures. Notably, more conservative savings from WCWDM Master Plans were selected to prevent underestimation of demand (*ibid*).

ii. In-catchment domestic use which is upstream of the Reconciliation Strategy Area and not supplied directly from the WSSs does nonetheless impact water availability; this was taken into account in quantification of the yields of the affected water resources (*ibid*).

iii. There is extensive irrigation in the various catchments which supply the Strategy Area, though the majority of the irrigation occurs in catchments upstream of the major dams and abstractions; as such, the impact of irrigation is accounted for in terms of water availability (dam yields), rather than as a downstream water requirement. There is notably limited provision for further irrigation in the Strategy Area; managing this water use will therefore be important in implementation of the Reconciliation Strategy (*ibid*).

iv. Ecological water requirements (EWRs) were accounted for by determining the impact on supply if EWRs are supported, rather than including same in water requirement projections. EWRs are an important consideration for ecological infrastructure (refer to Section 4.5 for further detail). The EWRs which were determined in the DWS Classification process have the following key impacts on water availability in the Reconciliation Strategy Area: firstly, there are no significant impacts on the Mgeni or Mooi River systems; secondly, there is a small reduction in the yield of the uMWP (some 5 million m3/a of the originally determined 220 million m3/a) (*ibid*).

A realistic reconciliation of water availability and water requirements requires the definition of the extent to which users can tolerate the undersupply of water (i.e. the assurance of supply). Such definition is also important for short-term operating rules under drought conditions. Such has been defined for the Reconciliation Strategy Water Supply Systems, and within each of these systems, a split between the different water use categories. One specific water user is not prioritised over another; low priority water use is rationed across water users such that it reflects the value of water as agreed upon by the stakeholders (DWS, 2017). As per the UW Masterplan (2019), the Mgeni WSS requires a 99% level of assurance of supply given the economic and strategic significance of the region. The Mdloti, uThukela and South Coast systems require a 98% level of assurance of supply, given the predominantly domestic nature of these areas.

Figure 4-6, Figure 4-7, and Figure 4-8 illustrate the projected water demands and system yields for the Mgeni, North Coast, and South Coast WSS's respectively.

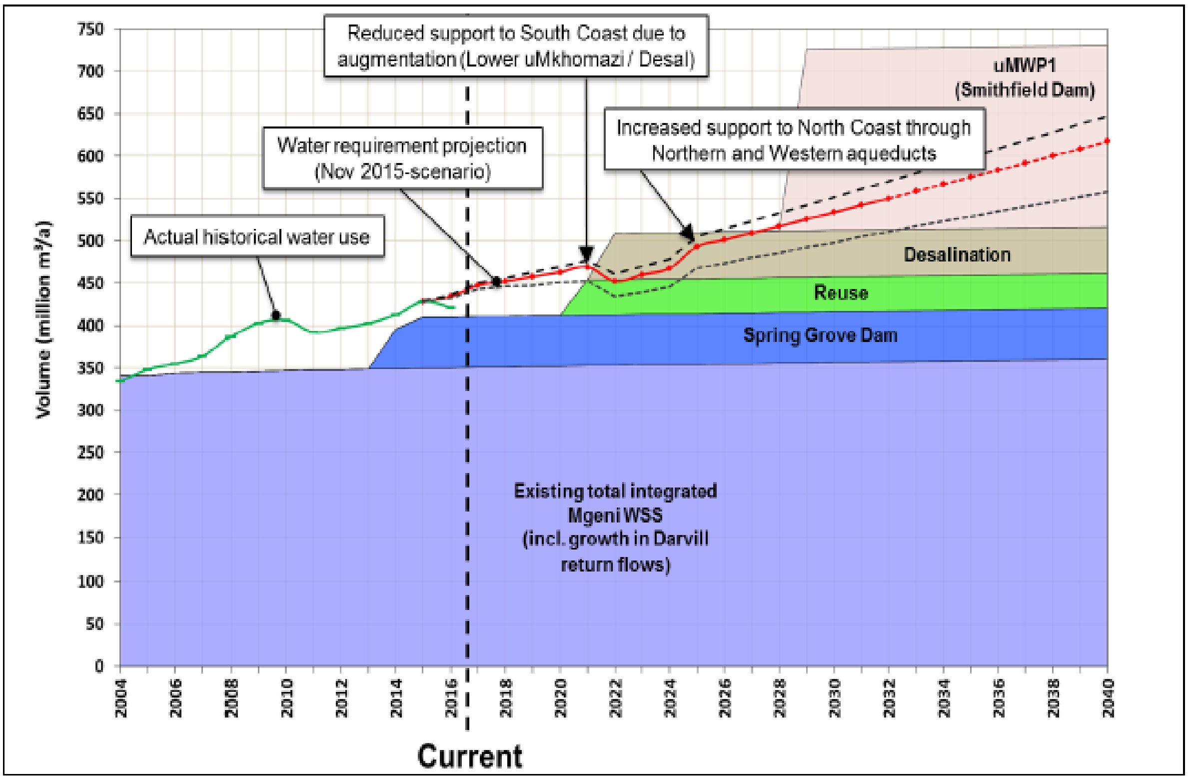


Figure 4-6: Mgeni WSS Water Balance (Reconciliation Strategy) with Interim Intervention and uMWP [Source: DWS, 2017]

The water balance for the Mgeni WSS shows the significant benefit of WC/WDM (lower envelope of projection), though it only reduces rather than eliminating the projected shortfalls. Further infrastructure developments are therefore required (DWS, 2017). The Reconciliation Strategy (DWS, 2017) investigated options around timing of the uMkhomazi Water Project and incorporation of reuse and/or desalination to increase system yield prior to uMWP. Key findings are as follows:

- Though the final phase of the MMTS has been completed, the Mgeni WSS remains in a shortfall situation after 2015.
- Re-use or desalination would enable a positive water balance from 2022; the uMWP is, however, still required by 2024.
- Both re-use and desalination being implemented allows delay of the uMWP for 4 to 5 years.
- If neither re-use nor desalination are implemented, the period of potential shortfall grows.
- In that re-use and desalination plants have high energy and running costs, it is conceivable these plants could be decommissioned when the uMWP (notably a gravity-driven system) is commissioned. It would be costly and impractical to commission such infrastructure for the purpose of reducing supply failure risks for a short period of time.

The Reconciliation Strategy (DWS, 2017) therefore motivates there is clear and urgent need for the implementation of the uMWP. Given the above considerations in the timing of the uMWP, a risk assessment of the projected shortfall (without any reuse or desalination measures) and the possible implications for water users in the Mgeni WSS was undertaken. Two scenarios were assessed: the first involved the full water requirement being targeted when water is in fact available in the system. The result is achievable assurances of supply decreasing with time, i.e. the risk of supply failure increases to unacceptably high levels. The second scenario involved curtailing water supply by considering the assurance of supply characteristics of the system and lower priority water users being curtailed to protect higher priority water users. Results showed an ever-increasing shortfall in supply. The severity of the situation increases if the implementation of the uMWP is further delayed; the risk of more regular water restrictions and negative socio-economic impacts should however be evaluated against cost saving should "interim" intervention options be implemented (*ibid*).

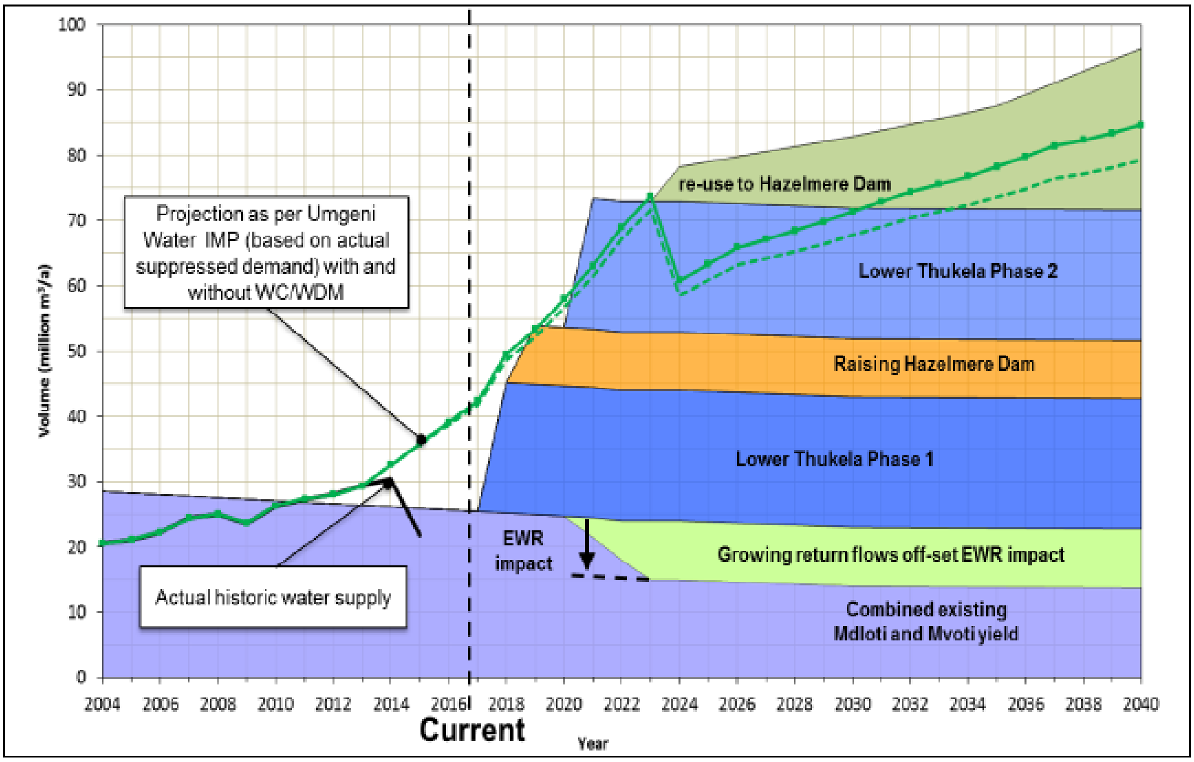


Figure 4-7: North Coast WSS Water Balance (Reconciliation Strategy) with Indirect Reuse [Source: DWS, 2017]

As per the Reconciliation Strategy (DWS, 2017), key observations relating to the North Coast WSS water balance include:

- The water requirements for the North Coast WSS are reduced when a portion of the area supplied from Hazelmere Dam is transferred onto the Mgeni WSS (when the uMWP is commissioned). This load-shift is clearly important for maintaining a positive water balance in the North Coast WSS.
- Implementation of the EWRs is estimated to result in a decrease of 10 million m^3/a in system yield, which could nonetheless be off-set through increased return flow volumes.
- Long term augmentation options include either iSithundu Dam or the indirect re-use (shown above) of wastewater via Hazelmere.

Cost considerations aside, the indirect re-use of treated wastewater via Hazelmere Dam would potentially address effluent discharge constraints in the relevant estuaries. Based on the projected growth in return flows available for the same purpose, the proposed iSithundu Dam could be delayed beyond the 30 year planning horizon. The feasibility of reuse is dependent on the period by which the iSithundu Dam could be delayed (*ibid*).

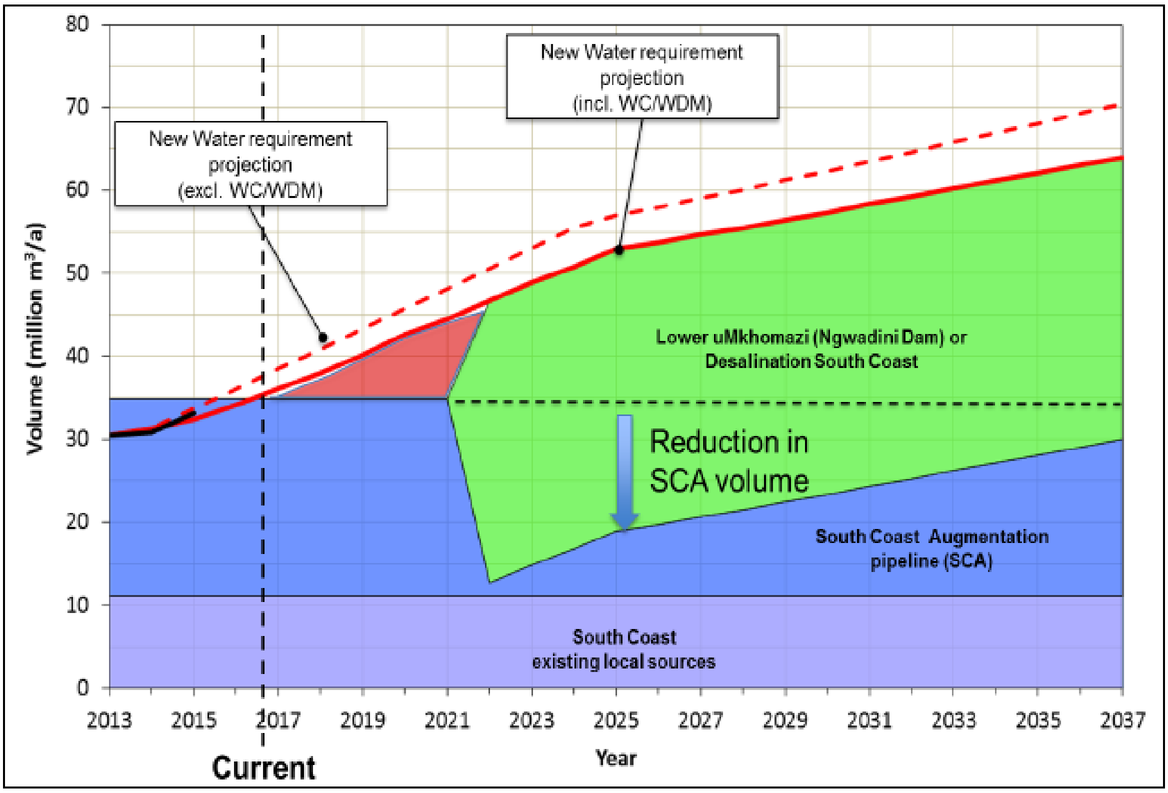


Figure 4-8: South Coast WSS Water Balance (Reconciliation Strategy) with Augmentation [Source: DWS, 2017]

Key observations for the South Coast WSS water balance, as defined by the Reconciliation Strategy (DWS, 2017), include:

- Augmentation of supply to the South Coast is required as soon as possible; a short-term deficit period is likely as the options for implementation require a reasonably long lead-time. WCWDM initiatives are critical for minimising supply shortfall risks in this period.

- Augmentation of the South Coast allows the volume supplied from the Mgeni WSS to be reduced for a period of time, thus providing some relief for the Mgeni WSS.

In terms of large scale surface water augmentation, the following options are listed in the UW Masterplan (2019):

- The uMkhomazi Water Project, comprising two dams viz. Smithfield Dam (Phase 1) and Impendle Dam (Phase 2), a new water treatment plant, and a conveyance system to transfer potable water into the areas currently supplied from the Umlaas Road sub-system. Pre-feasibility studies indicate a 99% level of assurance yield of 600 Ml/d could be obtained.
- The Lower Thukela Bulk Water Supply Scheme (North Coast WSS) can be upgraded from 55 Ml/d to a maximum capacity of 110 Ml/d when required in future.
- iSithundu Dam on the uMvoti River (North Coast WSS) can link into the Hazelmere / Lower Thukela supply system to supply some 127 Ml/d.
- A river abstraction on the lower reaches of the uMkhomazi River and a new WTW (known as the Lower uMkhomazi Bulk Water Supply Scheme) (South Coast WSS) can link into the existing south coast pipeline system to provide 100 Ml/d of potable water for a large portion of the south coast corridor, thereby reducing reliance of this area on the Mgeni WSS.

Additional augmentation and intervention options are presented in Section 4.7.

(d) Drought Management

Restrictions in the North Coast WSS were implemented in November 2014, and restrictions in the Mgeni WSS were effected from the end of 2016. Restrictions in the South Coast WSS were a result of the state of smaller local dams and the reliance on the stressed Mgeni WSS. The differences in restriction timing is driven by the availability of storage in the different WSSs and the response times of dams to dry and wet periods (i.e. the Mgeni WSS responds slower to low rainfall, but also has a slower recovery time in high rainfall periods). Restrictions were lifted in the first half of 2018 (DWS, 2017).

Following on from the impact of the drought, the latest Reconciliation Strategy (DWS, 2017) noted the difficulty in making allowance for the impact of the drought: current supply volumes are usually used as a baseline for updating projections, but restricted volumes represent a suppressed demand, and such is clear in the lower water supply volumes during the drought period. The Reconciliation Strategy assumes that water requirements will recover post-drought and trend toward original projections, though there was uncertainty in the rate and extent to which water requirements will respond. Possible reasons for this included (DWS, 2017):

- Savings achieved through drought-focused interventions and ability to maintain same;
- Water shedding having negative impacts on condition of pipes and therefore possible increase in leakage;
- Changes in consumer attitude and behaviour around water use;
- Changes in WSA behaviour towards managing and planning water resources; and
- Impacts on revenue (reduced sales) and tariff structures.

Based on the Umgeni Water Masterplan (UW, 2019), actual use and projected use indicates water requirements recovering to pre-drought levels by 2020; it is interesting to note the time taken for this to occur, perhaps attributable to some or all of the aforementioned considerations. It is also difficult to determine the impact population growth and new developments have had in the water requirement trends since the lifting of restrictions. Water conservation and awareness achieved during the drought period should be maintained as much as possible, particularly until augmentation to key systems can be implemented.

Umgeni Water has developed a Drought Management Plan in order to manage water supplies during uncontrolled events such as was experienced during the most recent drought event. While water restrictions are not desirable, it is sometimes the most effective means of coping with short-term drought conditions, especially considering infrastructure development for augmentation requires long time-frames for implementation. Therefore, while the short-term actions in the recent drought event were necessary, continuation of long-term planning and the implementation of the Reconciliation Strategy were agreed as critical for future water security (DWS, 2017); the above events reinforce the need for timeous implementation of augmentation projects which secure water supply (restrictions should not be viewed as a mechanism for coping with the consequences of delays to essential project planning and implementation).

4.4.2 Wastewater

(a) Sanitation Service Types

The split in sanitation services in the municipality has been determined by the Pollution Research Group (2016): Wastewater from 48% of all dwelling units in eThekwini is collected and conveyed to WWTWs. Where centralised sewer networks have not been constructed in affluent but peri-urban areas, either septic tanks or decentralised private sewer lines and package plants are used; this is the case for 11% of all households in the municipal area. Due to the backlog in providing formalised housing units, communal ablution blocks connected to the sewer networks are provided for informal settlements as a transitory means of sanitation for those households which will not be formalised in the near future; this accounts for 12% of all dwelling units. Where no connections are available for communal ablution blocks, toilets are each connected to their own VIP pits. In areas outside of the urban development line and therefore outside of the existing sewer network, the minimum level of service is the urinary diversion (UD) toilet, accounting for 9% of dwelling units. VIP latrines were previously installed in rural areas (4% of dwelling units), but are no longer built unless circumstance necessitates such. The remaining 16% of all dwelling units therefore have no formal sanitation system (PRG, 2016). This appears consistent with current backlog estimates stated in eThekwini's IDP (EM, 2019). There are currently trial projects underway to test the feasibility of using pour-flush toilets as an alternative to UD toilets, or low-volume flush toilets instead of standard flush toilets in low cost housing developments (PRG, 2016).

Septic tanks and conservancy tanks are emptied by vacuum tankers which are operated by private companies, the contents of which are only permitted to be discharged at Hammarsdale, Umhlatuzana, Southern, Amanzimtoti, or Phoenix WWTWs. The contents of UD toilets are emptied and buried on site by local companies contracted by the municipality. There is a pilot project where UD sludge is treated at a Black Soldier Fly Treatment facility, the end product being protein feed sold to livestock farmers. VIP sludge is separated into solid waste (sent to landfill) and sludge which is processed at the Latrine Dehydration and Pasteurization (LaDePa) treatment facility, which produces fertilizer pellets from the supplied sludge (*ibid*).

In terms of greywater disposal for un-serviced settlements, where plot sizes are larger than 500 square metres and water consumption is low, disposal of greywater is not a perceived problem. If plot sizes are smaller than 350 square metres, eThekwini planned for small purpose-built soakaways to be built at the same time UD toilets were rolled out (EWS, 2003), though it is unclear whether this was ever implemented.

(b) Bulk Wastewater Services

EWS owns and operates 27 WWTWs that treat a total of approximately 500 Ml/day of wastewater. Sewage is collected and conveyed through a network of 8 105 km of sewer pipelines (EM, 2019). In addition to the WWTWs owned and operated by EWS, there are some 76 privately owned and operated package plants situated around the municipality, with only 32 being monitored by EWS (PRG, 2016). Treated wastewater is either released to the nearest river or estuary, or in the case of the Southern Works, discharges to a sea outfall. Due to estuaries being environmentally sensitive areas, there are restrictions on effluent discharge in excess of current allocations as licensed by DWS; future plans consider construction of sea outfalls or reuse of wastewater for affected WWTWs (PRG, 2016). Figure 4-9 below illustrates the municipal WWTW locations and the extent of the sewer network. A summary of the WWTWs and their respective capacities is included in Appendix A: Model Inputs.

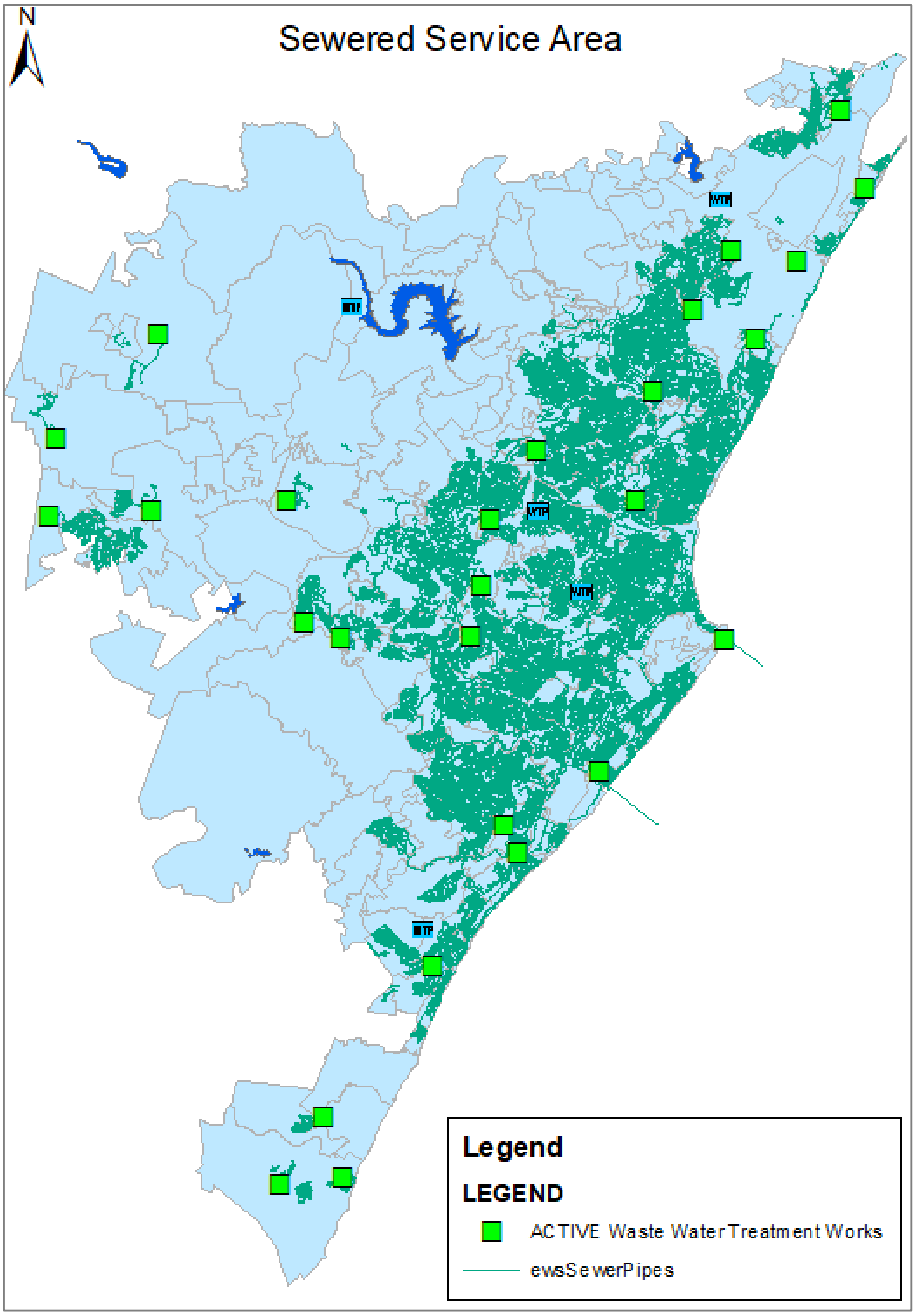


Figure 4-9: Sewer Network Coverage

The Green Drop assessment is a means of measuring the performance of WSAs and WSPs against standards which have been defined for the provision of wastewater services, and subsequently rewarding or penalising the municipality, as the case may be (DWS, 2011). As per the Green Drop Report for 2014, the annual average effluent quality compliance is over 90% for 13 facilities, over 80% for nine facilities, and over 70% for two facilities. The Northern Works – one of the larger treatment plants – achieved the lowest level of compliance at 55%, while also operating at 96% of the facility design capacity (PRG, 2016). There have since been upgrades and improvements to various treatment facilities, though there are, at present, no more recently dated Green Drop Reports to indicate new trends in compliance. The PRG (2016) further notes the sludge treatment process is not as well monitored or regulated as the wastewater treatment process.

eThekwini has decided to regionalise the existing WWTWs by decommissioning smaller plants and centralising treatment at uMkhomazi, Amanzimtoti, Southern, Central, Northern, KwaMashu, Phoenix, Umdloti, Tongaat, Umbilo, Umhlatuzana and Hammarsdale WWTWs. Plants identified for potential decommissioning include Kingsburgh, Isipingo, Umhlanga, KwaNdengezi, Dassenhoek, New Germany, Hillcrest, Mpumalanga and Fredville (EM, 2019). In conjunction with the aforementioned study, EWS plans to decommission small plants in the North and South and replace them with new WWTWs, the affected plants being uMkhomazi (20 Ml/d), uMdloti (initially 40 Ml/d and ultimately 125 Ml/d) and Tongaat (initially 25 Ml/d and ultimately 140 Ml/d). These plants will incorporate the latest technology and focus on nutrient recovery and energy. Furthermore, there is intent for uMdloti and Tongaat to include treatment for direct and/or indirect reuse. The study to assess the technical and economic feasibility and make recommendations for the regionalisation is underway (EM, 2019).

There are planned capacity upgrades at Hammarsdale and Phoenix: while the hydraulic capacity of Hammarsdale is adequate, the process requires improvement to cope with the high strength industrial effluent. Phoenix is being upgraded from 25 Ml/d to 50 Ml/d to accommodate growing developments in the catchment. In line with the planned upgrades of the Amanzimtoti WWTW as part of the regionalisation, outfall sewers will be constructed such that a number of sewer pumpstations can be decommissioned (EM, 2019).

DWS has concluded the Classification of Water Resources and Determination of the Comprehensive Reserve and Resource Quality Objectives in the Mvoti to Umzimkulu Water Management Area (DWS, 2015); this covered a number of important catchments in the Reconciliation Strategy area. Management of return flows to estuaries is a key issue where additional effluent flows would exceed the assimilative capacity of the estuary; the North Coast estuaries are particularly constrained (DWS, 2017). As summarised by DWS (2017), findings for the assessment of estuaries and management of indirect reuse of effluent are as follows:

- Wastewater generated in the uThonghati and uMdloti river catchments will eventually need to be reused indirectly by way of transfer to Hazelmere Dam. Tongaat WWTW is limited to discharge 20 Ml/d, and uMdloti WWTW is limited to discharge 55 Ml/d, above which transfer to Hazelmere Dam must occur. The indirect reuse volume is, however, limited to 140 Ml/d due to the assimilative capacity of the dam with regards to total dissolved solids concentration build-up.
- The recommended EWR for the uMngeni Catchment should be implemented, along with transfer of effluent from the Umhlanga Estuary to the Mgeni system.
- Additional wastewater effluent should not be discharged into the uMkhomazi Estuary.
- The Little Amanzimtoti and Mbokodweni river catchments may receive further effluent (from Kingsburgh and Amanzimtoti WWTWs, respectively) within limits such that recreation may still take place.

(c) Decentralised WWTWs

In contrast with the regionalisation of eThekwini’s WWTWs, there is an initiative where decentralised WWTWs are being piloted, though these pilot plants appear to be largely in answer to service delivery limitations in peri-urban areas where there is no existing sewer network.

In conjunction with Bremen Overseas Research and Development Association (BORDA) and University of Kwa-Zulu Natal's PRG, EWS established a pilot decentralised waste water treatment system (DEWATS) which has no operational power requirements such that technical limitations could be tested and operations and maintenance procedures established. There is one such pilot in the Newlands area, serving some 86 households, and four different DEWATS models in Frasers to test which configuration is most suited to treating communal ablution block waste. The DEWATS plant at Sarasvati Primary School includes other unique components too (rainwater harvesting, biogas use, reuse of effluent for community garden) (EWS, 2012). The DEWATS system is a potential sustainable sanitation solution for settlements in outlying areas which are isolated from the existing sewer infrastructure where it would prove challenging to provide a linkage.

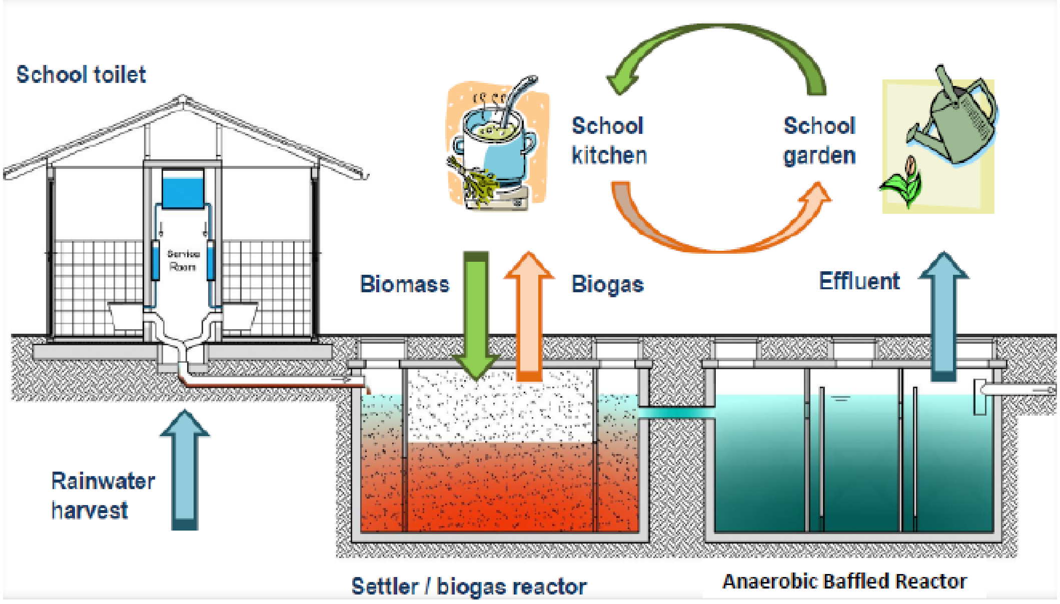


Figure 4-10: Sustainable Sanitation Solution (DEWATS) at Sarasvati Primary School [Source: EWS, 2012]

4.4.3 Catchments and Stormwater

eThekwini typically makes use of conventional piped stormwater systems in developed areas. The Guidelines And Policy For The Design Of Stormwater Drainage And Stormwater Management Systems (CSCM, 2008) do, however, advocate for stormwater controls to facilitate groundwater infiltration and attenuation of post-development flows. The CSCM focuses on linkages between stormwater and the built and natural environment, with interventions seemingly driven by adaptation to climate change and flood damage prevention (Armitage *et al*. 2014).

The Green Rivers programme aims to improve poor river water quality through minimising incidences of overflows from sewage systems. Activities centre on factors that may result in overflows from sewage systems, for example: infiltration and accumulation of silt; stormwater ingress as a result of illegal connections; accumulation of fats, oils and grease; failure of mechanical and electrical equipment at pump stations; and illegal discharges of toxic pollutants. Tracking effectiveness of interventions is achieved through continual monitoring and reporting (EWS, 2011).

The uMhlangane catchment, which covers the areas of Phoenix, Inanda, and Kwamashu, is representative of the various challenges within eThekwini. The uMhlangane Catchment Management project aims to implement adaptation principles at catchment level, demonstrate the benefits in doing so, and therefore potentially influence broader planning in future. There is also opportunity to investigate institutional features which help or hinder, as the case may be, projects of this nature. Adaptation responses adopted in the uMhlangane Catchment Management project include: rehabilitation of wetlands for flood control; food security through urban agriculture; stream cleaning and specialised maintenance for improved water quality; alternative town planning models; attenuation of runoff; and provision of “green” jobs. Other eThekwini Municipality interventions discussed elsewhere in this chapter are located in the project site (DEWATS, Green Rivers, community food gardens, and rainwater harvesting). This project is cited as an opportunity to investigate institutional characteristics that either enhance or undermine projects of such coordinated nature (EM, 2014).

4.5 Ecological Infrastructure

The Reconciliation Strategy (DWS, 2017) includes “support interventions” which focus on catchment-wide practices for improving the water quantity and quality of water resources and the protection of ecosystems, as opposed to the more common focus on infrastructure management or new infrastructure developments. Initiatives include catchment care, maintenance of ecological infrastructure, rainwater harvesting, and water quality management.

The Reconciliation Strategy (DWS, 2017) recognises the role of ecological infrastructure as “*naturally functioning ecosystems that produce and deliver valuable services to people*”. The uMngeni Ecological Infrastructure Partnership (UEIP) aims to maintain and invest in ecological infrastructure in the Mgeni catchment to maintain water quality and contribute to water security, as the degradation of ecological infrastructure compromises optimal performance in delivering water-related ecosystem services (namely dry season base flow and water quality maintenance, sustained water supply, erosion control and avoidance of sedimentation, and flood attenuation). There is, however, a current lack of quantifiable data for the improvements to water quality and water security as a result of catchment care. As such, catchment care is not explicitly accounted for in the Reconciliation Strategy scenarios and water balances. Nonetheless, the UEIP is recognised as an important opportunity to demonstrate the benefits of collaborative investment in ecological infrastructure for water security (DWS, 2017).

In addition to the impact on ecological functioning of natural systems, water quality of water resources impacts treatment: poorer quality water is typically more costly to treat, and if severe enough may necessitate an intervention such as additional treatment processes (DWS, 2017). While the water quality in the upper reaches of the Mgeni River is acceptable, it deteriorates downstream of the Nagle Dam at the confluence with the Msunduzi River. As a result of poor sewage infrastructure in the Mpophomeni region, Midmar Dam also experiences sewerage contamination. Agricultural activities further contribute to nutrient loading. Water quality has not generally had an impact on overall availability of water in the Reconciliation Strategy Area, and according to the Surface Water Resource Quality Assessment conducted by DWS (2015), the current overall water quality of the Reconciliation Strategy Area is of an acceptable level. Ongoing monitoring and ensuring discharges from treatment process are compliant with respective limits should, however, be maintained (DWS, 2017).

The Classification of Water Resources and Determination of the Comprehensive Reserve and Resource Quality Objectives in the Mvoti to Umzimkulu Water Management Area (DWS, 2015) has implications for wastewater discharge in the study area (refer to Section 4.4.2) as well as ecological water requirements (refer to Section 4.4.1). The Reconciliation Strategy (DWS, 2017) states that the eventual implementation of the Resource Quality Objectives (RQOs) and associated EWRs will require careful consideration in subsequent updates of the Reconciliation Strategy.

The role of rainwater harvesting in the Reconciliation Strategy Study Area is outlined in Section 4.7.3.

4.6 Climate Change

It is generally accepted that climate change could have an impact on water resources and therefore on water security (DWS, 2017). The Reconciliation Strategy (DWS, 2017) reported on the 2012 Umgeni Water *Assessment of the Potential Impact of Climate Change on the Long-Term Yield of Major Dams in the Mgeni River System*: the results for the total Mgeni WSS 1:100-year yield / 99% annual assurance of supply suggest a large variance in the future (time horizon 2046 to 2065) ranging from a 41% increase to a 45% decrease in system yield. If the highest and lowest outliers are excluded, the spread of results is much lower, ranging from a 25% increase to a 15% decrease in system yield. Paired with the water balance of the Mgeni WSS, the impact on the supplied region and the Reconciliation Strategy can be determined (illustrated in Figure 4-11):

- Up to 2025, the possible impact of climate change (whether an increase or decrease in yield) has a limited impact on the water balance. The impact becomes more pronounced over the longer term (2040 and beyond).
- A 15% decrease in system yield manifests as the full utilisation of the uMkhomazi Water Project by 2040.
- A 25% increase in system yield results in the uMkhomazi Water Project providing adequate supply for the Mgeni WSS beyond 2040.
- Important to note is that any climate change impacts do not impact the short-term requirement and timing for implementing the uMkhomazi Water Project.

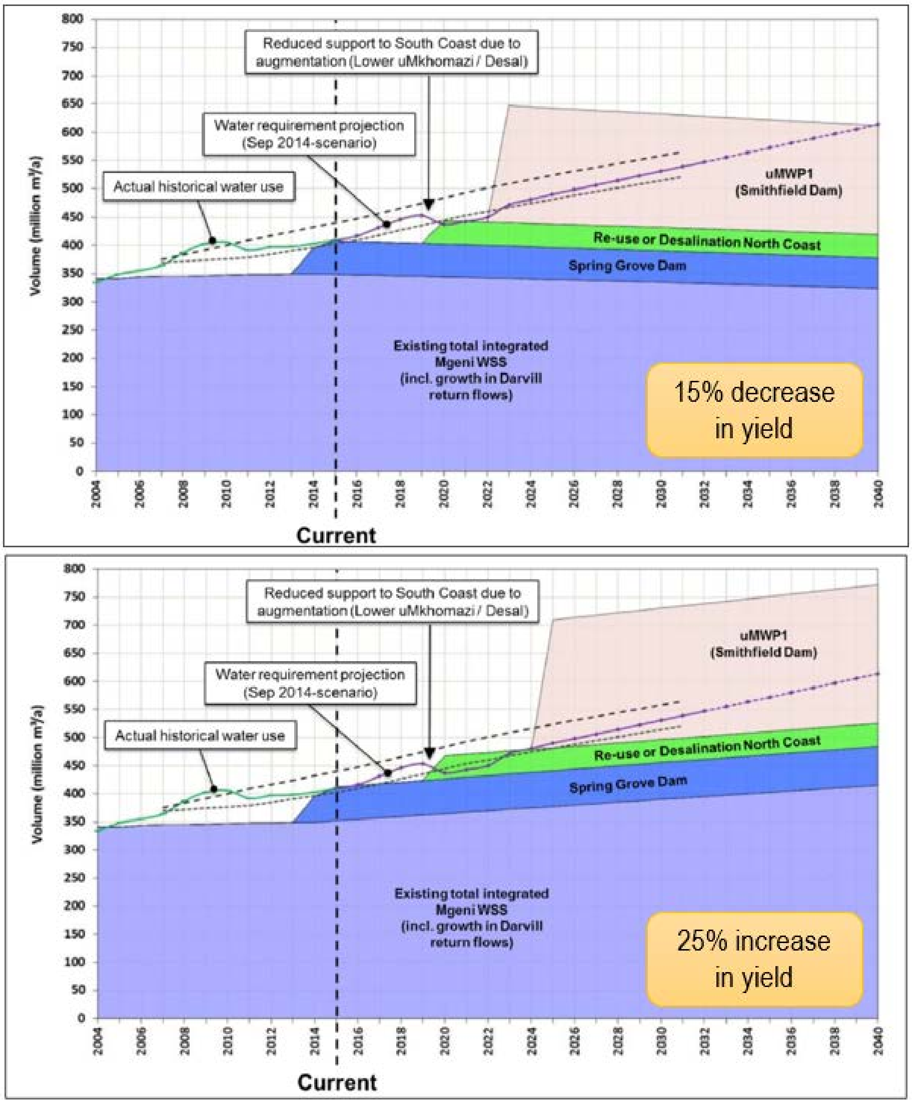


Figure 4-11: Mgeni WSS Water Balance with Assumed Changes in Yield [Adapted from DWS, 2017]

The UW Masterplan (UW, 2019) includes feedback on an update to the 2012 assessment of the Mgeni WSS (as detailed above):

- Evaporation is expected to increase, with the highest change in potential evaporation in the inland areas/western parts of Umgeni Water's operational area compared to the coastal areas, with highest changes occurring in hot years and summer months compared to cool years and winter months. High evaporation is predicted over the Lower Mooi River and the middle of the Mgeni system (*ibid*).
- Rainfall is predicted to increase in some areas and decrease in others, which is critical for understanding impacts on catchment runoff. Annual rainfall is likely to have less variability compared against specific seasons – summer rainfall having the lowest variability and winter rainfall having the highest variability. Summer remains the season with the highest rainfall. Seasonal variability further differs by area; in spring and autumn there is a projected increase in variability in the head water catchments – this is particularly important for Umgeni Water planning. Higher rainfall years have greater confidence in the results, whilst lower rainfall years have lower confidence in the results; within this, the winter months have the lowest confidence in the results (*ibid*).

- Streamflows are expected to increase in some areas and decrease in others. Higher accumulated streamflows can be expected along the Mkhomazi and Mgeni Rivers. While the confidence in the predicted rainfall is generally high, the confidence in the streamflow appears to be low (*ibid*).

While the uncertainty in climate change impacts remains, these impacts do not change the interventions recommended as part of the Reconciliation Strategy in the short-term. Effective water resources management – especially in the light of current hydrological variability – is recognised as an important climate change adaptation strategy. In the long term, results of climate change impact studies are expected to become more convergent, in which case planning can be improved (DWS, 2017).

4.7 System Augmentation and Interventions

eThekwini Municipality has undertaken a number of research and development initiatives in pursuit of sustainability in water, sanitation, solid waste, and energy. The interventions discussed herein are, however, limited to those which have direct impact on water supply, as is the focus of this study.

4.7.1 WCWDM

Water Conservation and Water Demand Management initiatives are quickest to implement and lower the demand curve. The impact of this is either reducing deficits or deferring implementation of other interventions to a later date, as the case may be. Predicting the extent of the success of WDM initiatives is challenging, and once targets are achieved, require on-going monitoring and management (UW, 2019). WSAs in the Reconciliation Strategy area have been encouraged to implement WCWDM initiatives; due to the interconnected nature of the supply systems which cross municipal boundaries, the impact of WCWDM initiatives has an effect on all water users in the region. Preliminary information from the 5-year WC/WDM Master Plans for the five WSAs in the Reconciliation Strategy Area was adopted for the water requirement projections, though the conservative scenario (i.e. the most probable) was selected as the high savings scenarios are not always achieved and would result in the water requirements being underestimated. A total saving for the Reconciliation Strategy Area of 40-48 million m^3/pa is indicated, 25.9 million m^3/pa of which is located within eThekwini (DWS, 2017).

WCWDM has seen significant investment in eThekwini, and has included focus areas such as, *inter alia*, pipe replacement programmes, pressure management and optimisation, leak detection, zone metering and monitoring, domestic leak repair programmes in low cost housing areas, and investigating alternative metering technologies. In eThekwini, WCWDM is driven through Non Revenue Water (NRW) Reduction programmes; while the set of solutions within WCWDM and NRW is essentially the same, NRW programmes tend to highlight the financial sustainability of service provision within the municipality.

The results of WCWDM in eThekwini has seen some success, but the target of 30% NRW by 2013/14 as stated in the WSDP (EWS, 2011) had proved elusive with NRW at 39.4% (EM, 2017). The NRW has since been reduced to 32.7% in 2017/18 (UW, 2019). For comparison, the NRW average for South Africa is 36.8%. Illegal connections and deteriorating infrastructure remain key problems (EM, 2017). As determined by Umgeni Water (2019), Figure 4-12 shows the NRW percentage for eThekwini compared to other WSAs within Umgeni Water's area of operation. The average Infrastructure Leakage Index (ILI) in KZN is 5.0, i.e. the leakage is on average five times higher than the theoretical lowest it could be.

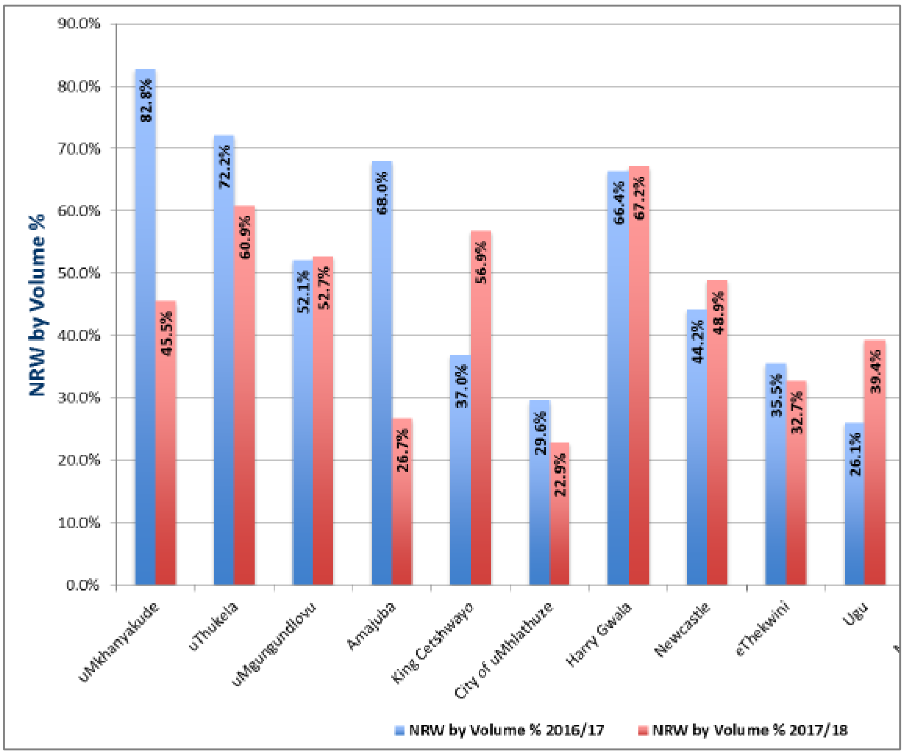


Figure 4-12: Non-Revenue Water Percentage by Volume for WSAs [Source: UW, 2019]

Notwithstanding on-going implementation of WCWDM measures, Umgeni Water (2019) note where regions are predicted to see economic development and improved levels of service, the effect of WCWDM could be off-set by the resulting growth.

4.7.2 Large-Scale Alternative Water Resources

EWS investigated direct reuse of treated wastewater via construction of recycling facilities at both KwaMashu and Northern WWTWs (both located in the northern areas of the municipality) to jointly transfer 110 Ml/d into the Northern Aqueduct (EWS, 2011; UW, 2019). Religious objections to the practice of wastewater reuse were raised by some members of the Muslim community in Durban, which lead to the potential project being halted. This was investigated in the WRC study *Islamic jurisprudence and conditions for acceptability of reclamation of wastewater for potable use by Muslim users* (Tayob, Deedat & Patel, 2015), with indications that water reclamation was, in fact, constructively supported. It was further found that majority of Muslim scholars supported indirect reuse, though there were remaining concerns around the possibility of hazardous pollutants (specifically medical) remaining in treated water.

The Umgeni Water Masterplan (UW, 2019) and eThekwini's IDP (EM, 2019) nonetheless include direct reuse as a potential project; indirect reuse would be the alternative if the public resistance cannot be overcome in future. Over time, with increasing water scarcity as well as direct reuse becoming established practice elsewhere, direct reuse may be better accepted. Notably, the Durban Water Recycling Project has been a proven success: in 1999, a 20-year concession contract for the operation of a 47.5 Ml/d water recycling plant (to near-potable standards) was initiated. The end-users are industrial establishments (EM, 2014). Umgeni Water also recognises the opportunity in wastewater reclamation to diversify the water resources portfolio and thereby improve resilience in the face of future supply variability. Umgeni Water is constructing a wastewater recycling plant at Darvill WWTW to aid the research and development of these treatment processes (UW, 2019).

In terms of indirect reuse, Section 4.4.2 outlined the possibility of indirect reuse via Hazelmere Dam, as described in the Reconciliation Strategy (DWS, 2017), which would be supplied by the Tongaat and uMdloti WWTWs. Further possibilities are included in the IDP, where (EM, 2019) notes the following: pumping effluent from Phoenix WWTW to Hazelmere Dam for indirect use; pumping effluent from Tongaat WWTW to the abstraction point for Tongaat Water Treatment WTP; and pumping effluent from Amanzimtoti and Kingsburgh WWTWs to blend with the incoming raw water at the Amanzimtoti WTP.

Desalination plants near uMdloti River estuary and Lovu River estuary, each supplying some 150 Ml/d, for the northern and southern portions of the municipality respectively are considered options for implementation in the Umgeni Water Masterplan (UW, 2019). Similarly, eThekwini is piloting (under construction) a desalination/wastewater remix plant where 50% seawater is mixed with 50% sewage for treatment to potable standards; the demonstration plant has a capacity of 6.25 Ml/d, and based on the outcome, the intent is to form a public-private partnership (PPP) to upgrade it to a 100 Ml/day remix plant.

The above alternative water resource options would relieve pressure on the Mgeni WSS (depending on the defined area of supply). Consideration must be given to the time required to commission any such large-scale alternative water supply options, especially in addressing existing and projected supply deficits. The spatial context of options is also important: the impact of developing any given option is linked to its area of supply and the respective predicted growth in water demands (UW, 2019).

4.7.3 Decentralised Alternative Water Resources

Further to the above larger-scale interventions, decentralised, alternative water resources – such as rainwater, stormwater, groundwater, and greywater – have been considered for the region; these are discussed below.

With regards to greywater reuse, vertical food gardens were piloted in the Johanna Road informal settlement. The pilot aimed to test suitability of the application in informal settlements and the safe use of greywater (EM, 2014). EWS and the Agricultural Management Unit (AMU) have collaborated implement small-scale greywater-supplied community food gardens. AMU was interested in further implementation in rural areas (*ibid*). It is unknown whether there has been further progress on these programmes. On the other hand, Carden *et al*. (2017) note that the benefits of greywater reuse – for example for such food gardens – in impoverished areas should be weighed against the potential health risks and (especially) impacts of infection on vulnerable community members.

As described by DWS (2017), the first stages of the Reconciliation Strategy considered rainwater harvesting as a potential means of supplementing water supply. Based on historical rainfall data and parameters for storage tank capacities, initial storage levels in tanks, number of tanks installed, average roof sizes, and rainfall-recovery ratios, the maximum volume which could be supplied without tanks emptying entirely (i.e. the “historical firm yield” of the storage tank system) was determined as varying between 7.6 and 13.5 million m³/annum. It was thus concluded that rainwater harvesting would not have a significant impact on the water balance of the Mgeni WSS. Local benefits such as support of subsistence food gardening, supplementing municipal water supply in drought conditions and/or restrictions or during supply interruptions, and the potential for creating public awareness of water use are nonetheless recognised (*ibid*).

The most recent update to the Reconciliation Strategy (DWS, 2017) included a more detailed assessment of rainwater harvesting to determine the yield under different scenarios and the benefits to municipalities and end-users. Four scenarios were assessed, each including differing prioritisation of rainwater use and end-uses. From the municipal perspective, for rainwater harvesting tanks being installed at all formal housing units in eThekwini, the total available yield varied between 33 to 43 million m³/annum, the lower bound being applicable to rainwater only being used for secondary and outdoor use (laundry, flushing of toilets, gardening and filling of swimming pools), and the upper bound being applicable to the prioritisation of rainwater and its use to satisfy all end-uses, with municipal supply only being used if no rainwater was available.

DWS (2017) cites the benefits to households as savings in the cost of water, possibility for subsistence gardening, water availability when restrictions are in place, and on-site flood attenuation to contribute to achieving the necessary pre-development flood flows as is required for new developments. Benefits to municipalities includes reduction in the overall operational cost of supplying water (the saving being even more pronounced for rural areas which are supplied with tankered water) and reduction in the demand on current and planned water resources. The Reconciliation Strategy (DWS, 2017) thus supports the implementation of rainwater harvesting within the Reconciliation Strategy Area as a “support intervention”, with suggestions to prioritise rainwater harvesting in rural areas, incentivising installation of tanks through subsidies, developing training programmes, and optimising the tank sizes for different areas in consideration of variability of rainfall and roof sizes.

eThekwini has already employed rainwater harvesting in particular areas: in vulnerable areas, EWS installed rainwater harvesting tanks and implemented community cooperative gardens, where the rainwater satisfies the irrigation requirements and other domestic needs. By 2012, 3 600 tanks had been installed in Inanda, KwaMashu, Clifton, Crowder, Zwelibomvu, and Mzinyathi (EM, 2014).

Based on the available information pertaining to the provision of bulk water services and municipal water services, stormwater harvesting (at scale larger than rainwater harvesting at individual properties) does not feature as a considered alternative water resource for eThekwini.

With regards to groundwater use, the majority of the Reconciliation Strategy Area is located in the KwaZulu-Natal Coastal Foreland and Northwestern Middleveld groundwater regions (DWS, 2017). As stated in the Reconciliation Strategy (DWS, 2017), there is limited potential for groundwater development; the use of groundwater resources is thus not a main source of supply of water for Reconciliation Strategy Area at present nor is it considered such for future.

Groundwater is, however, important for rural area supply and to augment surface water resources for irrigation and stock watering. As per UW (2019), private landowners, and augmentation for irrigation and stock watering are the main users of groundwater in the Mgeni catchment, as towns are largely supplied by surface water resources, the exception being the Nottingham Road and Rosetta areas supplied by production boreholes. Groundwater in Howick is abstracted and bottled for sale.

Decommissioned groundwater schemes could be refurbished to alleviate the impact of restrictions when in place. Decommissioned boreholes in rural development programme areas could be considered for recommissioning. In the past, poor water quality limited supply from boreholes and was a key factor in decommissioning of same; though new water treatment technologies may now be able to overcome this constraint. Refurbishment of borehole schemes could be a viable alternative for WSAs that currently tanker potable water to areas without current supply (DWS, 2017).

From a municipal perspective, Armitage *et al*. (2014) note the WSDP (EWS, 2011) for eThekwini does not include mention of groundwater management. The KwaZulu-Natal Groundwater Plan published by DWAF (2008) suggests the following with respect to eThekwini: the groundwater is generally heavily polluted, groundwater monitoring and data management thereof is lacking, and use of groundwater is primarily for industrial purposes (Armitage *et al*., 2014). Conversely, and at a later date than that of the above cited documents, the IDP (EM, 2019) makes mention of treating borehole water to potable standards, though the intended area or extent of supply is not stated.

4.8 Concluding Remarks on Case Study Area

As is the case with most South African cities, eThekwini faces population growth, urbanisation, developmental pressures, resultant increasing water demands, and already stressed water resources. This is set against a backdrop of challenges in service delivery, environmental concerns as a result of water practices, potential impacts of climate change in the future, and sustainability of service provision.

4.8.1 Bulk Water Provider Perspective

Based on the documentation available, it can be seen bulk water provision and those responsible for same (i.e. Umgeni Water and Department of Water and Sanitation) tend to focus on large-scale augmentation of surface water resources and alternative water resources (specifically reuse and desalination). The importance of WCWDM and its impact on system-wide water balances is, nonetheless, recognised. Other initiatives such as rainwater harvesting are viewed as support interventions, and recognised as being potentially beneficial to the municipality and consumers, rather than having appreciable impacts on water supply system yield. Use of boreholes is only encouraged in areas where there are limited alternative means of supply.

Of all the remaining options for the Mgeni system, the Umgeni Water Masterplan (UW, 2019) takes the same position as the Reconciliation Strategy (DWS, 2017): the uMkhomazi Water Project would provide the largest augmentation and meet the long-term requirements of the eThekwini region, also making use of the Western Aqueduct infrastructure when complete.

The uMWP would relieve demands on other Mgeni WSS raw water abstraction points. The earliest possible date for completion of the uMkhomazi Water Project is 2028, with the implication of a growing deficit in the system. The reuse or desalination options could be implemented by 2024, but would not negate the need for the earliest possible implementation of the uMkhomazi Water Project. DWS has therefore instructed TCTA and Umgeni Water to take the project forward (UW, 2019). An important observation is that the abovementioned timeframes for implementation of the uWMP and alternative water supply schemes are later than dates documented in the Reconciliation Strategy.

The reasoning presented in the Reconciliation Strategy clarifies surface water augmentation for the Mgeni WSS as preferred over alternative supply options. While wastewater recycling and desalination options may have higher operational costs, it stands to reason that in the long term there will be a requirement for such solutions (due to limited further feasible surface water augmentation options). These projects should therefore not be viewed as potential interim interventions, but rather as opportunities for WSAs to gain valuable experience in the life cycle of alternative water supply schemes.

The Lower Thukela Bulk Water Supply Scheme and the Raising of Hazelmere Dam and the potential to further augment the Mdloti system from the Northern Seawater Desalination Plant allows the requirements of the northern coastal region to be adequately addressed in the medium to long-term (UW, 2019).

The Lower uMkhomazi Bulk Water Supply Scheme is the preferred option (desalination was the alternative) for augmenting supply on the South Coast. Completion is expected to be complete by the end of 2023 (UW, 2019).

4.8.2 Municipal Perspective

It would appear eThekwini Municipality is investigating reuse and desalination as viable alternative water supply options. Rainwater harvesting and greywater reuse are options which have already been piloted in particular areas; use thereof could be extended further. eThekwini continues to invest in WCWDM initiatives and programmes; this will remain critical if the municipality is to improve on the current situation and prevent system attrition increasing the total system demand and result in inefficient use of limited resources.

5 System Modelling

This chapter presents the structure and function of the system model developed to support this study. Further detail can be found in Appendix A: Model Inputs and Appendix B: Additional Model Details.

5.1 Model Approach

In consideration of the challenges and constraints within the case study area, the core benefits of SUWM (a more natural water cycle; improved water security through diversification of sources; and resource efficiency) are appropriate objectives for potential SUWM interventions. While large-scale surface water augmentation has been shown to be essential in the medium term, the implementation timeframes for projects of such nature are spread over a number of years, and therefore may mean SUWM interventions implemented in the interim would improve the outlook on the current assurance of supply.

The model has been developed to include the following interventions:

- Water Conservation and Water Demand Management;
- Rainwater Harvesting;
- Stormwater Harvesting;
- Greywater Reuse;
- Groundwater;
- Wastewater Recycling; and
- Desalination.

While some of these interventions do not appear to be considered for future plans from either a bulk water provider or municipal perspective (e.g. stormwater harvesting), they have nonetheless been included as an option in the system model should any future users wish to test the impact thereof.

The system model developed is flexible enough for either individual interventions or combinations of interventions to be modelled and analysed. The following scenarios ("themes") have been selected for presentation and discussion in Chapter 6 (refer to Appendix C: Additional Model Results for key model results for all interventions):

i. Scenario 1: Water Conservation and Water Demand Management; this scenario includes WCWDM measures upstream and downstream of individual consumer connections. This scenario explores what could be achieved by a relatively conservative WCWDM programme. While eThekwini already invests in programmes aimed at reduction of real losses, measures which can be implemented at the household or individual consumer level (e.g. plumbing retrofits with water saving devices) are also included.

ii. Scenario 2: Rainwater harvesting with real loss reduction; this scenario explores rainwater harvesting, along with real loss reduction measures. This scenario is focussed on the decentralisation offered by rainwater harvesting as an alternative water source.

iii. Scenario 3: Greywater reuse with WCWDM; this scenario builds on Scenario 1, where in addition to other consumer-focused water-saving measures, greywater reuse is encouraged at a household or individual consumer level.

iv. Scenario 4: Wastewater recycling (to potable and non-potable standards) with real loss reduction; this scenario explores wastewater recycling, used in conjunction with real loss reduction measures.

In that WCWDM is already established in eThekwini municipality and is an all-encompassing strategy within the SUWM space, it appears in each of the above scenarios, though only Scenarios 1 and 3 include a variety of conservation measures adopted at the individual consumer level.

Modelled interventions were assessed based on overall system impacts such as, *inter alia*, demand on surface water resources, wastewater generated, contribution to urban runoff, and concentration of pollutants in systems. Asides from overall system impact, a composite score was determined based on selected criteria and indicators. The table of indicators from the review study of Rathnayaka, Malano & Arora (2016) formed the basis for indicator selection, each of which were then screened for applicability to this study (refer to Appendix E: Indicator Vetting Process for a summary of the outcomes of this procedure). Indicators of resource efficiency as defined by Farooqui, Renouf & Kenway (2016) have also been adopted:

i. Internal harvesting ratio: defined as the ratio of the volume of water harvested to the total volume of water supplied to meet demand.
ii. Internal recycling ratio: defined as the ratio of the volume of water recycled or reused to the total volume of water supplied to meet demand.
iii. Water extracted per capita, which specifically considers water supplied from centralised (bulk water) sources.
iv. Energy use per capita, considering energy requirements of bulk potable water, sanitation, and alternative water servicing options.

The above indicators provide valuable insights into the value-add of alternative water servicing options. In that projected water demands are a function of population growth, demand growth, and demand reductions as a result of water conservation measures, water extracted per capita is specifically useful in disaggregating from projections the impact of population growth.

Figure 5-1 summarises the indicators selected and the structuring of same to form a composite score for each analysis of the system.

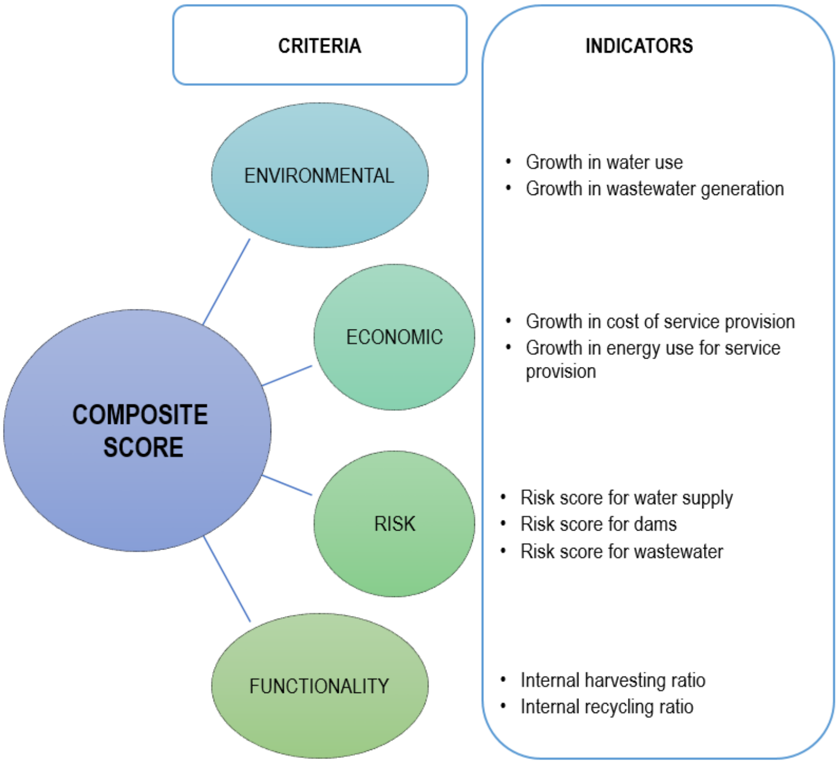


Figure 5-1: Structuring of Indicators and Criteria for Composite Scores

While the indicators for a comprehensive assessment of SUWM solutions could potentially be more extensive and detailed than those selected for the assessment in this study, the macro-scale nature of the developed model is not conducive to such and would require more in-depth analysis of the infrastructure in the study area. Social, institutional, governance, and public health matters are commonly included in multi-dimensional assessments of water supply systems but have been excluded here; in addition to being difficult to quantify or model, such assessments are more appropriately based on a participatory approach with stakeholders, which was beyond the scope of this study. Finally, Table 5-1 summarises the data sources used in developing parameters for the system model (Note: Literary sources of information are noted against specific parameters in Section 5.2).

Table 5-1: Summary of Data Sources

Data	Source	Type of Data
Population	Census 2011	GIS shapefiles (i.e. represented spatially)
Billed Metered Consumption	eThekwini COINS database	GIS shapefiles (i.e. represented spatially)
Reservoir Zones	eThekwini GIS database	GIS shapefiles (i.e. represented spatially)
Water network and facilities	eThekwini GIS database	GIS shapefiles (i.e. represented spatially)
Wastewater Treatment Works Drainage Areas	eThekwini GIS database	GIS shapefiles (i.e. represented spatially)
Sewer network and facilities	eThekwini GIS database	GIS shapefiles (i.e. represented spatially)
Dams	Umgeni Water GIS database	GIS shapefiles (i.e. represented spatially)
Dam storage-depth-area curves	Umgeni Water	Excel files
Bulk pipelines, aqueducts, and other water facilties	Umgeni Water GIS database	GIS shapefiles (i.e. represented spatially)
Historical waterworks production	Umgeni Water Masterplans, 2019	Report
Rainfall	South African Weather Service	Text files of daily rainfall data as recorded at rainfall stations
Naturalised catchment flows	WR2012 / WRSM/Pitman model runs	Text files of monthly flows modelled and calibrated
Evaporation	WRSM/Pitman model runs	Text files for evaporation data for catchments of interest
Cost and energy intensity of bulk water provision (abstraction and treatment)	Umgeni Water Finance Dept.; Umgeni Water Masterplans, 2019	Email; Report
Groundwater Availability	DWS NIWIS – based on GRA2	Excel files
Quaternary catchment areas; **Hydrological features;** **Gauging stations**	WR2012	GIS shapefiles (i.e. represented spatially)
Landform – Parcels and building footprints	eThekwini GIS database	GIS shapefiles (i.e. represented spatially)
Rivers and dams water quality data	Compilation of recorded data	Excel files

5.2 System Model Construction

5.2.1 Overall Model Structure and Simulation Settings

The system model was developed in GoldSim, and is a macro-scale model of the eThekwini municipal area's water services systems, comprising an integrated flow model and a contaminant transport model. Within this, there are sub-models which support the main model, each of which are discussed in the relevant sections of this chapter. Figure 5-2 presents a map of the systems model.

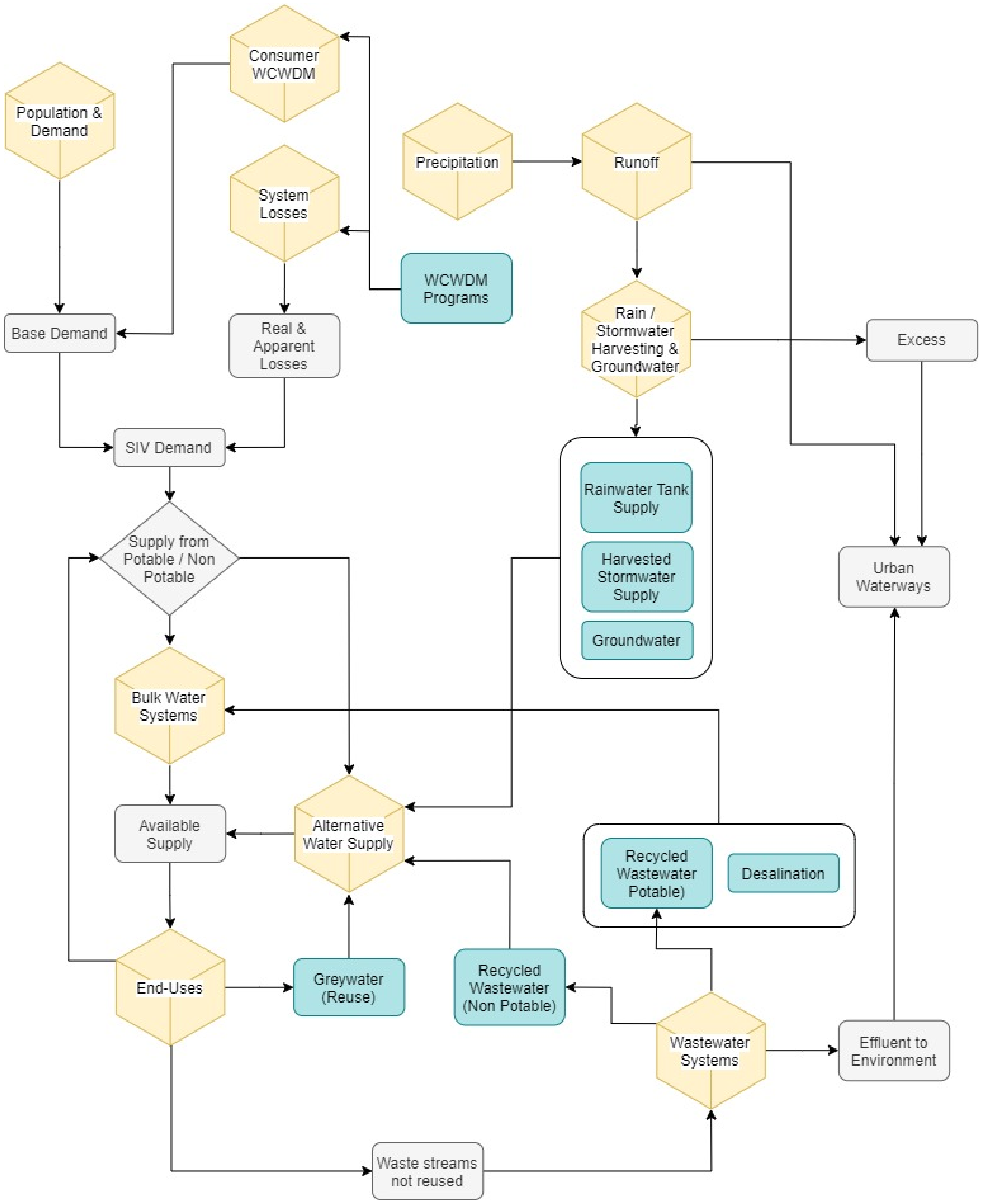
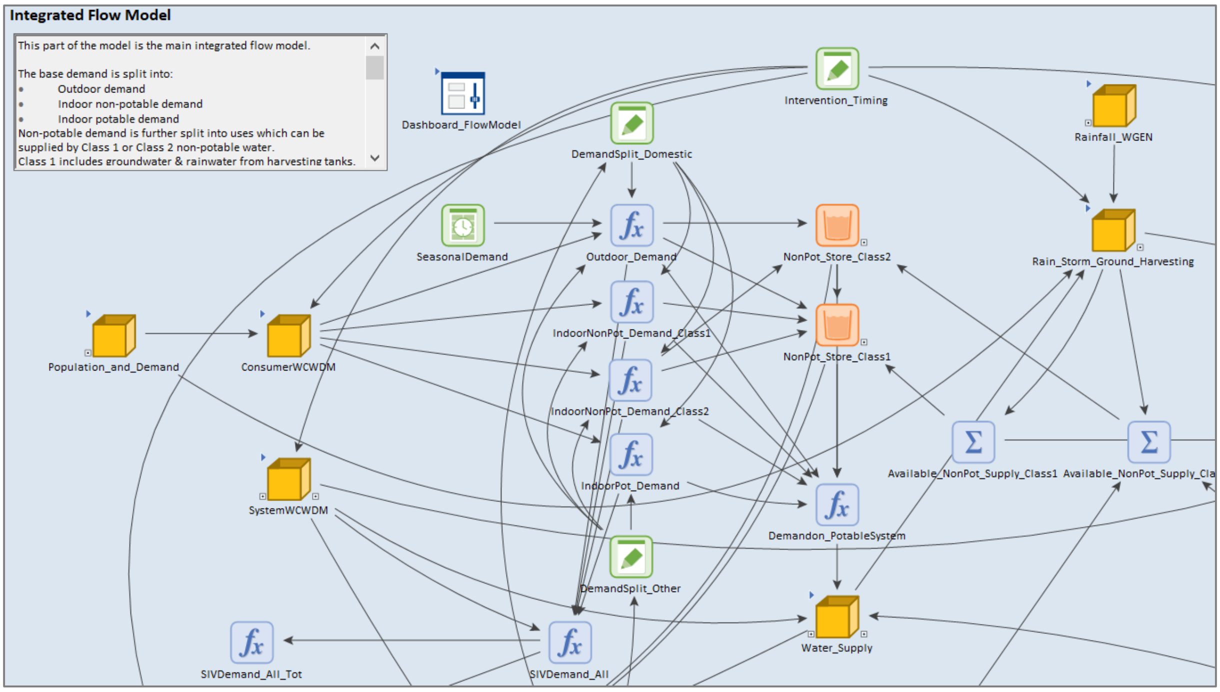


Figure 5-2: Systems Model Map

A sample view of a portion of the integrated flow model is included in Figure 5-3. A user interface has been facilitated through creation of a number of dashboards where input information may be entered and results of simulation runs viewed. Figure 5-4 is illustrative of a portion of one such dashboard.



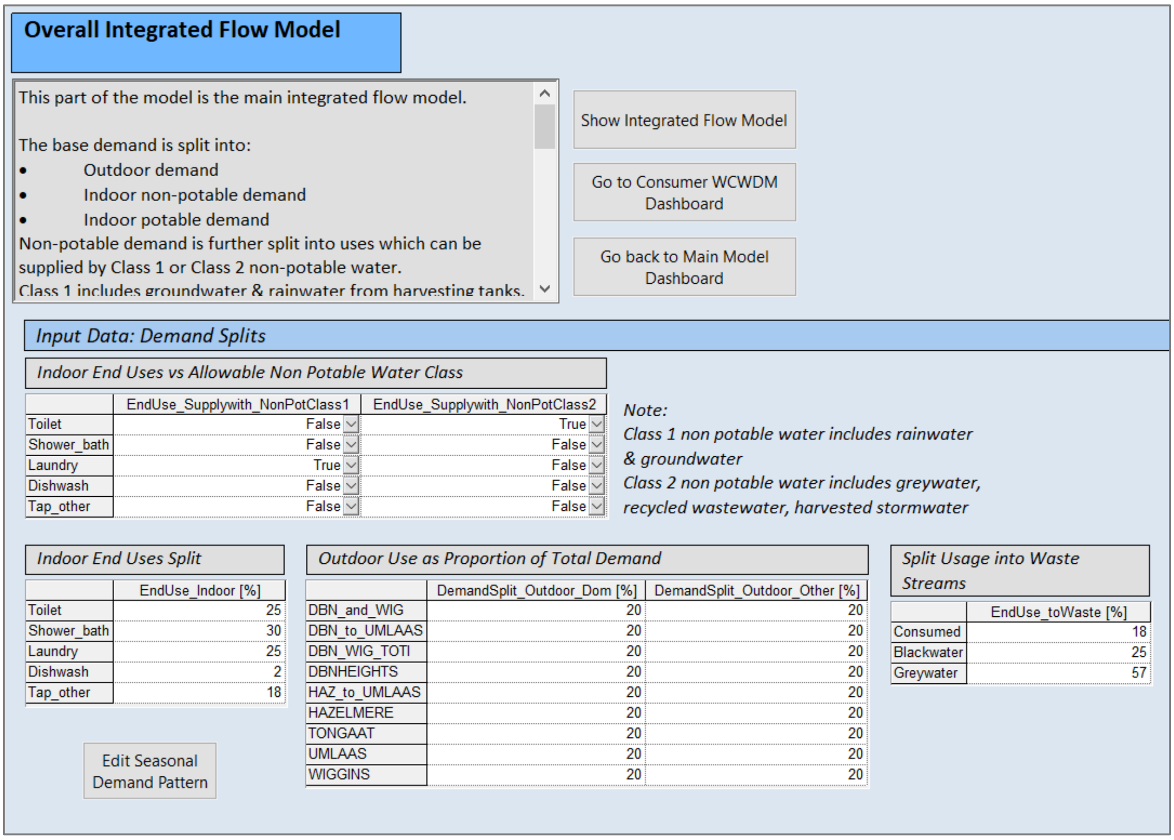
This part of the model is the main integrated flow model.

The base demand is split into:

- Outdoor demand
- Indoor non-potable demand
- Indoor potable demand

Non-potable demand is further split into uses which can be supplied by Class 1 or Class 2 non-potable water.
Class 1 includes groundwater & rainwater from harvesting tanks.

Figure 5-3: Sample View of Integrated Flow Model



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Class 1 includes groundwater & rainwater from harvesting tanks.

Indoor End Uses vs Allowable Non Potable Water Class

	EndUse_Supplywith_NonPotClass1	EndUse_Supplywith_NonPotClass2
Toilet	False	True
Shower_bath	False	False
Laundry	True	False
Dishwash	False	False
Tap_other	False	False

Note:
Class 1 non potable water includes rainwater & groundwater
Class 2 non potable water includes greywater, recycled wastewater, harvested stormwater

Indoor End Uses Split

	EndUse_Indoor [%]
Toilet	25
Shower_bath	30
Laundry	25
Dishwash	2
Tap_other	18

Outdoor Use as Proportion of Total Demand

	DemandSplit_Outdoor_Dom [%]	DemandSplit_Outdoor_Other [%]
DBN_and_WIG	20	20
DBN_to_UMLAAS	20	20
DBN_WIG_TOTI	20	20
DBNHEIGHTS	20	20
HAZ_to_UMLAAS	20	20
HAZELMERE	20	20
TONGAAT	20	20
UMLAAS	20	20
WIGGINS	20	20

Split Usage into Waste Streams

	EndUse_toWaste [%]
Consumed	18
Blackwater	25
Greywater	57

Figure 5-4: Sample View of User Interface / Dashboard

The simulation start time is set at 1st January 2020, and for purposes of assessing interventions over a period of time, the model run time is 15 years. These parameters may easily be changed, though certain input information would require adjustment to suit an alternative start time. The time increment (also known as a “time step”) has been set at 1 day, such that daily changes in flow regime may be captured. Given the scale (spatial and temporal) of the model, this is deemed reasonable: there would be little benefit in reducing the time increment for the particular application represented in the model, though for a detailed hydraulic model (of say, a water network) would justify a finer time scale where hourly variation in demand required computation.

5.2.2 Population and Base Demand Model

In terms of service provision, the entire municipal area may be considered subdivided into water supply zones (at a reservoir level) and wastewater treatment works drainage areas. Given the complex infrastructure linkages between reservoir zones, for purposes of the systems model and computations therein, the water supply areas are aggregated to a bulk supply level where areas are defined by the supplying water treatment facility. The bulk supply zones have therefore been defined as those with distinct supply areas which are not interlinked. For example, the output of Amanzimtoti WTW is augmented with potable water from Wiggins WTW; a single supply zone for the areas supplied by these two WTWs is therefore defined. Areas which will in future be supplied from another water supply system have also been separately defined; for example, the portion of the Durban Heights WTW supply zone which will in future be supplied by the Umlaas Road sub-system is defined as a unique area. Figure 5-5 and Figure 5-6 are illustrative of the defined water supply and wastewater drainage areas.

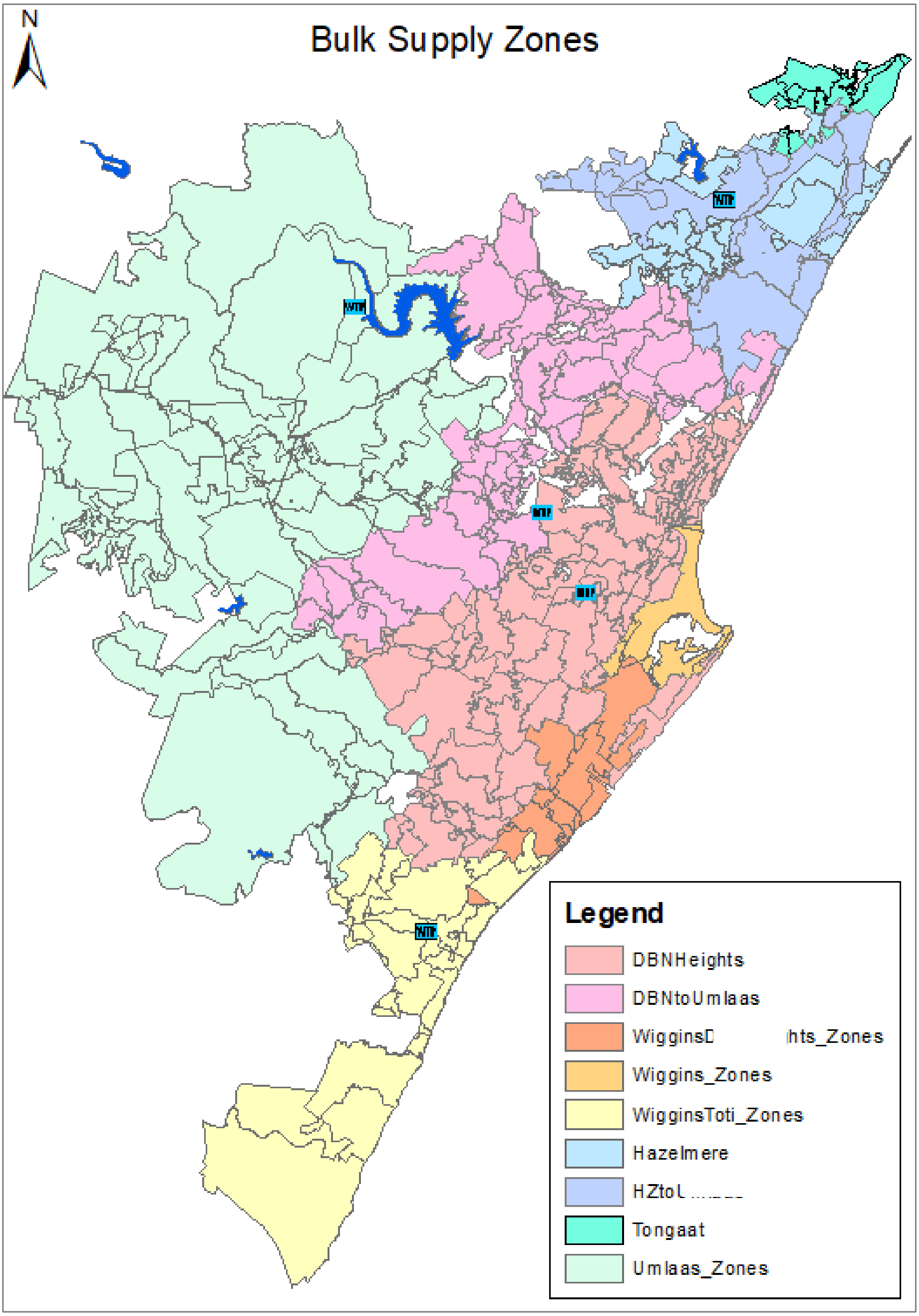


Figure 5-5: Defined Bulk Water Supply Zones

Note: "DBN to Umlaas" and "HZtoUmlaas" areas are currently supplied by Durban Heights and Hazelmere WTWs (respectively), and in future will be supplied by the Umlaas Road sub-system after the "load shift" operation has been completed.

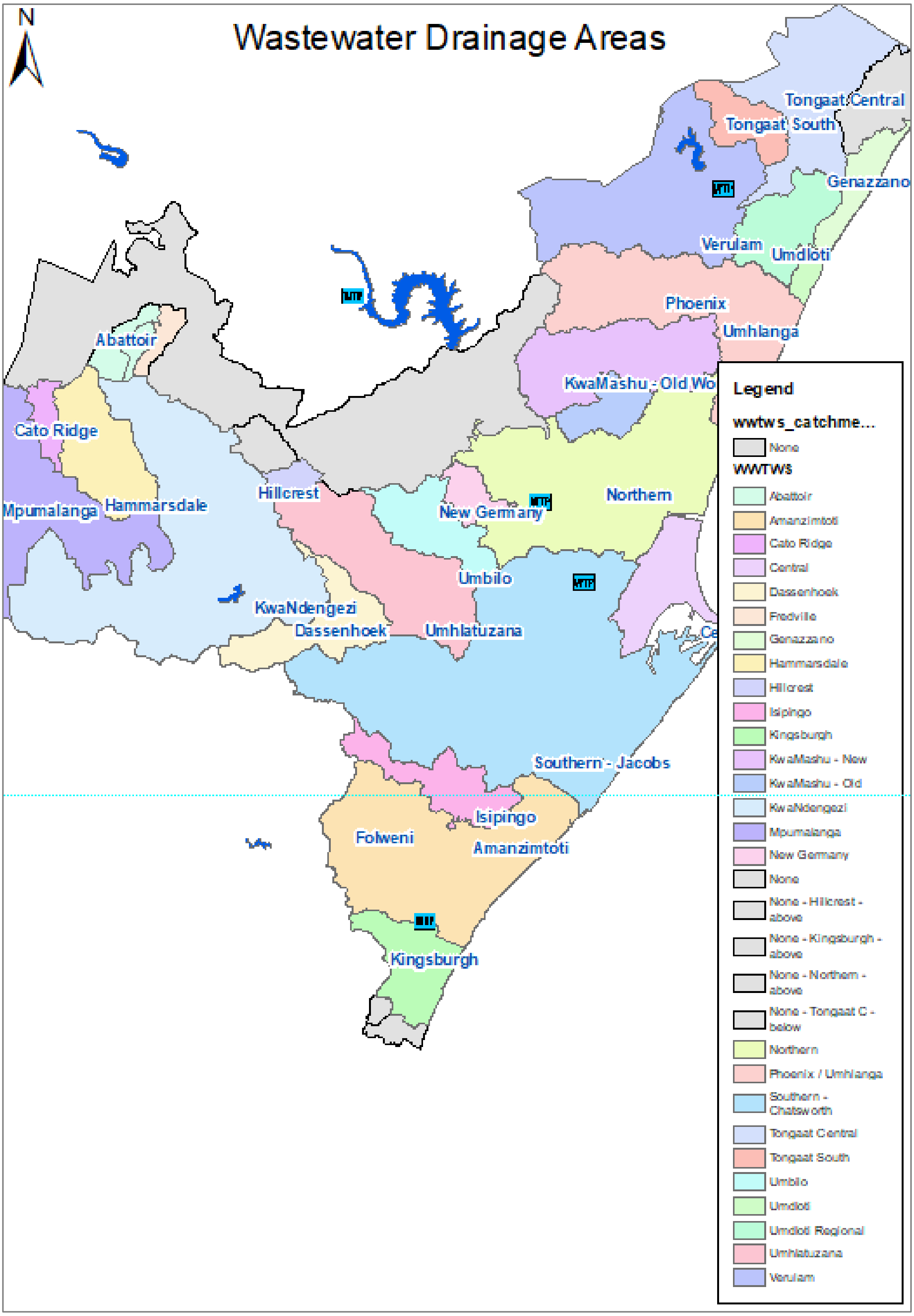
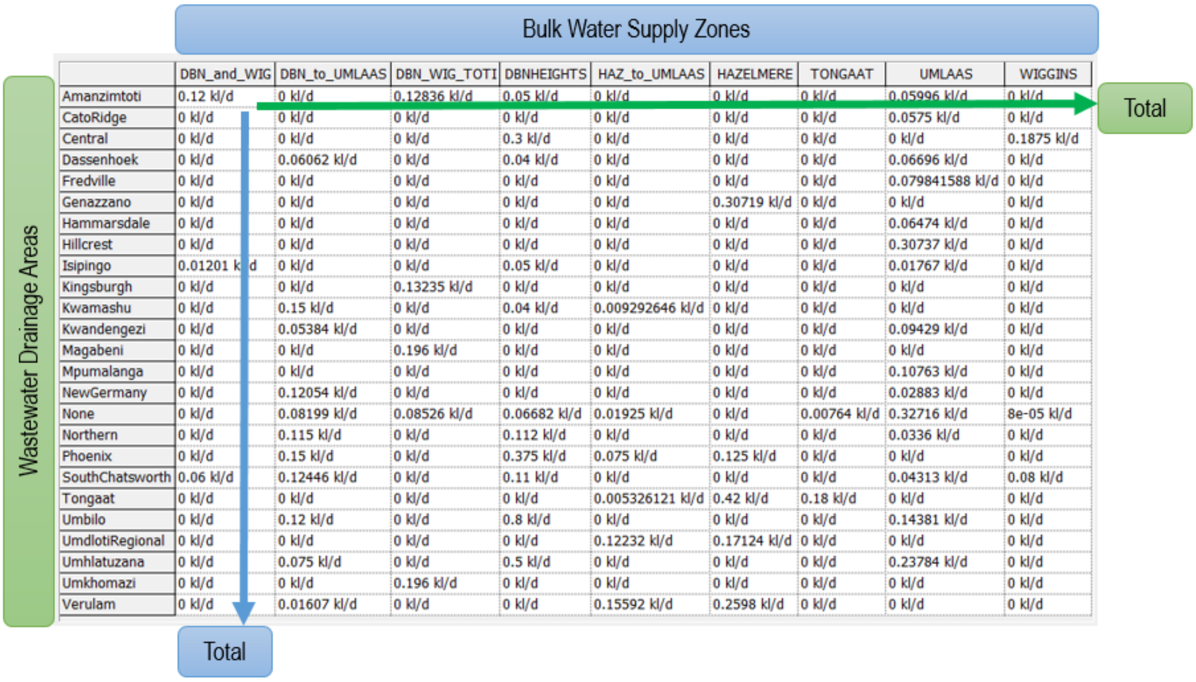


Figure 5-6: Wastewater Drainage Areas

The bulk water supply and wastewater drainage areas do not necessarily align (i.e. one bulk supply area may contain a number of wastewater drainage areas or parts thereof, or one wastewater drainage area may extend over more than one bulk supply area). The most efficient means of dealing with this spatial distribution of water and wastewater service areas was to create matrices of same. The components of the integrated flow model are therefore generally computed for these matrices comprising bulk water supply areas and wastewater treatment works drainage areas, such that the system input volume can be calculated for each bulk supply area, and the return flows can be calculated for each wastewater drainage area. WWTW drainage areas are simply defined as the catchment for each WWTW. Areas not connected to any WWTW (i.e. either there is no waterborne sanitation or septic/conservancy tanks are in use) are allocated to an area denoted as “None”.



	DBN_and_WIG	DBN_to_UMLAAS	DBN_WIG_TOTI	DBNHEIGHTS	HAZ_to_UMLAAS	HAZELMERE	TONGAAT	UMLAAS	WIGGINS
Amanzimtoti	0.12 kl/d	0 kl/d	0.12836 kl/d	0.05 kl/d	0 kl/d	0 kl/d	0 kl/d	0.05996 kl/d	0 kl/d
CatoRidge	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.0575 kl/d	0 kl/d
Central	0 kl/d	0 kl/d	0 kl/d	0.3 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.1875 kl/d
Dassenhoek	0 kl/d	0.06062 kl/d	0 kl/d	0.04 kl/d	0 kl/d	0 kl/d	0 kl/d	0.06696 kl/d	0 kl/d
Fredville	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.079841588 kl/d	0 kl/d
Genazzano	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.30719 kl/d	0 kl/d	0 kl/d	0 kl/d
Hammarsdale	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.06474 kl/d	0 kl/d
Hillcrest	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.30737 kl/d	0 kl/d
Isipingo	0.01201 k d	0 kl/d	0 kl/d	0.05 kl/d	0 kl/d	0 kl/d	0 kl/d	0.01767 kl/d	0 kl/d
Kingsburgh	0 kl/d	0 kl/d	0.13235 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d
Kwamashu	0 kl/d	0.15 kl/d	0 kl/d	0.04 kl/d	0.009292646 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d
Kwandengezi	0 kl/d	0.05384 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.09429 kl/d	0 kl/d
Magabeni	0 kl/d	0 kl/d	0.196 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d
Mpumalanga	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.10763 kl/d	0 kl/d
NewGermany	0 kl/d	0.12054 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.02883 kl/d	0 kl/d
None	0 kl/d	0.08199 kl/d	0.08526 kl/d	0.06682 kl/d	0.01925 kl/d	0 kl/d	0.00764 kl/d	0.32716 kl/d	8e-05 kl/d
Northern	0 kl/d	0.115 kl/d	0 kl/d	0.112 kl/d	0 kl/d	0 kl/d	0 kl/d	0.0336 kl/d	0 kl/d
Phoenix	0 kl/d	0.15 kl/d	0 kl/d	0.375 kl/d	0.075 kl/d	0.125 kl/d	0 kl/d	0 kl/d	0 kl/d
SouthChatsworth	0.06 kl/d	0.12446 kl/d	0 kl/d	0.11 kl/d	0 kl/d	0 kl/d	0 kl/d	0.04313 kl/d	0.08 kl/d
Tongaat	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.005326121 kl/d	0.42 kl/d	0.18 kl/d	0 kl/d	0 kl/d
Umbilo	0 kl/d	0.12 kl/d	0 kl/d	0.8 kl/d	0 kl/d	0 kl/d	0 kl/d	0.14381 kl/d	0 kl/d
UmdlotiRegional	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.12232 kl/d	0.17124 kl/d	0 kl/d	0 kl/d	0 kl/d
Umhlatuzana	0 kl/d	0.075 kl/d	0 kl/d	0.5 kl/d	0 kl/d	0 kl/d	0 kl/d	0.23784 kl/d	0 kl/d
Umkhomazi	0 kl/d	0 kl/d	0.196 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d
Verulam	0 kl/d	0.01607 kl/d	0 kl/d	0 kl/d	0.15592 kl/d	0.2598 kl/d	0 kl/d	0 kl/d	0 kl/d

Figure 5-7: Illustration of Water Supply Zone vs Wastewater Drainage Area Matrices

Domestic water demand is inherently stochastic, and is influenced by a number of factors: socio-economic (household size, income, stand area, social status, number of household appliances, social patterns, public and school holidays, tourism and water price), climatic (temperature, rainfall, humidity, time since last rainfall and the number of preceding hot days) and structural (number of users, water metering, plumbing fitting properties, pressure and network capacity) (Griffioen & Van Zyl, 2014). Stand area has been found to be most influential in determining demand, thus validating the approach of South African design guidelines (*ibid*). Billed metered consumption (BMC) information, as obtained from EWS, was nonetheless available for use in this study. A population-based demand model was selected for application in this study: the BMC data provides actual usage information, which inherently accounts for the abovementioned factors. Furthermore, the rural areas would likely skew demand estimates should it have been based on stand area – there are large tracts of land with little to no cadastral boundaries, making spatial analysis of stand areas challenging.

The base population figures were obtained from the most recent (2011) census data at ward level. The method by which the base population per area was derived was based on that utilised in the Reconciliation Strategy Water Requirements sub-report (DWS, 2008): utilising GIS software, the population per ward was first disaggregated into small polygons; these polygons were subsequently aggregated for each bulk supply and drainage area. The result is a total population per bulk supply and drainage area.

The BMC, which is represented spatially in GIS, was allocated to each bulk supply and drainage area. In that the BMC database includes classification of consumer type (i.e. domestic, industrial, institutional, commercial, etc.) the BMC in each area was divided into domestic and all other land use typologies (further subdivisions of land use types could be implemented, but this was deemed a reasonable simplification given the macro scale of the model). The end result is a matrix of base demand per capita for domestic use, and a matrix of base demand per connection for other land use types.

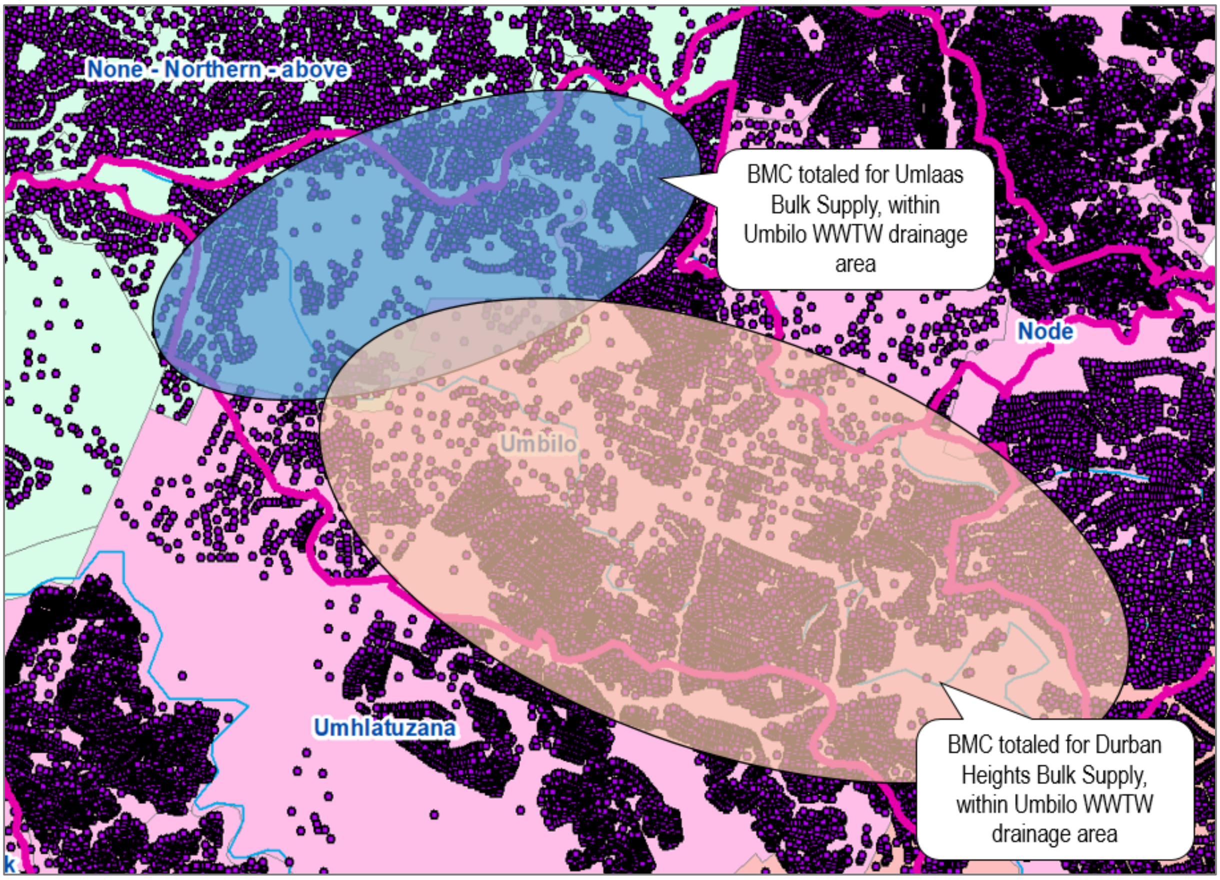


Figure 5-8: Example of Aggregating BMC per Bulk Water Supply and Wastewater Drainage Area

The Reconciliation Strategy Water Requirements sub-report (DWS, 2008) included research into low, medium, and high population growth rate trends through to 2030 which could further be disaggregated into primary systems or water supply “nodes” viz. North, South, Central, and West. Historically (sixties through to nineties), the central, inner west, and south areas saw the highest growth. More recently (ten years prior to the first KZN WRSS), the outer west and north have experienced higher growth in both population and economic activity. Forecasts favour the same trend of higher growth in the northern area (*ibid*).

The “high-road” (i.e. upper-bound) population projection up to 2030 for the respective areas was adopted for the model: the Reconciliation Strategy Studies (DWS, 2008; DWS, 2017) favour this more conservative approach, and the high-road population projection is more consistent with the later reported municipal population in the IDP (EM, 2019).

Table 5-2: Adopted Population Growth

Area	Water Treatment Works	Population Growth (% p.a.)
Central	Served by Durban Heights and Wiggins	0.4
South	Served by Wiggins and Amanzimtoti	0.6
West	Served by Midmar and DV Harris	1.2
North	Served by Hazelmere and Tongaat	1.6

In that population projections from the original Reconciliation Strategy Water Requirements sub-report (DWS, 2008) as well as the municipal IDPs extend to 2030, the model structure makes provision to define new growth rates past 2030 for scenario modelling. The Reconciliation Strategy (DWS 2008; DWS 2017) and Umgeni Water Masterplan (UW, 2019) indicate that in addition to population growth, increased or improved levels of service in particular areas will increase the base demand. The model makes allowance for same.

Further to calibration of the population and the BMC against available reports and records (refer to Section 5.2.12), the demand per capita determined from the population and demand model was compared to that contained in The Neighbourhood Planning and Design Guide (Department of Human Settlements, 2019) and a water demand study by Griffioen & Van Zyl (2014).

5.2.3 System Input Volume

The SIV – or total potable water requirement – comprises the billed metered consumption, real losses, and apparent water losses. Real losses represent all the physical water losses from the water distribution system, upstream of the consumer’s water meter (McKenzie & Lambert, 2002). Apparent losses represent the unauthorised consumption (theft or illegal use) and any inaccuracies in customer metering. Apparent losses should not constitute a major component of the water balance in most parts of South Africa; in a normal well-managed system, one could expect apparent losses constituting between 10% and 20% of the total losses. Exceptional cases occur where payment levels are low and/or flat rate tariffs are used: for example, in Johannesburg the apparent losses tend to be the same magnitude as real losses due to fixed monthly tariffs and high levels of non-payment. In Khayelitsha, large volumes of water are lost after the meter (poor plumbing fixtures) resulting in apparent losses as high as 80% (McKenzie & Lambert, 2002).

Initial real losses and apparent losses were included in the model based on reported figures contained in the eThekwini WSDP (EWS, 2011) and Umgeni Water Masterplan (UW, 2019). Further considerations may be found in Appendix B: Additional Model Details. Whether real loss reduction interventions are implemented or not, the model incorporates increasing real losses as a result of system attrition as the system ages, which is consistent with the approach taken in the latest revision of the Reconciliation Strategy (DWS, 2017) where water requirement projections included system attrition, with and without WCWDM interventions. The projection for system attrition, along with no real loss reduction interventions, yields the upper envelope of the SIV.

5.2.4 End-Use Model

End-uses were modelled such that return flows could be calculated, as intervention options require quantifying:

- The portion of daily demand suitable for different "classes" of non-potable water supply options. Section 5.2.10 includes an overview of "fitness for purpose" where the appropriate end-use is defined for alternative water sources;
- The volume of greywater available for reuse; and
- The volume of treated wastewater available for reuse.

Daily demand was subsequently split into outdoor demand, indoor potable demand, and indoor non-potable demand, and is a function of the percentage allocated to specific end-uses. The breakdown of end-uses was based on the typical values included in the recently updated Neighbourhood Planning and Design Guide (DHS, 2019). The allocations in the residential end-use model (REUM) developed by Jacobs and Haarhoff (2004) as applied to a stand of 1000m^2 are largely similar. Variation in seasonal demand has not been considered: the selected dataset of BMC analysed for development of the model parameters does not, in any case, indicate a discernible variation in demand over the year.

Wastewater comprises two broad waste streams, namely blackwater and greywater. Blackwater contains high concentrations of faecal matter and urine, and is therefore highly contaminated. Greywater is a result of all wastewater generated by all other water use processes and thus contains less organic matter (Armitage *et al*., 2014), though Carden *et al*. (2017) note this may not be true for greywater originating in informal and/or un-serviced settlements.

Based on the above considerations, Table 5-3 summarises proportion of total demand for each end-use, and the waste stream which the used water will enter.

Table 5-3: Summary of End-Use and Application in Model

End-Use	Proportion of Indoor Demand (%)	Proportion of Total Demand* (%)	Waste Stream
Outdoor	-	20	None
Consumptive	1	0.8	None
Tap / Kitchen	17	13.6	Greywater
Dishwasher	2	1.6	Greywater
Laundry	25	20	Greywater
Bathroom	30	24	Greywater
Toilet	25	20	Blackwater

**Note: The results in this column are based on an outdoor use of 20% of the total demand; during model calibration and in studying the respective defined areas in relation to the guidance given in The Neighbourhood Planning and Design Guide* (DHS, 2019)*, this was found appropriate for most areas. Where necessary, this value has been adjusted; tables of varying outdoor demand may be found in Appendix A: Model Inputs.*

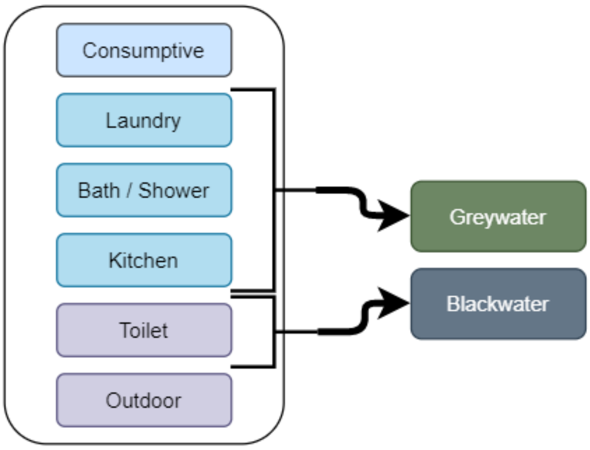


Figure 5-9: Illustration of End-Use and Application in Model

Based on the above, it can be seen that just less than 80% of the average daily demand becomes wastewater. Further detail on the computation of the volume of wastewater reaching a WWTW is outlined in Section 5.2.6.

Real losses in the distribution network occur upstream of consumer connection points, and are thus not accounted for in return flows. Any physical losses downstream of consumer connection points are metered and are thus already accounted for in the billed metered consumption. In that apparent losses represent a volume of water which is being consumed but not metered, along with metering inaccuracies, this volume of water is included in the end-uses which produce wastewater.

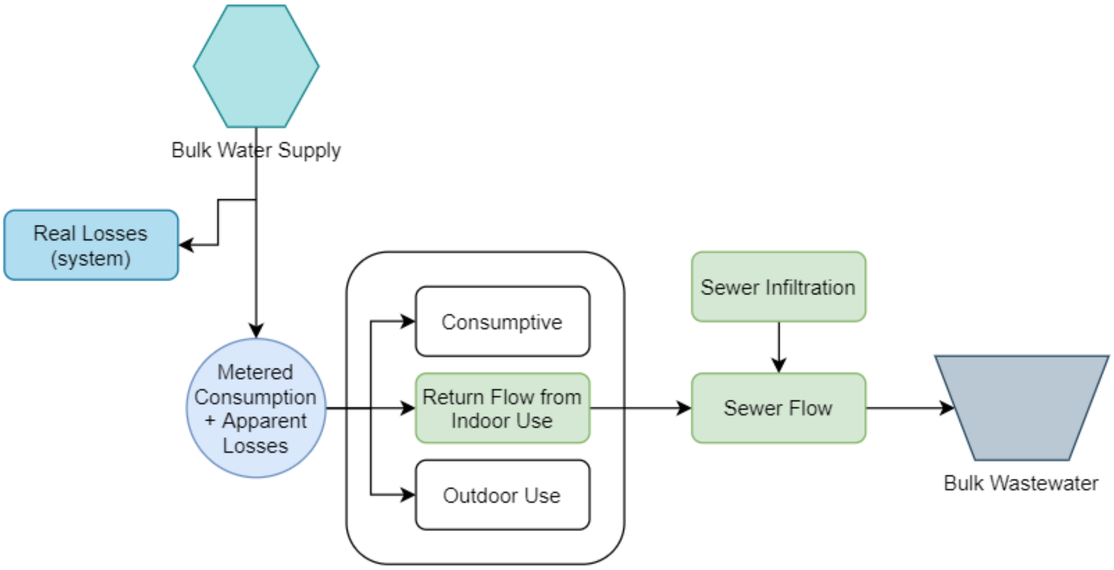


Figure 5-10: Summary of Water Balance from Bulk Supply to Wastewater Generation

5.2.5 Bulk Water Systems Model

Only water resources which are in some way connected to eThekwini are modelled; i.e. South Coast and North Coast sub-systems which only supply other municipalities are not included. The bulk supply areas defined in the model are “rolled up” to the main supply systems, viz. the Upper Mgeni System, the Lower Mgeni System, and the North Coast System – this approach has been adopted due to the integration within each of these supply systems to match demand and availability of water resources. It must be noted the model only considers limitations in supplying potable water as a result of WTW capacities and dam yields; infrastructure constraints relating to conveyance (pipelines) or storage (reservoirs) are not considered. This was based on the assumption that such constraints may be overcome – if indeed necessary.

Future augmentation, i.e. the Smithfield Dam which will transfer water from the Umkhomaas catchment to the Mgeni catchment as well as the Lower uMkomazi bulk water supply scheme on the South Coast is included in the model. Based on information in the Umgeni Water Masterplan (UW, 2019), Lower uMkomazi and Smithfield schemes have been assumed to be implemented in 2023 (t = 3 years) and at the end of 2028 (t =9 years) respectively. As described in Chapter 4, there are projects underway to facilitate a portion of the Durban Heights WTW and Hazelmere WTW areas being transferred onto the Umlaas Road (Upper Mgeni) sub-system. The transfer of demand is planned to occur prior to the implementation of the uMkhomazi Water Project, though the full demand cannot be accommodated due to limitations in Midmar Dam yield and Upper Mgeni treatment works capacities. The “load shift” operation has been included in the model structure, though allowance has been made to do so in two stages, where a portion of the demand is transferred prior to the uMWP, and the remainder after the uMWP is commissioned.

Figure 5-11is illustrative of the respective water supply systems.

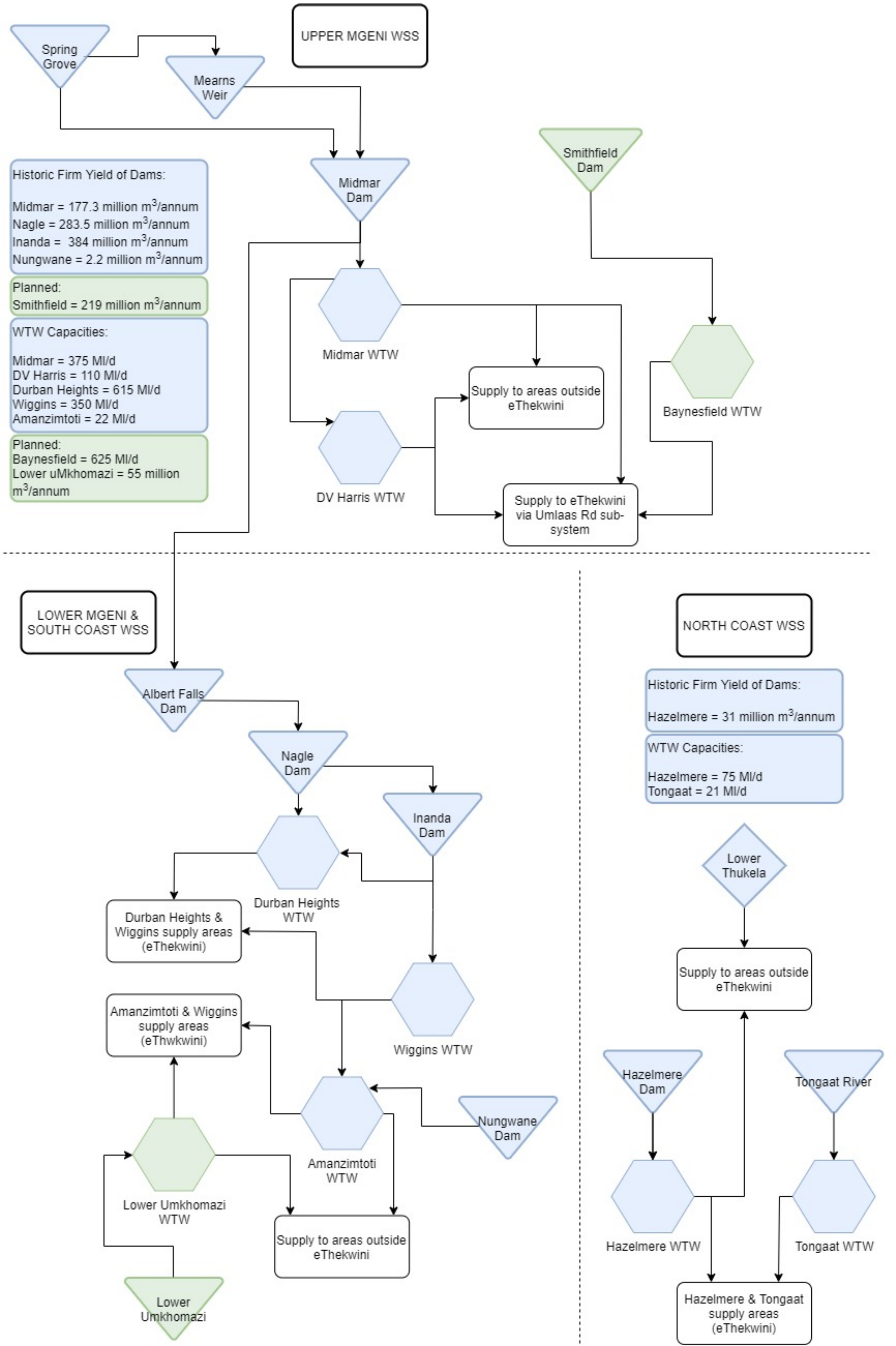


Figure 5-11: Schematic of Bulk Water Supply Systems

Each dam in the respective supply systems was modelled as a reservoir, each of which comprising of and influenced by the following aspects:

i. Active storage volume: The active storage volumes are as per Umgeni Water's database of dams in their areas of operation.

ii. Sedimentation: Sedimentation in dams has the effect of reducing the available storage capacity, and thus the available yield of the water resource. Umgeni Water has record of surveyed dam storage at different points of the asset's life cycle; where more than one data point was available, the sedimentation rate was estimated as the difference in the storage volumes over the defined period of time between surveys. Where this information was not available, the results of the WRC study Sediment Yield Prediction for South Africa: 2010 Edition (Msadala et al., 2010) were applied to the dam catchments in question.

iii. Total inflows: Streamflows are required at sites of interest, and may be based on the rainfall runoff models or on measured flows. Modelling of alternative scenarios or policies should incorporate naturalised flows – that which would have occurred under natural conditions (i.e. without influence of upstream regulation, storage, or diversion). Naturalised flows may be estimated from gauged flows (adjusted to remove upstream interferences) or rainfall-runoff modelling (Loucks & Van Beek, 2005). The Water Resources of South Africa, 2012 Study (WR2012) and preceding studies (originating in 1952) have provided key hydrological information to professionals involved in water resource planning and management water resource managers in South Africa (Bailey & Pitman, 2015). One of the study outputs are sets of time series of naturalised flows (monthly) from 1920 to 2009 for gauged and ungauged catchments (based on similarities in geology, topography, soil type, natural vegetation and climate to calibrated model parameters). The model ignores alien vegetation, afforestation, and paved flows, and there are no reductions in catchment area for irrigation and mining activities (ibid). Total inflows to each dam are thus based on naturalised stream flow series (per quaternary catchment) as available through the WR2012 Study. The temporal scale of this data is monthly; while longer than the temporal scale of the model, it is deemed acceptable given the use of same in other hydrological models and the time taken for large reservoirs to react to changes in demand or inflow. Importantly, the naturalised flow time series are based on hydrological models which have been developed and calibrated by experts in the field of water resources engineering and hydrology. The GoldSim model could, in future, be expanded to include rainfall runoff modelling as executed by the WRSM/Pitman program.

iv. Evaporation: The evaporation for each water body is based on the evaporation rate and the water body areal coverage, which is governed by the storage-depth-area relationship particular to each dam. Evaporation rates were obtained from outputs of the WRSM/Pitman program.

v. Total water requirements or requested outflows: Environmental flow requirements, or rather compensation flows as is the case for dams in the Mgeni WSS, are imposed on each water resource. Information on environmental flows and compensation flows was obtained from the Reconciliation Strategy documents (DWS, 2008; DWS, 2010; DWS, 2017). The downstream demands referred to each dam are a function of the modelled demands, the interconnected nature of the Mgeni WSS dams, and the general operating rules of the dams in the Mgeni WSS.

vi. Available or firm yield: The model allows for selection of whether or not yield limits are to be applied or not (refer to Chapter 4 for the importance of dam withdrawals remaining within allowable yield limits). Yield information was obtained from the Umgeni Water Masterplans (UW, 2019). Based on the outcomes of climate change modelling as discussed in Chapter 4, the model allows for selection of either an increase or decrease in water resource yields.

vii. Operating rules: Optimising the available water resources in the Mgeni catchment has required the development of operating rules, a summary of which is included in the Umgeni Water Masterplan (UW, 2019). These operating rules have been modelled, though are likely simplified compared to actual system operation. Operating rules include: (1) maximising the transfer from Spring Grove Dam and Mearns Weir, the split in conveyance from the two sources being dependent on storage levels in Spring Grove Dam; (2) supplying the full water requirement of Durban Heights WTW from Nagle Dam under gravity flow when this water resource is full, and Nagle Dam is in turn supported by the larger Albert Falls Dam upstream; (3) supplementing supply to Durban Heights WTW by pumping from Inanda Dam when Nagle Dam is not full, and maximising the volume of water pumped from Inanda Dam to Durban Heights WTW (limited to 240 Ml/d); and (4) instituting restrictions when the net storage capacity of the Mgeni WSS is less than 70% at the start of the low-rainfall season (May).

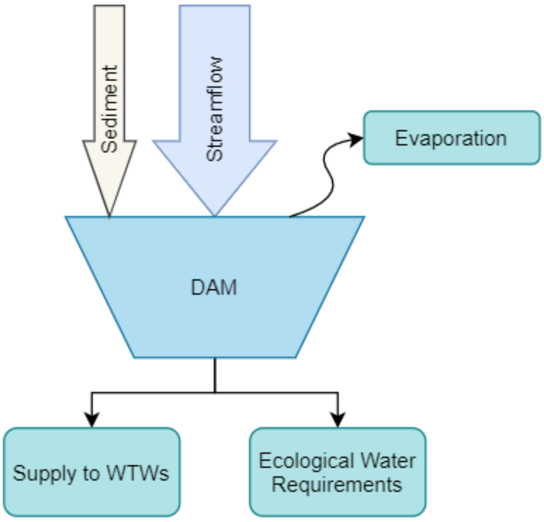


Figure 5-12: Basic Schematic of Dams (Stocks) and Connecting Flows in Model

Treatment capacities in the region provide the upper limit of the volume of water which can be supplied to the system (provided the upstream water resources are able to match same).

Finally, there are water requirements (demands) external to eThekwini municipality which draw from the same water resources and therefore impact on the availability of water within the study area. These demands are accounted for in the model, and were obtained from the Umgeni Water Masterplans (UW, 2019).

Throughout the simulation, the model tracks the demand against the available supply; if there is a deficit in supply, this is factored into the model as the volume of water which is then available for end-use (i.e. the volume of waste which may be generated is therefore influenced).

Key inputs for modelling the respective water resources are summarised in Appendix A: Model Inputs.

5.2.6 Bulk Waste Systems Model

Waste “streams” returned to bulk wastewater systems include greywater and blackwater. The model makes this distinction such that portions of the greywater stream may be recycled in the flow model if greywater reuse is implemented as an intervention.

Leakage on consumers’ properties contributes to the sewer baseflow: in addition to water end-uses that result in wastewater generation, as per Stephenson & Barta (2005) a proportion of sewer inflow is a result of, *inter alia*, leaking plumbing fixtures, building foundation drains, cooling water discharges; this portion of the wastewater volume can be difficult to quantify and is commonly measured with infiltration. The BMC per capita (as used in this study) includes such volumes downstream of consumer meter connections, and therefore requires no additional component in the calculation of wastewater flows.

The presence of a high groundwater table results in leakage into sewer pipelines through joints and cracks. As per The Neighbourhood Planning and Design Guide (DHS, 2019), the infiltration for any one segment of pipeline is related to the length of the pipe and the outside diameter of the pipe, where 0.03 to 0.04 litres/min per length of pipe per pipe diameter should be allowed for (DHS, 2019), though Stephenson & Barta (2005) state these values may vary depending on sewer age and pipe materials present. Although there is limited information on infiltration into sewer systems in South Africa, up to 35 percent of the Dry Weather Flow (DWF) has been recorded in localities’ pipelines (Stephenson & Barta, 2005). Infiltration is accounted for in the modelled daily sewer flows through the above relationship, considering the average pipeline size and the cumulative network length for each drainage area, and is assumed always present (i.e. not restricted to occurring only during or immediately after rainfall events). Ingress into sewers during storm events has not been included in the model, as only average daily flows are modelled, not peak flows within any given day.

When the elevation of sewer pipes is greater than the groundwater table, exfiltration of sewage through pipeline joints into the surrounding ground can occur, resulting in contamination of groundwater with (but not limited to) nitrates, heavy metals, sulphate, and organic compounds. Sewerage network age is thought to be the most significant factor in determining exfiltration (Stephenson & Barta, 2005). Exfiltration is not accounted for in the model as there is not sufficient information to make reasonable assumptions at a catchment level, but this could be included in a more detailed model.

In addition to distinct zones which are not connected to a wastewater drainage area, there are consumers within wastewater drainage areas who may not be connected. Based on the proximity of consumers to the sewer network, the portion of consumers potentially not connected (per drainage area) was estimated and built into the model.

5.2.7 Rainfall Model

The integrated flow model includes a stochastic weather generator, which makes use of existing rainfall data to generate a synthetic daily rainfall timeseries with statistical similarity to the existing dataset.

WGEN is one such stochastic weather generator originally developed in the 1980s at the US Department of Agriculture Agricultural Research Service (Richardson and Wright 1984). WGEN is capable of generating timeseries of precipitation, maximum temperature, minimum temperature, and solar radiation. The precipitation portion of the WGEN weather model (reconstructed by Goldsim, 2020) was integrated into the main model. The precipitation is determined by a first-order Markov chain-gamma model, where the probability of rain on any given day depends on whether there was rain the previous day. WGEN requires long time series of daily weather data to estimate model parameters; rainfall data for selected rainfall stations was obtained from SAWS from 1980 to 2020.

The generated rainfall sequences were used as inputs to model catchment runoff, the function of rainwater tanks, and the function of stormwater harvesting facilities.

5.2.8 Runoff Model

The integrated flow model includes a rainfall runoff generator, which uses the stochastic rainfall sequences and a rainfall runoff model to calculate catchment flows. For purposes of the model, continuous rainfall runoff modelling – versus design flood estimation – was a key criterion in selecting the type of rainfall runoff model. As outlined by Boughton (2004), the Australian water balance model (AWBM) was developed in the early 1990s and is now one of the most widely used rainfall–runoff models in Australia. The model may be used for simulating either daily flows or flood runoff at hourly timesteps. A significant feature and benefit of the model are calibration procedures which are specific to and based on the model structure versus trial and error testing parameter values (*ibid*).

As noted by Ndiritu (2013), the AWBM structure is robust and relatively straightforward to calibrate. The ACRU model (Schulze 1989), while widely used for daily catchment modelling in South Africa, is data-intensive and is not structured for manual-automatic calibration (Ndiritu, 2013). While recorded and simulated flow information is available through WR2012 or the WRSM/Pitman model, the temporal scale (monthly) would be at odds with the purpose for which this specific sub-model is used: namely, modelling daily runoff for potential capture via stormwater harvesting (which, due to size, is generally more sensitive to daily change in inflows than large dams), and the build-up and wash-off of pollutants at a daily time scale. The AWBM was thus selected for incorporation into the model.

The AWBM is a conceptual model based on concepts of saturation overland flow generation of runoff. Saturation overland flow is defined as the excess rainfall remaining after the surface storage capacity of a catchment has been replenished, and is thus dependant on the antecedent moisture conditions; i.e. no runoff occurs until the capacity of the surface stores is exceeded. Larger catchments also require attenuation at the catchment outlet in order to reproduce the variation in arrival times occurring in a natural catchment; the discharge from the attenuation (store) is adjusted to match the recession characteristics of recorded streamflow. A fraction of the runoff from the surface stores is transferred to baseflow stores such that the baseflow discharge is highest at the end of surface runoff and receding thereafter (Boughton, 2004).

The AWBM structure may be described as follows: The model uses three surface stores to simulate partial areas of runoff, where the water balance of each surface store is calculated independently. At each defined time step, rainfall is added and evapotranspiration is subtracted from each store. A negative value of moisture in a store resets the moisture to zero. Moisture in excess of store capacity becomes runoff, and the moisture reset to the store capacity. A fraction of all runoff is routed to baseflow stores – also known as the baseflow index. Baseflow stores and surface runoff routing stores are depleted at a rate related to recession constants (GoldSim, 2020). Figure 5-13 illustrates the model structure. The AWBM model (reconstructed by Goldsim, 2020) was integrated into the main model.

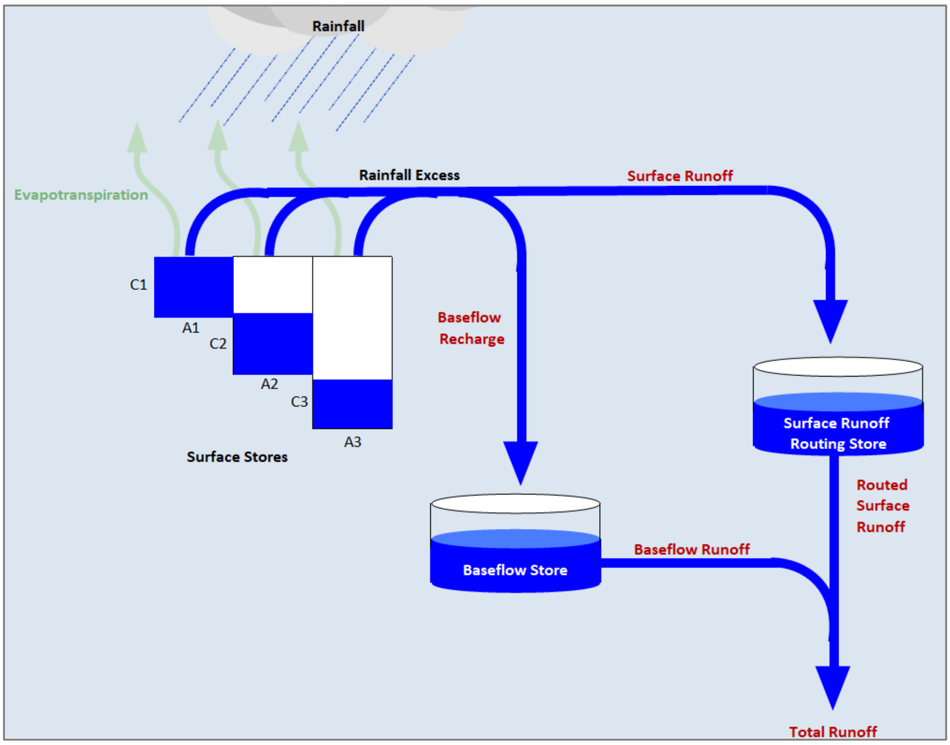


Figure 5-13: Schematic of AWMB Model Structure [Source: GoldSim Model Library Documentation, 2020]

In terms of runoff modelling and the interaction with rainwater and stormwater harvesting activities, it is a model limitation that the effect of harvesting activities on within-day urban waterway peak flows is not captured; this would be useful functionality for more detailed analyses which could then include optimisation of harvesting facility design.

In addition to the runoff generated in each catchment, the pollutant build-up and wash-off was modelled. During a rainfall event, especially following a dry period, the initial runoff which washes over impervious surfaces generates stormwater with a greater concentration of pollutants. This event, also known as the “first flush”, has been recognized as typical of urbanised areas. Runoff from urban environments tends to convey pollutants (concentrations depending on land use) such as settleable solids, nutrients, bacteria, oil, grease and heavy metals into stormwater systems and can be a major contributor to deterioration in urban river environments (Modugno *et al*., 2015).

After Tu & Smith (2018), while different build-up and wash-off equations are available, literature most often reports on the parameters specifically for the exponential forms of these equations; such were therefore incorporated into the model. Tu & Smith (2018) note research has either made use of computer modelling or small-scale field measurements to determine the parameters associated with the build-up and wash-off equations. Tu & Smith (2018) reviewed such parameters determined in other studies and found there is great variation between locations due to local and climatic factors. Most studies focus on parameters for total suspended solids (TSS) loading, and only a limited number address nitrogen (TKN) and phosphorous (TP) parameters. Given the limited information, only TSS values as based on the findings of the aforementioned study have been included in the build-up and wash-off portion of the model.

5.2.9 Water Quality Model

Water quality management is a critical component of overall integrated water resources management: most water users require adequate water quality; if not met, treatment costs either increase or users are exposed to higher risks associated with using lower quality water. With growing populations and economies, greater volumes of wastewater – and therefore pollutants – are released to the environment (Loucks & Van Beek, 2005).

Water quality models can be applied to a variety of water systems and typically require hydrologic characteristics and constituent inputs. Models will include terms for the transport of constituents (the hydrodynamics of water bodies determine whether dispersive and/or advective transport occurs) as well as reactions between constituents (Loucks & Van Beek, 2005). Water quality models are based on the principle of mass balance, where the water system may be divided into a number of segments (also known as computational cells), and for each segment, there is a mass balance of each constituent over time. The mass balance considers transport into and out of a segment, processes occurring within a segment, and sources/discharges to or from the segment. Advective transport is a result of transport by flowing water. Dispersive transport occurs as a result of concentration differences. Processes include those which are physical, (bio)chemical or biological (Loucks & Van Beek, 2005). While most water quality models cannot accurately predict actual physical conditions, they remain useful to understand actual conditions and estimate – at least – the relative impact on water quality as a result of changing system parameters arising from, for example, water or land management practices (Loucks & Van Beek, 2005).

The Contaminant Transport Module of GoldSim enables dynamic modelling of mass transport and was used in this study for the purpose of modelling the water quality at the different points in the water infrastructure cycle – namely fresh water resources, water treatment works, non-potable water resources, wastewater, treated wastewater, and urban waterways downstream of the aforementioned processes. Outputs which are provided by the GoldSim Contaminant Transport Module include predicted masses and mass transfer rates at defined system locations, and predicted concentrations within defined media in the system (GoldSim, 2018).

As per the process described by Loucks & Van Beek (2005), the numerical modelling of environmental systems requires system components to be discretised into finite volumes for computation. While the Contaminant Transport Module of GoldSim would enable honing into specific areas of interest (for example, a particular dam) and discretising the water body into a number of vertical layers and areal sections to better understand water quality differentials within that water body, in this study, single finite volumes define each major component within the water infrastructure cycle. Furthermore, volumes have been aggregated for the entire study area, as the Contaminant Transport model cannot accommodate vector and matrix operations other than that involving defined pollutants or “species”. While sub-models for each individual area could be defined, the number of model elements required would have far exceeded that allowable for the utilised software licence (academic). This is deemed an appropriate simplification, given the purpose of this portion of the study is only to provide a broad overview of general water quality trends.

The pollutants included in the model are those more commonly measured and monitored in water services infrastructure, though are not exhaustive by any means and could be expanded upon:

- Chemical oxygen demand (COD)
- Total Kjeldahl Nitrogen (TKN)
- Inorganic Nitrogen
- Total Phosphorous (TP)
- Total Solids (TS)
- Sodium (Na)
- Magnesium (Mg)
- Calcium (Ca)
- Fluoride (F)
- Chlorine (Cl)
- Free Chlorine
- Sulphate (SO4)
- Silicon (Si)
- Potassium (K)
- Total Coliforms
- Escherichia Coli (E. Coli)
- Fats, oils, and grease (FOG)

The pollutant loading in the system is defined as follows (further detail may be found in Appendix A: Model Inputs):

Finally, the model has been limited to pollutant addition, transport, removal, and settling – no complex reactions or biochemical processes have been modelled.

Table 5-4: Defining Water System Pollutants

Location	Pollutant Definition and Loading
Dams	Inorganic concentrations for study area obtained from nation-wide study of rivers and dams (Huizenga *et al*., 2013); Microbial monitoring data extracted from DWS National Water Management System (DWS, 2019)
Water Treatment Works	Defined by inflow from upstream dams
Water Storage	Defined by inflow from water treatment works, where a fraction of pollutants are removed as part of the treatment process. Addition of free chlorine as an approximation of the disinfection process.
Wastewater Influent	Defined by volume of wastewater generated and greywater and blackwater loading as determined from studies of sewage characteristics (Von Sperling, 2007; Metcalf & Eddy, 2003; Vuppaladadiyam, 2019; Oteng-Peprah, 2018)
Wastewater Effluent	Fraction of influent pollutants removed. Addition of free chlorine as an approximation of the disinfection process.
Catchment Runoff	Function of pollutant build-up during “dry” days and wash-off resulting in “wet” days

5.2.10 Intervention Modelling

The modelled interventions have the flexibility to be implemented with varying temporal and spatial extents.

The allocation of non-potable water sources to end-uses is critical for determining the impact on demands and therefore system flows. As detailed by Armitage *et al*. (2014), a “fit for purpose” approach is central to WSUD concepts in that not all water consumption end-uses need to be satisfied with potable water.

The quality of harvested rainwater depends on the water quality of precipitation and any contamination of the catchment (i.e. rooftops). Ordinarily rainwater is slightly acidic, and may be increased by industrial pollution. Filtered rainwater is generally suitable for all non-potable uses (Department of Human Settlements, 2019). While precipitation usually contains little contamination, once passing over urban surfaces, stormwater runoff tends to wash off large pollution loads, containing microbial pathogens and other hazardous substances (*inter alia*, litter, heavy metals, nutrients, rotting vegetation) that are determined by the characteristics of the catchment. Malfunctioning or non-existent sanitation systems and inappropriate waste disposal practises are the most significant contributors (in the form of raw sewage and household greywater) to microbiological pollution of urban stormwater. Despite the fact that urban stormwater is the largest source of contaminants to surface waters, this has received little operational attention. The aforementioned considerations would inform the need for treatment of harvested stormwater (Armitage *et al*., 2014).

Without treatment, greywater is not fit for human consumption; greywater is most appropriate for use where human contact is limited – for example, garden irrigation and toilet flushing (Armitage *et al*., 2014; Carden *et al*., 2017). Furthermore, as per Carden *et al*. (2017), greywater originating from the kitchen is expressly excluded from greywater available for reuse. Wastewater which is recycled at centralised facilities may be treated to potable or non-potable standards. Sewer mining (where wastewater is extracted from a bulk sewer pipeline and treated nearby for non-potable uses) is also an option, though has not been considered in this study.

Table 5-5, after Landcom (2004), summarises the evaluation of alternative water sources against the suitability for end-uses.

Table 5-5: Compatibility of Water Sources and Appropriate Uses [Source: Landcom, 2004]

Water Source	Garden	Kitchen		Laundry		Toilet	Bathroom	
		Hot	Cold	Hot	Cold		Hot	Cold
Potable	3	2	1	2	1	3	2	1
Treated wastewater	1	4	4	4	4	1	4	4
Greywater	2	4	4	4	4	2	4	4
Roof runoff	2	1	2	1	1	2	1	2
Other stormwater	2	4	4	4	4	2	4	4

Where: (1) Preferred use; (2) Compatible use; (3) Non-preferred use; and (4) Not compatible.

Applying the concept of source and end-use compatibility to the model development, it was most appropriate to classify the alternative supplies into two different classes, where “Class 1” may supply all non-consumptive end-uses, and “Class 2” is restricted to supply low-contact end uses such as toilet flushing and outdoor use.

Table 5-6: Defined Classes of Non-Potable Supply

Non-Potable Supply	Non-Potable Class
Rainwater	1
Recycled Wastewater (Potable)	1
Desalinated Water	1
Groundwater	1
Stormwater	2
Greywater	2
Recycled Wastewater (Non-Potable)	2

The model allows for a trickle-down approach in modelling the demand on each water source, potable or otherwise: where Class 2 non-potable water is not available or does not fully satisfy the end-uses for which it may be used, Class 1 non-potable water may then be used (if indeed available). Demand which is not satisfied by either of these non-potable classes is then to be met with potable water supply.

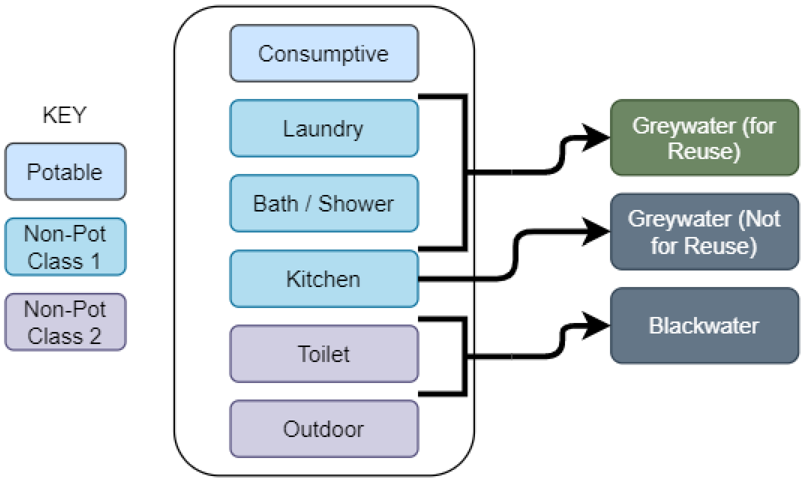


Figure 5-14: Illustration of End-Use and Application to Classes of Non-Potable Water

Depending on the nature and/or application, Armitage *et al*. (2014) note the facilitation of non-potable supply may require a third pipe system through which non-potable water is distributed. For example, wastewater treated to non-potable standards or treated stormwater would require such infrastructure. On the other hand, rainwater harvesting or greywater reuse could be grouped for developments or suburbs and a third pipe system introduced, or such measures adopted at the household level. The model does not detail the hydraulics or requirements of such third pipe systems, as such leaving the implementation and means of distribution of alternative supplies open-ended, only focussing on the extent of alternative supplies and the impact on the system water balance. It is, nonetheless pertinent to note that retrofitting an additional reticulation system in developed urban environments is challenging and costly, and thus more appropriate for less dense areas and greenfield sites. Consideration of dual reticulation systems is often further hampered by perceived cost compared to potable water (though this depends on the configuration of non-potable and potable schemes and concomitant operational costs), the perception of unreliability, and concerns about public health in the event of cross-connections to potable networks (Armitage *et al*., 2014). Such issues would need due consideration in planning and design of any non-potable supply schemes.

(a) Water Conservation and Water Demand Management

WCWDM has been applied to the model in two distinct areas: system-wide interventions (measures which reduce system losses upstream of consumer meters, also known as real loss reduction) and consumer interventions (measures which reduce consumption within consumer properties); the latter decreases the base demand, and the former reduces the physical losses in the supply system.

While there are a host of system-side WCWDM measures which can be classed into different types of strategies (institutional, social, technical, etc.), the model focuses on the combined effect of a complete WCWDM strategy rather than on specific interventions by setting a target for real loss reduction, and a timeframe for achieving such. The initial apparent losses are added to the BMC, but decreasing apparent losses do not change the SIV: the apparent loses are not a physical loss which can be reduced, but rather would represent reduction in metering inaccuracies and unauthorised consumption. As such, reduction of apparent losses essentially represents a volume which was previously unaccounted for, moving into the BMC component of the water balance.

An important concept in the assessment of water losses is the relationship between the minimum theoretical and actual levels of leakage (also termed current annual real losses – CARL). As described by McKenzie & Lambert (2002), no water distribution system can have zero leakage; the minimum level of leakage is termed the unavoidable annual real losses (UARL) which would be achieved if the system is in good condition, well maintained, reported leaks are repaired efficiently, and active leakage control is practised. The UARL is dependent on the length of mains, the number of service connections, and the average operating pressure at the average zone point (refer to Appendix B: Additional Model Details for equations). The UARL is generally well below the economic level of leakage (ELL) at which the savings achieved are balanced by the cost of implementation of real loss reduction measures; the UARL is therefore not a suitable target for water utilities (else budget is allocated to activities without adequate return). Targets are usually set by applying a factor (the Target Loss Factor) to the UARL, which is somewhat arbitrary but usually based on analysis of areas with similar characteristics to the area in question (McKenzie & Lambert, 2002). For example, as noted by McKenzie & Lambert (2002), a factor of 2 is often appropriate for well-managed areas which do not include any high-leakage areas. A factor of 10 could apply to areas with high leakage and poor infrastructure, though the target loss factors can be reduced over time as the management of the area improves. After further studies in South Africa and in developing the BENCHLEAK software, McKenzie *et al*. (2006) later found an upper limit target factor of 5 may be more appropriate. The model makes provision for defining the Target Loss Factor for each bulk supply area. Figure 5-15 illustrates the relationship between UARL, ELL, and CARL.

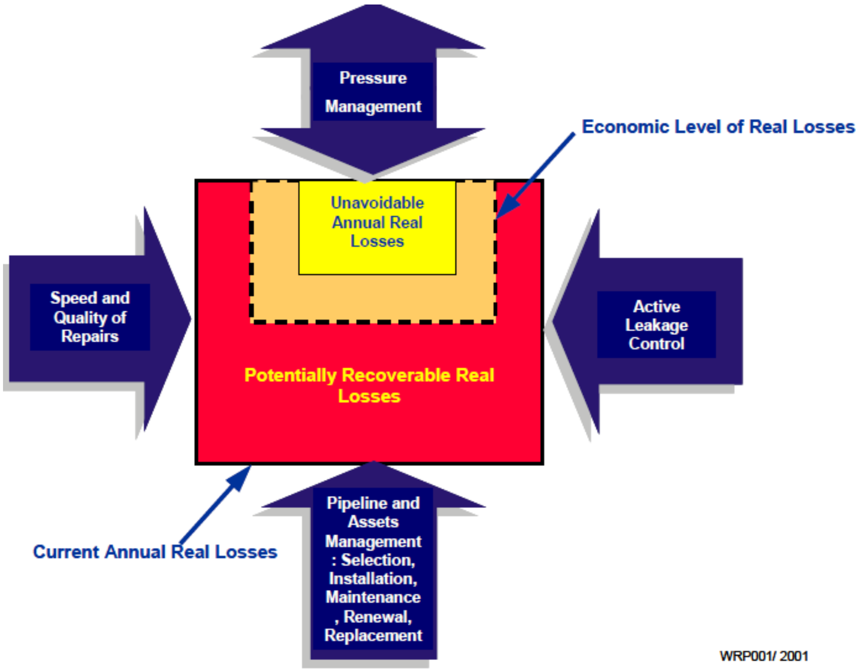


Figure 5-15: Relationship between CARL, ELL, and UARL [Source: McKenzie & Lambert, 2002]

McKenzie & Lambert (2002) note while there is agreement that most distribution systems will experience an increasing rise in leakage over time, there are differing schools of thought on the progression: on one hand, it is believed the leakage will eventually stabilise when the leakage and system pressure are balanced. On the other hand, it is thought the leakage will continue rising if there are no interventions; based on the assumption the pressure remains constant, and thus more water being supplied to the system. A combination of the two approaches is likely: increasing leakage will gradually lessen due to system pressure decreasing as a result of rising losses (*ibid*). The Reconciliation Strategy (DWS, 2017) recognises the growing levels of understanding of increasing water losses as infrastructure ages and no WCWDM measures are implemented. It is therefore no longer realistic to impose a reduction of real losses on a base scenario (function of projected population and economic growth and increasing levels of service) where the current real losses are held constant. The approach taken in this study is consistent with that of the Reconciliation Strategy (DWS, 2017) where the base scenario includes the effects of system attrition as the system ages and infrastructure deteriorates. The impacts of WCWDM measures are then imposed on this new base scenario.

The consumer-focussed WCWDM sub-model simulates the proportion of consumers with interventions in place, which may increase or decrease as time passes (i.e. to reflect WCWDM programs that are rolled out over a period of time, or as consumers revert back to the status quo). Consumer-focussed measures are broadly classed into leak repair programmes, plumbing retrofits with water-saving devices, xeriscaping, and tariff increases, the effectiveness of which are based on the study by Jacobs and Haarhoff (2004). Brick, De Martino & Visser (2017) investigated the effect of behavioural nudges on water conservation in households in Cape Town during the recent drought, though these specific measures have not been modelled in this study.

Variable inputs to the model included:

- The initial CARL, based on reported real losses as contained in the WSDP (EWS, 2011);
- Target Loss Factors, which inform the target CARL;
- Timeframes to achieve the target CARL;
- Annual increase in real losses (as a result of system attrition);
- The rate at which the proportion of consumers with interventions in place increases (or decreases); and
- Consumer focussed intervention effectiveness.

(b) Rainwater Harvesting

Teston *et al*. (2018) conducted a theoretical investigation into the impact of rainwater harvesting on the drainage system in Curitiba; in addition to being able to meet non-potable water requirements, surface runoff into stormwater systems was reduced through rainwater harvesting systems operating as source control solutions. Higher tank capacity resulted in both higher reliability of supply (being particularly important for periods of lower rainfall), and reduction of runoff, though larger demands are favourable for reducing peak flows (i.e. larger tanks take longer to fill in rainfall events, and larger daily demands delay potential tank overflows) (*ibid*). Burns *et al*. (2015) studied existing rainwater tank installations in a selection of Australian households; tank water use was found to be highly variable and therefore has an impact on how demand models should be structured. Nonetheless, the findings of other studies were reinforced by the observation that large, regular demands are necessary to achieve meaningful potable water use reduction and retention of runoff. Defining end-uses and tank use recommendations is important for determining potable demand reduction and run-off retention outcomes. From the perspective of the water balance, the total demand on the rainwater harvesting system needs to be large enough to off-set the run-off from impervious portions of the property. A retention strategy where tank overflows are directed to vegetated infiltration systems could restore the equivalent initial loss to almost natural conditions, and increases the total effective demand on the system (*ibid*). In terms of maintenance, Burns *et al*. (2015) note that household maintenance of these systems can be poor as a result of limited expertise and/or awareness. Nonetheless, any risks associated with failure of an individual system is effectively decentralised. The findings of the studies by Teston *et al*. (2018) and Burns *et al*. (2015) are, of course, dependent on the particular context in terms of climate and end-users in which these studies exist.

Variable inputs to the model included:

- Precipitation: The precipitation which may be captured in the tanks is an output of the rainfall sub-model (refer to Section 5.2.7);

- Storage tank capacities, where the storage tank capacity may be varied for households and other land uses;
- Average roof size for the study area, which were obtained through analysis of building footprints as captured in the GIS database;
- Percentage of all consumer units with rainwater tanks installed;
- Rainfall-recovery efficiency, which has been based on recommended values in The Neighbourhood Planning and Design Guide (DHS, 2019); and
- Demand on rainwater tanks: For the purposes of this study, rainwater use is allocated to outdoor and all non-potable indoor uses. This is consistent with the recommended uses in The Neighbourhood Planning and Design Guide (DHS, 2019) and some of the scenarios assessed in the Reconciliation Strategy (DWS, 2017).

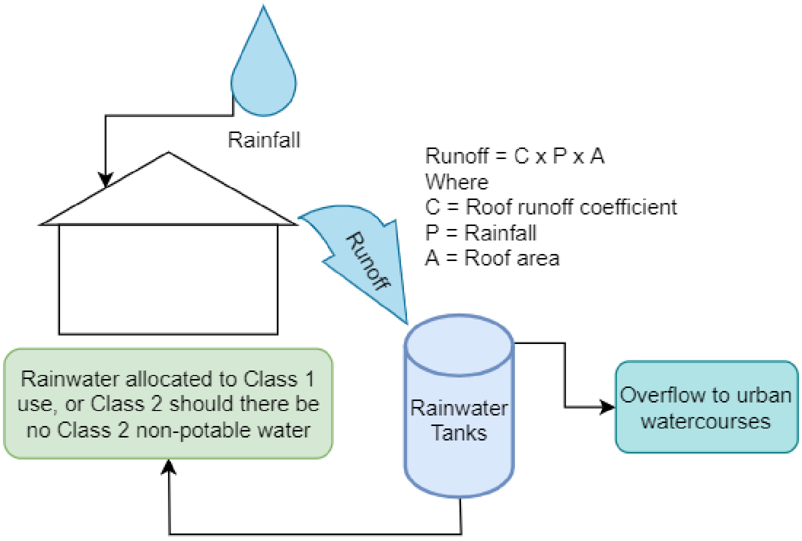


Figure 5-16: Schematic of Rainwater Harvesting at Level of Single Unit

The above image is an illustration of rainwater harvesting as applied to a single unit. The model then aggregates the results (i.e. volume available, volume utilised, and volume overflowing to watercourses) to each predefined area (bulk supply and drainage).

(c) Stormwater Harvesting

While stormwater harvesting is not included as one of the scenarios which are specifically analysed and discussed, it remains an option for implementation in the model; the results of which are included in Appendix C: Additional Model Results.

Walsh, Fletcher & Burns (2012) investigated urban stormwater as a “new class” of environmental flow problem. Where conventional drainage systems are in place, urban stormwater is conveyed – unfiltered – to receiving water through pipes; such systems convey stormwater to receiving waters at every occurrence of sufficient rain to generate runoff from impervious surfaces. The result is more frequent and larger flood peaks of poor quality runoff. The means by which urbanisation results in degradation of waterways are multifarious, but can often be recognised as the impact of a few land-use practices, for example, the proportion of impervious areas (*ibid*). While it is clear both aspects of urban areas – land-use practices and drainage system type – contribute to urban waterway degradation, Walsh, Fletcher & Burns (2012) note there are limited studies which distinguish between the impact of urbanisation and conventional drainage systems on urban waterways. There are nonetheless, some studies which show waterway ecological function can be maintained, even where there is extensive urbanisation but a lack of conventional drainage systems. It is thus important to consider the proportion of impervious areas which are connected to conventional drainage systems, and the hydraulic efficiency of alternative drainage systems in attenuating flow and concomitant pollutants, such that runoff reaches urban waterways with appropriate temporal pattern. In that urban waterway degradation is largely attributable to hydrologic problems, the solutions are therefore in the approaches to environmental flow management (*ibid*). There has been some tendency for water resource managers to consider extraction from urban waterways for stormwater harvesting projects, though it has been shown that despite such initiatives, degradation of waterway ecology persists. Instead, the environmental flow problem can largely be solved by harvesting stormwater before it reaches waterways; maximum environmental benefit is realised if a volume of stormwater equivalent to pre-development evapotranspiration is harvested and infiltration measures are implemented to restore pre-urban sub-surface flows, thus restoring downstream flow regimes (*ibid*).

The principles of SuDS recognise the above environmental flow problem. SuDS is the management of stormwater runoff where the aim is to reduce downstream flooding, allow infiltration, improve the quality of stormwater, reduce pollution to water bodies, and enhance biodiversity, as opposed to conventional stormwater systems (networks of pipes and culverts) which collect and discharge stormwater as efficiently as possible. SuDS includes solutions such as rainwater harvesting, green roofs, permeable pavements, soakaways, swales, infiltration trenches, bio-retention areas, detention ponds, retention ponds, wetlands, etc. (Armitage *et al*., 2014).

The above principles have guided the model intent to focus on harvesting stormwater before reaching waterways, instead of abstracting water from urban waterways. The same informed the preference for rainwater harvesting over stormwater harvesting in the development of the respective scenarios. The model does not specify the type of harvesting scheme or its configuration, but is rather restricted to macro-scale hydrological function in support of determining the urban water balance. To this end, specifying the storage volume is important. The storage volume should be sufficient to provide some environmental flow benefit (as detailed by Walsh, Fletcher & Burns (2012).

Variable inputs to the model included:

- Precipitation: The precipitation which may be captured in the tanks is an output of the rainfall sub-model (refer to Section 5.2.7);
- Catchment area for stormwater harvesting facilities; and
- Storage volume of facilities.

(d) Greywater Reuse

While greywater is defined as all household wastewater other than that originating from toilet flushing, greywater from kitchen sinks, dish washing machines and other uses which could result in contamination with harmful pathogens are excluded from the household water balance as a potential resource. Greywater should be reused with considerable care (Department of Human Settlements, 2019). Carden *et al*. (2017) note that greywater reuse in informal and/or un-serviced settlements is generally not recommended as being officially sanctioned; oftentimes water in such areas has already been reused for different purposes and is considered pathogenically and chemically hazardous. In these areas, greywater management should rather be focussed on safe disposal. Such considerations have been built into the model. Figure 5-17 summarises the permissibility of greywater use, as defined by Carden *et al*., (2017), and also adopted by The Neighbourhood Planning and Design Guide (DHS, 2019).

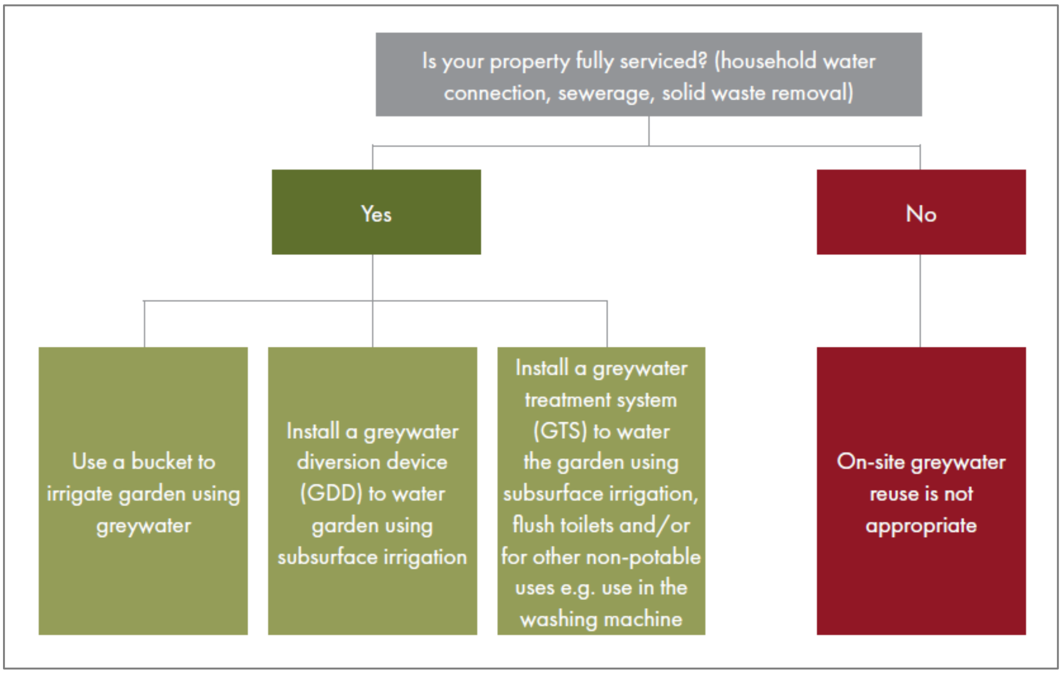


Figure 5-17: Permissibility of Greywater Use [Source: Carden et al., 2017; DHS, 2019]

The end-uses defined (refer to Section 5.2.4) enable automatic calculation of the total volume of greywater available for reuse. The recommended end-uses cannot be enforced at consumer level; education and awareness of safe practises is thus a necessity, should greywater reuse at household level be encouraged by WSAs.

Variable inputs to the model include:

- The proportion of consumers (whom are fully serviced) partaking in greywater reuse activities, as it would be unrealistic to assume complete adoption of greywater reuse; and
- The proportion of greywater produced which is captured for reuse, as it would be unrealistic to assume all greywater produced (which is also permitted for reuse) will be captured. The remaining greywater is directed to the bulk wastewater systems.

(e) Wastewater Recycling

The reclamation of wastewater is becoming more viable because of advancement in technology. Community acceptance may increase as awareness of water sensitivity increases and wastewater recycling becomes a more widely established practice.

In the system model, wastewater may either be treated to potable standards and introduced into the potable water system (as has been proposed for eThekwini, of course relying on the assumption that public participation will in future yield favourable outcomes), or wastewater may be treated to lower standards and then used for industrial and/or other non-potable end uses. Treatment of wastewater from industrial areas to high (potable) standards can be difficult due to the presence of specific contaminants such as heavy metals; as such, the wastewater characteristics from facility catchment areas must be taken into consideration (Department of Human Settlements, 2019). In the system model, the volume of wastewater available to recycle is directly linked to the inflow (to wastewater treatment works) volume, a portion of which can then be specified for recycling. Indirect reuse via Hazelmere Dam has not been considered in the systems model; in that there are plans to regionalise the treatment facilities on the North Coast and extend the drainage area catchments, there is uncertainty with regards to the extent of the catchments which would effectively contribute to indirect reuse.

(f) Groundwater

While groundwater use is not included as one of the scenarios which are specifically analysed and discussed, it remains an option for implementation in the model; the results of which are included in Appendix C: Additional Model Results. The available groundwater – for each quaternary catchment – is based on the Groundwater Resource Assessment Phase II (GRA2) Project which aimed to quantify all groundwater resources in South Africa. The level of detail for this portion of the model and its interaction with other flows in the water cycle is otherwise limited.

(g) Desalination

While desalination is not included as one of the scenarios which are specifically analysed and discussed, it remains an option for implementation in the model; the results of which are included in Appendix C: Additional Model Results. The desalination volumes available for integration with the bulk water supply system are informed by possible projects as identified in Chapter 4. The level of detail for this portion of the model is otherwise limited.

(h) Summary of Scenario Modelling

Table 5-7 (overleaf) outlines the scale and implementation details as modelled for each scenario.

Table 5-7: Summary of Scenario Details

Intervention	Scale	Implementation Extent / Details
WCWDM	- Combination of consumer-focussed measures (within households) and real loss reduction in system (municipal-wide)	- Uptake in consumer-focussed WCWDM interventions is assumed to occur gradually over time, and allowance is made for some consumers to revert back to the status quo at some point in the future. Percentage effectiveness in reducing demand is assumed for each type of water conservation measure. - Real loss reduction targets a 20% reduction in real losses.
Rainwater Harvesting and Loss Reduction	- Rainwater harvesting for individual properties and/or households; - Real loss reduction across municipal systems	- Rainwater is harvested from roofs of individual properties/consumers, and subsequently stored in individual tanks and supplied to the same property. No treatment is specified or modelled (though some consumers may do so of their own accord). Rainwater harvesting tanks are installed for some 75% of all properties. Harvested rainwater may be used for end-uses designated to all non-potable uses. Potable and remaining unmet non-potable demand is then obtained from the bulk potable water supply system. - Real loss reduction targets a 20% reduction in real losses.
Greywater Reuse and WCWDM	- Greywater reuse within individual properties and/or households; - Consumer-focussed WCWDM; - Real loss reduction across municipal systems	- Greywater reuse has been applied conservatively: it is assumed that greywater reuse is only permitted for consumers connected to sewer networks, and of these consumers, some 75% of consumers will capture an average of 50% of produced greywater for reuse. No treatment is specified or modelled (though some consumers may do so of their own accord). Greywater is only permitted for end-uses such as outdoor use and toilet flushing. Potable and remaining unmet non-potable demand is then obtained from the bulk potable water supply system. - Uptake in consumer-focussed WCWDM interventions is assumed to occur gradually over time, and allowance is made for some consumers to revert back to the status quo at some point in the future. Percentage effectiveness in reducing demand is assumed for each type of water conservation measure. - Real loss reduction targets a 20% reduction in real losses.
Wastewater Recycling and Loss Reduction	- Wastewater recycling to potable standards at regional scale; - Wastewater recycling to non-potable standards within same drainage "zones" - Real loss reduction across municipal systems	- The volume of wastewater treated at centralised treatment facilities is dependent on the percentage of consumers connected to the bulk sanitation infrastructure. All wastewater is treated to standards suitable for discharge to the environment; thereafter effluent may undergo further treatment for reuse. - Wastewater recycling to potable standards at three of the larger plants identified by EWS for same. - Wastewater recycling to non-potable standards at two larger plants within predominantly industrial areas where such water could be used. - Real loss reduction targets a 20% reduction in real losses.

WCWDM interventions are introduced to the system two years into the simulation; this is deemed reasonable as such does not require major infrastructure refurbishments or upgrades which require a long lead time for implementation. That is not to say the measures are complete after two years, but rather are implemented from that point onward. It is important that realistic views are taken on the impact of WCWDM measures so as not to underestimate long term water requirements in the event WCWDM targets are not realised. The target leakage factors were set so as to achieve a 20% reduction in the CARL; the implication is reducing real losses (for the entire municipal area) from 25% to 20% of the SIV. Such is deemed reasonable in that eThekwini has on-going real loss reduction programmes. The target losses may in fact be below the economic level of leakage in some cases; the ELL for each bulk supply area was not, however, explored in this study. In that real loss reduction and monitoring activities require continuous effort, a long timeframe of 10 years has been set. Conservation effectiveness (in reducing consumer demand) is based on data included in the end-use model as developed by Jacobs and Haarhoff (2004). Specific details are included in Appendix A: Model Inputs. The rate of uptake of WCWDM measures for consumers is based on conservative roll-out rates for programmes which either require municipal intervention (i.e. domestic leak repair and tariff increases) or consumer-driven interventions (i.e. plumbing retrofits and xeriscaping). The rate of uptake – 5% per annum – equates to some 45 000 consumers per annum and is deemed reasonable. The rate at which consumers may revert to the status quo after a period of time (one year) is defined as half the rate of uptake. The effect is that of slowing the overall rate at which consumer WCWDM measures are added to the system.

Rainwater harvesting is introduced to the system five years into the simulation, and real loss reduction after two years into the simulation. Whether implemented by consumers themselves, the municipality, or a combination thereof, adeqaute time would be required for widespread installation of rainwater tanks. The linkages between parameters and outcomes relating to rainwater harvesting as outlined by Teston *et al*. (2018) and Burns *et al*. (2015) were considered in the modelled size of rainwater tanks. Commonly available tank sizes are also considered. A 5 000 litre rainwater tank was selected: based on the analysis of the billing data, the average monthly domestic consumption per consumer unit which could be satisfied with harvested rainwater is ± 12 500 litres; the selected tank size thus provides some 2.5 months' worth of storage (assuming there is no rainfall in the same period, and the tank is full at the start of said period).

Greywater reuse, along with consumer-focussed WCWDM and real loss reduction, is introduced to the system two years into the simulation. This allows some time for roll-out of municipal campaigns and/or consumer education and awareness programmes to highlight the importance of such activities and, importantly, safe practises for greywater reuse. The maximum number of consumers participating in greywater reuse is dependent on the proportion connected to bulk sanitation systems in each wastewater drainage area (i.e. greywater reuse is not encouraged for those without full waterborne sanitation systems). It is further assumed that 75% of these consumers will participate in greywater reuse activities. A further consideration is the proportion of greywater produced which is captured for reuse; in that greywater use is only permitted for outdoor use and toilet flushing, the volume of greywater produced exceeds the maximum volume of greywater which could be used to meet the aforementioned end-use demands. An average of 50% greywater is assumed captured for reuse; this parameter is subjected to a probability distribution to account for the potential for high variability.

Wastewater recycling to potable and non-potable standards is introduced to the system five years into the simulation, and real loss reduction after two years into the simulation. Recycled wastewater volumes to potable standards have been determined to suit planned projects, totalling some 110 Ml/d between KwaMashu and Northern WWTWs. Recycled wastewater to non-potable standards is limited to those wastewater drainage areas for larger WWTWs and with a large percentage of industrial consumers – namely Amanzimtoti and Central WWTWs.

5.2.11 Modelling Uncertainty

The importance of considering uncertainty in modelling process is discussed in Chapter 2. Uncertainty has been considered in the modelling process through identification of parameters which are uncertain and specifying these inputs as probability distributions; allowing random sampling from historical time series; or specifying random events which may have an impact on the system outcomes. GoldSim has the capability to run Monte Carlo analyses, such that a range – or probability distribution – of results may be generated. Table 5-8 summarises the model components and parameters which incorporate uncertainty.

Table 5-8: Parameters for Modelling Uncertainty

Scenario / Intervention	Parameter
Baseline Model	Population growth
	Demand growth (as a result of increasing level of service)
	Daily demand fluctuation
	Inflows to dams
	Precipitation
	Loading of pollutants in the water cycle
WCWDM	Growth in losses
	Effectiveness of real loss reduction / factor by which target real loss is “missed”
	Effectiveness of consumer-side interventions
Rainwater Harvesting	Precipitation
	Demand drawdowns on tanks
Stormwater Harvesting	Precipitation
	Demand drawdowns on harvesting facilities
Greywater Reuse	Percentage greywater recycled per household or consumer unit (of those undertaking greywater recycling)
Wastewater	Demand fluctuations impact wastewater volumes generated

5.2.12 Model Calibration

The various reports and data collected were used to calibrate the baseline model as follows:

i. In that the population is based on 2011 census data and the model start date is 2020, allowance for population growth within this period was accounted for. The simulated population was compared to Statistics South Africa estimates and population forecasts as stated in eThekwini’s IDP.

ii. The Umgeni Water Masterplan includes total outputs for each WTW; the system input volume at the start of the simulation modelled for the bulk supply areas was totalled (as appropriate) and calibrated against the respective WTW outputs. The base demand values and real and apparent losses were adjusted (within reason) to suit.

iii. The Water Services Development Plan states average daily inflows to each WWTW as at 2010/11 as well as expected projections to 2020 and 2030 for some of the more critical WWTW's, against which the modelled inflow to each facility could be calibrated. The breakdown between end-uses and the infiltration parameters were adjusted (within reason) to suit.

iv. The AWBM parameters were calibrated against WR2012 naturalised flows for the catchments in question. Given the different time scales between the AWBM model (daily) and the WR2012 flows (monthly), the calibration was done by comparing the annual cumulative values and running a Monte Carlo simulation in GoldSim. Calibration of the runoff volumes requires adjustment of the surface store capacities, where the adjusted calibration procedure as outlined by Boughton (2004) was adopted.

The calibration process and resulting differences between modelled and target values is detailed in Appendix B: Additional Model Details.

5.2.13 Composite Score Model

The purpose of a composite score is to facilitate and demonstrate an integrated evaluation of the alternative scenarios and is a means to condense a large amount of information, though it should be noted is secondary to the interpretation of key results for purposes of this study.

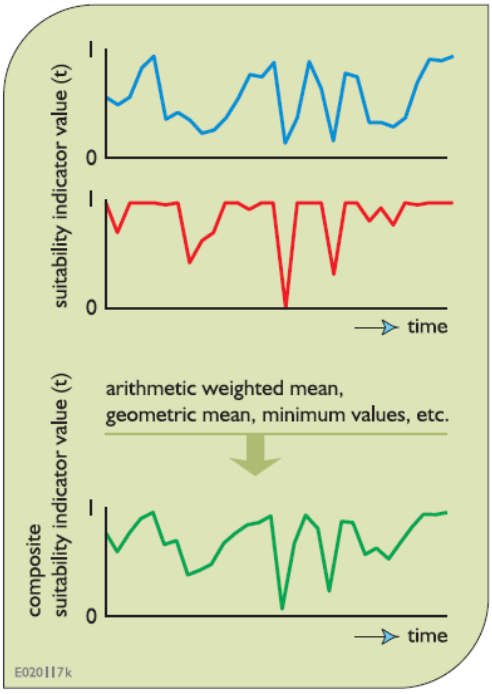


Figure 5-18: Illustration of Composite Indicators and Application to Time Series Data [Source: Loucks & Van Beek, 2005]

As described by Loucks & Van Beek (2005), and as is the case for this study, models of water resource systems produce time series of values. It is necessary to define the relationship between model outputs and performance indicators, such that time series of performance indicator values can be plotted and eventually combined into a single time series. This is useful for system performance comparisons where multiple criteria are to be considered and for mapping results (*ibid*). Figure 5-18 demonstrates the procedure.

(a) Criteria and Indicators

The performance indicators within each criterion have been defined as follows:

i. Environmental indicators: Potable water supplied and wastewater flows generated are the key environmental indicators; i.e. a reduction in volumes is rewarded.

ii. Economic indicators: The operational costs and energy intensity associated with bulk water and wastewater are estimated in the model based on costs and energy intensity per unit volume, and the volumes associated with: raw water abstraction; water treatment; water distribution; wastewater collection; wastewater treatment; and supply of alternative water sources. Costs and energy intensity per unit volume relating to bulk water supply were based on information obtained from Umgeni Water, the Umgeni Water Masterplan (UW, 2019), and research conducted by Frost & Sullivan (2011). Costs and energy intensity per unit volume relating to bulk sanitation services were based on the findings of Naidoo *et al*. (2016), Scheepers & van der Merwe-Botha (2012), and Frost & Sullivan (2011). Costs and energy intensity per unit volume relating to alternative water sources were based on the findings of studies by Vieira *et al*. (2014) and Knutsson & Knutsson (2021). Further detail is contained in Appendix A: Model Inputs.

iii. Risk: In the context of this study, the Risk criterion is defined by the availability of water to supply the demand in the study area and the ability of the sanitation system to treat the volumes of wastewater produced. As per Loucks & Van Beek (2005), measures of reliability, resilience and vulnerability are useful for analysis and comparisons. Risk, or rather lack thereof, was quantified through these three indicators in the model: Reliability can be defined as the number of data points being in a satisfactory state (above or below a threshold value, as the case may be) compared to the total number of data points in a time series. Reliability does not describe system recovery following an unsatisfactory value, nor the magnitude of an unsatisfactory value. Resilience and vulnerability provide some insight to these aspects of system performance. Resilience is expressed as the probability that if an unsatisfactory value occurs, the next value or state will be satisfactory. Vulnerability measures the extent of the differences between a threshold value and unsatisfactory time series data points (Loucks & Van Beek, 2005).

iv. Functionality: Functionality has been measured by the ability of the interventions to meet the demand of end-uses with appropriate ("fit for purpose") supply; the internal harvesting and recycling ratios were here adopted as indicators of functionality.

In all cases, the performance indicators are based on the average outputs of the Monte Carlo analyses, such that the criteria scores and composite scores are based on the mean system performance.

(b) Data Normalisation

The variables linked to performance indicators are often measured in various units; normalisation is therefore required prior to aggregation (Nardo *et al*., 2008) such that the scale effect of different units of measurement is removed, without compromising the relative distance between observations (Carden, 2013). There are a number of normalisation methods; for example: ranking, standardisation, min-max, distance to a reference, categorical scales, indicators above/below mean, cyclical indicators, balance of opinions, percentage of annual differences over consecutive years (Nardo *et al*., 2008). Selection of the normalisation method must consider the characteristics of the data at hand and the objectives of the indicators as well as that of the composite indicator or score. Considerations could include, *inter alia*, whether: data is quantitative or qualitative; rewarding or penalising exceptional behaviour is important; information on absolute levels is important; benchmarking against a reference is needed, variance in the indicators needs to be reflected (Nardo *et al*., 2008).

Distance to a reference value was most appropriate for the performance indicators which were based on evolving volumes, costs, and energy consumption. Risk and functionality indicators, by virtue of their definition, were already normalised.

(c) Indicator Aggregation

Weighting may have a significant impact on the outcomes of overall composite indicators and therefore ranking of alternatives or scenarios. There are a variety of weighting techniques, some of which are based on statistical models, and others which are the outcomes of participatory methods. Irrespective of the selected weighting method, weights are in essence value judgements (Nardo *et al*., 2008) or can be indicative of the substitution rates between variables (Carden, 2013). Weights may also be used to adjust for unequal variances (i.e. unequal levels of certainty) found in different variables (*ibid*). As described by Carden (2013), the Environmental Sustainability Index (ESI) adopts equal weighting, based on the principle that there is no objective means of assigning value judgements to the different aspects of urban water sustainability, thereby providing a neutral distribution of importance for all indicators. In that this study is in essence centred on urban water sustainability, an equal weighting approach has been adopted for this study.

A composite index is the result of aggregating a number of indicators as a means of summarising large amounts of information (Carden, 2013). As described by Nardo *et al*. (2008), aggregation methods may be linear or geometric. In either case, weights express trade-offs between indicators in that a deficit in one indicator can be compensated by another; this implies an inconsistency in the conception of weights as measuring importance of variables and the actual meaning or outcome when different aggregation methods are adopted. Linear aggregations reward indicators proportionally to weights adopted, while geometric aggregations reward those indicators with higher scores. The compensability is constant for linear aggregation, while compensability is lower for geometric aggregation where low values exist in the composite indicator. Geometric aggregations are more suitable if it is important to maintain some non-compensability between individual indicators, i.e. that poor performance in one area should not be able to be compensated for by good performance in another. If different objectives are equally important and the effects of compensability cannot be permitted, then non compensatory multi-criteria approach (MCA) methods would be a more suitable approach (*ibid*). A weighted linear sum has been adopted for the calculation of the composite score in this study. While the shortcomings of linear aggregation are noted, negative and zero values of normalised indicators can be accommodated.

If indicators are grouped into criteria and aggregated into a composite score, applying equal weighting across all indicators will result in criteria with the larger number of indicators holding more weight in the composite score (Nardo *et al*., 2008). To avoid one criterion having greater contribution to the composite score, the aggregation was carried out in two steps: indicators were first aggregated to obtain a criterion score, following which criterion scores were aggregated to obtain the final composite score. Equations illustrating such are contained in Appendix B: Additional Model Details.

6 Results and Discussion

This chapter presents the key results of the scenarios as identified in Chapter 5. Further model outputs and the results of the remaining interventions built into the system model are contained in Appendix C: Additional Model Results.

The model outputs presented herein for the key scenarios focus on changes to the flows in the system. The water quality (contaminant transport sub-model) results, aggregated for the entire study area, are only indicative of net changes to the system which may be expected, and are contained in Appendix C: Additional Model Results.

The portion of the transfer of demand from the Lower Mgeni to Upper Mgeni WSS prior to implementation of the uMWP is an important consideration for system operation. An analysis of the transfer of demand in two stages (with the proportion thereof prior to the uMWP varying) was undertaken and is documented in Appendix C: Additional Model Results. As a result of this assessment and for subsequent modelling, it was assumed that no demand transfer would take place prior to the uMWP. All of the modelled scenarios include the planned Lower uMkhomazi Bulk Water Supply Scheme being commissioned in 2023 and contributing 130 Ml/d to the Mgeni system water balance.

While the results illustrated herein are generally for the entire study area, results may be generated for each of the areas defined within the model.

6.1 Comparison of Key Outcomes

6.1.1 Key Flows

Monte Carlo simulations were carried out for each of the selected scenarios to determine a range of system performance possibilities. The variability for each intervention, combined with the variability in parameters from the baseline scenario, yields the resulting time series shown in Figure 6-1 to Figure 6-8.

Figure 6-1 shows the total real losses across bulk supply areas, as adjusted by loss reduction measures to reach the pre-defined targets, and the reduction in base demand as a result of consumer-focussed WCWDM interventions. Figure 6-2 indicates the cumulative volume of greywater which is reused; the cumulative rainwater tank outflows as a result of the available volume and the demand (as determined by the defined end-uses); the total volume of wastewater recycled to potable standards prior to being distributed to selected bulk supply areas; and the total volume of wastewater recycled to non-potable standards. Figure 6-3 to Figure 6-5 then aggregate the bulk water supplied per major system – i.e. Upper Mgeni, Lower Mgeni, and the North Coast (Hazelmere / Tongaat). The time series here include demands external to eThekwini, as these areas affect the availability of water for the study area itself (i.e. if there is a supply limitation in the Upper Mgeni system, eThekwini and upstream areas such as Pietermaritzburg would both be affected). Figure 6-6 illustrates the total bulk water supplied across all water supply systems, but is limited to eThekwini itself. Figure 6-7 shows the cumulative dam storage across all water supply systems. Lastly, Figure 6-8 indicates the cumulative inflow of wastewater to wastewater treatment works in the study area.

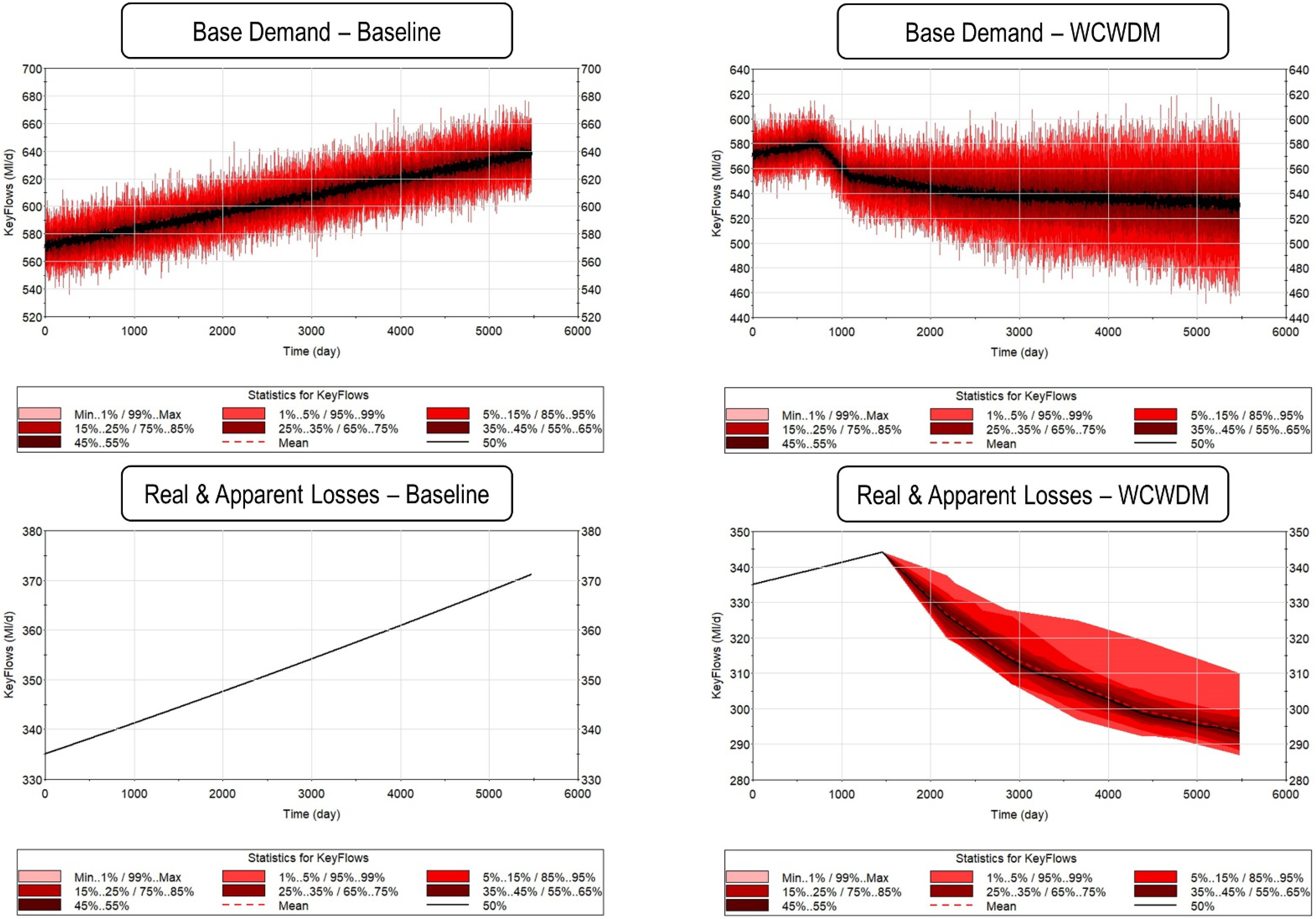
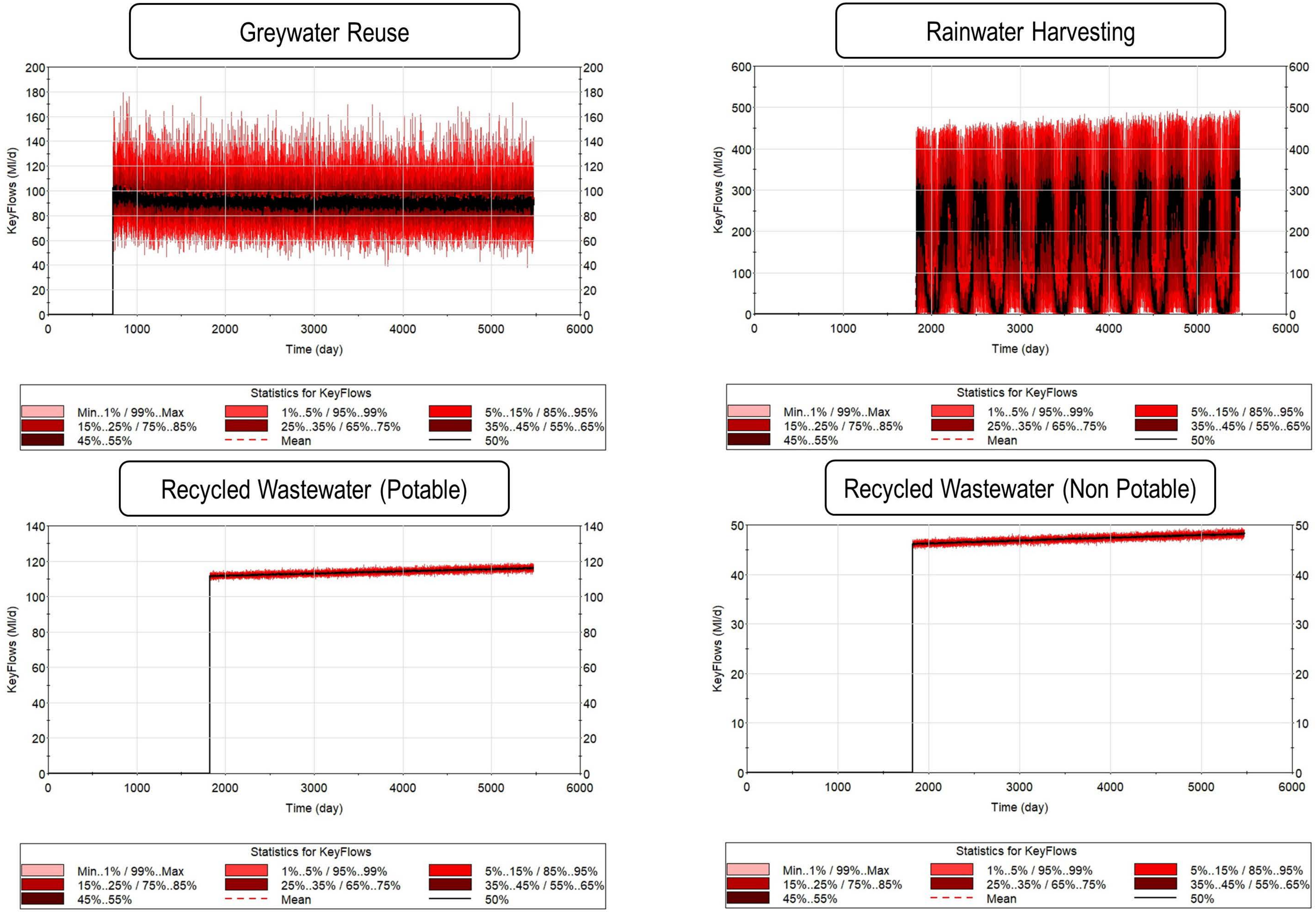


Figure 6-1: Monte Carlo Analysis of Total Base Demand and Real & Apparent Losses, Performance Across Scenarios

Note: The scenarios involving rainwater harvesting and wastewater recycling yield the same results as the baseline scenario. The greywater recycling scenario includes WCWDM and therefore yields the same result as the WCWDM scenario.



Greywater Reuse

Rainwater Harvesting

Recycled Wastewater (Potable)

Recycled Wastewater (Non Potable)

Figure 6-2: Monte Carlo Analysis of Total Alternative Water Sources for All Systems

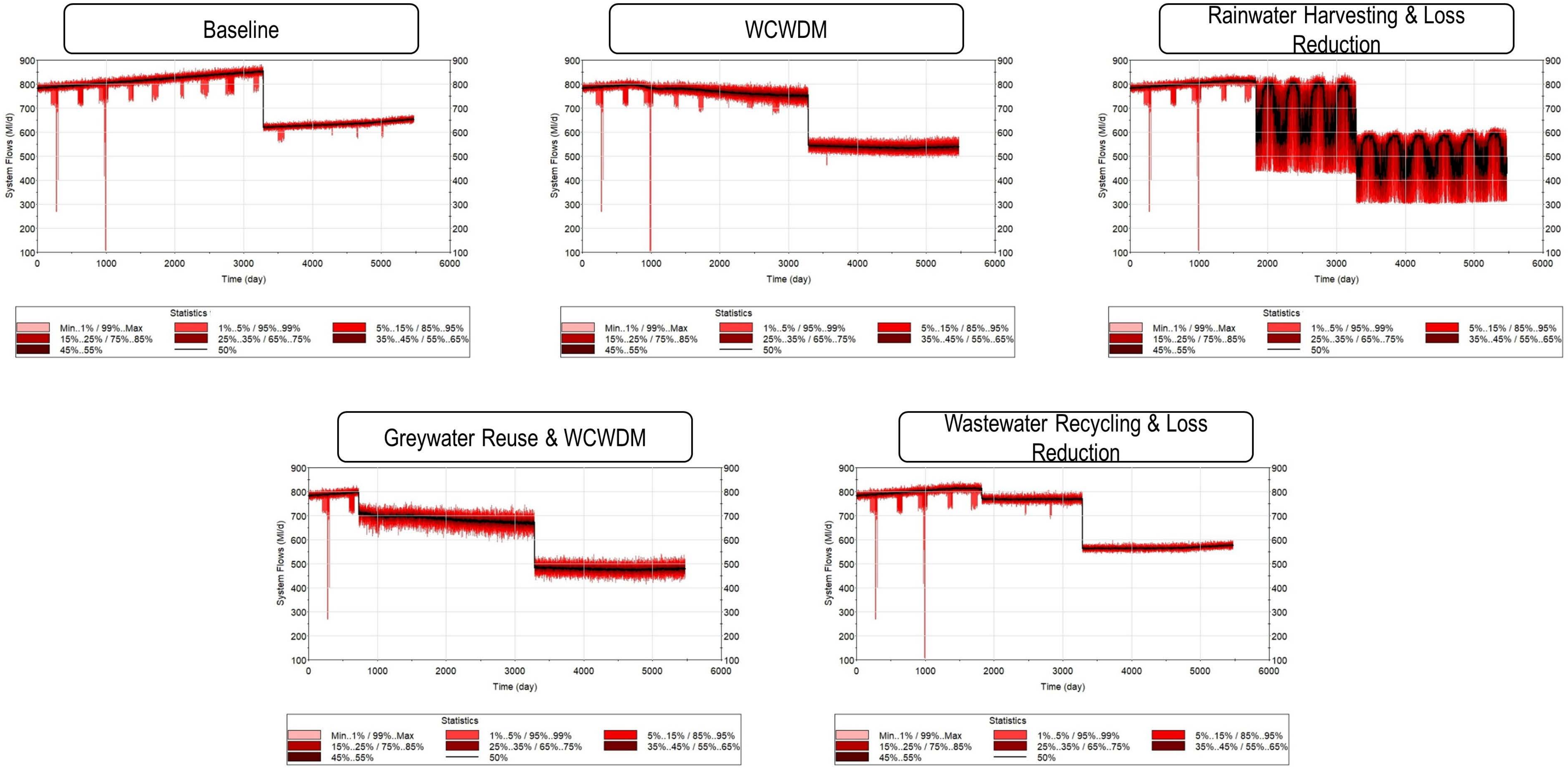


Figure 6-3: Monte Carlo Analysis of Bulk Water Supply in Lower Mgeni System, Performance across Scenarios

Note: The drop in supplied volume around 9 years into the simulation is a result of the transfer of demand from the Lower Mgeni to Upper Mgeni WSS once the uMWP is commissioned.

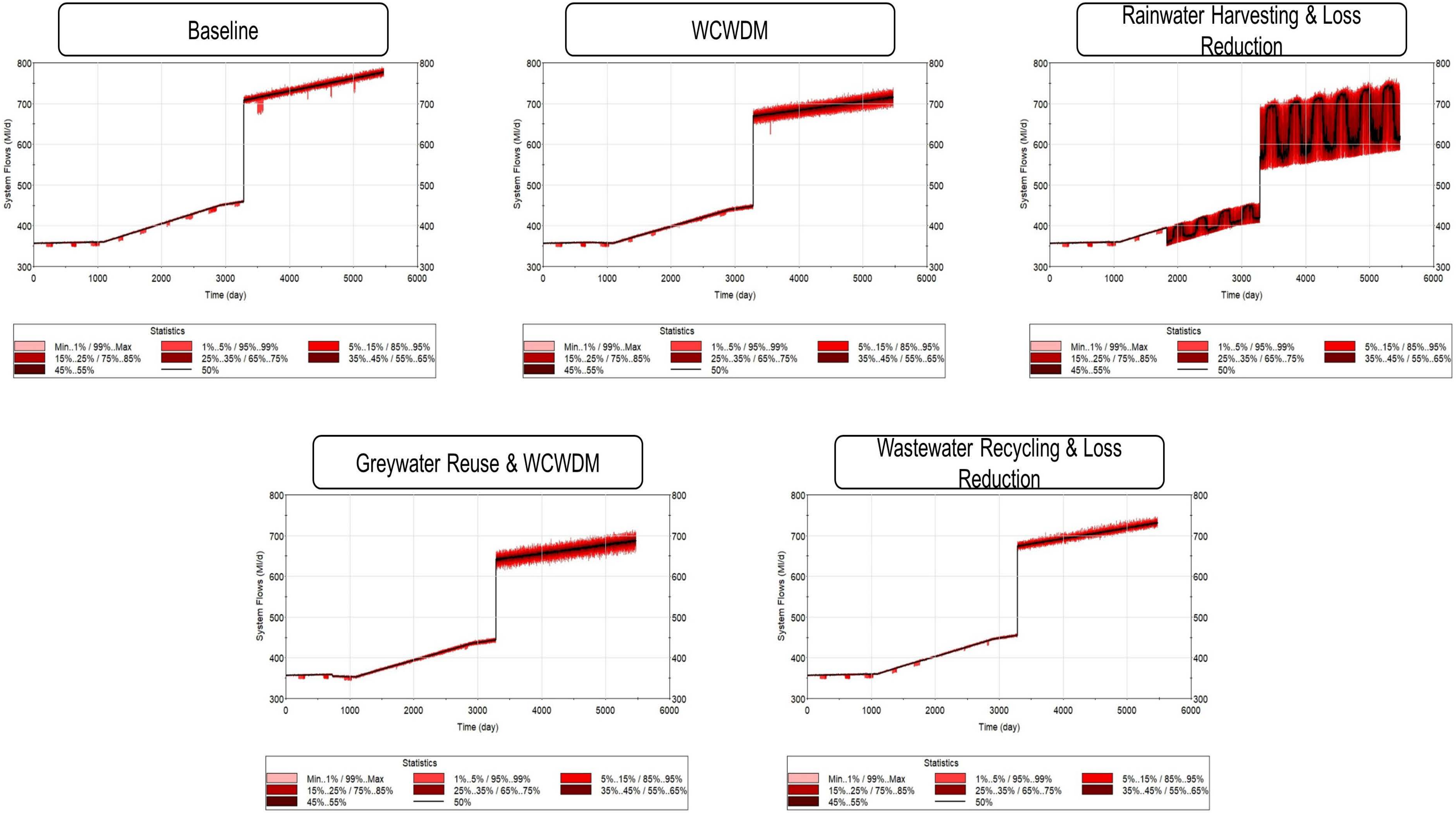
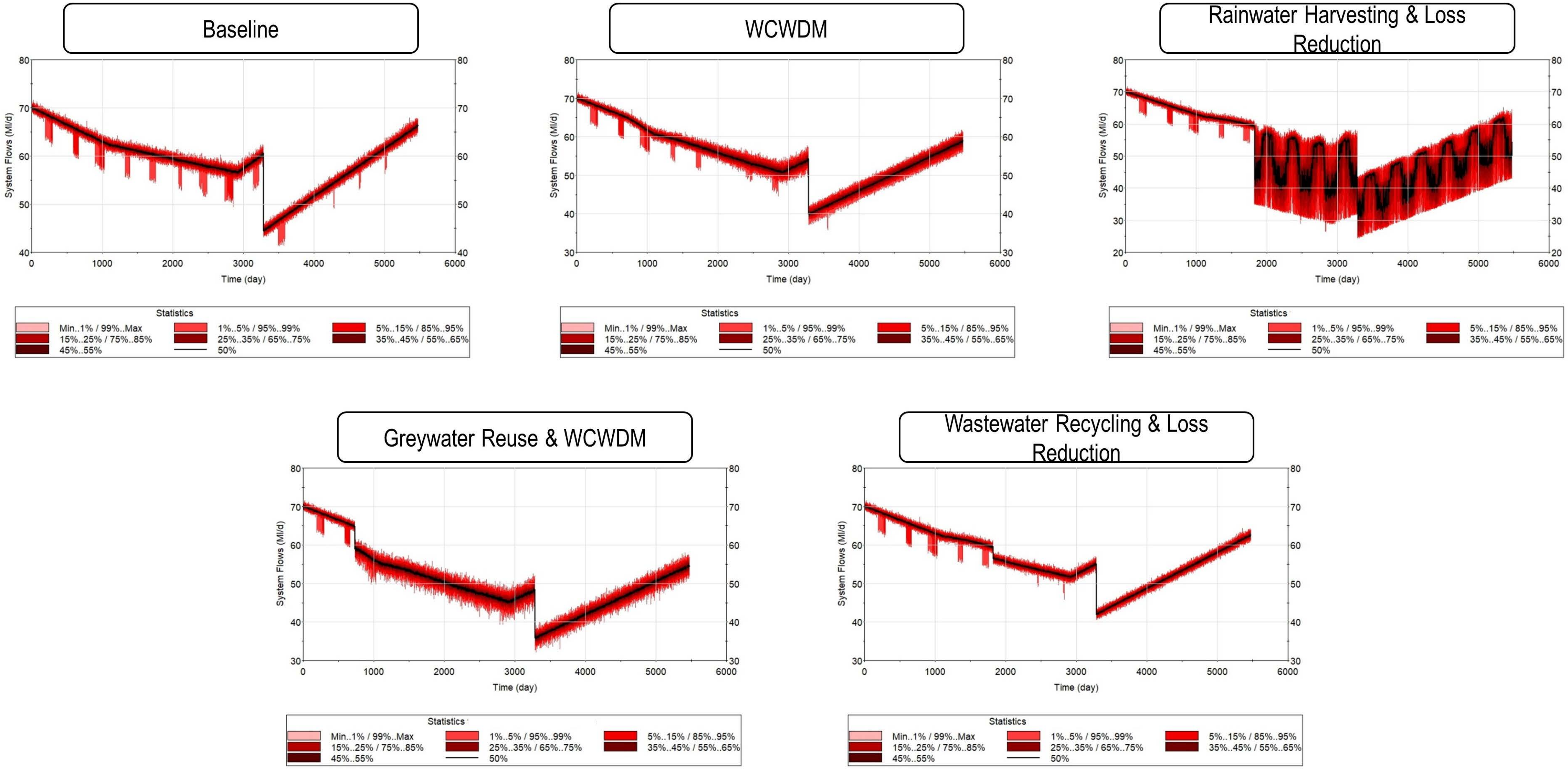


Figure 6-4: Monte Carlo Analysis of Bulk Water Supply in Upper Mgeni System, Performance across Scenarios

Note: The increase in supplied volume around 9 years into the simulation is a result of the transfer of demand from the Lower Mgeni to Upper Mgeni WSS once the uMWP is commissioned.


Baseline

WCWDM

Rainwater Harvesting & Loss Reduction

Greywater Reuse & WCWDM

Wastewater Recycling & Loss Reduction

Figure 6-5: Monte Carlo Analysis of Bulk Water Supply in North Coast System, Performance across Scenarios

Note: The gradual but marked decrease and subsequent increase in supply from the Hazelmere/Tongaat systems is a result of (1) a portion of external demands being shifted onto other supply schemes in the North Coast WSS; and (2) subsequent uptake in external demands as other supply schemes in the North Coast WSS are expanded to supply new areas. The drop in supplied volume around 9 years into the simulation is a result of the transfer of demand from the Lower Mgeni to Upper Mgeni WSS once the uMWP is commissioned.

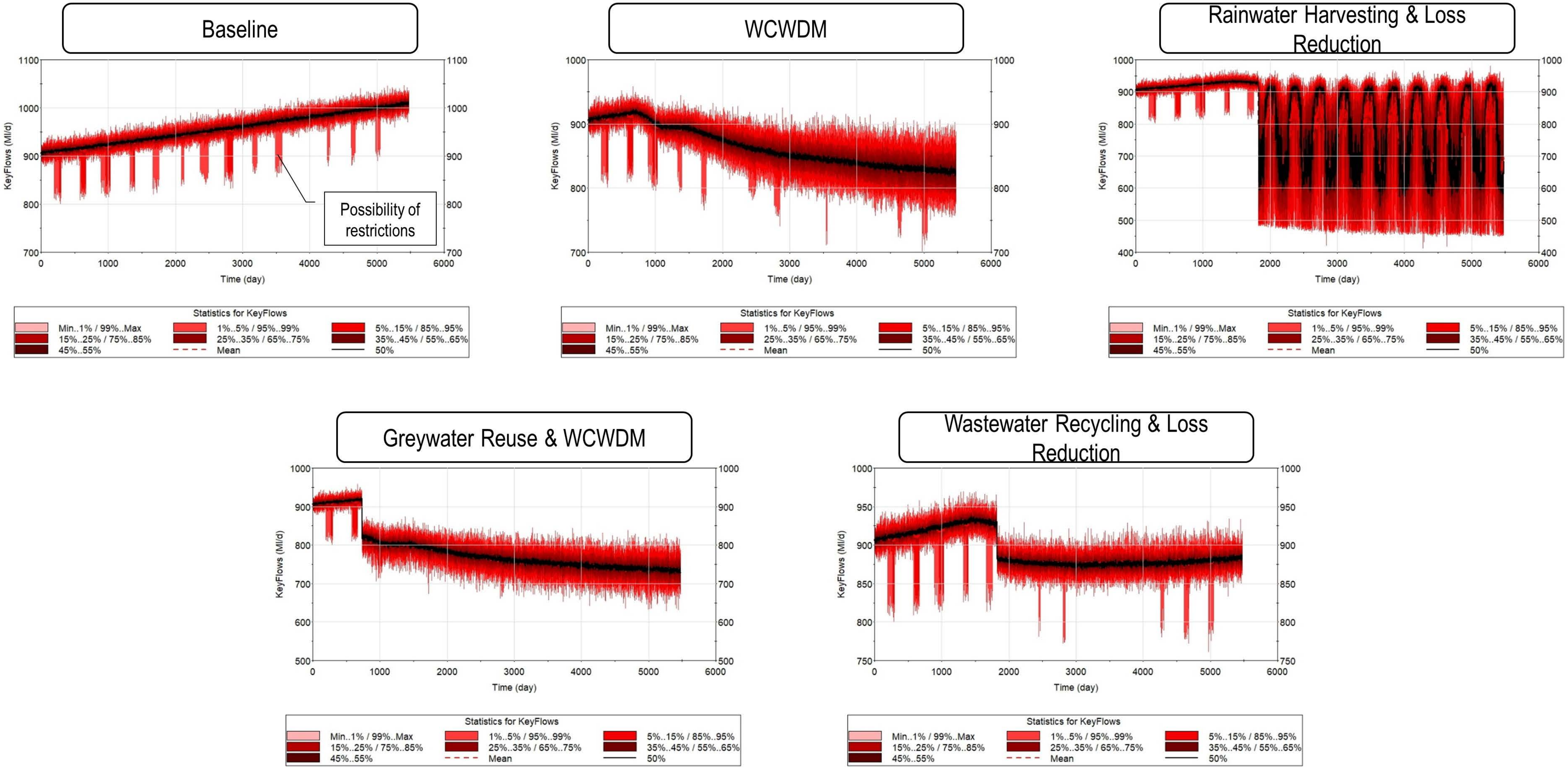


Figure 6-6: Monte Carlo Analysis of Total Bulk Water Supplied for All Systems, Performance across Scenarios

Note: Sudden reductions in supplied water over discrete periods indicate possibility of restrictions. Bulk water supplied shown here is for eThekwini only (i.e. external demands are excluded).

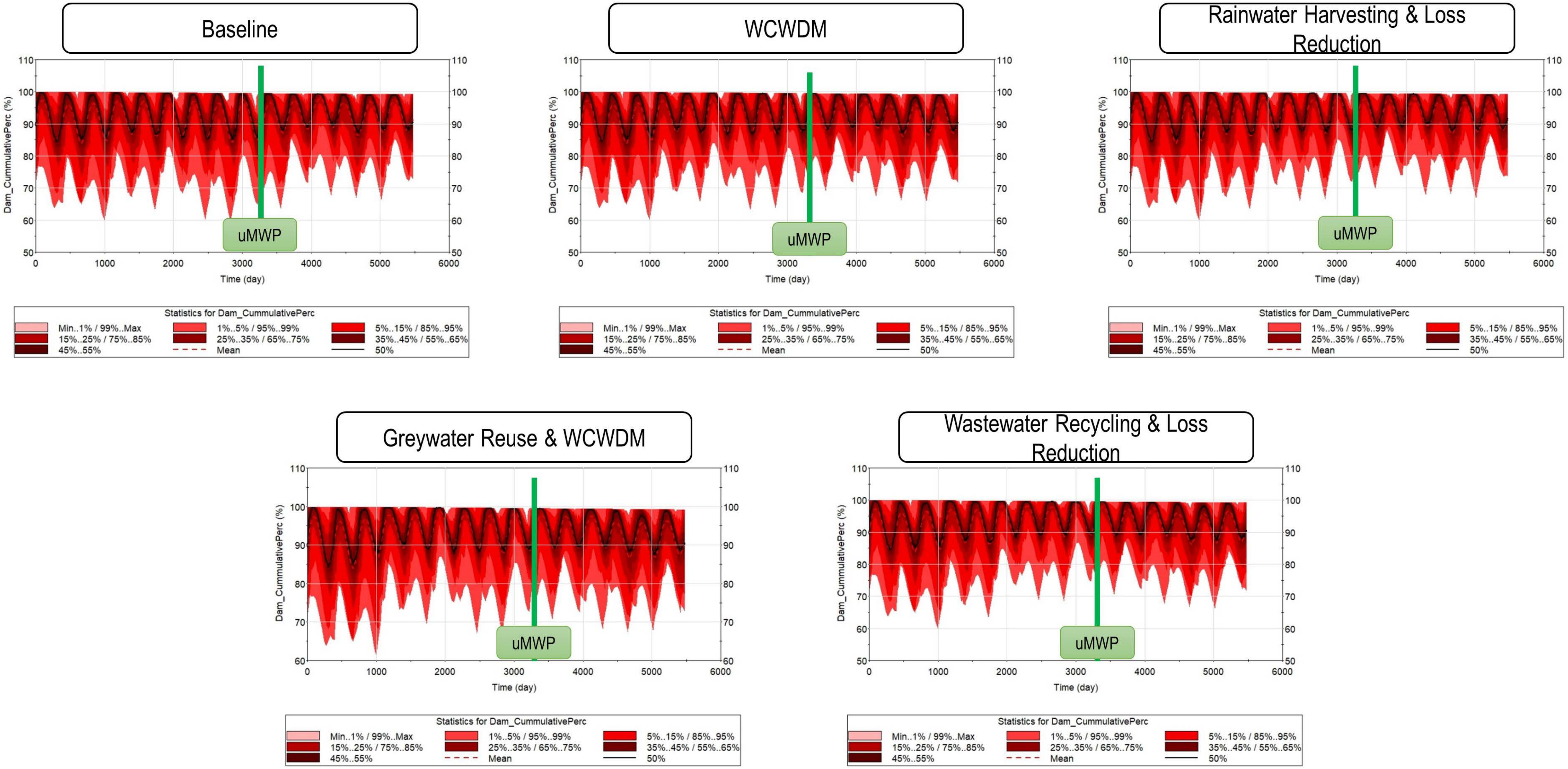


Figure 6-7: Monte Carlo Analysis of Cumulative Dam Storage, Performance across Scenarios

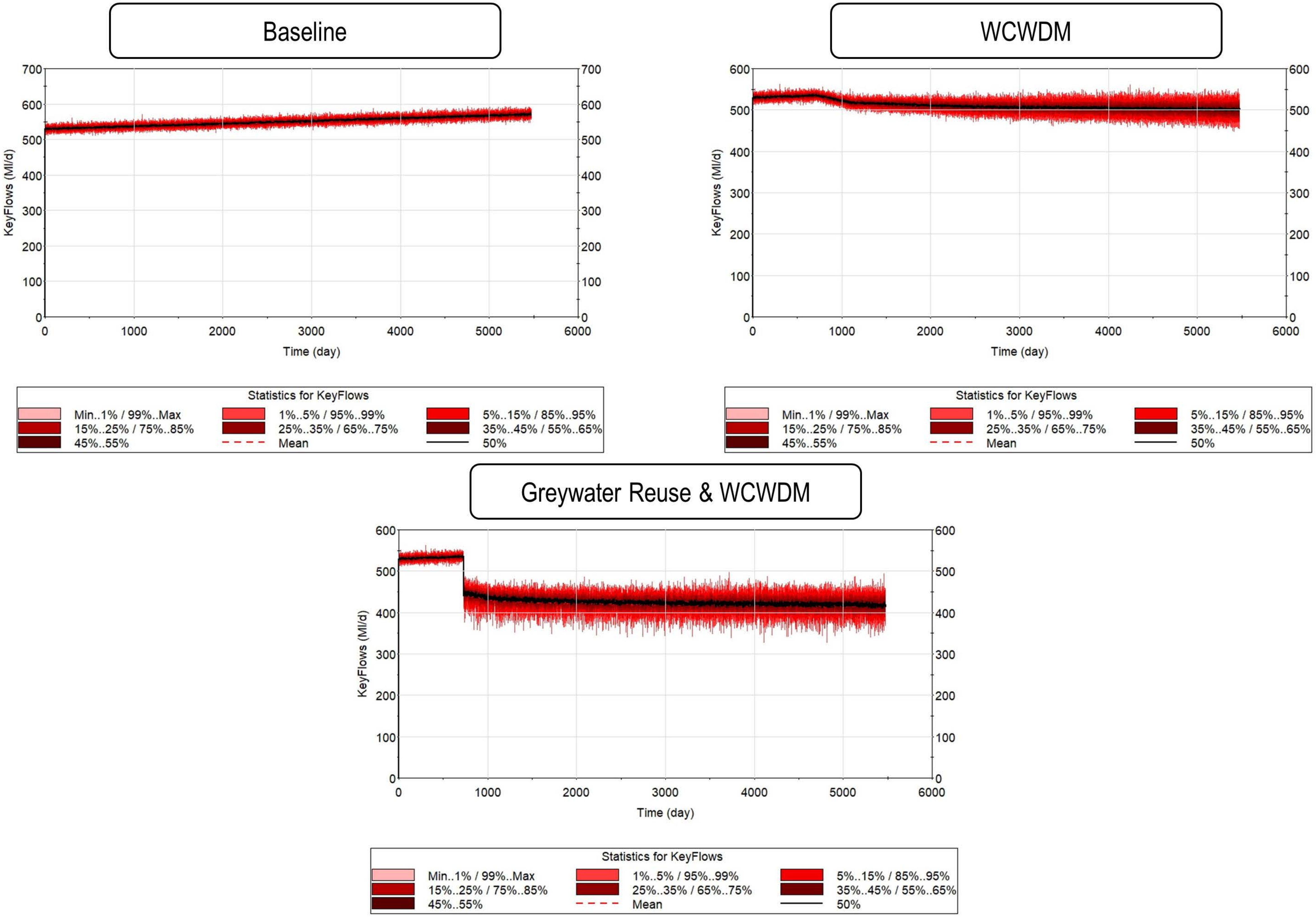


Figure 6-8: Monte Carlo Analysis of Total Inflow to Wastewater Treatment Works

Note: The scenarios involving rainwater harvesting and wastewater recycling yield the same results as the baseline scenario.

All four intervention scenarios are successful in reducing the demand on the bulk water systems supplying eThekwini Municipality. The sharp reductions in supplied volumes over discrete time periods indicates the possibility of restrictions being enforced as a result of low dam levels at the start of the dry season (winter). Each of the scenarios see a reduction in the frequency of potential restrictions.

The impact of WCWDM on the total demand is notable for the scenarios which include consumer-focussed WCWDM measures (WCWDM and greywater scenarios).

With regards to the rainwater harvesting scenario, the total demand fluctuates with rainwater tank usage. When the availability of rainwater falls to zero in periods of low rainfall, the total demand on the bulk water system reaches the same values which would occur if there were indeed no rainwater tanks in the system. This effect could be mitigated or reduced by increasing tank size (notably the tank size required may not be practical), and modifying the demand on tanks to reflect consumers conserving tank water in periods of low rainfall (though the balance of demand will then at least partially need to be satisfied with potable sources, thereby still resulting in periodical increased demands on the bulk water system). Such complexity has not been explored in this study. These are important observations for bulk infrastructure planning; the introduction of rainwater tanks does not perpetually reduce demand on bulk infrastructure, though it could have temporally cumulative benefits on water resource storage volumes.

With regards to the wastewater recycling scenario, the drop in demand five years into the simulation is a result of non-potable recycled water being made available for non-potable (Class 2) end-uses (only those bulk supply areas which also coincide with Amanzimtoti and Central WWTWs are affected). The supply of wastewater recycled to potable standards has no impact on the demand on the potable water system; as planned by eThekwini, this water would be “injected” into the bulk potable water infrastructure for distribution, but does not change the volume of potable water required to meet end-uses.

The cumulative dam storage in Figure 6-7 shows there is not much variation between interventions, but it is evident that implementation of the uMkhomazi Water Project has a positive impact on stabilising the system storage.

As a downstream effect of consumer-focussed WCWDM measures, the volume of wastewater produced and therefore influent volumes to WWTW’s is reduced. The wastewater inflow to plants only accounts for those consumers connected to bulk sewerage infrastructure, as well as infiltration, as this contributes to the daily volume which requires treatment and safe disposal.

With the aim of capturing the variability throughout the simulation and summarising the effect each scenario has on the flows in the water cycle, the 50th percentile values (based on generated cumulative frequency diagrams) for the entire simulation period are shown in Figure 6-9. The cumulative frequency diagrams used to determine these figures are presented in Appendix C: Additional Model Results.

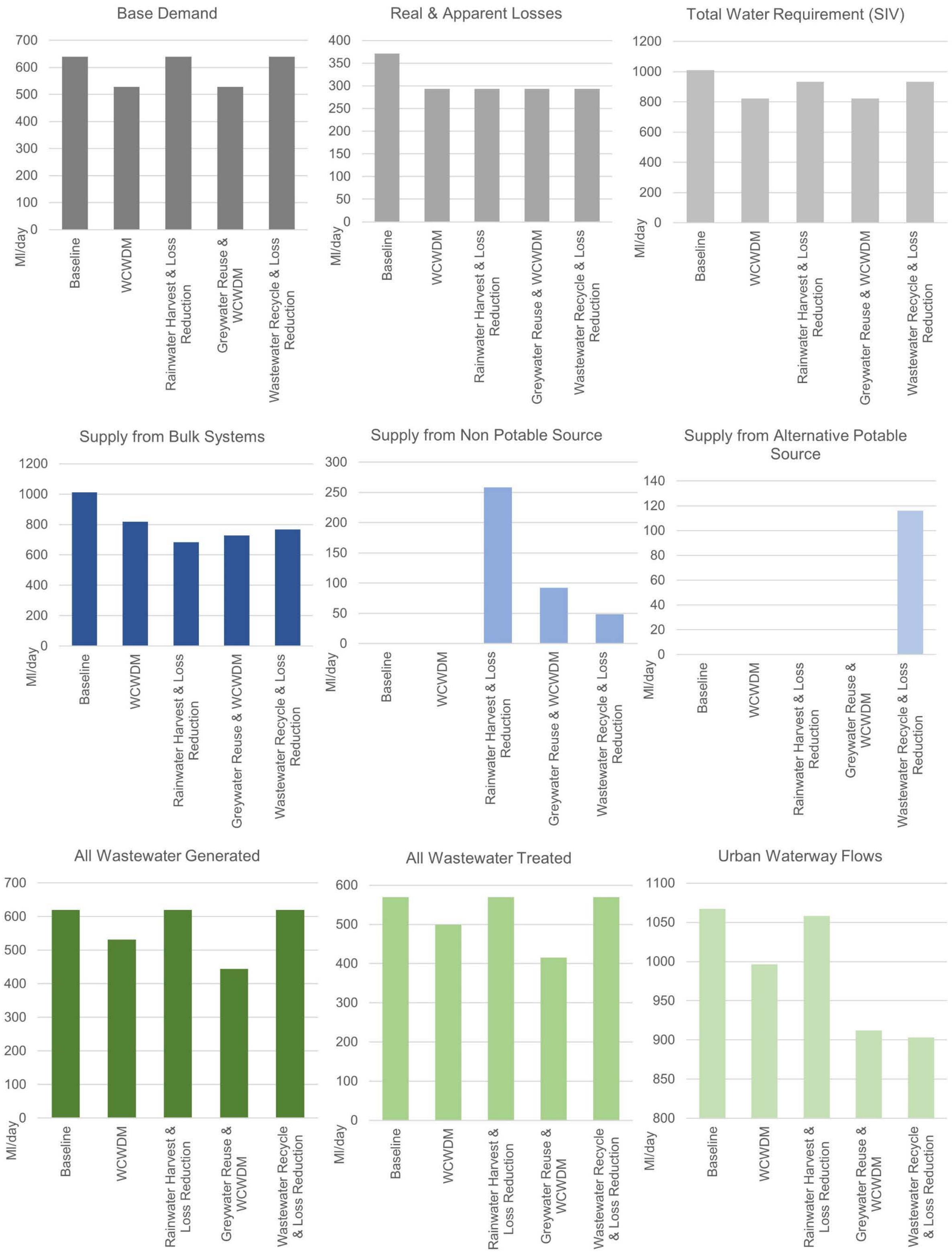


Figure 6-9: 50th Percentile Values for (Total) Key Flows for Study Area, Performance across Scenarios

All four intervention scenarios include loss reduction – the effect of which can be seen in the total water requirement. Scenarios involving consumer-focused WCWDM and greywater reuse result in further decrease in the total water requirement. The total water requirement may be met with bulk (potable) or alternative water sources (driven by defined end-uses). Rainwater harvesting, greywater reuse, and wastewater recycling provide alternative sources of water; the effect of which is seen in the reduced volume of water supplied from bulk (potable) water systems. The volume of wastewater generated and treated is reduced by the scenarios involving consumer-focused WCWDM and greywater reuse. The effect of reduced effluent volume is seen in the urban waterway flows. Here, the wastewater recycling scenario also contributes to a reduction in effluent reaching urban waterways.

6.1.2 Resource Efficiency

Figure 6-10 summarises the potable water supplied per capita, summarised for the whole study area. Figure 6-11 (overleaf) shows a breakdown of the potable water supplied per capita for the respective water supply systems. Interesting to note is that while greywater reuse provides a consistently low per capita potable water use over the simulation period (Figure 6-10), rainwater harvesting yields the lowest per capita potable water use when considering the 50th percentile of the cumulative distribution function over the entire simulation timeline (Figure 6-11).

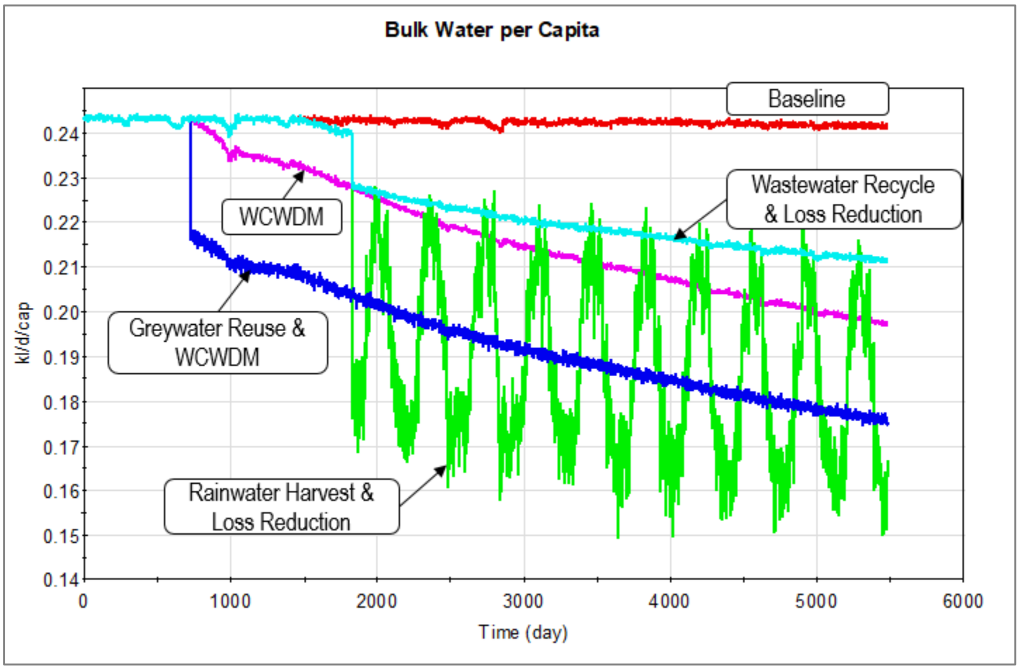


Figure 6-10: Potable Water Supplied per Capita

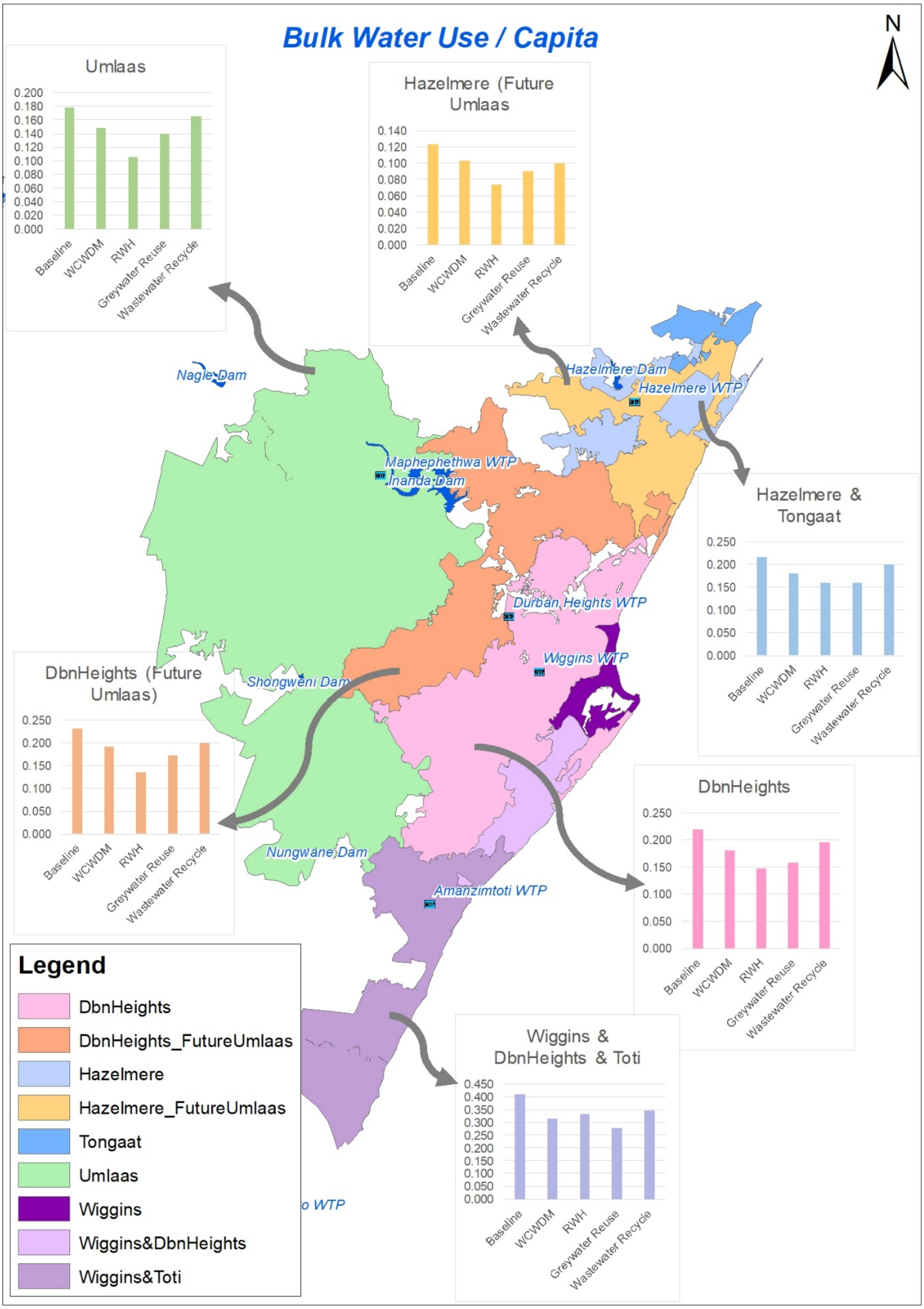


Figure 6-11: Map of Bulk Water Supplied per Capita

6.1.3 Composite Score

The composite score for each scenario is illustrated in Figure 6-12. The indicators are based on the mean outputs of each time series following a Monte Carlo analysis. Individual indicator performance and criteria scores are included in Appendix C: Additional Model Results. Overall, it can be seen that greywater reuse with WCWDM measures consistently achieves the highest composite score. The other intervention scenarios yield comparable composite score results over the simulation period. The small spike in the time series for greywater reuse with WCWDM is a result of a more beneficial risk score following a deficit in available supply (supply system recovery is more pronounced for this scenario).

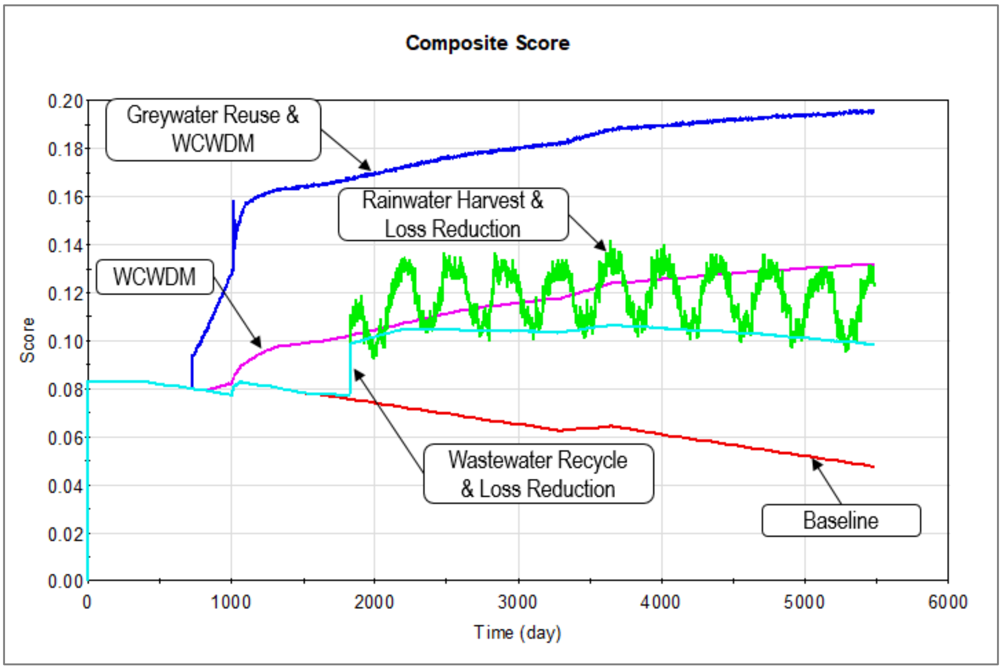


Figure 6-12: Composite Scores

6.1.4 Mgeni System Water Balances

The Mgeni Water Supply System provides water to a large portion of eThekwini Municipality and is therefore of particular interest to this study.

In the event the uMWP is significantly delayed, simulations were run where the concomitant increase in system yield and treatment capacity was excluded from the analysis. The results presented from Figure 6-13 to Figure 6-15 assume the baseline scenario (i.e. no interventions).

Figure 6-13 illustrates the cumulative dam storage for two scenarios: firstly, where the uMWP is implemented within 9 years; secondly, where the uMWP is not implemented within the model simulation time. In that the latter case yields more frequent occurrences of dam storage dropping below 70%, there is greater probability of system-wide water restrictions.

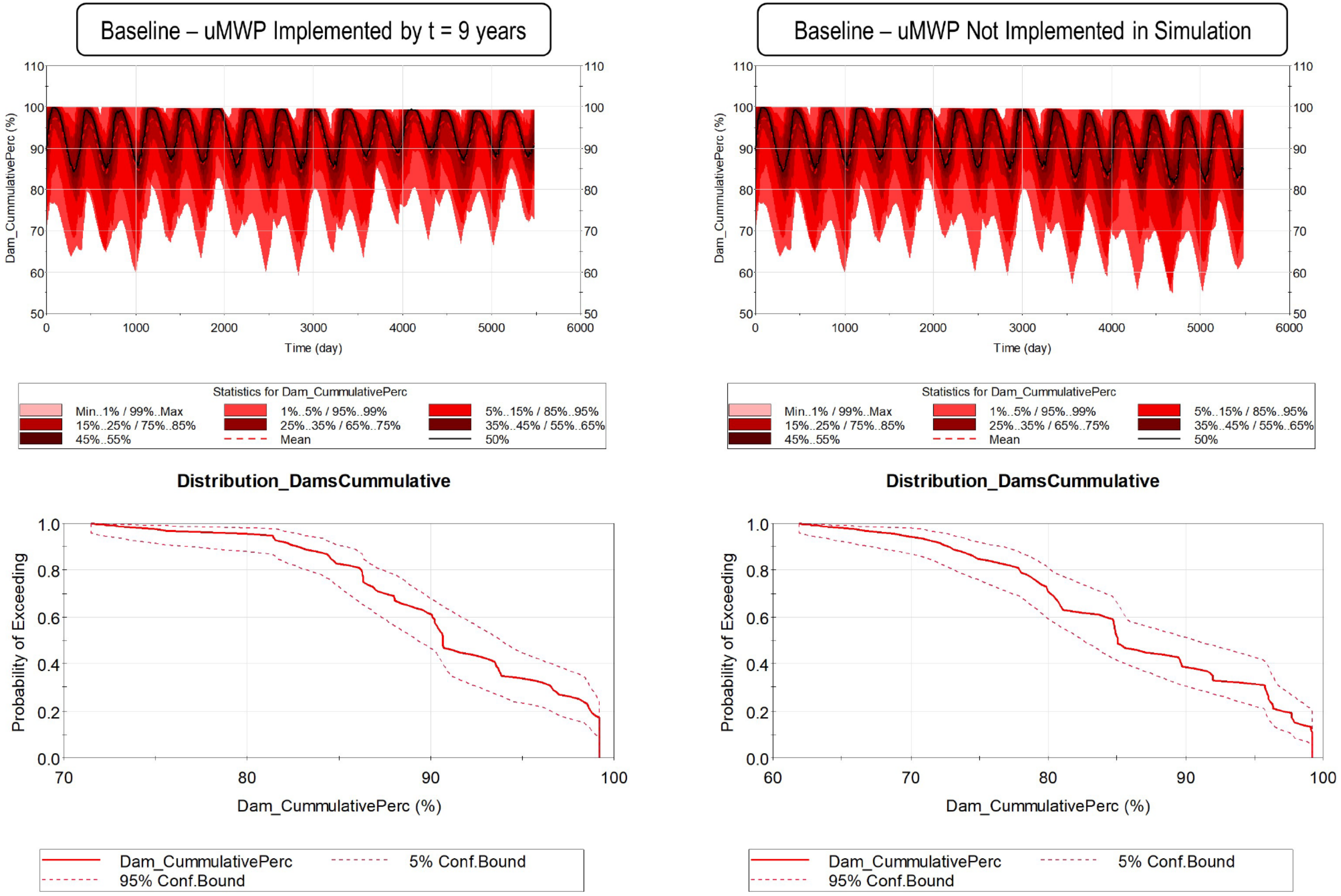


Figure 6-13: Cumulative Dam Storage: uMWP Implementation Time

A long-range simulation was run (50 years) where there is no implementation of the uMWP which aimed to test the possibility of any severe supply failures within the defined period. Figure 6-14 plots the demand and available supply for one possible "realisation" of the system model; the dam yield and treatment capacity of the Upper Mgeni system is far exceeded from t ± 16 years. The treatment capacity of the Lower Mgeni system is exceeded toward the end of the simulation time. While there are no severe supply failures in the Lower Mgeni system, there are possible periods of water restrictions when dam storage is low in dry seasons. The yield of the Hazelmere system is exceeded from t ± 19 years, though demands external to eThekwini (within the Hazelmere supply area) can be taken up by implementing Phase 2 of the Lower Thukela Bulk Water Supply Scheme.

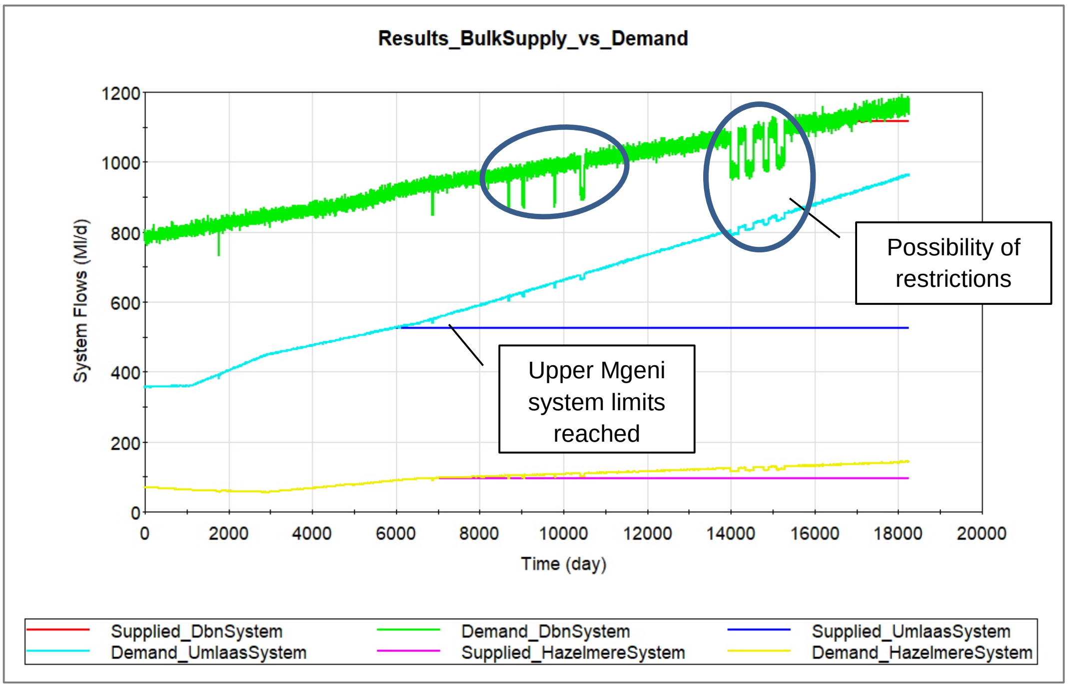


Figure 6-14: Demand vs Availability for Water Supply Systems: uMWP Not Included

Figure 6-15 shows the results of a Monte Carlo analysis of the system where the uMWP is not implemented. While there appears to be no (modelled) possibility of a severe supply failure, frequent restrictions when dam storage levels necessitate such are probable. Conditions of frequent restrictions is not sustainable nor a preferred means of system operation, and would likely have detrimental effects on growth and economic activity in the region.

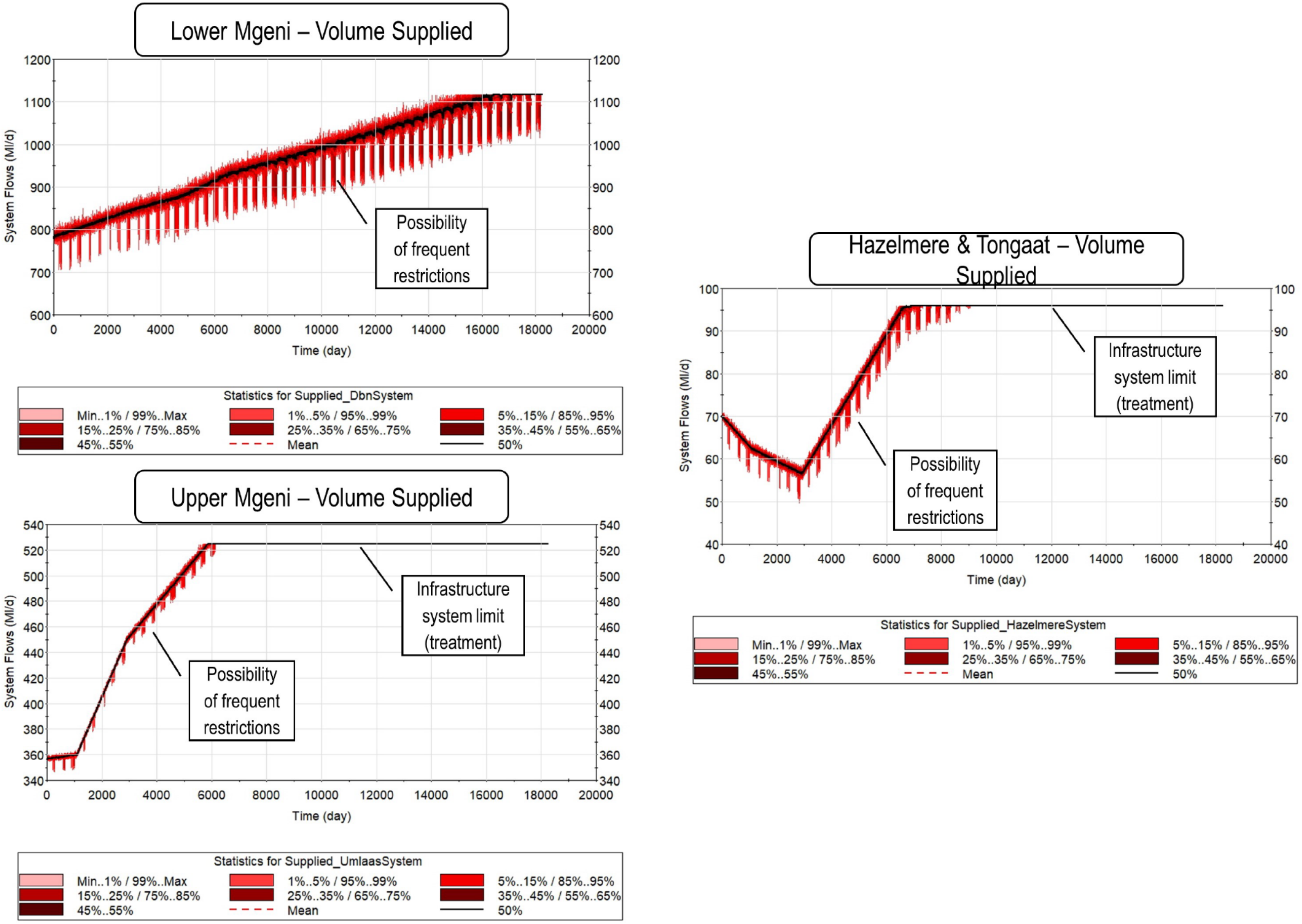
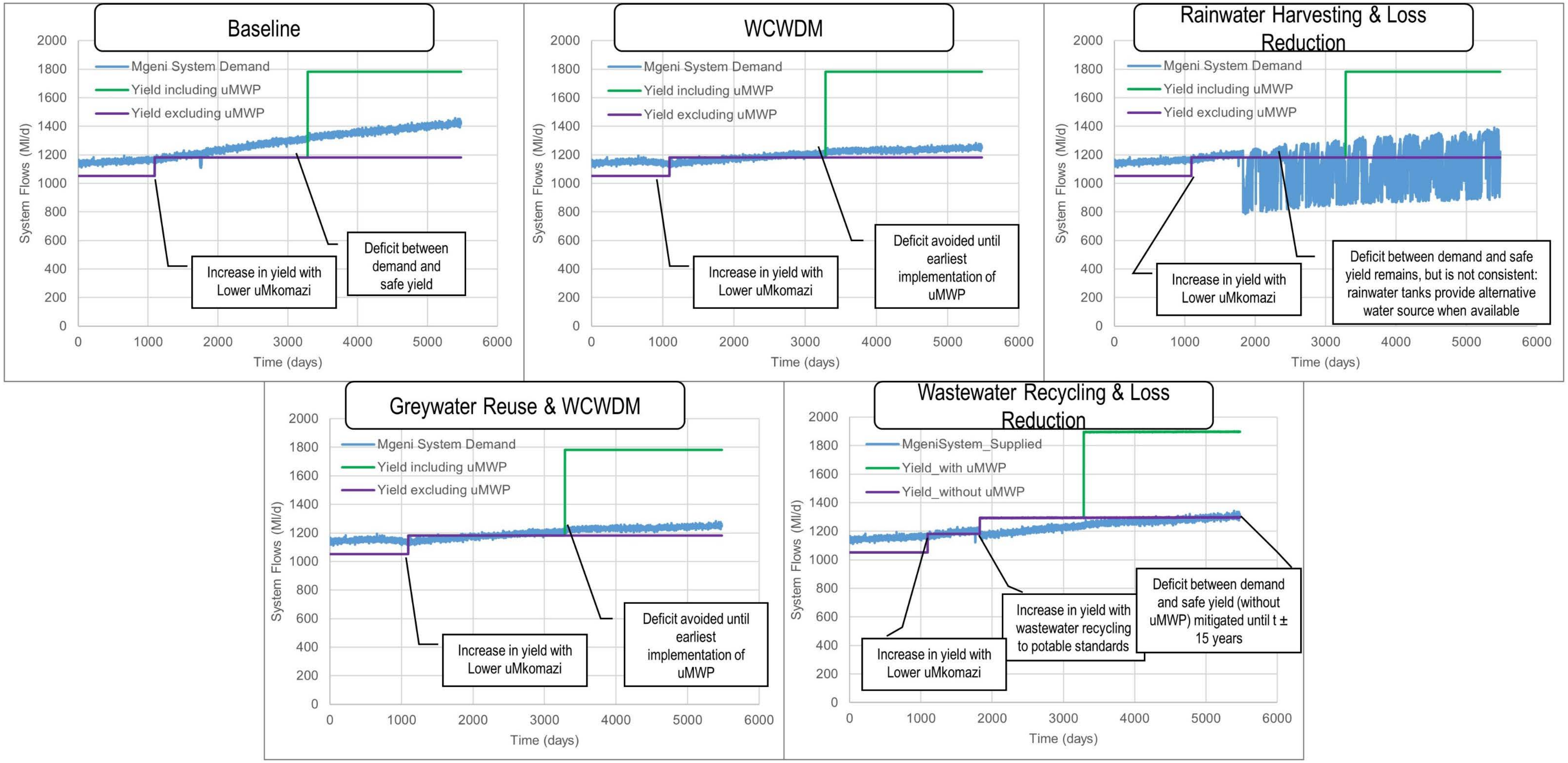


Figure 6-15: Volumes Supplied to Water Supply Systems: uMWP Not Included

As detailed by the Umgeni Water Masterplan (UW, 2019) and the Reconciliation Strategy (DWS, 2017), the actual demand on the Mgeni WSS currently exceeds the total water resource system yield, thus increasing the risk of supply shortfalls until such time the system deficit is removed. While the uMWP has shown to be a necessity for long-term water security of the Mgeni WSS, the interventions associated with each of the key scenarios in this study have the potential to reduce the system deficit and thus improve security of supply until uMWP is implemented. Figure 6-16 shows the impact of each intervention on the water balance of the Mgeni WSS. The greywater reuse and wastewater recycling scenarios could potentially afford more time for implementation of the uMWP. It must further be noted that the Lower uMkhomazi Bulk Water Supply Scheme (planned for completion at such time corresponding to three years into the simulation) greatly contributes to improving the water balance in the short term.


Baseline

Increase in yield with Lower uMkomazi

Deficit between demand and safe yield

WCWDM

Increase in yield with Lower uMkomazi

Deficit avoided until earliest implementation of uMWP

Rainwater Harvesting & Loss Reduction

Increase in yield with Lower uMkomazi

Deficit between demand and safe yield remains, but is not consistent: rainwater tanks provide alternative water source when available

Greywater Reuse & WCWDM

Increase in yield with Lower uMkomazi

Deficit avoided until earliest implementation of uMWP

Wastewater Recycling & Loss Reduction

Increase in yield with Lower uMkomazi

Increase in yield with wastewater recycling to potable standards

Deficit between demand and safe yield (without uMWP) mitigated until t ± 15 years

Figure 6-16: Mgeni System Water Balances for each Scenario

6.2 Concluding Remarks on Model Analyses

As expected based on the water balances produced for the Reconciliation Strategy (DWS, 2017) and Umgeni Water Masterplan (UW, 2019), the model highlights the current pressure on the Mgeni WSS until such time augmentation projects have been commissioned.

Even though the real loss reduction and consumer-focussed WCWDM interventions modelled for this study are conservative, it is clear these interventions could play an important role in sustainability of supply by curbing unchecked growth in demand; such is especially important in the short to medium term prior to implementation of the uMkhomazi Water Project, where interventions are a necessity to close a growing gap between demand and firm system yield. As a by-product of consumer-focussed WCWDM, this scenario also slows the growth in the generated volumes of wastewater.

While rainwater harvesting is advantageous in reducing the cumulative demand on the bulk potable water system, it does not perpetually reduce the demand in that there will be occurrences where rainwater tanks are empty, and the total demand is to be fulfilled by the bulk potable water system. In other words, the introduction of rainwater tanks does not automatically imply an increase in system yield, especially not of equivalent level of assurance as provided by the bulk potable water system. Rainwater harvesting also has the effect of reducing the volume of runoff reaching urban waterways; further analysis would be required to determine whether the volumes removed from the urban catchment runoff are in fact appropriate and do not have a negative environmental impact.

The introduction of greywater reuse results in a drop in demand on the bulk potable water systems, and the WCWDM interventions curb the demand curve through time. When the full WCWDM intervention is coupled with greywater reuse, there is an appreciable reduction in the volumes of wastewater generated, and thus correspondingly less treated effluent discharged to the environment, which is important if the requirements of the estuarine reserve determinations are to be met in future, especially prior to implementation of indirect reuse via Hazelmere Dam. Wastewater recycling provides a consistent additional volume to the system, and is beneficial for reducing the gap between demand and firm system yield.

While rainwater harvesting, greywater reuse, and consumer-focussed WCWDM interventions result in considerable positive effects on the performance of the system, these interventions are highly dependent on consumer behaviour, which cumulatively drives the system wide impact of the respective scenarios. The Monte Carlo analysis of these scenarios does, however, account for variability, though further study and analysis would be required to determine whether the variability represented is in fact appropriate.

Finally, it should be noted that the system model and the results discussed herein are focussed on the water balance of the water cycle and resource efficiency, rather than on the practicalities and indirect impacts around implementation of SUWM solutions. Another study approaching the same problem, but from a different perspective of evaluation, may draw different conclusions; for example, establishment of third pipe infrastructure may have a negative environmental impact.

7 Conclusion and Recommendations

7.1 SUWM and Hybrid Water Services

The literature review explored the concept of Sustainable Urban Water Management in contrast with traditional modes of service provision. Decentralisation and integration to allow consideration of the total water cycle are cornerstones of SUWM approaches (Marlow *et al*., 2013; Leigh & Lee, 2019). There are positive drivers for both centralised and decentralised systems; there is, however, both theoretical and experiential evidence that the current infrastructure archetype could benefit from inclusion of decentralised systems and a more integrated approach to the management of the water cycle. A complete transition to alternative water provision models is neither economical nor practically feasible in already developed areas, necessitating innovations in new areas and as retrofits to existing systems, such systems where the water services configuration is evolving are termed hybrid systems (Marlow *et al*., 2013, Sapkota *et al*., 2015).

Alternative water provision models bring dynamic changes to existing systems which may not be intuitive: the complexity of urban water systems and the resulting uncertainty means an intervention may achieve one SUWM objective yet undermine another. Thorough evaluations of alternative water provision models are therefore essential, while recognising that less learned experience on the performance of innovative solutions means uncertainty remains part of the evaluation (Marlow *et al*., 2013). Incorporating variability and uncertainty in forecasts and assessment and subsequent management of associated risks is crucial for ensuring suitable operational performance of alternative water supply schemes (West, Kenway & Yuan, 2015).

7.2 Case Study Area

eThekwini municipality was selected as the case study area for this research. Akin to most South African cities, this region is home to a diverse range of consumers (fully serviced urban suburbs, informal settlements, peri-urban settlements, and rural areas), is experiencing urbanisation and growth in demand, and is supplied by catchments whose water resources are fully developed and are at risk of becoming significantly stressed. This is set against a backdrop of challenges in service delivery, environmental concerns as a result of water practices, potential impacts of climate change in the future, and ultimately sustainability of service provision.

Chapter 4 explored the future water security of the region from the perspective of water resource custodian (Department of Water and Sanitation), bulk water provider (Umgeni Water) and Water Service Authority (eThekwini Municipality). Ensuring water security includes necessary large-scale surface water augmentation projects; the uMkhomazi Water Project is critical for the Mgeni Water Supply System to maintain appropriate assurance of supply in future, considering the social and economic importance of the region. Alternative water supply options are included as means to ensure water security, though there does appear to be preference for large-scale schemes for wastewater recycling and possibly desalination. Rainwater harvesting, on the other hand, is categorised as a support intervention which mostly benefits the consumer, and to an extent, the municipality. WCWDM is recognised as an important on-going programme for ensuring sustainability of supply and service provision, though it would appear the focus is on the overall infrastructure network and not on gains to be made by encouraging consumers to engage water sensitive practices. Interestingly, despite groundwater forming an integral part of the water cycle, there are no apparent plans for the management of interactions between groundwater and other elements of the water cycle.

There are opportunities to extend existing interventions further; WCWDM programmes could include consumer engagement to encourage water saving practices, including best practice guidelines for greywater reuse activities and rainwater harvesting; rainwater harvesting tanks could be installed across the municipal area; and the wastewater recycling successes of the Durban Recycling Plant could be implemented in other industrial areas or for recycling to potable standards (subject to public acceptance). Establishing extensive third pipe systems for non-potable supplies (e.g. for non-potable recycled wastewater) could, however, prove prohibitive in terms of cost and technical feasibility in already developed areas, and would require careful consideration in conjunction with the potential benefits.

7.3 Assessment Framework and Systems Dynamics Model

Studies on sustainability of water systems commonly includes steps of identifying solution options, developing scenario paths, and evaluation against a set of criteria. Assessment (for evaluation) considers sustainability of water supply and demand management options through embedding selected options in the total urban water cycle and then implementing a modelling approach (Rathnayaka, Malano & Arora, 2016). The assessment framework for this study comprises defining the problem, setting objectives, formulating performance criteria, investigating existing conditions, developing intervention options and scenarios for testing, and finally applying the aforementioned aspects to a system analysis tool. The system analysis model includes the ability to assimilate composite scores for each scenario path as a convenient way of summarising information-rich model outputs.

There is evidence of a wide range of modelling approaches, though the selection of such is informed by the nature of the problem and the desired outputs; i.e. the modelling approach must suit the problem structure. As noted by Winz & Brierley (2007) complex systems are by nature embedded with uncertainty; systems dynamic models will not yield precise answers, and are therefore limited in usefulness when dealing with well-defined problems. On the other hand, where uncertainty exists, detailed models would not hold value. A model’s level of detail should suit the problem and be able to address the complete problem (*ibid*). Being able to assess the changes to flow regimes and contaminant compositions of the water cycle is critical for determining the impact of SUWM solutions on the total water cycle, requiring consideration of the interconnectedness and relationships between components of the water cycle in modelling efforts. Detailed hydraulic and water quality models which consider each component of the water cycle are not ordinarily well suited to such problems; this is where systems dynamics models which are capable of simulating the entire system and accounting for system variability and uncertainty are useful. Systems models do not replace more detailed models, but are complementary to same (Rodrigo *et al*., 2012). For example, the systems dynamic model may be used to determine overall system impacts and determine, in broad terms, the performance of solutions; detailed models may then use systems dynamics model outputs to inform parameters for further modelling. In that the performance of SUWM solutions in the case study area is unknown, the modelling of such was based on a “top-down” approach which involved development of a systems dynamics model, with the view that detailed models would be able to utilise the findings of the systems dynamics model for project scoping.

The developed systems dynamics model is central to the study and is a macro-scale integrated flow model, capable of assessing implementation of water servicing scenarios (specifically any combination of Water Conservation and Water Demand Management, rainwater harvesting, stormwater harvesting, groundwater use, greywater reuse, wastewater recycling, and desalination) at a regional level. Monte Carlo analyses were carried out to test system sensitivity to uncertainty in particular parameters.

7.4 Scenario Performance

Five scenario paths were assessed: (1) Baseline, or “business as usual”, (2) WCWDM, (3) rainwater harvesting and real loss reduction, (4) greywater reuse and WCWDM, and (5) wastewater recycling and real loss reduction. Considered against the three core benefits of SUWM, the following conclusions are noted:

i. A more natural water cycle: Rainwater harvesting reduces the volume of roof runoff reaching urban waterways; while the volume reduction is small (1.8%, considering 50th percentile values over the simulation period) compared to the significant urban waterway flows, it will also have the effect of reducing within-day peak flows, but this did not form part of the analysis. Consumer-focussed WCWDM measures, wastewater recycling, and greywater reuse all have the effect of reducing the total volume of treated effluent which is discharged to the environment.

ii. Improved water security through diversification of sources: Each of the intervention scenarios improves the security of supply and reduces the deficit between projected demands and current system yield until such time the uMkhomazi Water Project (large-scale surface water augmentation) is implemented, also indicating that delays (that is not to say such should be entertained) could be accommodated without jeopardising supply security. While a severe supply failure does not appear probable (based on modelled outcomes), if the uMkhomazi Water Project was seriously delayed, the frequency of restrictions is likely to increase as dam storage volumes are affected.

iii. Resource efficiency: While WCWDM would ordinarily be part of the arsenal of any municipality trying to improve resource efficiency, the other intervention measures are beneficial in improving resource efficiency too. Rainwater harvesting and greywater reuse scenarios consistently perform best in terms of the bulk potable water supplied per capita, though rainwater harvesting may yield an increase in the total system energy utilisation per capita, depending on whether or not individual rainwater tanks include pumps for distribution around the property.

7.5 Evaluation of Model Function

The systems dynamics model developed has been useful in determining the overall (broad) impacts of the different scenario paths, each of which appear to add value to the urban metabolism of eThekwini municipality. Detailed hydraulic and water quality models of targeted areas could be developed, making use of the range of possible system operation as determined by the systems dynamics model for model input parameters.

7.6 Recommendations for Refinement and Future Research

The application of the systems dynamics modelling approach in this study has made a contribution to the body of knowledge on integrating SUWM with existing centralised infrastructure. There is, however, ample scope for model refinement; recommendations in this regard are outlined below.

The developed model includes determination of end-uses such that non-potable water sources may be assigned appropriately; as a slightly different approach, there may be merit in development of a “consumer unit sub-model” where a single consumer unit is modelled, and as such provide decision makers the opportunity to test and understand changes to flows and contaminants at the level of a single consumer unit. The model could be applied to different housing and land-use typologies, and integrated back into the larger overall flow model.

With regards to the runoff sub-model, further investigation into the daily and within-day flow regimes of the waterways of the study area would be beneficial to optimise the environmental benefit of rainwater and stormwater harvesting activities. A finer timescale within the runoff sub-model would enable modelling of within-day peak flows and the impact of SuDS interventions on same. Calibration of such model refinements against observed data at the same timescale may, however, prove problematic. A more comprehensive approach to interactions of groundwater with urban waterways and piped infrastructure would also be a beneficial refinement.

At present, the water quality sub-model considers water bodies for each component of the total water cycle, each of which being aggregated in terms of volume and flow for the entire study area to provide indicative results of changes to species concentrations. This sub-model could be improved by modelling specific water bodies; for example, considering each wastewater treatment works separately. Modelling of additional contaminants may be considered; for example, metals which originate from rainwater harvesting activities and travel through the water cycle, possibly reacting with other contaminants. Reactions in sewers and formation of corrosive compounds have not been considered; this could provide valuable insight to the changing nature of wastewater and potential impacts on infrastructure networks, though may be more appropriately modelled in a detailed water quality model. As is the case with the integrated flow model, the interlinking of groundwater and aquifers with other components of the water cycle, along with the respective pollutants, would be beneficial; for example, there could be further investigation into harvested stormwater and treated wastewater forming part of a managed aquifer recharge initiative. Finally, the level of detail representing water and wastewater treatment processes could be increased.

The operational cost of service provision and total energy use is only explored at a high level in the system model; further investigation of capital costs, operational costs, and electricity use associated with alternative water supply options, specifically for application in South Africa, would be valuable to refine these outputs.

While the developed model has embedded within it functions to represent uncertainty and variability, further investigation to better represent the types and characteristics of probability distributions would be invaluable.

The system model and the results presented herein are focussed on the water balance of the water cycle and resource efficiency, rather than on the practicalities and indirect impacts around implementation of SUWM solutions. There is thus significant scope for further investigation into other aspects of hybrid water systems (such as social, institutional, governance, and public health issues) in the study area (and elsewhere in South Africa). Amongst other research methods, systems dynamics models centred on these issues could be constructed through thorough participative processes with stakeholders. The systems dynamics model developed has nonetheless been useful in highlighting the value of a hybrid water supply system which incorporates and is supported by SUWM-based solutions.

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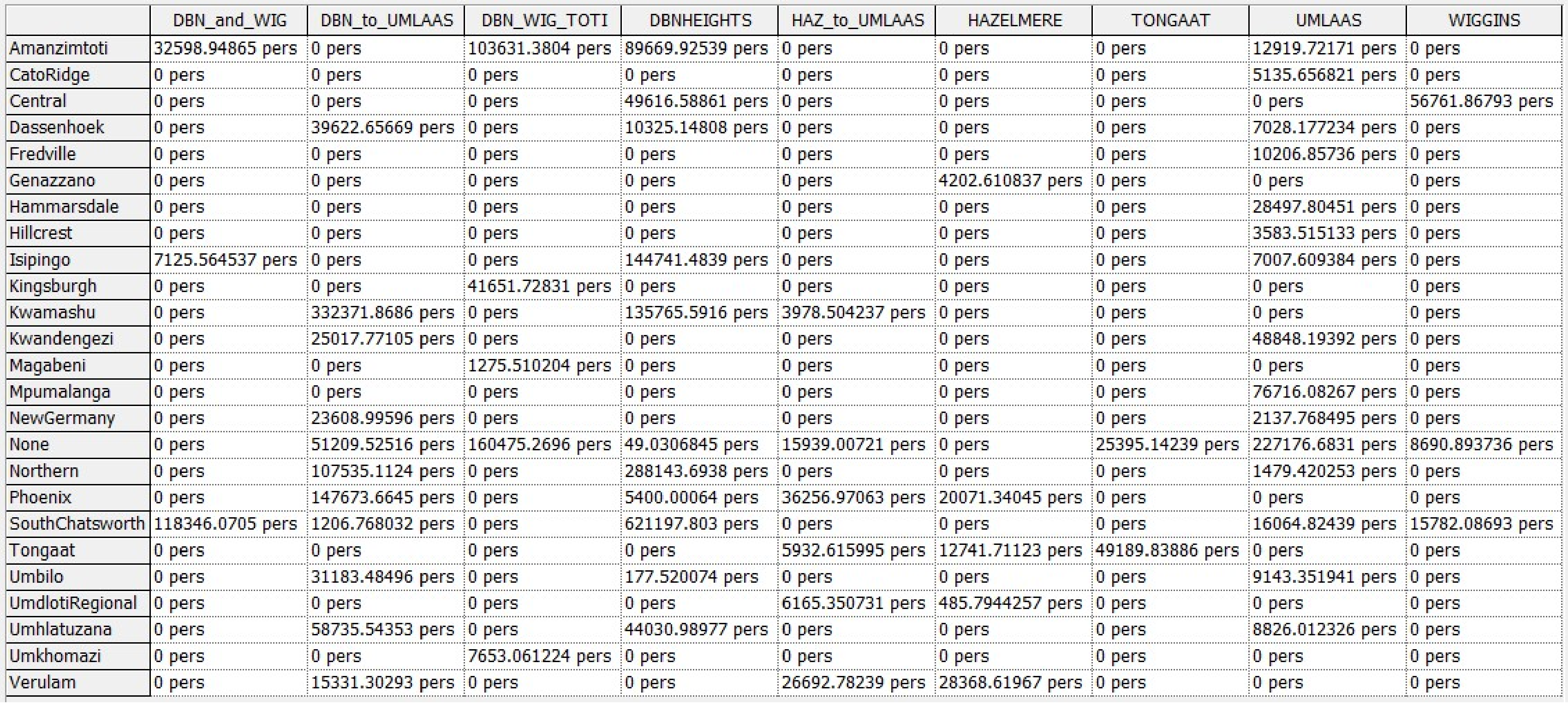
Appendix A: Model Inputs

Population & Demand Model Inputs

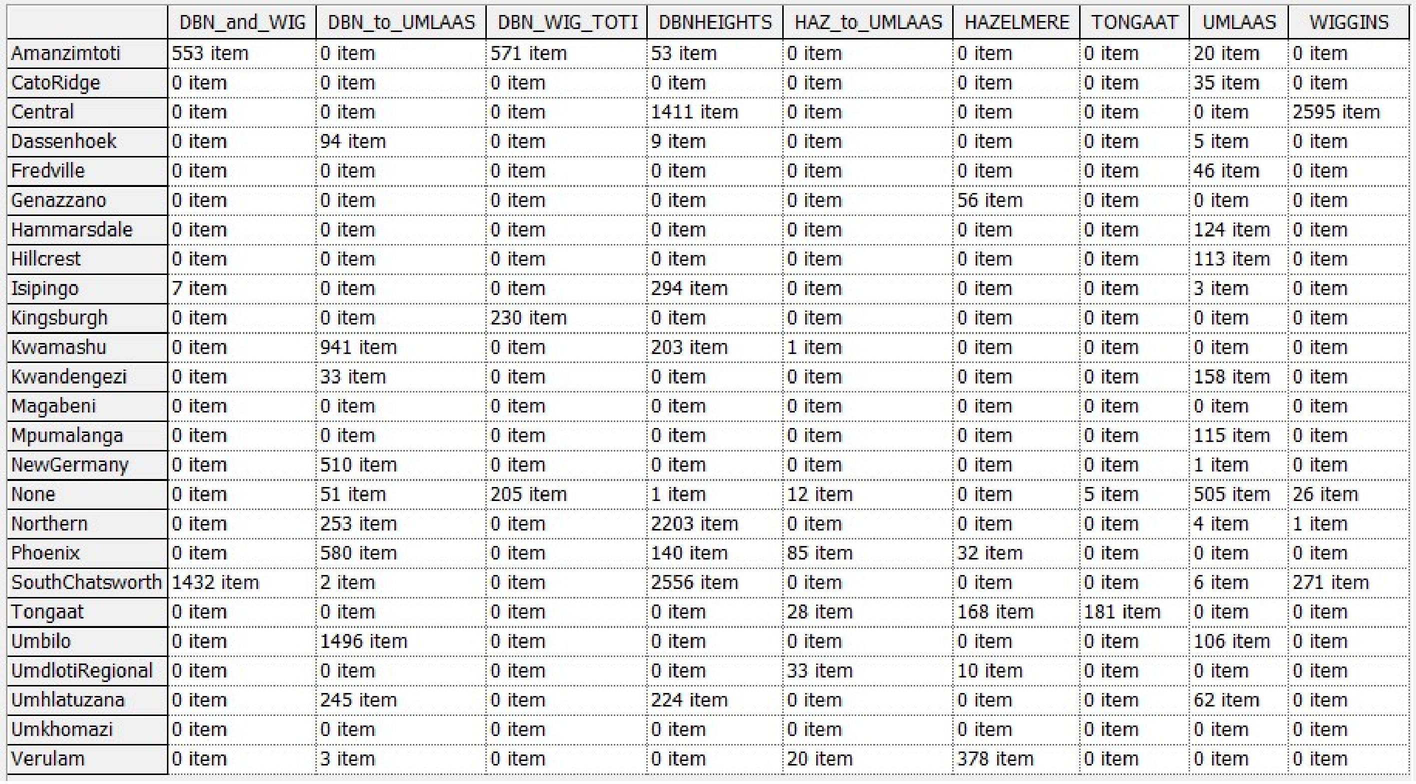
Table A-1 to Table A-4 show the results of the population and billed metered consumption analysis, which were in turn key inputs to the population and base demand model.

Table A-1: Population at Last Census (2011)



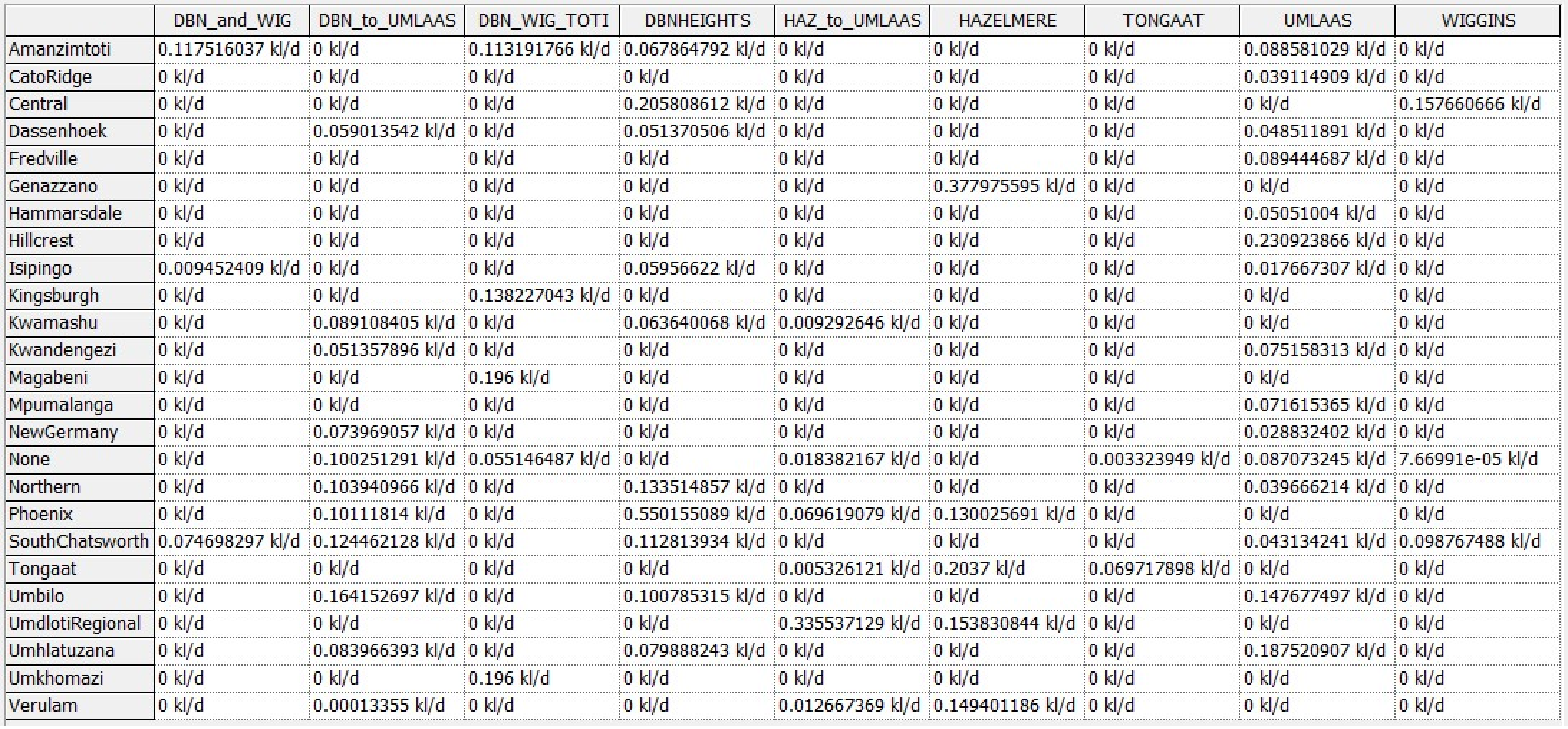
	DBN_and_WIG	DBN_to_UMLAAS	DBN_WIG_TOTI	DBNHEIGHTS	HAZ_to_UMLAAS	HAZELMERE	TONGAAT	UMLAAS	WIGGINS
Amanzimtoti	32598.94865 pers	0 pers	103631.3804 pers	89669.92539 pers	0 pers	0 pers	0 pers	12919.72171 pers	0 pers
CatoRidge	0 pers	0 pers	0 pers	0 pers	0 pers	0 pers	0 pers	5135.656821 pers	0 pers
Central	0 pers	0 pers	0 pers	49616.58861 pers	0 pers	0 pers	0 pers	0 pers	56761.86793 pers
Dassenhoek	0 pers	39622.65669 pers	0 pers	10325.14808 pers	0 pers	0 pers	0 pers	7028.177234 pers	0 pers
Fredville	0 pers	0 pers	0 pers	0 pers	0 pers	0 pers	0 pers	10206.85736 pers	0 pers
Genazzano	0 pers	0 pers	0 pers	0 pers	0 pers	4202.610837 pers	0 pers	0 pers	0 pers
Hammarsdale	0 pers	0 pers	0 pers	0 pers	0 pers	0 pers	0 pers	28497.80451 pers	0 pers
Hillcrest	0 pers	0 pers	0 pers	0 pers	0 pers	0 pers	0 pers	3583.515133 pers	0 pers
Isipingo	7125.564537 pers	0 pers	0 pers	144741.4839 pers	0 pers	0 pers	0 pers	7007.609384 pers	0 pers
Kingsburgh	0 pers	0 pers	41651.72831 pers	0 pers	0 pers	0 pers	0 pers	0 pers	0 pers
Kwamashu	0 pers	332371.8686 pers	0 pers	135765.5916 pers	3978.504237 pers	0 pers	0 pers	0 pers	0 pers
Kwandengezi	0 pers	25017.77105 pers	0 pers	0 pers	0 pers	0 pers	0 pers	48848.19392 pers	0 pers
Magabeni	0 pers	0 pers	1275.510204 pers	0 pers	0 pers	0 pers	0 pers	0 pers	0 pers
Mpumalanga	0 pers	0 pers	0 pers	0 pers	0 pers	0 pers	0 pers	76716.08267 pers	0 pers
NewGermany	0 pers	23608.99596 pers	0 pers	0 pers	0 pers	0 pers	0 pers	2137.768495 pers	0 pers
None	0 pers	51209.52516 pers	160475.2696 pers	49.0306845 pers	15939.00721 pers	0 pers	25395.14239 pers	227176.6831 pers	8690.893736 pers
Northern	0 pers	107535.1124 pers	0 pers	288143.6938 pers	0 pers	0 pers	0 pers	1479.420253 pers	0 pers
Phoenix	0 pers	147673.6645 pers	0 pers	5400.00064 pers	36256.97063 pers	20071.34045 pers	0 pers	0 pers	0 pers
SouthChatsworth	118346.0705 pers	1206.768032 pers	0 pers	621197.803 pers	0 pers	0 pers	0 pers	16064.82439 pers	15782.08693 pers
Tongaat	0 pers	0 pers	0 pers	0 pers	5932.615995 pers	12741.71123 pers	49189.83886 pers	0 pers	0 pers
Umbilo	0 pers	31183.48496 pers	0 pers	177.520074 pers	0 pers	0 pers	0 pers	9143.351941 pers	0 pers
UmdlotiRegional	0 pers	0 pers	0 pers	0 pers	6165.350731 pers	485.7944257 pers	0 pers	0 pers	0 pers
Umhlatuzana	0 pers	58735.54353 pers	0 pers	44030.98977 pers	0 pers	0 pers	0 pers	8826.012326 pers	0 pers
Umkhomazi	0 pers	0 pers	7653.061224 pers	0 pers	0 pers	0 pers	0 pers	0 pers	0 pers
Verulam	0 pers	15331.30293 pers	0 pers	0 pers	26692.78239 pers	28368.61967 pers	0 pers	0 pers	0 pers

Table A-2: Number of Other Connections



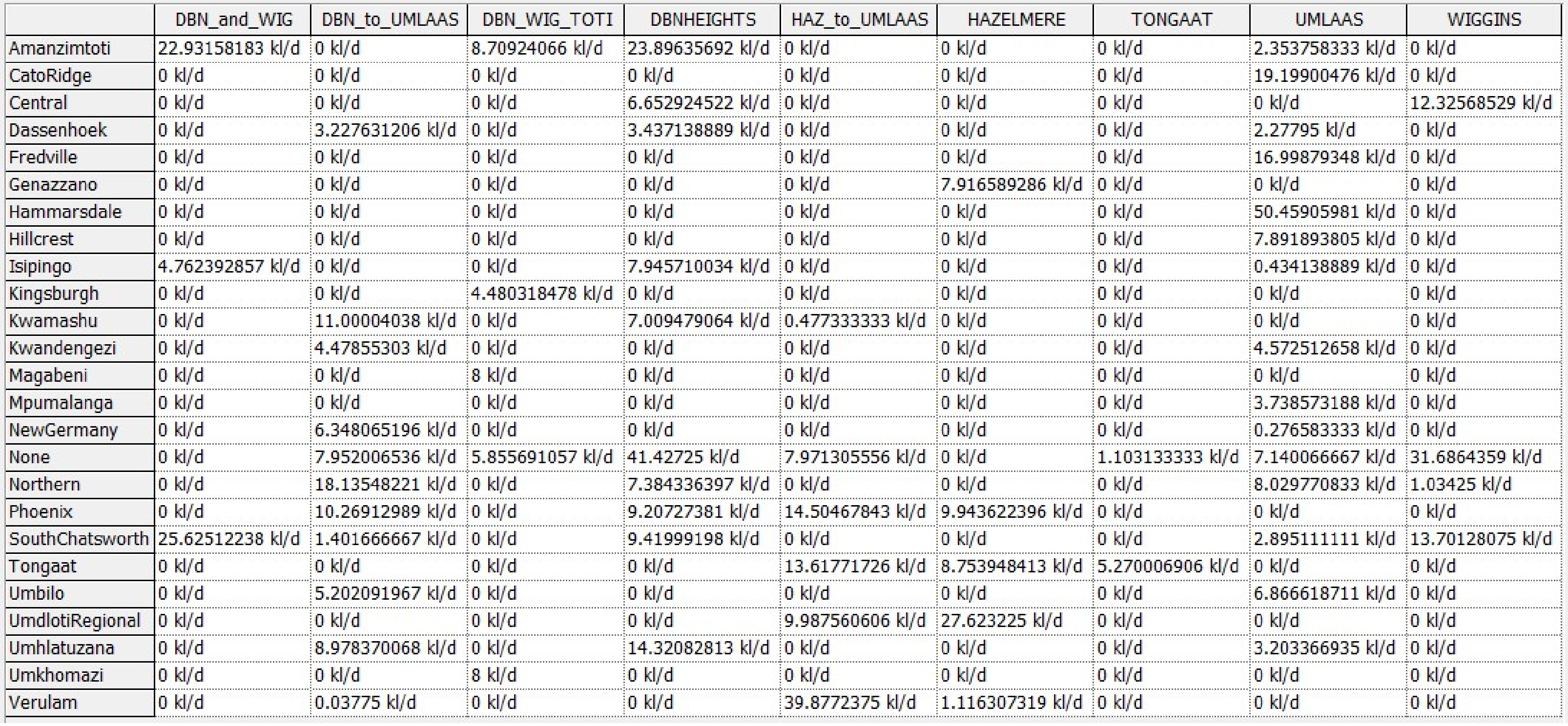
	DBN_and_WIG	DBN_to_UMLAAS	DBN_WIG_TOTI	DBNHEIGHTS	HAZ_to_UMLAAS	HAZELMERE	TONGAAT	UMLAAS	WIGGINS
Amanzimtoti	553 item	0 item	571 item	53 item	0 item	0 item	0 item	20 item	0 item
CatoRidge	0 item	0 item	0 item	0 item	0 item	0 item	0 item	35 item	0 item
Central	0 item	0 item	0 item	1411 item	0 item	0 item	0 item	0 item	2595 item
Dassenhoek	0 item	94 item	0 item	9 item	0 item	0 item	0 item	5 item	0 item
Fredville	0 item	0 item	0 item	0 item	0 item	0 item	0 item	46 item	0 item
Genazzano	0 item	0 item	0 item	0 item	0 item	56 item	0 item	0 item	0 item
Hammarsdale	0 item	0 item	0 item	0 item	0 item	0 item	0 item	124 item	0 item
Hillcrest	0 item	0 item	0 item	0 item	0 item	0 item	0 item	113 item	0 item
Isipingo	7 item	0 item	0 item	294 item	0 item	0 item	0 item	3 item	0 item
Kingsburgh	0 item	0 item	230 item	0 item	0 item	0 item	0 item	0 item	0 item
Kwamashu	0 item	941 item	0 item	203 item	1 item	0 item	0 item	0 item	0 item
Kwandengezi	0 item	33 item	0 item	0 item	0 item	0 item	0 item	158 item	0 item
Magabeni	0 item	0 item	0 item	0 item	0 item	0 item	0 item	0 item	0 item
Mpumalanga	0 item	0 item	0 item	0 item	0 item	0 item	0 item	115 item	0 item
NewGermany	0 item	510 item	0 item	0 item	0 item	0 item	0 item	1 item	0 item
None	0 item	51 item	205 item	1 item	12 item	0 item	5 item	505 item	26 item
Northern	0 item	253 item	0 item	2203 item	0 item	0 item	0 item	4 item	1 item
Phoenix	0 item	580 item	0 item	140 item	85 item	32 item	0 item	0 item	0 item
SouthChatsworth	1432 item	2 item	0 item	2556 item	0 item	0 item	0 item	6 item	271 item
Tongaat	0 item	0 item	0 item	0 item	28 item	168 item	181 item	0 item	0 item
Umbilo	0 item	1496 item	0 item	0 item	0 item	0 item	0 item	106 item	0 item
UmdlotiRegional	0 item	0 item	0 item	0 item	33 item	10 item	0 item	0 item	0 item
Umhlatuzana	0 item	245 item	0 item	224 item	0 item	0 item	0 item	62 item	0 item
Umkhomazi	0 item	0 item	0 item	0 item	0 item	0 item	0 item	0 item	0 item
Verulam	0 item	3 item	0 item	0 item	20 item	378 item	0 item	0 item	0 item

Table A-3: Domestic Demand per Capita



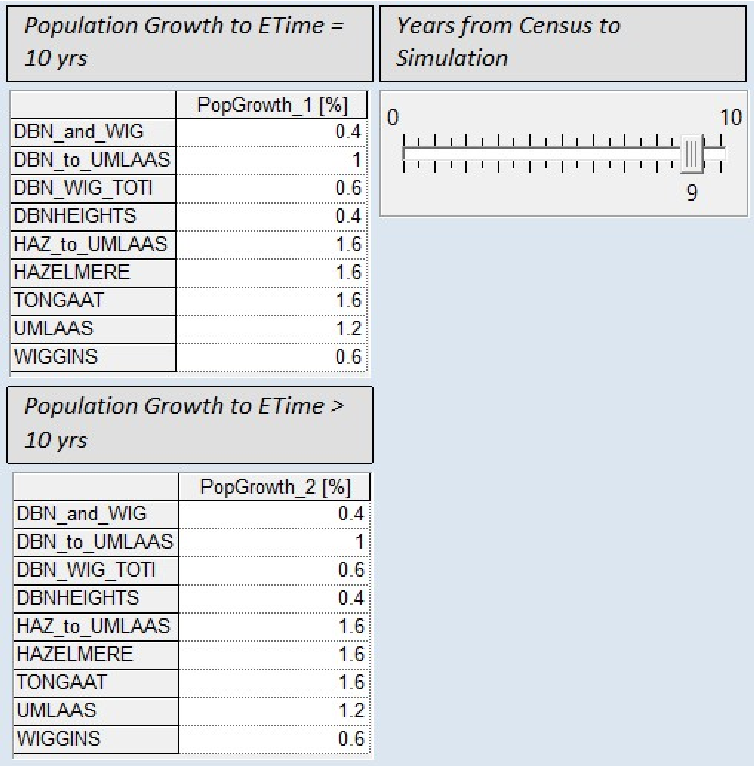
	DBN_and_WIG	DBN_to_UMLAAS	DBN_WIG_TOTI	DBNHEIGHTS	HAZ_to_UMLAAS	HAZELMERE	TONGAAT	UMLAAS	WIGGINS
Amanzimtoti	0.117516037 kl/d	0 kl/d	0.113191766 kl/d	0.067864792 kl/d	0 kl/d	0 kl/d	0 kl/d	0.088581029 kl/d	0 kl/d
CatoRidge	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.039114909 kl/d	0 kl/d
Central	0 kl/d	0 kl/d	0 kl/d	0.205808612 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.157660666 kl/d
Dassenhoek	0 kl/d	0.059013542 kl/d	0 kl/d	0.051370506 kl/d	0 kl/d	0 kl/d	0 kl/d	0.048511891 kl/d	0 kl/d
Fredville	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.089444687 kl/d	0 kl/d
Genazzano	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.377975595 kl/d	0 kl/d	0 kl/d	0 kl/d
Hammarsdale	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.05051004 kl/d	0 kl/d
Hillcrest	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.230923866 kl/d	0 kl/d
Isipingo	0.009452409 kl/d	0 kl/d	0 kl/d	0.05956622 kl/d	0 kl/d	0 kl/d	0 kl/d	0.017667307 kl/d	0 kl/d
Kingsburgh	0 kl/d	0 kl/d	0.138227043 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d
Kwamashu	0 kl/d	0.089108405 kl/d	0 kl/d	0.063640068 kl/d	0.009292646 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d
Kwandengezi	0 kl/d	0.051357896 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.075158313 kl/d	0 kl/d
Magabeni	0 kl/d	0 kl/d	0.196 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d
Mpumalanga	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.071615365 kl/d	0 kl/d
NewGermany	0 kl/d	0.073969057 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.028832402 kl/d	0 kl/d
None	0 kl/d	0.100251291 kl/d	0.055146487 kl/d	0 kl/d	0.018382167 kl/d	0 kl/d	0.003323949 kl/d	0.087073245 kl/d	7.66991e-05 kl/d
Northern	0 kl/d	0.103940966 kl/d	0 kl/d	0.133514857 kl/d	0 kl/d	0 kl/d	0 kl/d	0.039666214 kl/d	0 kl/d
Phoenix	0 kl/d	0.10111814 kl/d	0 kl/d	0.550155089 kl/d	0.069619079 kl/d	0.130025691 kl/d	0 kl/d	0 kl/d	0 kl/d
SouthChatsworth	0.074698297 kl/d	0.124462128 kl/d	0 kl/d	0.112813934 kl/d	0 kl/d	0 kl/d	0 kl/d	0.043134241 kl/d	0.098767488 kl/d
Tongaat	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.005326121 kl/d	0.2037 kl/d	0.069717898 kl/d	0 kl/d	0 kl/d
Umbilo	0 kl/d	0.164152697 kl/d	0 kl/d	0.100785315 kl/d	0 kl/d	0 kl/d	0 kl/d	0.147677497 kl/d	0 kl/d
UmdlotiRegional	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.335537129 kl/d	0.153830844 kl/d	0 kl/d	0 kl/d	0 kl/d
Umhlatuzana	0 kl/d	0.083966393 kl/d	0 kl/d	0.079888243 kl/d	0 kl/d	0 kl/d	0 kl/d	0.187520907 kl/d	0 kl/d
Umkhomazi	0 kl/d	0 kl/d	0.196 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d
Verulam	0 kl/d	0.00013355 kl/d	0 kl/d	0 kl/d	0.012667369 kl/d	0.149401186 kl/d	0 kl/d	0 kl/d	0 kl/d

Table A-4: Other Land Use Demand per Connection



	DBN_and_WIG	DBN_to_UMLAAS	DBN_WIG_TOTI	DBNHEIGHTS	HAZ_to_UMLAAS	HAZELMERE	TONGAAT	UMLAAS	WIGGINS
Amanzimtoti	22.93158183 kl/d	0 kl/d	8.70924066 kl/d	23.89635692 kl/d	0 kl/d	0 kl/d	0 kl/d	2.353758333 kl/d	0 kl/d
CatoRidge	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	19.19900476 kl/d	0 kl/d
Central	0 kl/d	0 kl/d	0 kl/d	6.652924522 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	12.32568529 kl/d
Dassenhoek	0 kl/d	3.227631206 kl/d	0 kl/d	3.437138889 kl/d	0 kl/d	0 kl/d	0 kl/d	2.27795 kl/d	0 kl/d
Fredville	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	16.99879348 kl/d	0 kl/d
Genazzano	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	7.916589286 kl/d	0 kl/d	0 kl/d	0 kl/d
Hammarsdale	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	50.45905981 kl/d	0 kl/d
Hillcrest	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	7.891893805 kl/d	0 kl/d
Isipingo	4.762392857 kl/d	0 kl/d	0 kl/d	7.945710034 kl/d	0 kl/d	0 kl/d	0 kl/d	0.434138889 kl/d	0 kl/d
Kingsburgh	0 kl/d	0 kl/d	4.480318478 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d
Kwamashu	0 kl/d	11.00004038 kl/d	0 kl/d	7.009479064 kl/d	0.477333333 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d
Kwandengezi	0 kl/d	4.47855303 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	4.572512658 kl/d	0 kl/d
Magabeni	0 kl/d	0 kl/d	8 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d
Mpumalanga	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	3.738573188 kl/d	0 kl/d
NewGermany	0 kl/d	6.348065196 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0.276583333 kl/d	0 kl/d
None	0 kl/d	7.952006536 kl/d	5.855691057 kl/d	41.42725 kl/d	7.971305556 kl/d	0 kl/d	1.103133333 kl/d	7.140066667 kl/d	31.6864359 kl/d
Northern	0 kl/d	18.13548221 kl/d	0 kl/d	7.384336397 kl/d	0 kl/d	0 kl/d	0 kl/d	8.029770833 kl/d	1.03425 kl/d
Phoenix	0 kl/d	10.26912989 kl/d	0 kl/d	9.20727381 kl/d	14.50467843 kl/d	9.943622396 kl/d	0 kl/d	0 kl/d	0 kl/d
SouthChatsworth	25.62512238 kl/d	1.401666667 kl/d	0 kl/d	9.41999198 kl/d	0 kl/d	0 kl/d	0 kl/d	2.895111111 kl/d	13.70128075 kl/d
Tongaat	0 kl/d	0 kl/d	0 kl/d	0 kl/d	13.61771726 kl/d	8.753948413 kl/d	5.270006906 kl/d	0 kl/d	0 kl/d
Umbilo	0 kl/d	5.202091967 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	6.866618711 kl/d	0 kl/d
UmdlotiRegional	0 kl/d	0 kl/d	0 kl/d	0 kl/d	9.987560606 kl/d	27.623225 kl/d	0 kl/d	0 kl/d	0 kl/d
Umhlatuzana	0 kl/d	8.978370068 kl/d	0 kl/d	14.32082813 kl/d	0 kl/d	0 kl/d	0 kl/d	3.203366935 kl/d	0 kl/d
Umkhomazi	0 kl/d	0 kl/d	8 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d	0 kl/d
Verulam	0 kl/d	0.03775 kl/d	0 kl/d	0 kl/d	39.8772375 kl/d	1.116307319 kl/d	0 kl/d	0 kl/d	0 kl/d

The model allows for population growth to be defined for the first ten years of the simulation, i.e. up until 2030, and for a different population growth to be defined thereafter.



Population Growth to ETime = 10 yrs

	PopGrowth_1 [%]
DBN_and_WIG	0.4
DBN_to_UMLAAS	1
DBN_WIG_TOTI	0.6
DBNHEIGHTS	0.4
HAZ_to_UMLAAS	1.6
HAZELMERE	1.6
TONGAAT	1.6
UMLAAS	1.2
WIGGINS	0.6

Years from Census to Simulation

Population Growth to ETime > 10 yrs

	PopGrowth_2 [%]
DBN_and_WIG	0.4
DBN_to_UMLAAS	1
DBN_WIG_TOTI	0.6
DBNHEIGHTS	0.4
HAZ_to_UMLAAS	1.6
HAZELMERE	1.6
TONGAAT	1.6
UMLAAS	1.2
WIGGINS	0.6

Figure A-1: Population Growth Parameters

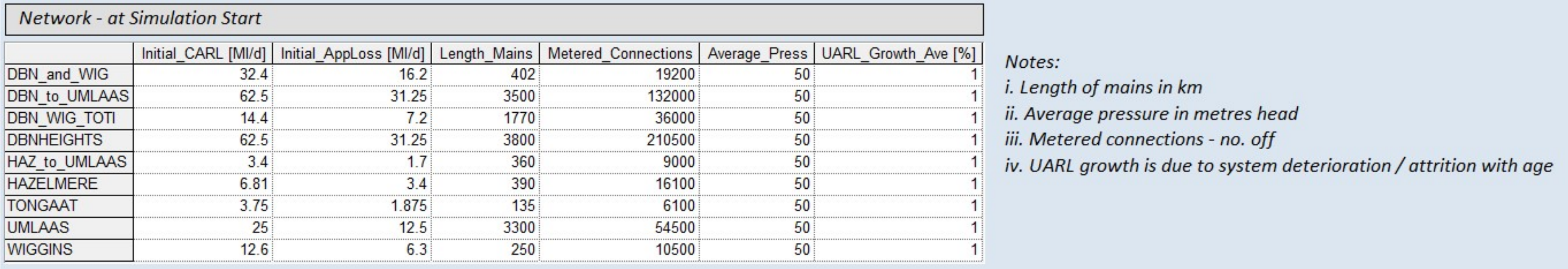
As a result of increasing levels of service, growth in the demand per capita may be increased. Outlying areas and those with high proportions of rural and informal dwellings were assumed to have higher growth in base demand:

Table A-5: Demand Growth per Annum

Bulk Supply Zone	Demand Growth per Annum (%)		
	2020	2030	2040
DBN_and_WIG	1	1	1
DBN_to_UMLAAS	1	2.5	2.5
DBN_WIG_TOTI	1	1	1
DBNHEIGHTS	1	1	1
HAZ_to_UMLAAS	1	2.5	2.5
HAZELMERE	1	2.5	2.5
TONGAAT	1	2.5	2.5
UMLAAS	1	2.5	2.5
WIGGINS	1	1	1

System Input Volume Inputs

Current annual real losses and apparent losses were added to the billed metered consumption to obtain the system input volume. The unavoidable annual real losses are defined as a function of the water network's characteristics.



Network - at Simulation Start

	Initial_CARL [Ml/d]	Initial_AppLoss [Ml/d]	Length_Mains	Metered_Connections	Average_Press	UARL_Growth_Ave [%]
DBN_and_WIG	32.4	16.2	402	19200	50	1
DBN_to_UMLAAS	62.5	31.25	3500	132000	50	1
DBN_WIG_TOTI	14.4	7.2	1770	36000	50	1
DBNHEIGHTS	62.5	31.25	3800	210500	50	1
HAZ_to_UMLAAS	3.4	1.7	360	9000	50	1
HAZELMERE	6.81	3.4	390	16100	50	1
TONGAAT	3.75	1.875	135	6100	50	1
UMLAAS	25	12.5	3300	54500	50	1
WIGGINS	12.6	6.3	250	10500	50	1

Notes:
i. Length of mains in km
ii. Average pressure in metres head
iii. Metered connections - no. off
iv. UARL growth is due to system deterioration / attrition with age

Figure A-2: System Characteristics Defining Real Losses, Apparent Losses, and UARL

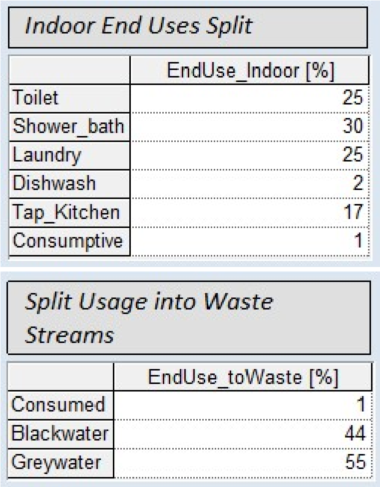
The final values adopted for current annual real losses and apparent losses were based on the calibration of the system input volume – refer to Appendix B: Additional Model Details. The length of mains and number of connections was extracted from the EWS GIS database for water services. The average zone pressure (AZP) was assumed by considering an average of upper and lower limits commonly applied to design of water reticulation systems. The growth in unavoidable annual real losses was based on that adopted for system attrition in the Reconciliation Strategy (DWS, 2017).

Table A-6: Resulting UARL per Bulk Supply Area

Bulk Supply Zone	UARL (Ml/d)
DBN_and_WIG	1.13
DBN_to_UMLAAS	8.43
DBN_WIG_TOTI	3.03
DBNHEIGHTS	11.84
HAZ_to_UMLAAS	0.68
HAZELMERE	1.00
TONGAAT	0.37
UMLAAS	5.15
WIGGINS	0.65

End-Use Inputs

Below are the defined indoor end-uses and the resulting waste stream splits. Kitchen end-uses are directed to blackwater such that this portion of the waste stream is not available for greywater reuse. Table A-7 (overleaf) shows the outdoor demand as a proportion of the total base demand. The model makes allowance for defining different proportions of outdoor use for domestic and non-domestic consumption; however, given the wide range of non-domestic land uses and in the absence of factual and applicable information, the domestic outdoor proportion of consumption has been applied. The same approach was taken for indoor end-uses.



Indoor End Uses Split

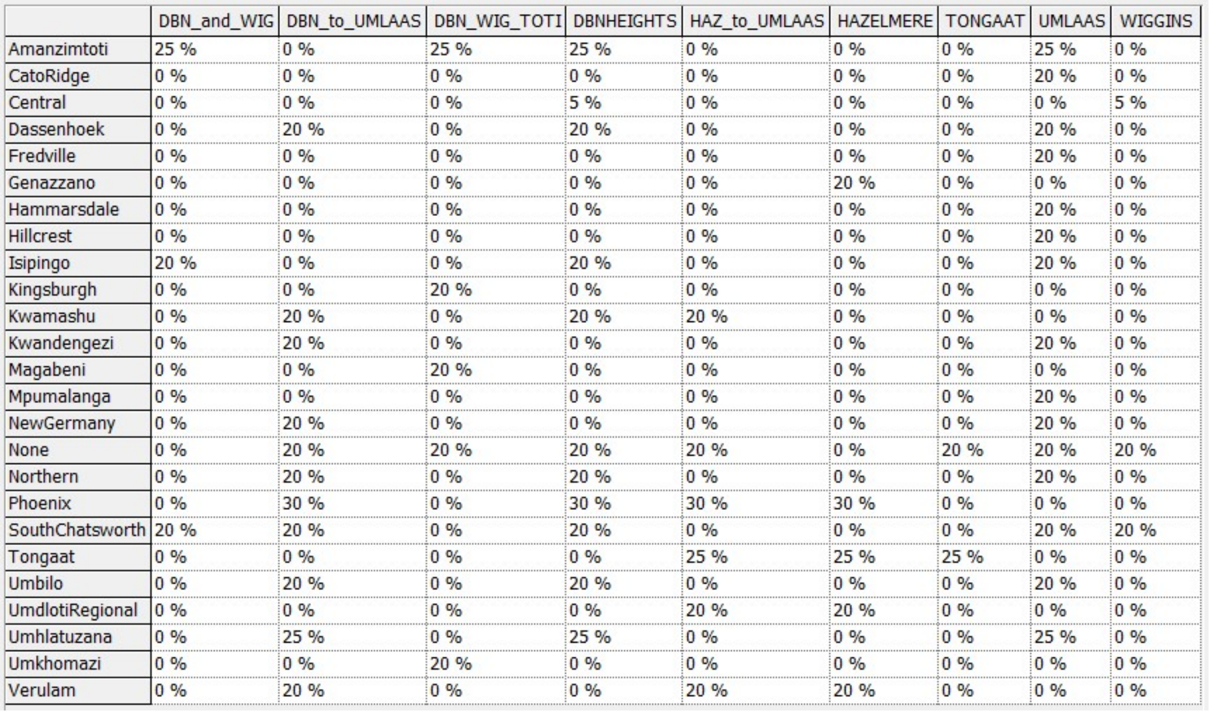
	EndUse_Indoor [%]
Toilet	25
Shower_bath	30
Laundry	25
Dishwash	2
Tap_Kitchen	17
Consumptive	1

Split Usage into Waste Streams

	EndUse_toWaste [%]
Consumed	1
Blackwater	44
Greywater	55

Figure A-3: Indoor End Use Split and Waste Stream Split

Table A-7: Outdoor Demand Split for Domestic & Other Land Uses



	DBN_and_WIG	DBN_to_UMLAAS	DBN_WIG_TOTI	DBNHEIGHTS	HAZ_to_UMLAAS	HAZELMERE	TONGAAT	UMLAAS	WIGGINS
Amanzimtoti	25 %	0 %	25 %	25 %	0 %	0 %	0 %	25 %	0 %
CatoRidge	0 %	0 %	0 %	0 %	0 %	0 %	0 %	20 %	0 %
Central	0 %	0 %	0 %	5 %	0 %	0 %	0 %	0 %	5 %
Dassenhoek	0 %	20 %	0 %	20 %	0 %	0 %	0 %	20 %	0 %
Fredville	0 %	0 %	0 %	0 %	0 %	0 %	0 %	20 %	0 %
Genazzano	0 %	0 %	0 %	0 %	0 %	20 %	0 %	0 %	0 %
Hammarsdale	0 %	0 %	0 %	0 %	0 %	0 %	0 %	20 %	0 %
Hillcrest	0 %	0 %	0 %	0 %	0 %	0 %	0 %	20 %	0 %
Isipingo	20 %	0 %	0 %	20 %	0 %	0 %	0 %	20 %	0 %
Kingsburgh	0 %	0 %	20 %	0 %	0 %	0 %	0 %	0 %	0 %
Kwamashu	0 %	20 %	0 %	20 %	20 %	0 %	0 %	0 %	0 %
Kwandengezi	0 %	20 %	0 %	0 %	0 %	0 %	0 %	20 %	0 %
Magabeni	0 %	0 %	20 %	0 %	0 %	0 %	0 %	0 %	0 %
Mpumalanga	0 %	0 %	0 %	0 %	0 %	0 %	0 %	20 %	0 %
NewGermany	0 %	20 %	0 %	0 %	0 %	0 %	0 %	20 %	0 %
None	0 %	20 %	20 %	20 %	20 %	0 %	20 %	20 %	20 %
Northern	0 %	20 %	0 %	20 %	0 %	0 %	0 %	20 %	0 %
Phoenix	0 %	30 %	0 %	30 %	30 %	30 %	0 %	0 %	0 %
SouthChatsworth	20 %	20 %	0 %	20 %	0 %	0 %	0 %	20 %	20 %
Tongaat	0 %	0 %	0 %	0 %	25 %	25 %	25 %	0 %	0 %
Umbilo	0 %	20 %	0 %	20 %	0 %	0 %	0 %	20 %	0 %
UmdlotiRegional	0 %	0 %	0 %	0 %	20 %	20 %	0 %	0 %	0 %
Umhlatuzana	0 %	25 %	0 %	25 %	0 %	0 %	0 %	25 %	0 %
Umkhomazi	0 %	0 %	20 %	0 %	0 %	0 %	0 %	0 %	0 %
Verulam	0 %	20 %	0 %	0 %	20 %	20 %	0 %	0 %	0 %

Water Supply Inputs

Below presented are parameters relevant to the major water resources which affect eThekwini. Dam lower bound and upper bound limits were based on information contained in the Umgeni Water Masterplans (UW, 2019).

Table A-8: Lowerbound Limits for Water Sources

Water Source	% of Full Supply
Albert Falls	0.35
Hazelmere	5
Inanda	4
Mearns	0
Midmar	0
Nagle	0.01
Nungwane	2.76
Spring Grove	0

Table A-9: Full Supply Capacity of Water Sources

Water Source	Volume (Ml)
Albert Falls	290075
Hazelmere	37130
Inanda	246560
Mearns	5116
Midmar	240097
Nagle	23237
Nungwane	2133.959

Water Source	Volume (Ml)
Spring Grove	140065

Volume-depth and volume-area relationships were obtained from the Umgeni Water dams database. Given the storage volume at any point in time, these relationships were used to determine the depth and area of water bodies, and therefore the evaporation over the surface area of same.

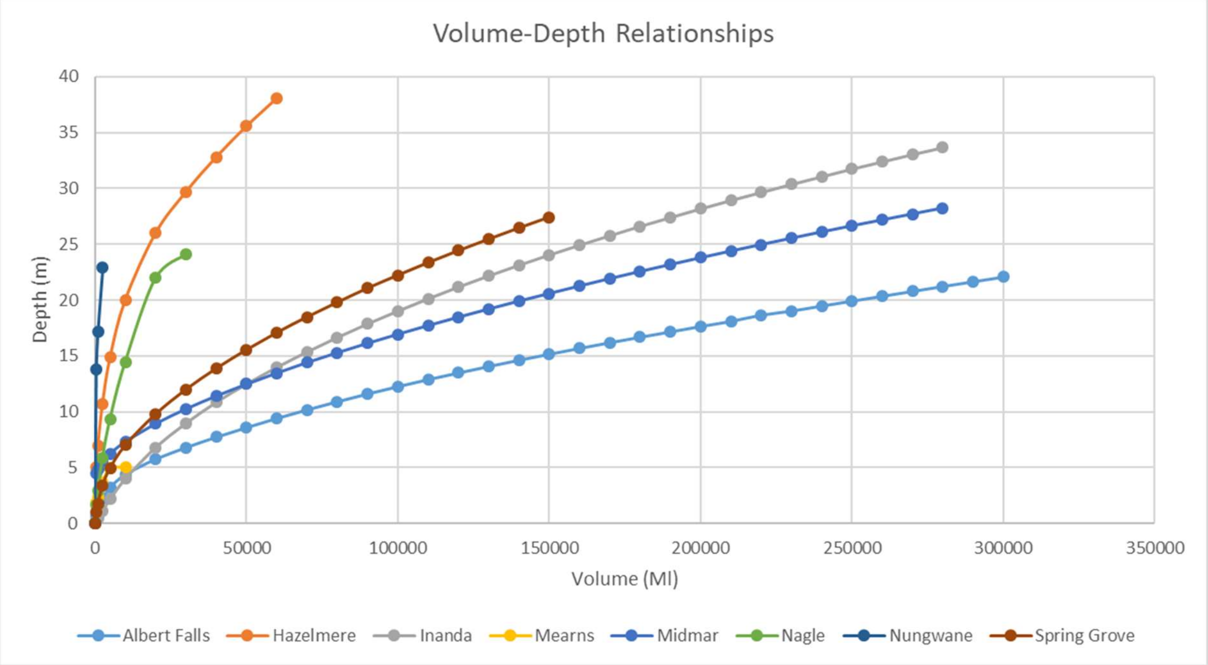


Figure A-4: Volume-Depth Relationships for Various Dams

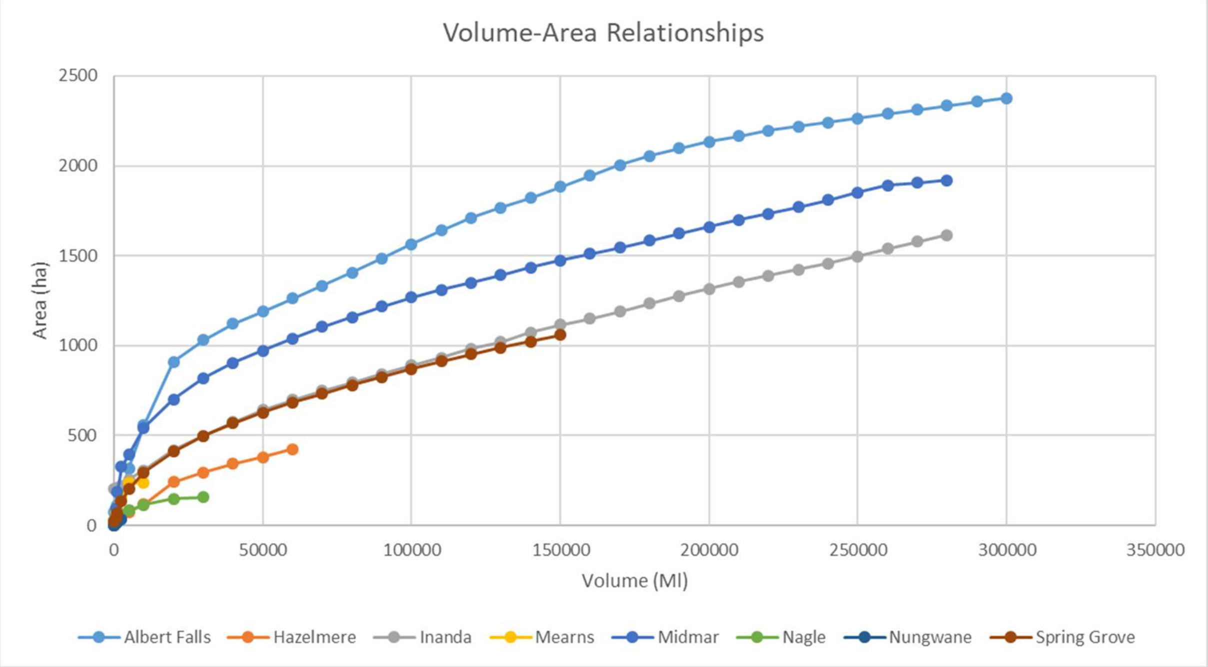


Figure A-5: Volume-Area Relationships for Various Dams

Sedimentation of dams was determined primarily from stated results of dam surveys; where this information is not available, the methods and calculations as set out in the Sediment Yield Prediction for South Africa (Msadala et al., 2010) were applied.

Table A-10: Sedimentation of Dams

Water Source	Sedimentation (m^3/yr)
Albert Falls	17315
Hazelmere	357140
Inanda	46565
Mearns	0
Midmar	11700
Nagle	54440
Nungwane	5421
Spring Grove	47165

Information on firm yield was obtained from Umgeni Water Masterplans (UW, 2019) and the Reconciliation Strategy (DWS, 2008; DWS, 2010).

Table A-11: Firm Yield of Dams

Water Source	Firm Yield (m^3/yr)
Albert Falls	Not defined
Hazelmere	31 000 000
Inanda	384 000 000
Mearns	Not defined
Midmar	177 300 000
Nagle	283 500 000
Nungwane	2 200 000
Spring Grove	Not defined

Evaporation information was extracted from the relevant catchments and components of the WRSM/Pitman model runs.

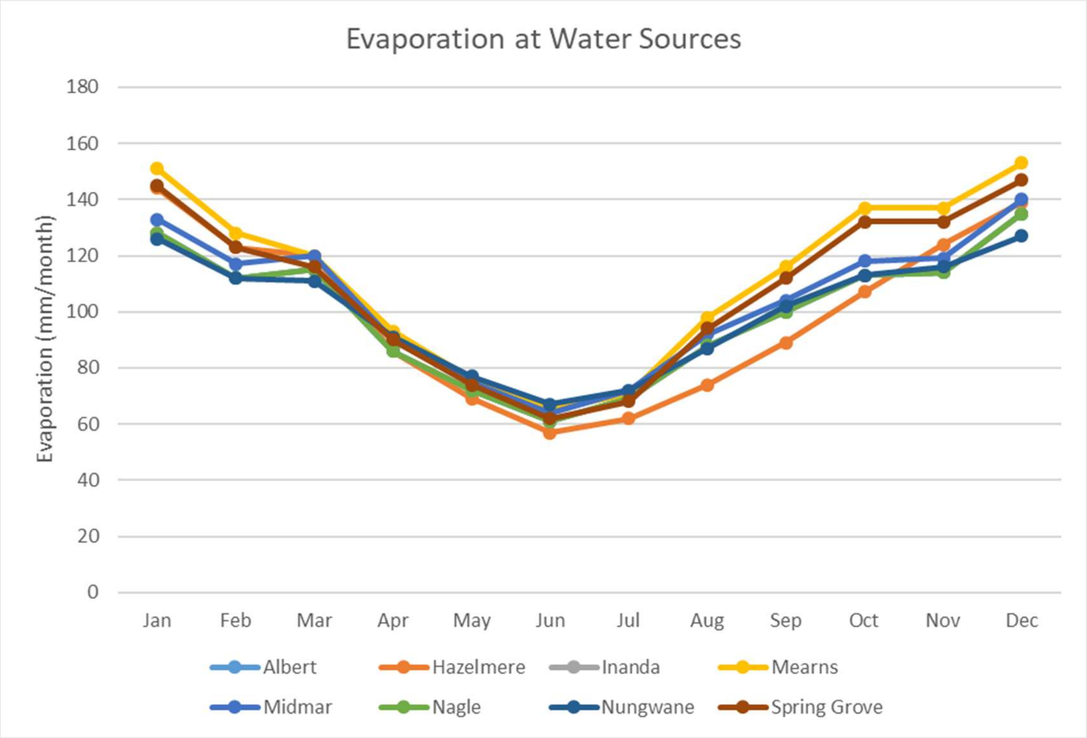


Figure A-6: Monthly Evaporation at each Water Source

Table A-12: Standard Deviation of Monthly Evaporation

Water Source	Evaporation Std Deviation
Albert	24.02
Hazelmere	30.53
Inanda	24.02
Mearns	30.94
Midmar	24.84
Nagle	24.02
Nungwane	20.78
Spring Grove	29.75

Information on environmental flows and compensation flows was obtained from the Reconciliation Strategy documents (DWS, 2008; DWS, 2010; DWS, 2017).

Table A-13: Environmental Flow Requirements / Compensation Flows

Water Source	Environmental Flow Requirements (m^3/yr)
Albert Falls	22 410 000
Hazelmere	9 300 000
Inanda	47 340 000
Mearns	Not defined
Midmar	28 400 000
Nagle	Not defined
Nungwane	Not defined
Spring Grove	Not defined

Time series of naturalised flows as extracted from the WR2012 Study which are relevant to the study area are illustrated in Figure A-7 to Figure A-15.

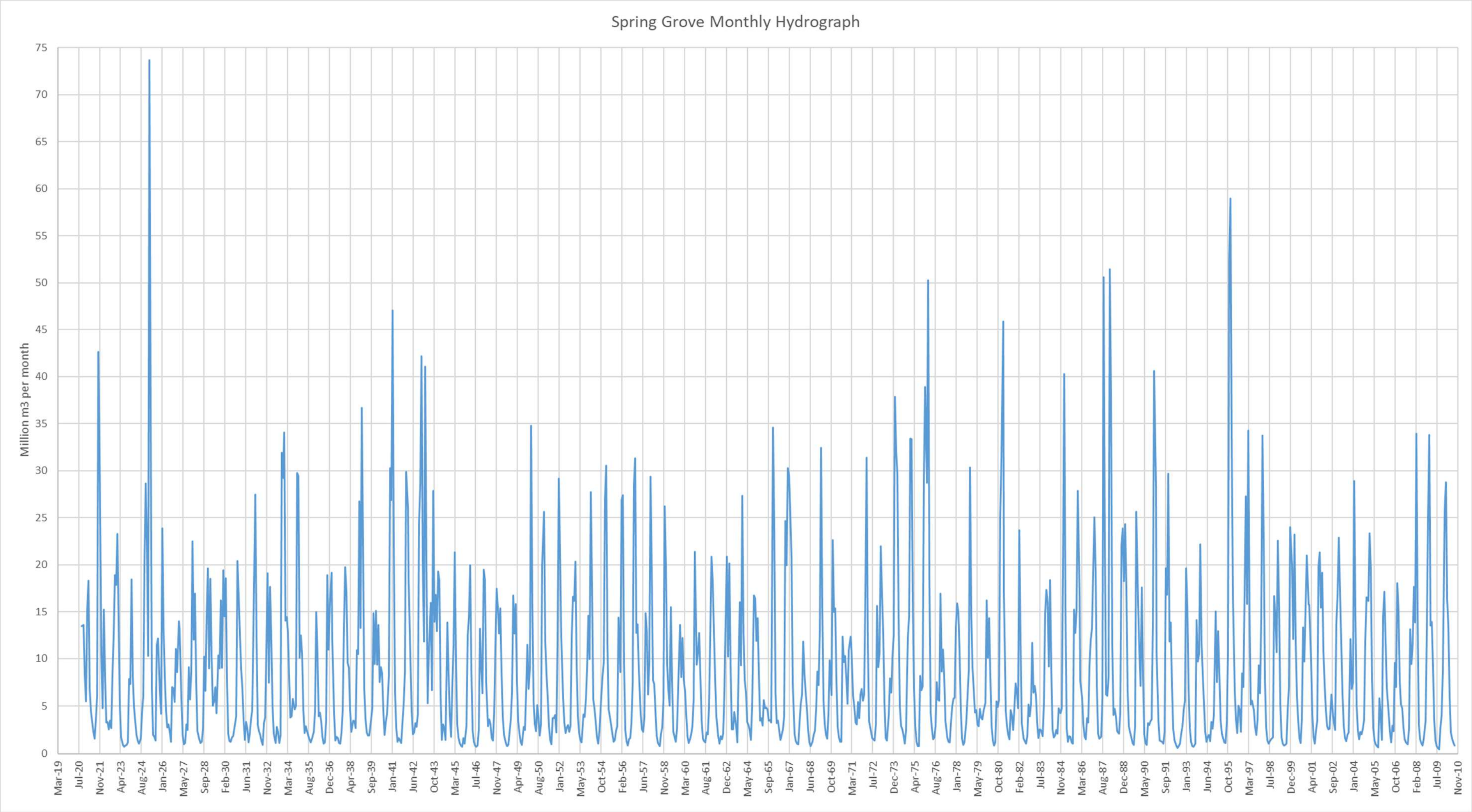


Figure A-7: Naturalised Flows – Spring Grove Dam Inflow

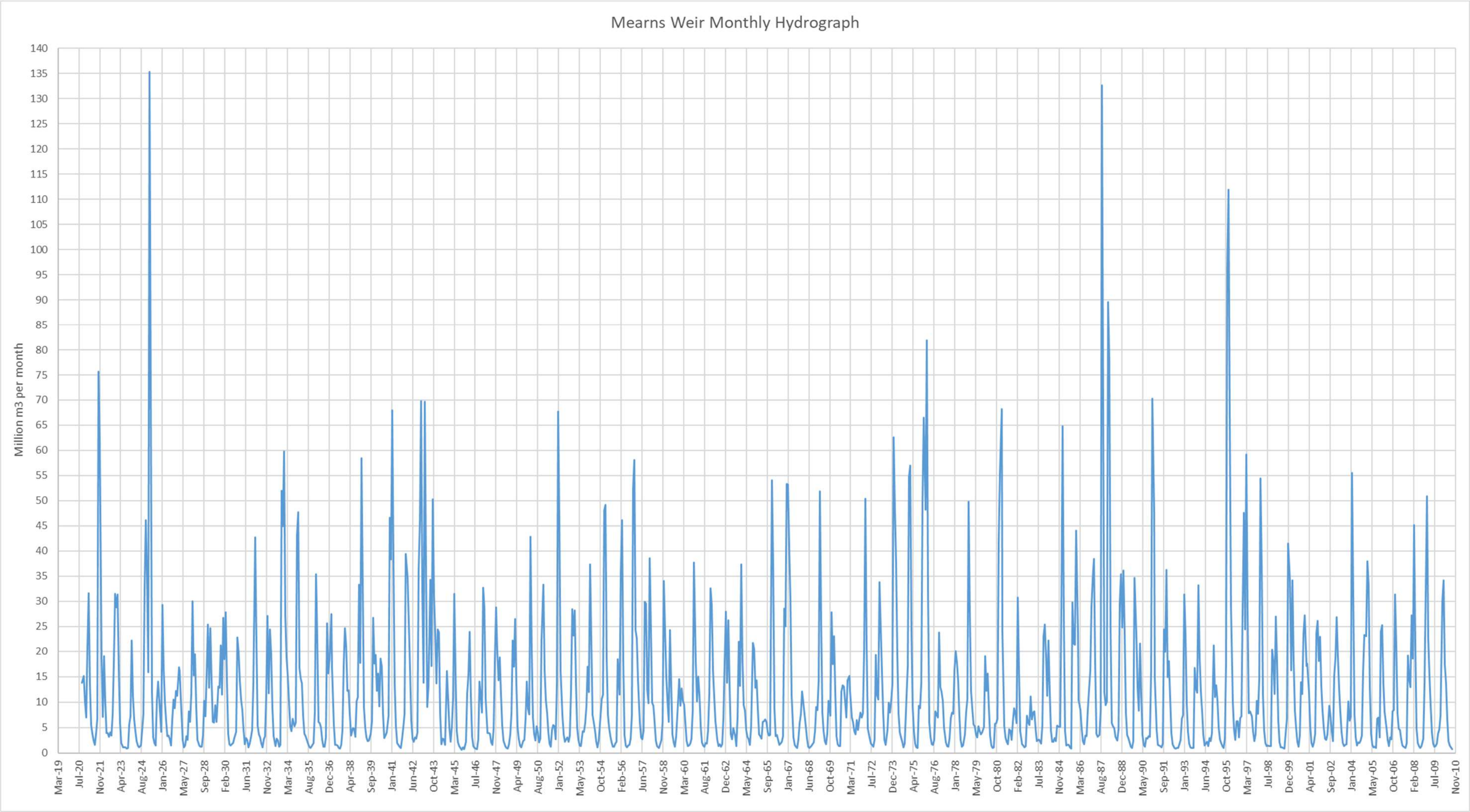


Figure A-8: Naturalised Flows – Mearns Weir Inflow

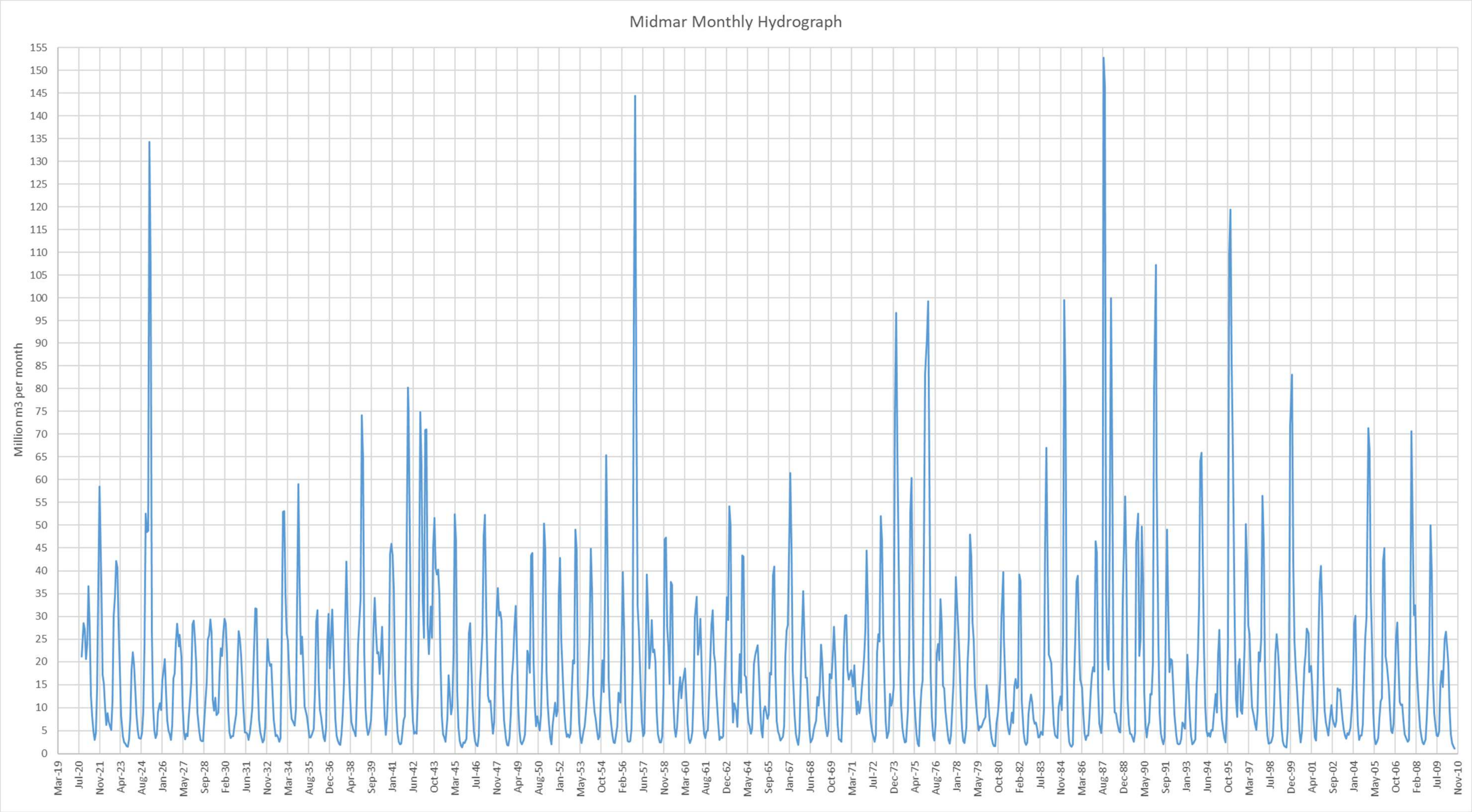


Figure A-9: Naturalised Flows – Midmar Dam Inflow

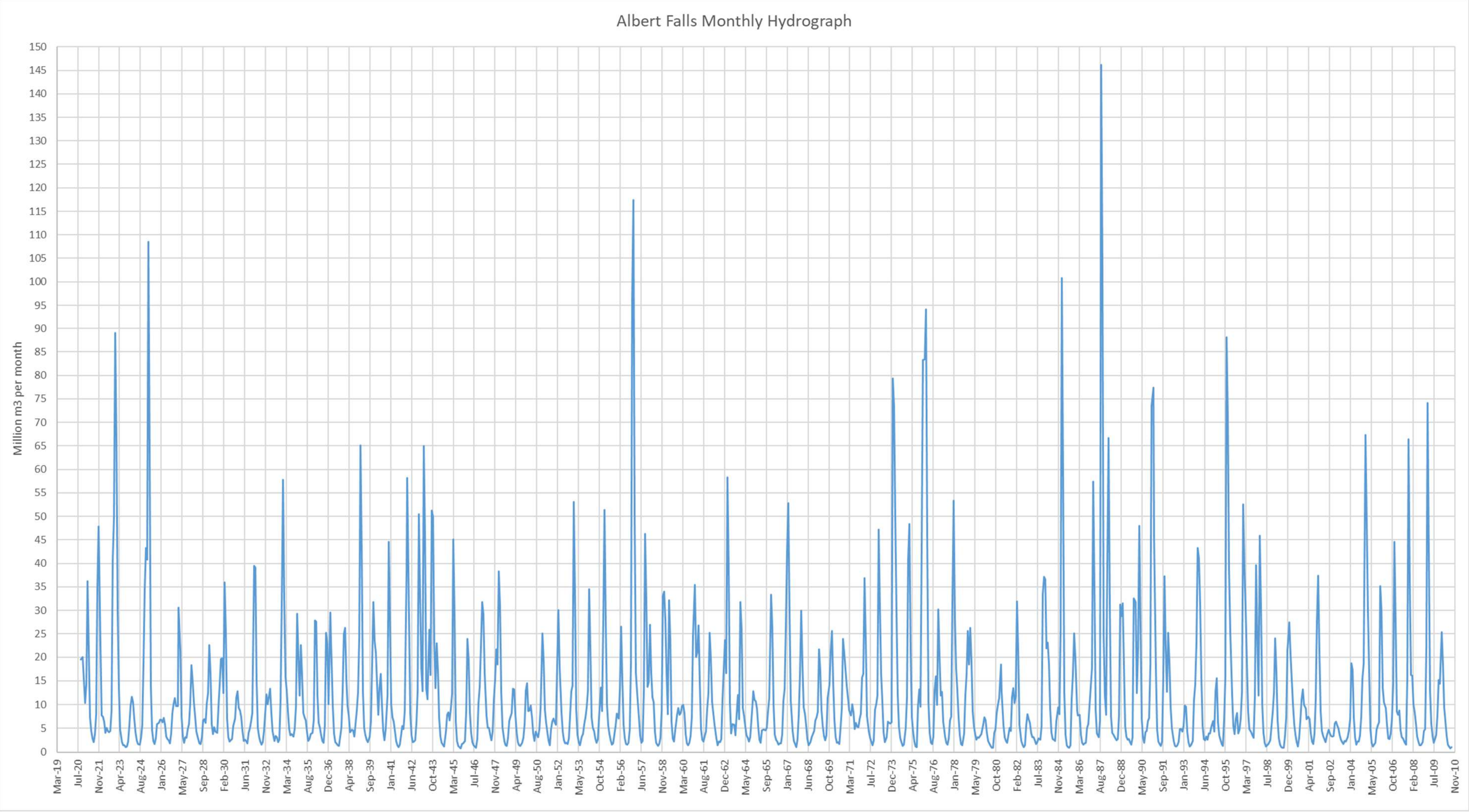


Figure A-10: Naturalised Flows – Albert Falls Dam Inflow

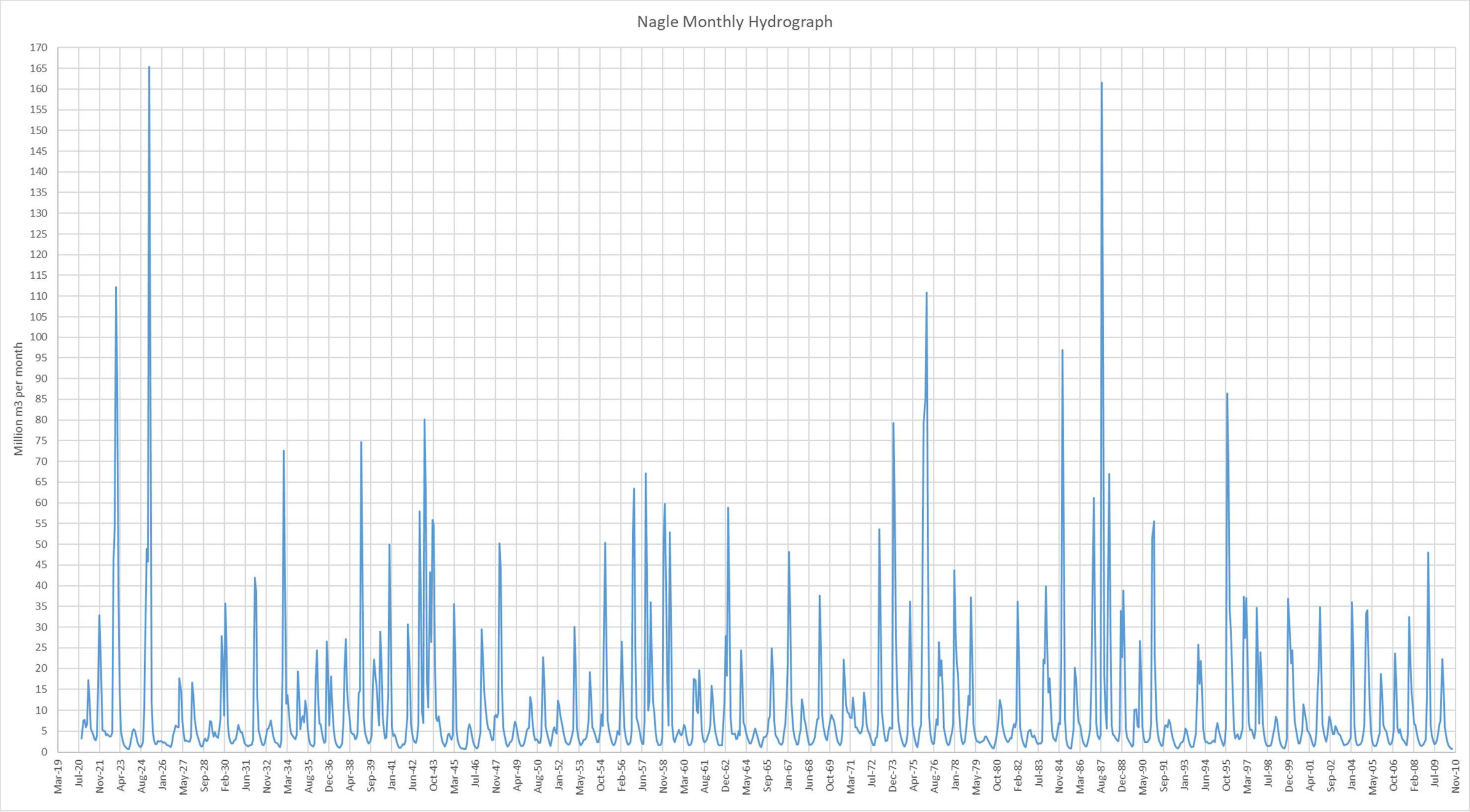


Figure A-11: Naturalised Flows – Nagle Dam Inflow

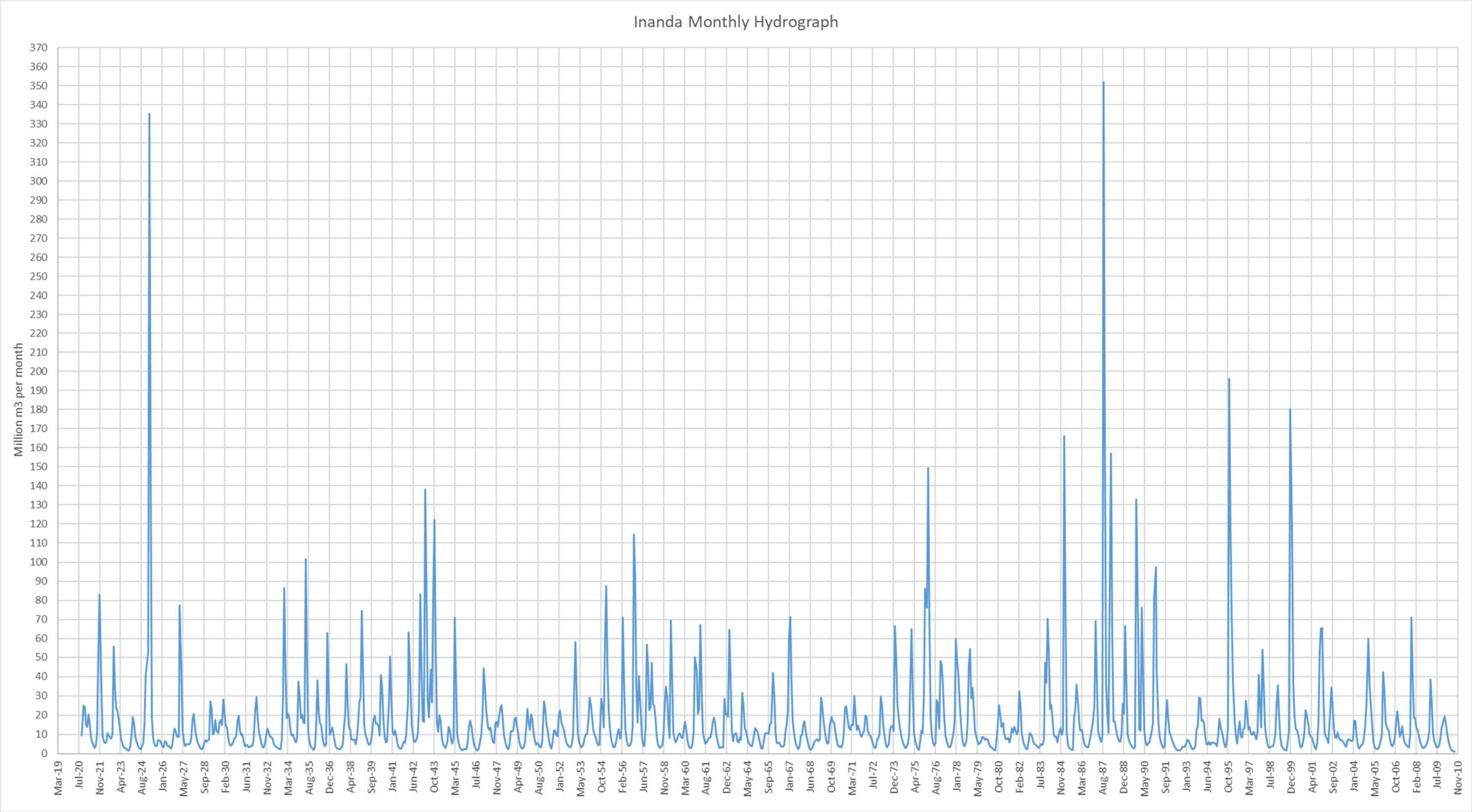


Figure A-12: Naturalised Flows – Inanda Dam Inflow

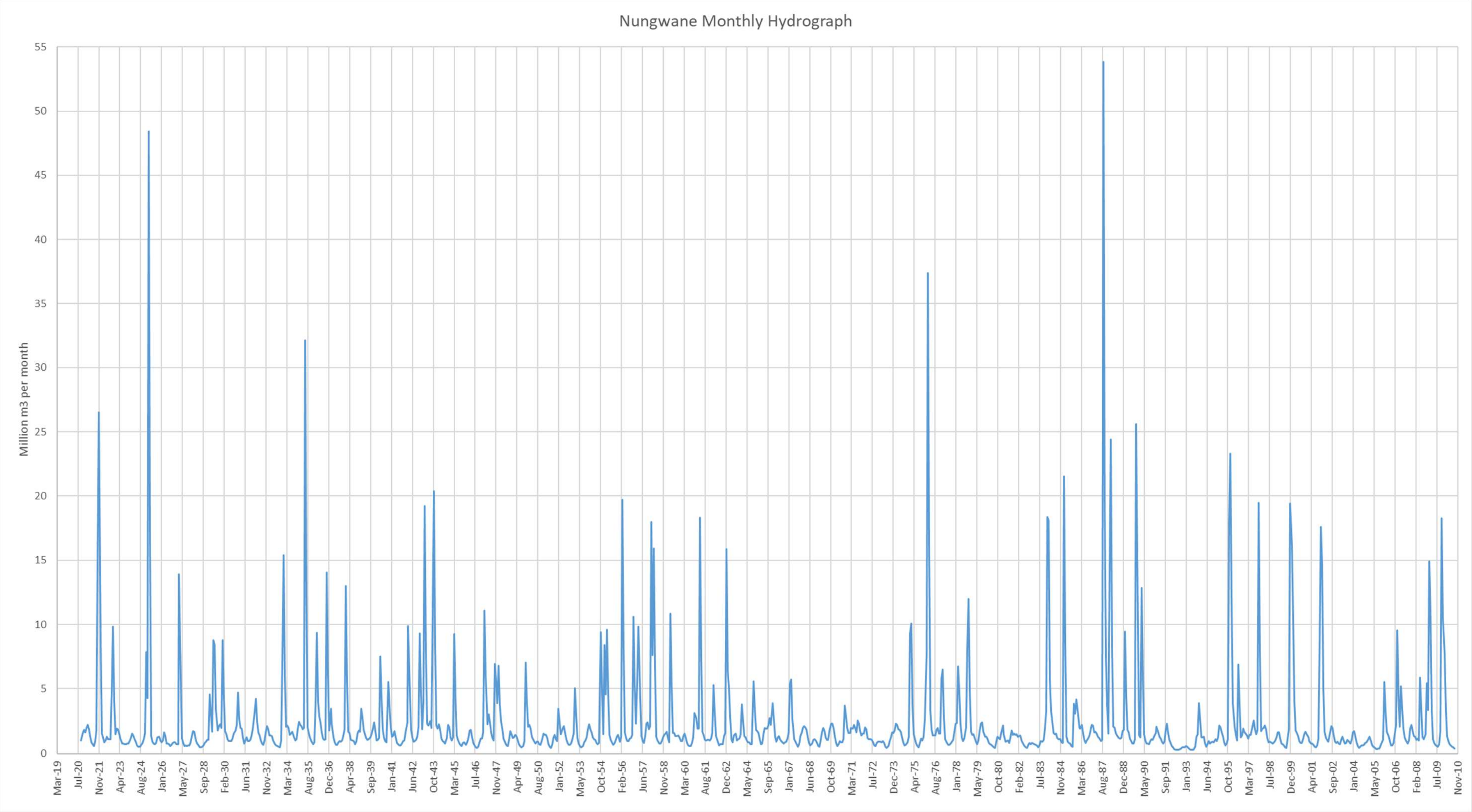


Figure A-13: Naturalised Flows – Nungwane Dam Inflow

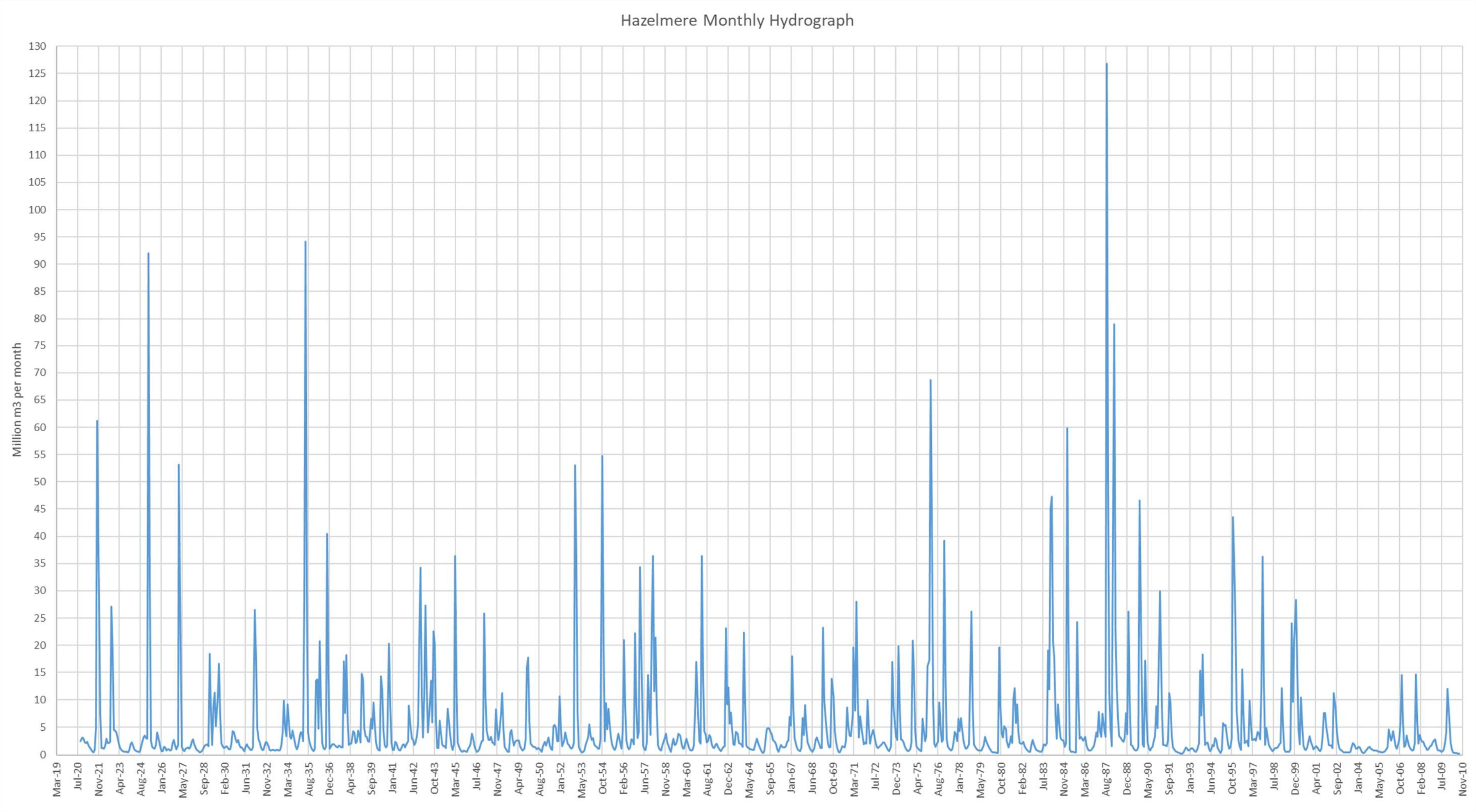


Figure A-14: Naturalised Flows – Hazelmere Dam Inflow

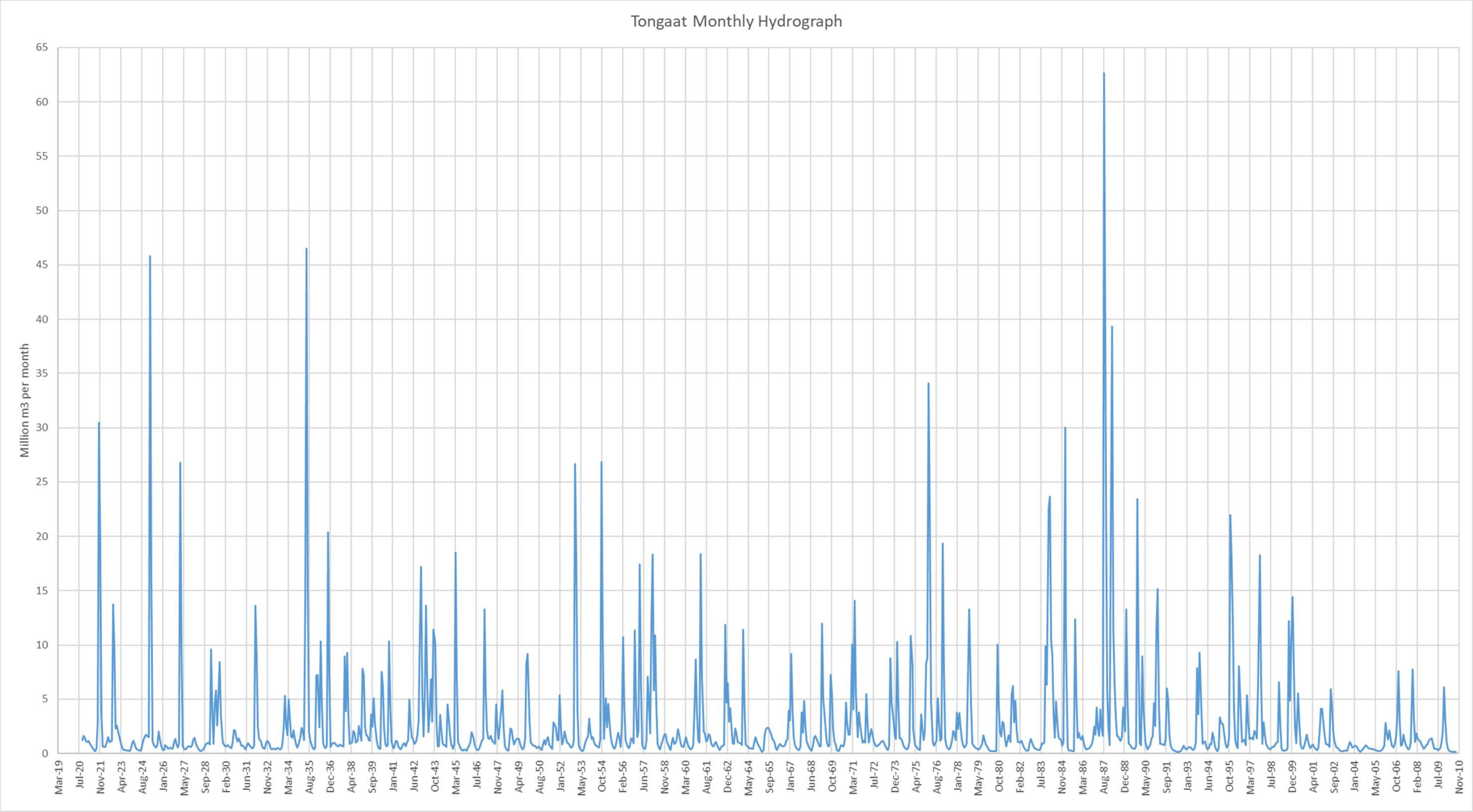


Figure A-15: Naturalised Flows – Tongaat River Inflow

External demands affecting water resources which in turn supply the study area are summarised below:

Table A-14: External Demands in Mooi River System Affecting Study Area

Mooi River System - Demands Outside eThekwini	
Year	**Demand**
2018	0
2023	19.1
2028	19.1
2038	26.6
2048	36.7

Table A-15: External Demands in Upper Mgeni System Affecting Study Area

Upper Mgeni System - Demands Outside eThekwini	
Year	**Demand**
2018	262.317
2023	262.317
2028	347.123
2038	428.593
2048	546.723

Table A-16: External Demands in South Coast System Affecting Study Area

South Coast System - Demands Outside eThekwini	
Year	**Demand**
2018	16.5
2023	30.9
2028	45.35
2033	51.1
2038	79.3
2048	87.9

Table A-17: External Demands in Hazelmere System Affecting Study Area

Hazelmere System - Demands Outside eThekwini	
Year	**Demand**
2018	25.64
2023	9.43
2028	0
2038	30.96
2048	36.03

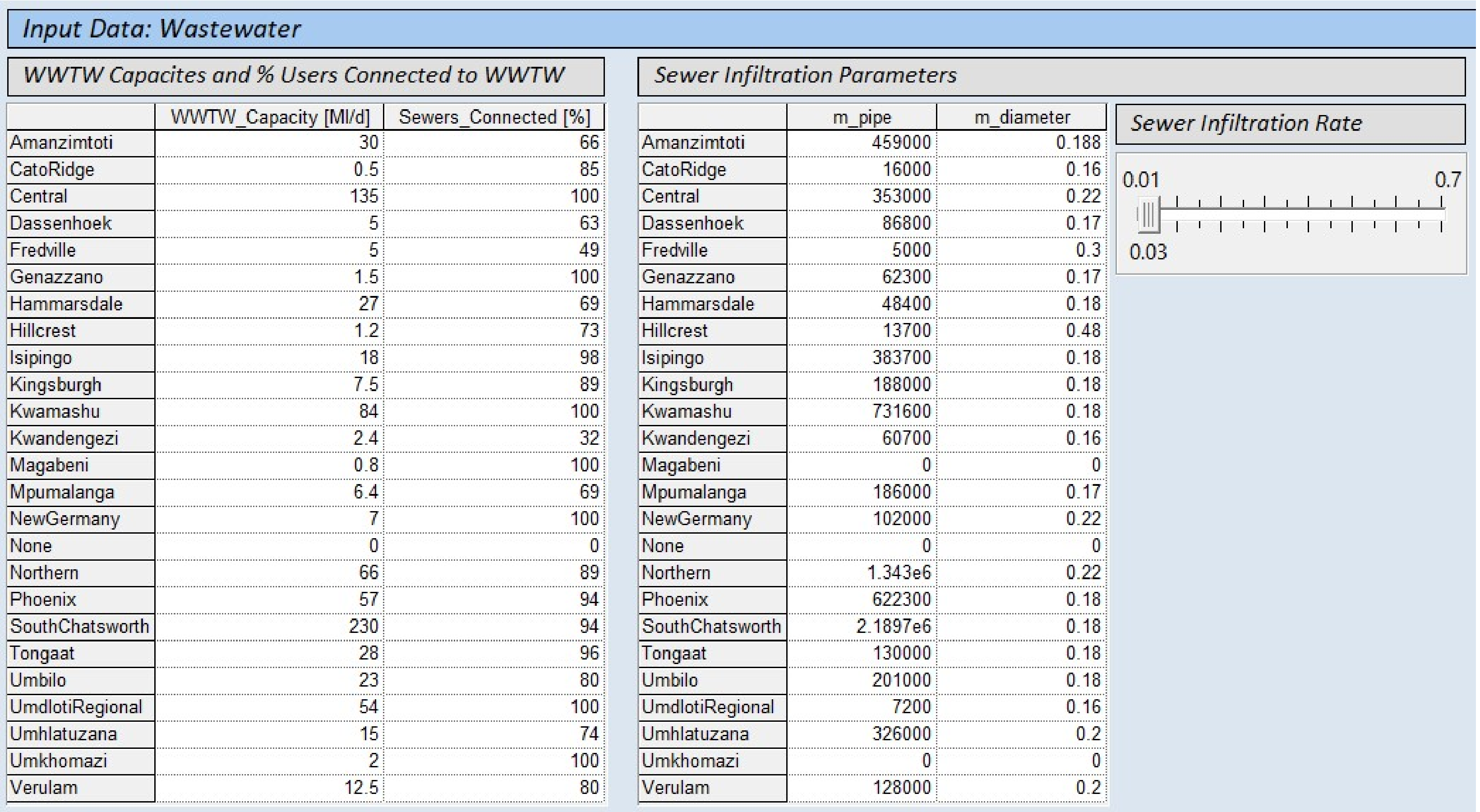
The water treatment works capacities were as defined in the Umgeni Water Masterplans (UW, 2019):

Table A-18: Water Treatment Works & Capacities

Supply System	Water Treatment Works	Capacity (Ml/d)	Status
Upper Mgeni	Midmar	375	No further upgrades
	DV Harris	110	No further upgrades
	Baynesfield	625	Planned
Lower Mgeni	Durban Heights	615	No further upgrades
	Wiggins	350	No further upgrades
South Coast	Amanzimtoti	22	No further upgrades
	Lower Umkhomazi	130	Planned
North Coast	Hazelmere	75	No further upgrades
	Tongaat	21	No further upgrades

Wastewater Inputs

Below are the key inputs for the wastewater system; WWTW capacities were based on information contained in the WSDP (EWS, 2011). Where WWTW upgrades are underway or have since been completed, the upgraded capacities have been used. The percentage consumers in each catchment connected to the bulk sewer network was based on a spatial analysis of the sewer network in relation to billing database point locations. Infiltration parameters were based on the total length of sewer mains and the length-weighted average pipe diameter.



Input Data: Wastewater

WWTW Capacites and % Users Connected to WWTW

	WWTW_Capacity [Ml/d]	Sewers_Connected [%]
Amanzimtoti	30	66
CatoRidge	0.5	85
Central	135	100
Dassenhoek	5	63
Fredville	5	49
Genazzano	1.5	100
Hammarsdale	27	69
Hillcrest	1.2	73
Isipingo	18	98
Kingsburgh	7.5	89
Kwamashu	84	100
Kwandengezi	2.4	32
Magabeni	0.8	100
Mpumalanga	6.4	69
NewGermany	7	100
None	0	0
Northern	66	89
Phoenix	57	94
SouthChatsworth	230	94
Tongaat	28	96
Umbilo	23	80
UmdlotiRegional	54	100
Umhlatuzana	15	74
Umkhomazi	2	100
Verulam	12.5	80

Sewer Infiltration Parameters

	m_pipe	m_diameter
Amanzimtoti	459000	0.188
CatoRidge	16000	0.16
Central	353000	0.22
Dassenhoek	86800	0.17
Fredville	5000	0.3
Genazzano	62300	0.17
Hammarsdale	48400	0.18
Hillcrest	13700	0.48
Isipingo	383700	0.18
Kingsburgh	188000	0.18
Kwamashu	731600	0.18
Kwandengezi	60700	0.16
Magabeni	0	0
Mpumalanga	186000	0.17
NewGermany	102000	0.22
None	0	0
Northern	1.343e6	0.22
Phoenix	622300	0.18
SouthChatsworth	2.1897e6	0.18
Tongaat	130000	0.18
Umbilo	201000	0.18
UmdlotiRegional	7200	0.16
Umhlatuzana	326000	0.2
Umkhomazi	0	0
Verulam	128000	0.2

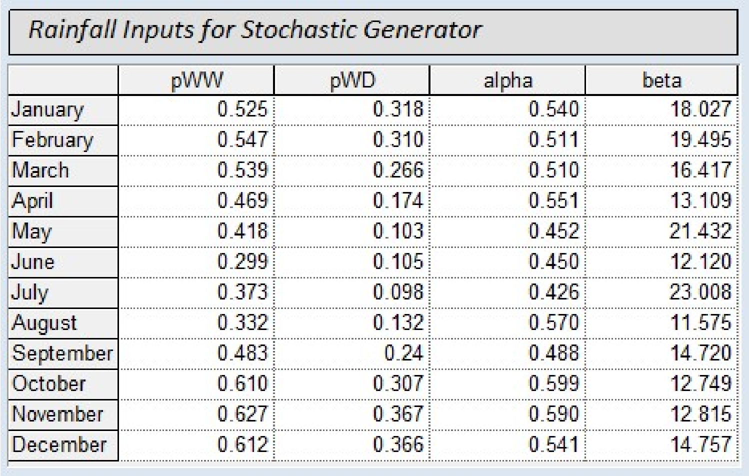
Sewer Infiltration Rate

Figure A-16: Wastewater System Parameters

Rainfall Inputs

The WGEN stochastic rainfall generator model first runs an analysis of historical rainfall data to determine appropriate parameters upon which the synthetic rainfall timeseries computations are based. Below are the outputs of this analysis, where pWW and pWD are probabilities of rainfall following a “wet” day and rainfall following a “dry” day (respectively), and alpha and beta represent distribution functions.

Table A-19: Rainfall Parameters



Rainfall Inputs for Stochastic Generator

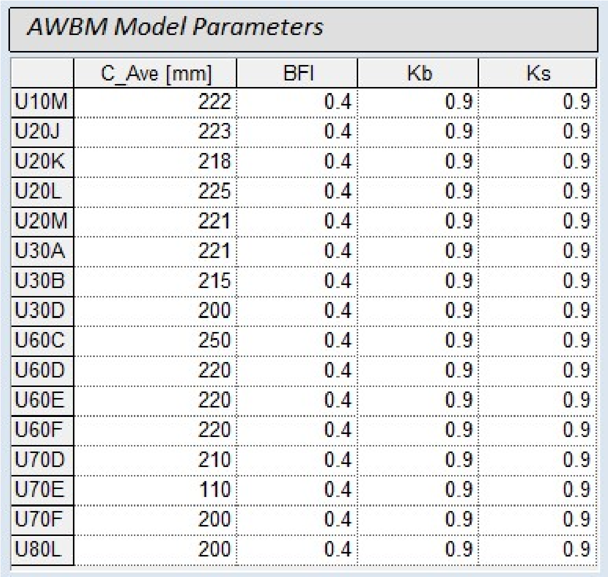
	pWW	pWD	alpha	beta
January	0.525	0.318	0.540	18.027
February	0.547	0.310	0.511	19.495
March	0.539	0.266	0.510	16.417
April	0.469	0.174	0.551	13.109
May	0.418	0.103	0.452	21.432
June	0.299	0.105	0.450	12.120
July	0.373	0.098	0.426	23.008
August	0.332	0.132	0.570	11.575
September	0.483	0.24	0.488	14.720
October	0.610	0.307	0.599	12.749
November	0.627	0.367	0.590	12.815
December	0.612	0.366	0.541	14.757

Runoff Inputs

The average surface store value for each quaternary catchment was obtained through calibration of the AWBM against naturalised flows (as extracted from the WR2012 Study) for each catchment. While calibration against the present day flows would have been more technically correct (these flows take into account land use changes), it would have been necessary to remove the influence of upstream abstractions, impoundments, and return flows. Such was not investigated in this study.

The baseflow index was determined based on a low flow study conducted in South Africa by Smakhtin & Watkins (1997). The recession constants for surface flow (Ks) and base flow (Kb) determine the temporal flow pattern (not the cumulative runoff volume) were assumed equal at 0.9; this is consistent with findings for a selection of catchments in the study area as determined by Smakhtin & Watkins (1997). These values could be refined with daily flow records for gauged catchments.

Table A-20: AWBM Parameters

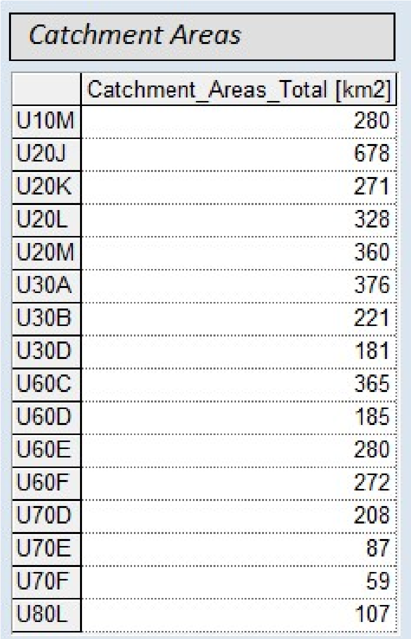


AWBM Model Parameters

	C_Ave [mm]	BFI	Kb	Ks
U10M	222	0.4	0.9	0.9
U20J	223	0.4	0.9	0.9
U20K	218	0.4	0.9	0.9
U20L	225	0.4	0.9	0.9
U20M	221	0.4	0.9	0.9
U30A	221	0.4	0.9	0.9
U30B	215	0.4	0.9	0.9
U30D	200	0.4	0.9	0.9
U60C	250	0.4	0.9	0.9
U60D	220	0.4	0.9	0.9
U60E	220	0.4	0.9	0.9
U60F	220	0.4	0.9	0.9
U70D	210	0.4	0.9	0.9
U70E	110	0.4	0.9	0.9
U70F	200	0.4	0.9	0.9
U80L	200	0.4	0.9	0.9

The WR2012 GIS database was used to extract the area of each quaternary catchment in the study area:

Table A-21: Quaternary Catchment Areas



Catchment Areas

	Catchment_Areas_Total [km2]
U10M	280
U20J	678
U20K	271
U20L	328
U20M	360
U30A	376
U30B	221
U30D	181
U60C	365
U60D	185
U60E	280
U60F	272
U70D	208
U70E	87
U70F	59
U80L	107

Build-up and wash-off equation parameters – specifically for TSS – were based on the review conducted by Tu & Smith (2018):

Table A-22: Buildup & Washoff Pollutant Parameters

Constants for Buildup & Washoff Equations	Values for TSS
Washoff Coefficient	0.13

Constants for Buildup & Washoff Equations	Values for TSS
Washoff Exponent	1.2
Maximum Buildup	18 kg/ha
Buildup Rate	0.3 1/day

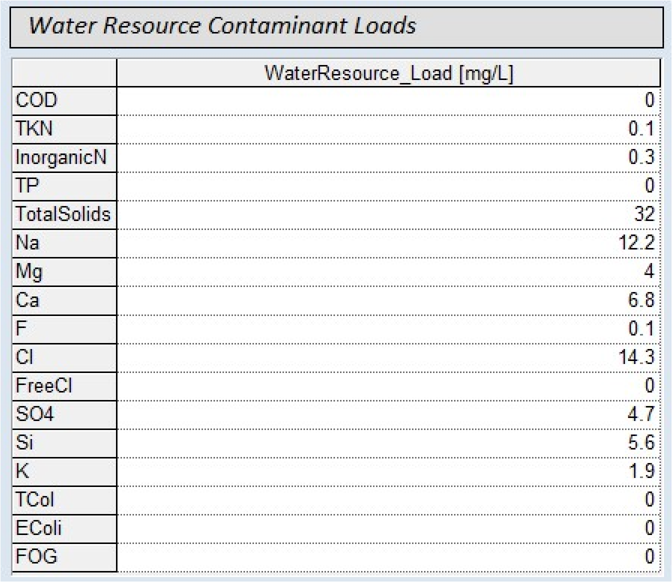
Water Quality Inputs

Table A-23: Contaminants Defined for Contaminant Transport Model

Species ID	Atomic Weight	Decay Rate	Description
COD	15.999	0.35 day-1	Chemical oxygen demand
TKN	14.0067	0.026 day-1	Total Kjeldahl Nitrogen
InorganicN	54.005	0.89 day-1	Nitrate and Nitrite
TP	30.9738	0.038 day-1	Total Phosphorus
TotalSolids	1	0.0 yr-1	Suspended, dissolved and settleable
Na	22.9898	0.0 yr-1	Sodium
Mg	24.305	0.0 yr-1	Magnesium
Ca	40.078	0.0 yr-1	Calcium
F	18.9984	0.0 yr-1	Flouride
Cl	35.453	0.09 day-1	Cloride
FreeCl	35.453	0.09 day-1	Free chlorine
SO4	96.06	0.0 yr-1	Sulfate
Si	28.085	0.0 yr-1	Silicon
K	39.0983	0.0 yr-1	Potassium
TCol	22000	3.25 day-1	Total Coliforms
EColi	22000	3.25 day-1	Escerichia Coli
FOG	885	0.0 yr-1	Fats, oil & grease

Inorganic concentrations for rivers and dams in the study area were extracted from the database prepared by Huizenga *et al*. (2013). Microbial monitoring data for rivers and dams in the study area was extracted from the DWS National Water Management System (DWS, 2019):

Table A-24: Contaminant Loading of Water Resources

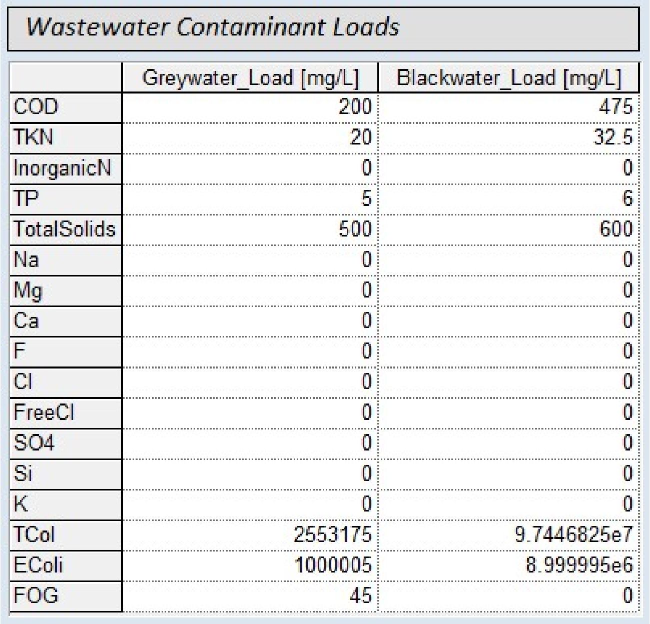


Water Resource Contaminant Loads

	WaterResource_Load [mg/L]
COD	0
TKN	0.1
InorganicN	0.3
TP	0
TotalSolids	32
Na	12.2
Mg	4
Ca	6.8
F	0.1
Cl	14.3
FreeCl	0
SO4	4.7
Si	5.6
K	1.9
TCol	0
EColi	0
FOG	0

Greywater and blackwater contaminant loading was determined from various studies and guidelines (Von Sperling, 2007; Metcalf & Eddy, 2003; Vuppaladadiyam, 2019; Oteng-Peprah, 2018):

Table A-25: Contaminant Loading of Wastestreams



Wastewater Contaminant Loads

	Greywater_Load [mg/L]	Blackwater_Load [mg/L]
COD	200	475
TKN	20	32.5
InorganicN	0	0
TP	5	6
TotalSolids	500	600
Na	0	0
Mg	0	0
Ca	0	0
F	0	0
Cl	0	0
FreeCl	0	0
SO4	0	0
Si	0	0
K	0	0
TCol	2553175	9.7446825e7
EColi	1000005	8.999995e6
FOG	45	0

Free chlorine has been included for the water and wastewater treatment components, and were based on the specified constituent limits defined for water treatment (SANS 241:2015) and limits defined by legislation for wastewater effluent released to the environment:

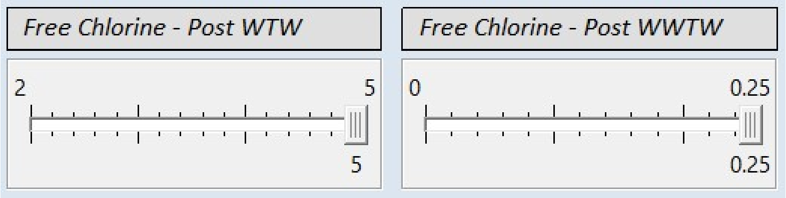
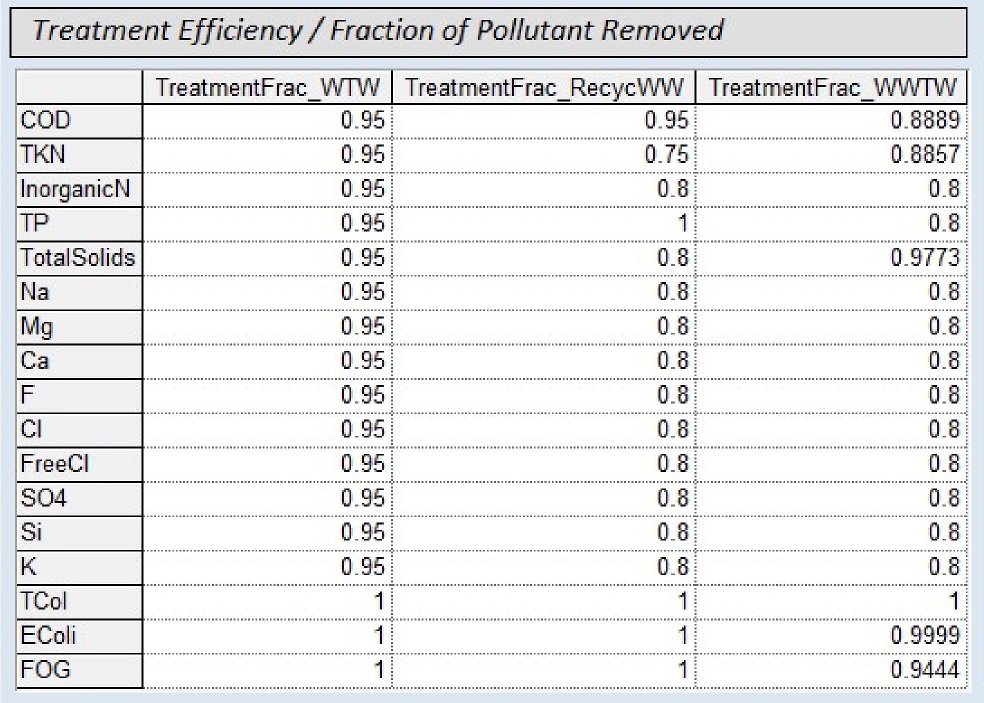


Figure A-17: Chlorine Dosing for Disinfection – Water and Wastewater Treatment

Treatment efficiencies have been estimated based on the specified average loadings and the constituent limits defined for water treatment (SANS 241:2015) and limits defined by legislation for wastewater effluent released to the environment:

Table A-26: Treatment Efficiency for Water Treatment, Wastewater Treatment, and Effluent Treatment to Potable Standards

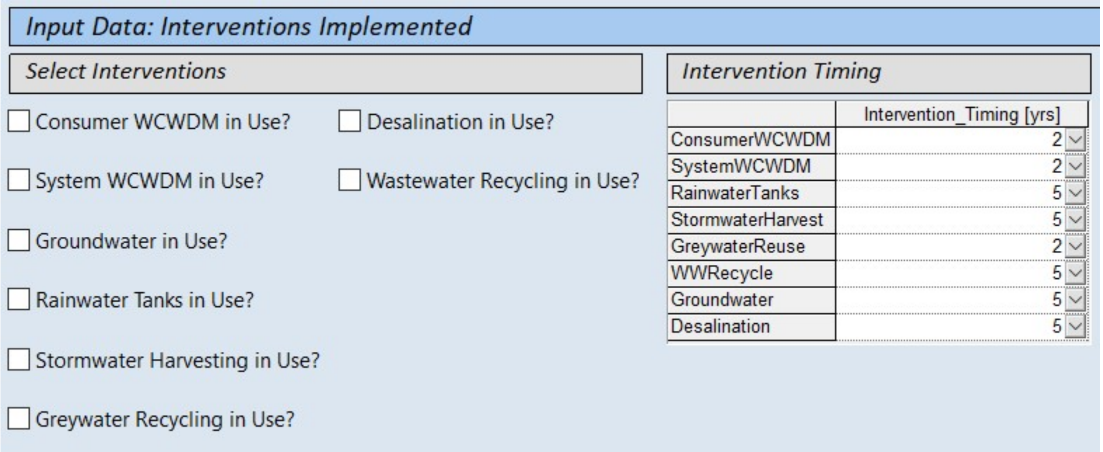


Treatment Efficiency / Fraction of Pollutant Removed

	TreatmentFrac_WTW	TreatmentFrac_RecycWW	TreatmentFrac_WWTW
COD	0.95	0.95	0.8889
TKN	0.95	0.75	0.8857
InorganicN	0.95	0.8	0.8
TP	0.95	1	0.8
TotalSolids	0.95	0.8	0.9773
Na	0.95	0.8	0.8
Mg	0.95	0.8	0.8
Ca	0.95	0.8	0.8
F	0.95	0.8	0.8
Cl	0.95	0.8	0.8
FreeCl	0.95	0.8	0.8
SO4	0.95	0.8	0.8
Si	0.95	0.8	0.8
K	0.95	0.8	0.8
TCol	1	1	1
EColi	1	1	0.9999
FOG	1	1	0.9444

Intervention Inputs

Figure A-18 illustrates the user-interface for selection of combinations of interventions and the timing of their implementation. Note that the scenario manager within the model automatically selects the relevant interventions for implementation.



Input Data: Interventions Implemented

Select Interventions

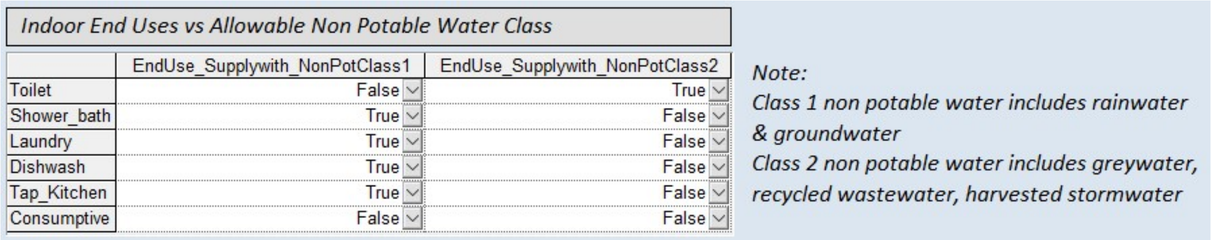
☐ Consumer WCWDM in Use?
☐ System WCWDM in Use?
☐ Groundwater in Use?
☐ Rainwater Tanks in Use?
☐ Stormwater Harvesting in Use?
☐ Greywater Recycling in Use?
☐ Desalination in Use?
☐ Wastewater Recycling in Use?

Intervention Timing

	Intervention_Timing [yrs]
ConsumerWCWDM	2
SystemWCWDM	2
RainwaterTanks	5
StormwaterHarvest	5
GreywaterReuse	2
WWRecycle	5
Groundwater	5
Desalination	5

Figure A-18: Selection of Interventions and Timing

The selection of the classes of non-potable water and their applicability to end-uses was based on the guidance given in Armitage *et al*. (2014), Department of Human Settlements (2019), Carden *et al*. (2017), and Landcom (2004), though may be altered should the modeller wish to run different end-use scenarios.



Indoor End Uses vs Allowable Non Potable Water Class

	EndUse_Supplywith_NonPotClass1	EndUse_Supplywith_NonPotClass2
Toilet	False	True
Shower_bath	True	False
Laundry	True	False
Dishwash	True	False
Tap_Kitchen	True	False
Consumptive	False	False

Note:
Class 1 non potable water includes rainwater & groundwater
Class 2 non potable water includes greywater, recycled wastewater, harvested stormwater

Figure A-19: Selection of Fit-for-Purpose End Uses

WCWDM

The rate of uptake of WCWDM measures for consumers and the rate at which consumers revert to the status quo after a period of time is summarised below.

Table A-27: Parameters to Determine Cumulative Proportion of Consumers with WCWDM Measures in Place

WCWDM Intervention	Initial Proportion of Consumers	Proportion Consumers Added / yr	Proportion Consumers Removed / yr
Plumbing Retrofit	0	0.05	0.02
Domestic Leak Repair	0	0.05	0.02
Xeriscaping	0	0.05	0.02
Tariff Increase	0	1	0

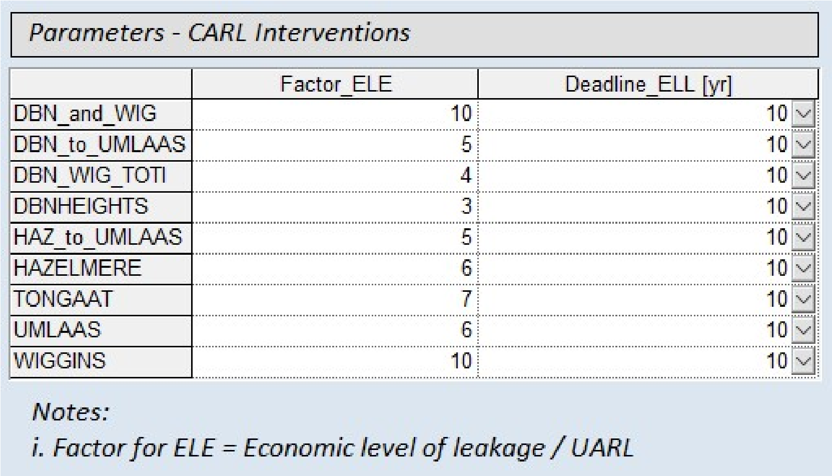
Consumer-side measures were broadly classed as follows, with conservation effectiveness (in reducing demand) as determined by Jacobs and Haarhoff (2004):

Table A-28: Consumer WCWDM Interventions and Effectiveness (Demand Reduction)

Non-Potable Supply	Effectiveness (%)
Leak repair programmes	8.4

Non-Potable Supply	Effectiveness (%)
Plumbing retrofits – water-saving devices	19.1
Xeriscaping	5.4
Tariff increases	5.0
Total	**37.9**

Target loss reduction factors (ratio between UARL and target loss) have been set for each bulk supply area such that a 20% reduction in real losses is achieved:



Parameters - CARL Interventions

	Factor_ELE	Deadline_ELL [yr]
DBN_and_WIG	10	10
DBN_to_UMLAAS	5	10
DBN_WIG_TOTI	4	10
DBNHEIGHTS	3	10
HAZ_to_UMLAAS	5	10
HAZELMERE	6	10
TONGAAT	7	10
UMLAAS	6	10
WIGGINS	10	10

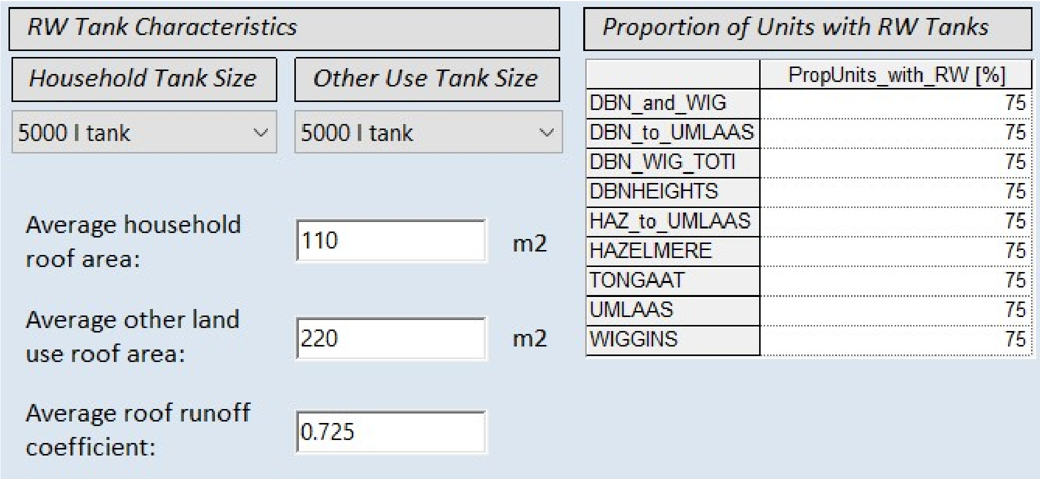
Notes:

i. Factor for ELE = Economic level of leakage / UARL

Figure A-20: Targets for Real Loss Reduction & Timeframes for Implementation

Rainwater Harvesting

Adopted rainwater harvesting parameters are presented below.



RW Tank Characteristics

Household Tank Size: 5000 l tank

Other Use Tank Size: 5000 l tank

Average household roof area: 110 m2

Average other land use roof area: 220 m2

Average roof runoff coefficient: 0.725

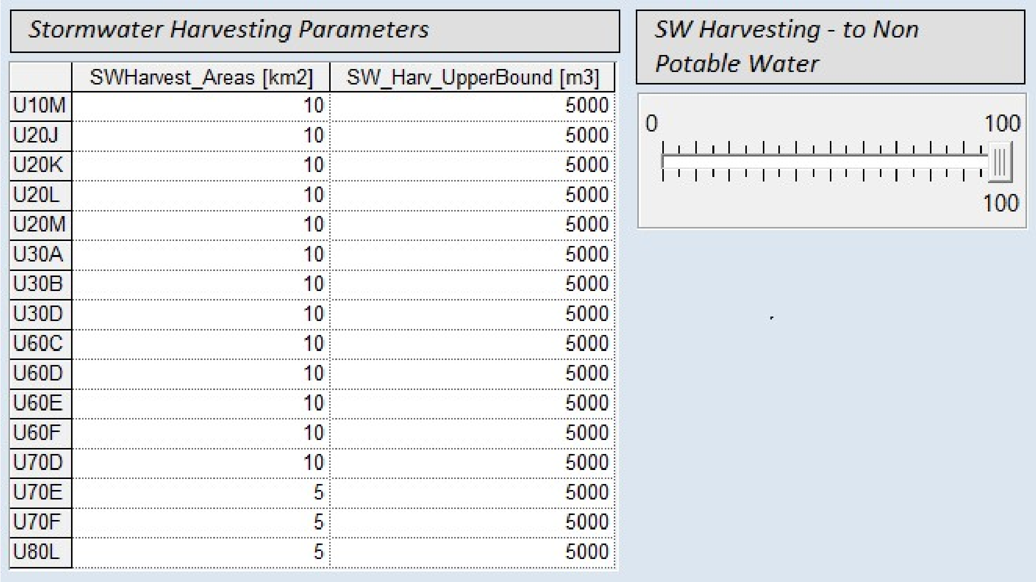
Proportion of Units with RW Tanks

	PropUnits_with_RW [%]
DBN_and_WIG	75
DBN_to_UMLAAS	75
DBN_WIG_TOTI	75
DBNHEIGHTS	75
HAZ_to_UMLAAS	75
HAZELMERE	75
TONGAAT	75
UMLAAS	75
WIGGINS	75

Figure A-21: Parameters for Rainwater Harvesting

Stormwater Harvesting

The areas per quaternary catchment associated with stormwater harvesting activities were taken as some 10% of the total catchment area, and cumulative storage (not necessarily in one location) per catchment as 5 Ml, totalling 80 Ml storage for the study area (equivalent to some 9% of the total daily SIV for eThekwini).


Stormwater Harvesting Parameters

	SWHarvest_Areas [km2]	SW_Harv_UpperBound [m3]
U10M	10	5000
U20J	10	5000
U20K	10	5000
U20L	10	5000
U20M	10	5000
U30A	10	5000
U30B	10	5000
U30D	10	5000
U60C	10	5000
U60D	10	5000
U60E	10	5000
U60F	10	5000
U70D	10	5000
U70E	5	5000
U70F	5	5000
U80L	5	5000

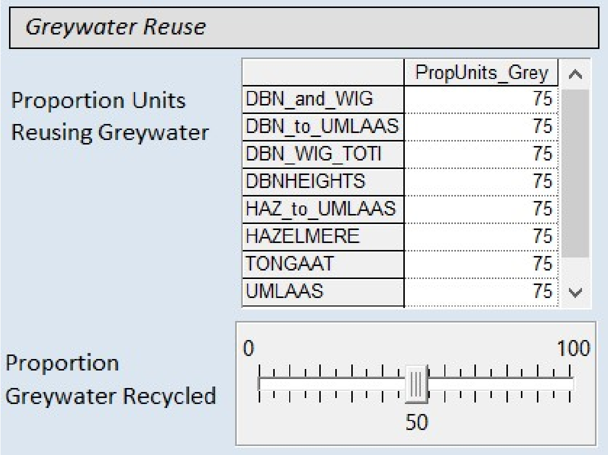
SW Harvesting - to Non Potable Water

100

Figure A-22: Stormwater Harvesting Parameters

Greywater Reuse

Adopted greywater reuse parameters are presented below.


Greywater Reuse

Proportion Units Reusing Greywater

	PropUnits_Grey
DBN_and_WIG	75
DBN_to_UMLAAS	75
DBN_WIG_TOTI	75
DBNHEIGHTS	75
HAZ_to_UMLAAS	75
HAZELMERE	75
TONGAAT	75
UMLAAS	75

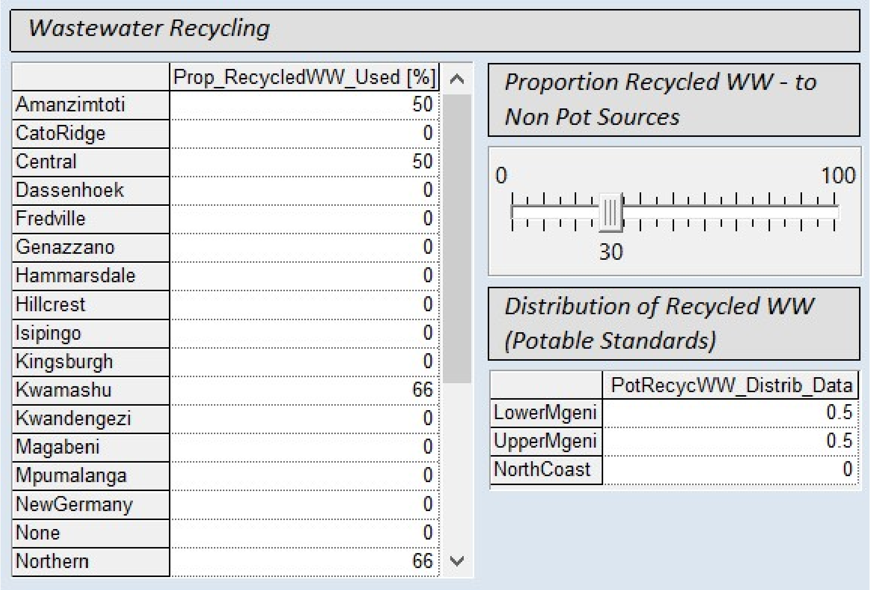
Proportion Greywater Recycled

50

Figure A-23: Greywater Reuse Parameters

Wastewater Recycling

Adopted wastewater recycling parameters are presented below.



Wastewater Recycling

	Prop_RecycledWW_Used [%]
Amanzimtoti	50
CatoRidge	0
Central	50
Dassenhoek	0
Fredville	0
Genazzano	0
Hammarsdale	0
Hillcrest	0
Isipingo	0
Kingsburgh	0
Kwamashu	66
Kwandengezi	0
Magabeni	0
Mpumalanga	0
NewGermany	0
None	0
Northern	66

Proportion Recycled WW - to Non Pot Sources

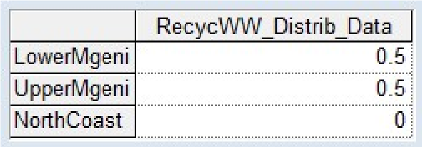
30

Distribution of Recycled WW (Potable Standards)

	PotRecycWW_Distrib_Data
LowerMgeni	0.5
UpperMgeni	0.5
NorthCoast	0

Figure A-24: Wastewater Recycling Parameters

Table A-29: Distribution of Recycled Wastewater (Potable Standard)

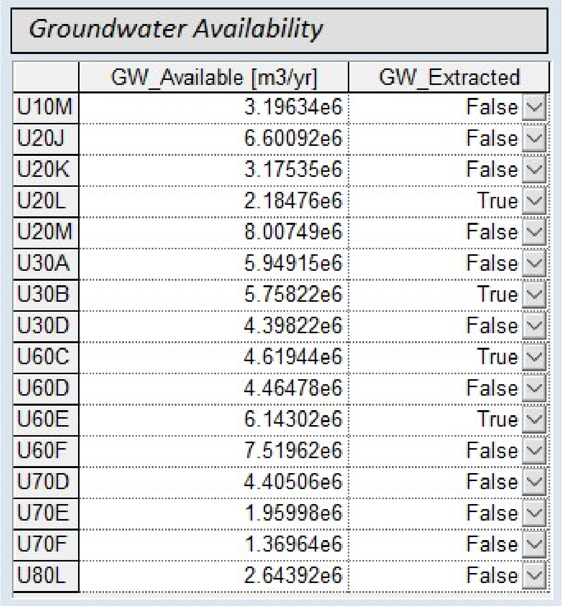


	RecycWW_Distrib_Data
LowerMgeni	0.5
UpperMgeni	0.5
NorthCoast	0

Groundwater

Groundwater available for extraction is based on the outcomes of the GRA2 Project. The model makes provision for definition of whether or not groundwater is extracted from each catchment or not – the below conditions being based on catchments largely comprising outlying and rural areas, such that application is consistent with recommendations in the Reconciliation Strategy (DWS, 2017).

Table A-30: Available Groundwater per Quaternary Catchment


Groundwater Availability

	GW_Available [m3/yr]	GW_Extracted
U10M	3.19634e6	False
U20J	6.60092e6	False
U20K	3.17535e6	False
U20L	2.18476e6	True
U20M	8.00749e6	False
U30A	5.94915e6	False
U30B	5.75822e6	True
U30D	4.39822e6	False
U60C	4.61944e6	True
U60D	4.46478e6	False
U60E	6.14302e6	True
U60F	7.51962e6	False
U70D	4.40506e6	False
U70E	1.95998e6	False
U70F	1.36964e6	False
U80L	2.64392e6	False

Desalination

Supplies available for desalination were based on planned projects (totals some 300 Ml/d).

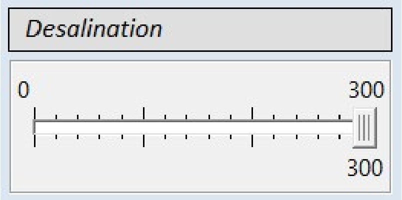
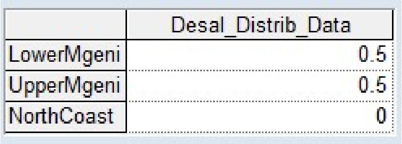


Figure A-25: Volume of Desalinated Supply

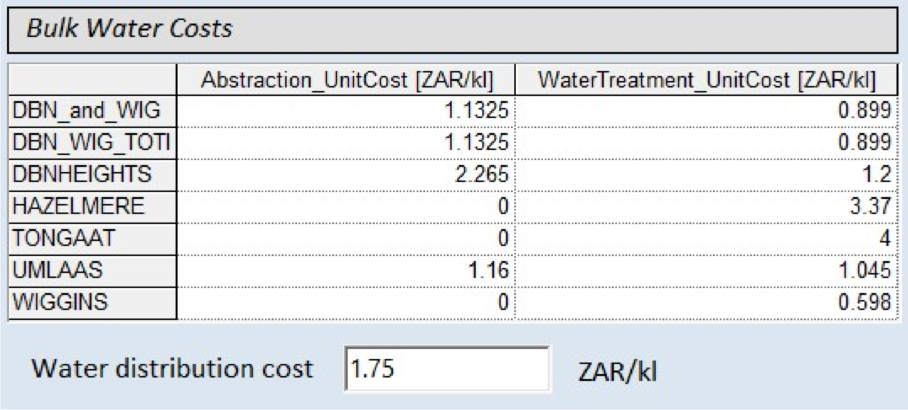
Table A-31: Distribution of Desalinated Supply



	Desal_Distrib_Data
LowerMgeni	0.5
UpperMgeni	0.5
NorthCoast	0

Economic & Energy Data

Raw water abstraction and treatment costs per bulk supply area were based on information obtained from Umgeni Water. Water distribution cost was taken as the average of the range given by Frost & Sullivan (2011). It must be noted that treatment costs are based on volumes treated and do not account for changes to raw water quality (such would require a more detailed model, which is beyond the scope of this study).



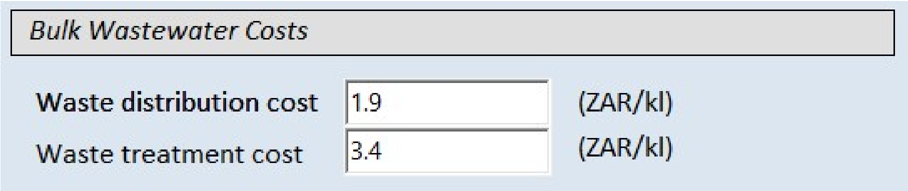
Bulk Water Costs

	Abstraction_UnitCost [ZAR/kl]	WaterTreatment_UnitCost [ZAR/kl]
DBN_and_WIG	1.1325	0.899
DBN_WIG_TOTI	1.1325	0.899
DBNHEIGHTS	2.265	1.2
HAZELMERE	0	3.37
TONGAAT	0	4
UMLAAS	1.16	1.045
WIGGINS	0	0.598

Water distribution cost 1.75 ZAR/kl

Figure A-26: Bulk Water Costs for Abstraction, Treatment, and Distribution

Wastewater treatment costs and wastewater conveyance costs are dependent on scales of economy (i.e. volumes treated at facilities); Naidoo *et al*. (2016) developed wastewater services operational cost curves for South African municipalities which are dependent on cumulative wastewater system capacity. Such deduced for eThekwini are presented below.



Bulk Wastewater Costs

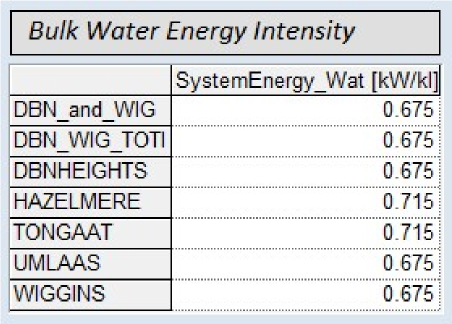
Waste distribution cost 1.9 (ZAR/kl)

Waste treatment cost 3.4 (ZAR/kl)

Figure A-27: Wastewater Costs for Collection and Treatment

The energy intensity per bulk supply area was based on information contained in the Umgeni Water Masterplan (UW, 2019) where the energy intensity per water supply scheme has been measured on actual use.

Table A-32: Energy Intensity of Bulk Water Systems

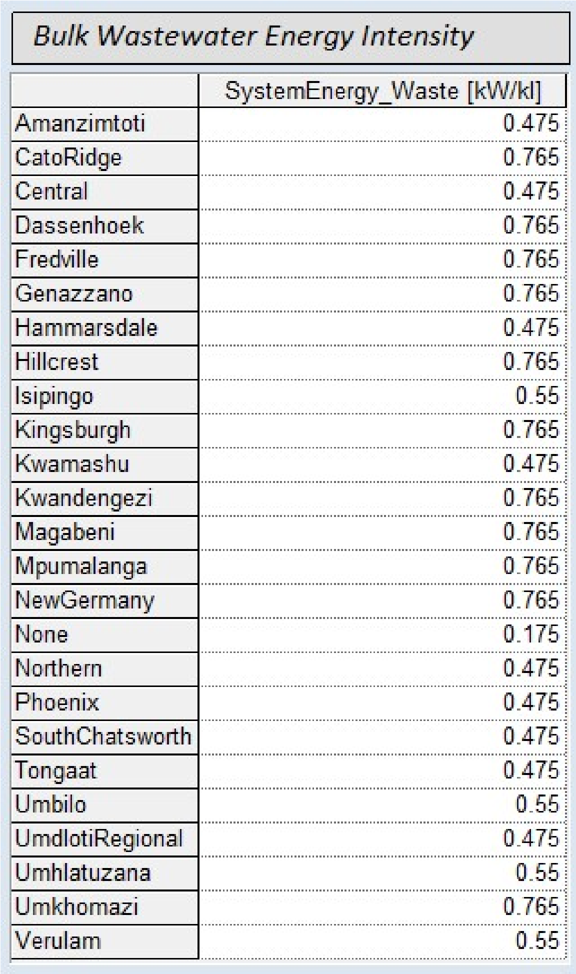


Bulk Water Energy Intensity

	SystemEnergy_Wat [kW/kl]
DBN_and_WIG	0.675
DBN_WIG_TOTI	0.675
DBNHEIGHTS	0.675
HAZELMERE	0.715
TONGAAT	0.715
UMLAAS	0.675
WIGGINS	0.675

Scheepers & van der Merwe-Botha (2012) determined energy intensity of wastewater treatment, depending on the treatment facility size. Energy intensity of wastewater collection and conveyance was based on information contained in Frost & Sullivan (2011). The total bulk wastewater energy consumption is summarised below:

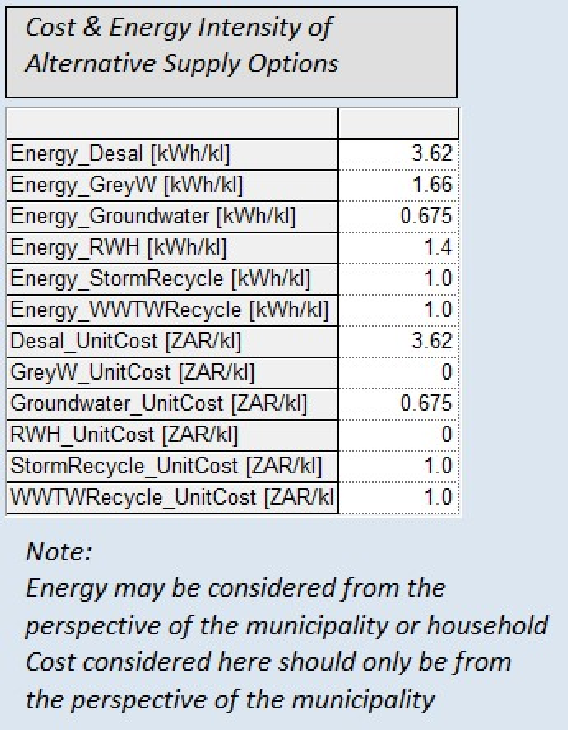
Table A-33: Energy Intensity of Bulk Wastewater Systems



Bulk Wastewater Energy Intensity

	SystemEnergy_Waste [kW/kl]
Amanzimtoti	0.475
CatoRidge	0.765
Central	0.475
Dassenhoek	0.765
Fredville	0.765
Genazzano	0.765
Hammarsdale	0.475
Hillcrest	0.765
Isipingo	0.55
Kingsburgh	0.765
Kwamashu	0.475
Kwandengezi	0.765
Magabeni	0.765
Mpumalanga	0.765
NewGermany	0.765
None	0.175
Northern	0.475
Phoenix	0.475
SouthChatsworth	0.475
Tongaat	0.475
Umbilo	0.55
UmdlotiRegional	0.475
Umhlatuzana	0.55
Umkhomazi	0.765
Verulam	0.55

Information on the energy intensity of rainwater harvesting, greywater reuse, recycled wastewater, and desalination were obtained from Vieira *et al*. (2014) & Knutsson & Knutsson (2021). Energy intensity of groundwater was assumed similar to system energy for bulk water supply, and energy intensity of stormwater harvesting was assumed similar to that of recycled wastewater. Costs of alternative water supply was based on the energy intensity and an average energy cost of R 1/kWh. While the below figures are unverified for applicability in South Africa, these are deemed reasonable estimations for use in this model.



Cost & Energy Intensity of Alternative Supply Options

Energy_Desal [kWh/kl]	3.62
Energy_GreyW [kWh/kl]	1.66
Energy_Groundwater [kWh/kl]	0.675
Energy_RWH [kWh/kl]	1.4
Energy_StormRecycle [kWh/kl]	1.0
Energy_WWTWRecycle [kWh/kl]	1.0
Desal_UnitCost [ZAR/kl]	3.62
GreyW_UnitCost [ZAR/kl]	0
Groundwater_UnitCost [ZAR/kl]	0.675
RWH_UnitCost [ZAR/kl]	0
StormRecycle_UnitCost [ZAR/kl]	1.0
WWTWRecycle_UnitCost [ZAR/kl	1.0

Note:
Energy may be considered from the perspective of the municipality or household
Cost considered here should only be from the perspective of the municipality

Figure A-28: Summary of Costs and Energy Intensity Associated with Alternative Water Sources

Appendix B: Additional Model Details

Key Equations

Below are presented a selection of equations used in the systems model; further detail is contained in the model itself.

1. Stock-flow relationship:

The equations describing stocks and flows are fundamental building blocks of systems dynamics models. Below is presented the generic form (after Mashaly & Fernald, 2020); the system model itself contains a variety of stocks, inflows, and outflows which describe the movement of water through the urban water cycle in the study area.

$$Stock(t) = \int_{ts}^{t} [Inflow(s) - Outflow(s)]ds + Stock(ts)$$

$$\frac{dStock(t)}{ds} = Inflow(s) - Outflow(s)$$

Where:
(s) represents any specific time between the original time (ts) and current time (t);
Inflows and Outflows correspond to inflow and outflow values at time (s); and
Stock(t) is the stock value at time (t).

2. Exponential form of build-up and wash-off equations:

The build-up and wash-off of pollutants in urban areas is described by the below equations:

$$Buildup = C1\ x\ (1 - e^{-C2\ x\ t})$$

$$Washoff\ = C3\ x\ Runoff^{C4} x\ Buildup$$

Where:
Build-up is the pollutant build-up mass per unit area;
Wash-off the wash-off load in mass per unit time;
C1 is the maximum build-up possible (mass per unit area);
C2 is the build-up rate constant which determines the rate of pollutant build-up (1/days);
C3 is the wash-off coefficient; and
C4 is the wash-off exponent.

3. Reliability, resilience, and vulnerability:

$$Reliability = \frac{Number\ time\ periods\ where\ X_t\ \geq XT}{n}$$

Where:
X_t represents the values of a particular variable in the time series;
XT represents the threshold value related to the variable in question; and

n is the total number of data points in the time series (i.e. defined by simulation length and time steps).

$$Resilience = \frac{[Number\ of\ times\ a\ satisfactory\ value\ follows\ an\ unsatisfactory\ value]}{[Occurences\ of\ unsatisfactory\ values]}$$

$$Vulnerability = \frac{|\sum XT - X_t|}{[number\ of\ unsatisfactory\ occurences]}$$

Where:
X_t represents the values of a particular variable in the time series; and
XT represents the threshold value related to the variable in question.

4. Resource efficiency:

The following measures of resource efficiency are applied to the system model outputs to compare the scenario performance:

$$Internal\ harvesting\ ratio = \frac{RWH + GW + SWH}{SIV}$$

$$Internal\ recycling\ ratio = \frac{GreyW + WW}{SIV}$$

$$Bulk\ Water\ per\ Capita = \frac{Supply_p}{Population}$$

$$Energy\ per\ Capita = \frac{E_{tot}}{Population}$$

Where:
RWH is the volume of utilised harvested rainwater;
GW is the volume of utilised groundwater;
SWH is is the volume of utilised harvested stormwater;
GreyW is the volume of utilised greywater;
WW is is the volume of utilised recycled wastewater;
$Supply_p$ is the volume of potable water supplied from bulk water supply schemes; and
E_{tot} is the total energy consumption for bulk water and sanitation services, and water supplied through alternative water sources.

5. System Input Volume:

$$SIV = Billed\ Metered\ Consumption + Apparent\ Losses + Real\ Losses$$

6. Unavoidable Annual Real Losses:

Equations have been developed to determine the UARL, the form suitable for use in South Africa as follows:

$$UARL = (18\ x\ Lm + 0.8\ x\ Nc)\ x\ P$$

Where:
Lm = Length of mains (km);
Nc = Number of service connections (i.e. metered connection points off mains); and
P = Average operating pressure at average zone point (m).

7. AWBM Recession Rate:

$$Recession\,rate = \ {}^{1-K}/_{\Delta t}$$

Where:
Recession rates for baseflow and surface runoff determine the temporal distribution of runoff;
K is the recession constant – defined separately for baseflow and surface runoff; and
Δt is the defined timestep.

8. Sewer infiltration rate:

$$Infiltration = I_{nf}\ x\ \emptyset\ x\ l$$

Where:
I_{nf} is the infiltration rate in litres/min / m pipe / m Ø;
Ø is the pipe diameter in metres; and
l is the pipe length in metres.

9. Normalisation:

Distance to a reference value, at time t = 0, takes into account the development of indicators over the simulation time. Centring on zero, the indicator may be defined as:

$$x_j = \frac{X_t - X_{t=0}}{X_{t=0}}$$

Where:
X_t represents the values of a particular variable in the time series; and
X_t represents the values of a particular variable at simulation time t = 0.

10. Computing Scores:

The weighted sum method (summation of weighted and normalised indicators) has been applied to the scoring of each scenario.

For each criterion:

$$C_i = \sum\nolimits_{j=1}^{n} w_j x_j \quad i = 1, \dots, n$$

Where:
C_i is the composite score for a given criterion (e.g. environmental);
w_j is the j^{th} weight given to variable x_j;
x_j is the normalised variable in the dataset for the given criterion; and
n are the number of indicators within the dataset for the given criterion.

Similarly, for the final composite score:

$$Composite\ Score\ = \sum\nolimits_{j=1}^{n} w_j C_j \quad i = 1, \dots, n$$

Where:
w_j is the j^{th} weight given to criterion C_j;
C_j is the criterion score; and
n are the number of criterion dimensions contributing to the composite score.

Calibration of Water System Input Volumes

The modelled SIVs were calibrated against the SIVs obtained from the Umgeni Water Masterplan (UW, 2019), which contains record of the average daily outputs from the respective WTWs (Figure B-1). Below is summarised key throughput information for each WTW and the system input volume selected for model calibration.

Midmar WTW:

- In 2018, plant throughput exceeded 200 Ml/d 97% of the time, and exceeded 250 Ml/d 50% of the time.
- The most recent average output is recorded as 265.5 Ml/d, and predicted to reach 330 Ml/d in 2020.

DV Harris WTW:

- The most recent average output is recorded as 61.1 Ml/d, and predicted to reach 75 Ml/d in 2020.

At present, eThekwini utilises approximately 28% of the Upper Mgeni resource. It was therefore deemed reasonable to target a value between 91 Ml/d and 113 Ml/d for the Umlaas Road sub-system supplying eThekwini; 91 Ml/d corresponding to the SIV at end 2018, and 113 Ml/d corresponding to the predicted SIV in 2020.

Durban Heights WTW:

- In 2018, plant throughput exceeded 460 Ml/d 95% of the time, and exceeded 492 Ml/d 46% of the time.
- Prior to the drought, throughput averaged some 510 Ml/d; the most recent average output is recorded as just below 500 Ml/d, indicating demands on the system recovering to pre-drought levels.

- The model therefore targeted an SIV of 500 Ml/d.

Wiggins WTW:

- In 2018, plant throughput exceeded 240 Ml/d 90% of the time, and exceeded 260 Ml/d 50% of the time.
- Prior to the drought, throughput averaged 280 Ml/d; the most recent average output is recorded as 265 Ml/d. There is no significant increase predicted up until 2020.

The model therefore targeted an SIV of 265 Ml/d. Some of this volume supplies the Amanzimtoti WTW with potable water which is in turn distributed to the supply area of Amanzimtoti WTW; the target SIV for the area which is only supplied by Wiggins WTW was therefore 198.6 Ml/d.

Amanzimtoti WTW:

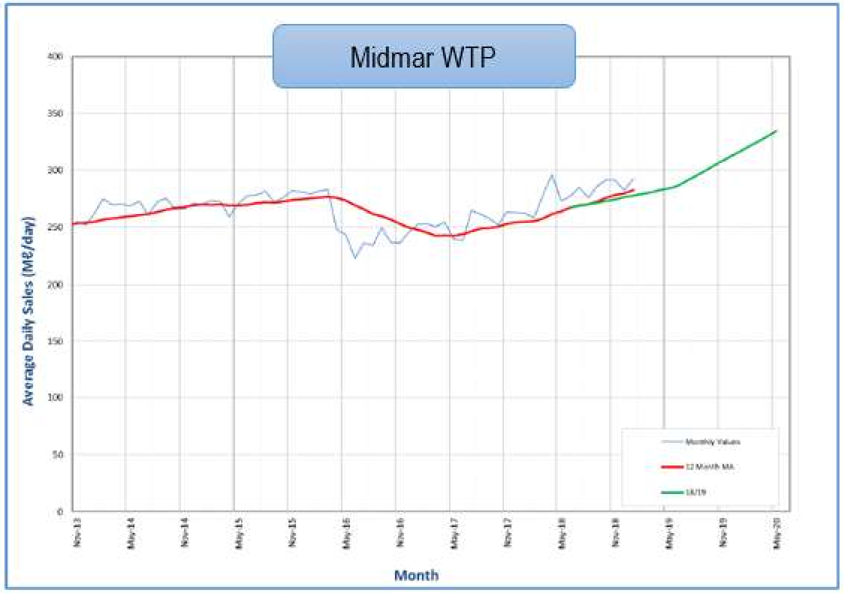
- In 2018, Amanzimtoti treated approximately 13.6 Ml/d.
- Including the inflow from the Wiggins system, the Amanzimtoti supply area was provided with some 80 Ml/d.
- The model therefore targeted an SIV of 80 Ml/d.

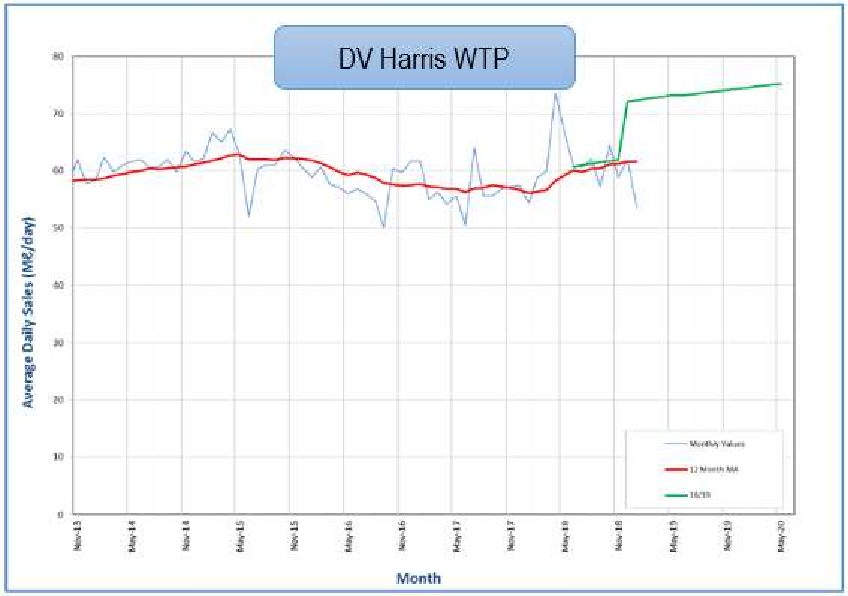
Hazelmere WTW:

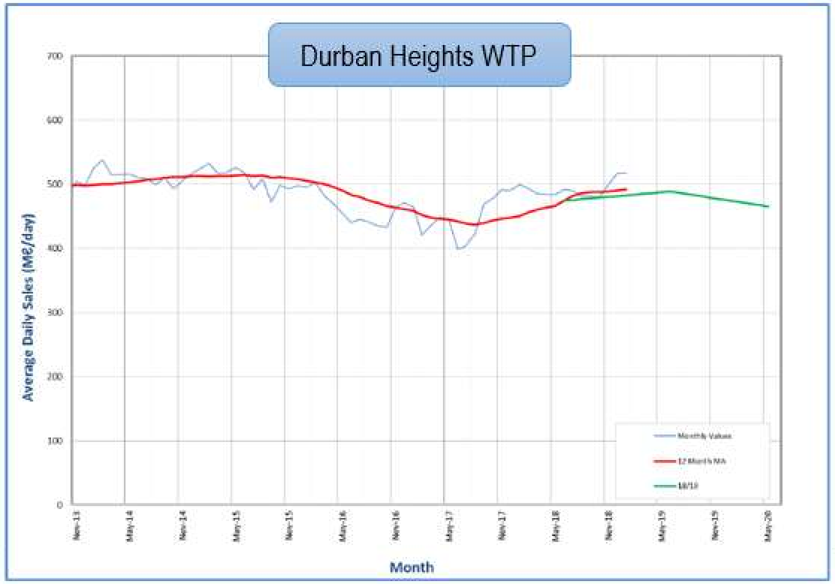
- In 2018, plant throughput exceeded 45 Ml/d 95% of the time, and exceeded 55 Ml/d 50% of the time.
- The most recent average output is recorded as 51 Ml/d, and predicted to reach 72 Ml/d in 2020 as eThekwini requires more water to supply developments on the North Coast.
- A target SIV of between 50 Ml/d to 70 Ml/d was adopted; it is unknown whether or not the predicted demand will have come to fruition.

Tongaat WTW:

- As stated in the WSDP (EWS, 2011), the average plant output was 13.5 Ml/d.
- Allowing for growth in demand, a target SIV of 15 Ml/d has been adopted.


Midmar WTP
Average Daily Sales (Mℓ/day)
400
350
300
250
200
150
100
50
0
Nov-13
May-14
Nov-14
May-15
Nov-15
May-16
Nov-16
May-17
Nov-17
May-18
Nov-18
May-19
Nov-19
May-20
Month
Monthly Values
12 Month MA
18/19


DV Harris WTP
Average Daily Sales (Mℓ/day)
80
70
60
50
40
30
20
10
0
Nov-13
May-14
Nov-14
May-15
Nov-15
May-16
Nov-16
May-17
Nov-17
May-18
Nov-18
May-19
Nov-19
May-20
Month
Monthly Values
12 Month MA
18/19


Durban Heights WTP
Average Daily Sales (Mℓ/day)
700
600
500
400
300
200
100
0
Nov-13
May-14
Nov-14
May-15
Nov-15
May-16
Nov-16
May-17
Nov-17
May-18
Nov-18
May-19
Nov-19
May-20
Month
Monthly Values
12 Month MA
18/19


Wiggins WTP
Average Daily Sales (Mℓ/day)
350
300
250
200
150
100
50
0
Nov-13
May-14
Nov-14
May-15
Nov-15
May-16
Nov-16
May-17
Nov-17
May-18
Nov-18
May-19
Nov-19
May-20
Month
Monthly Values
12 Month MA
18/19

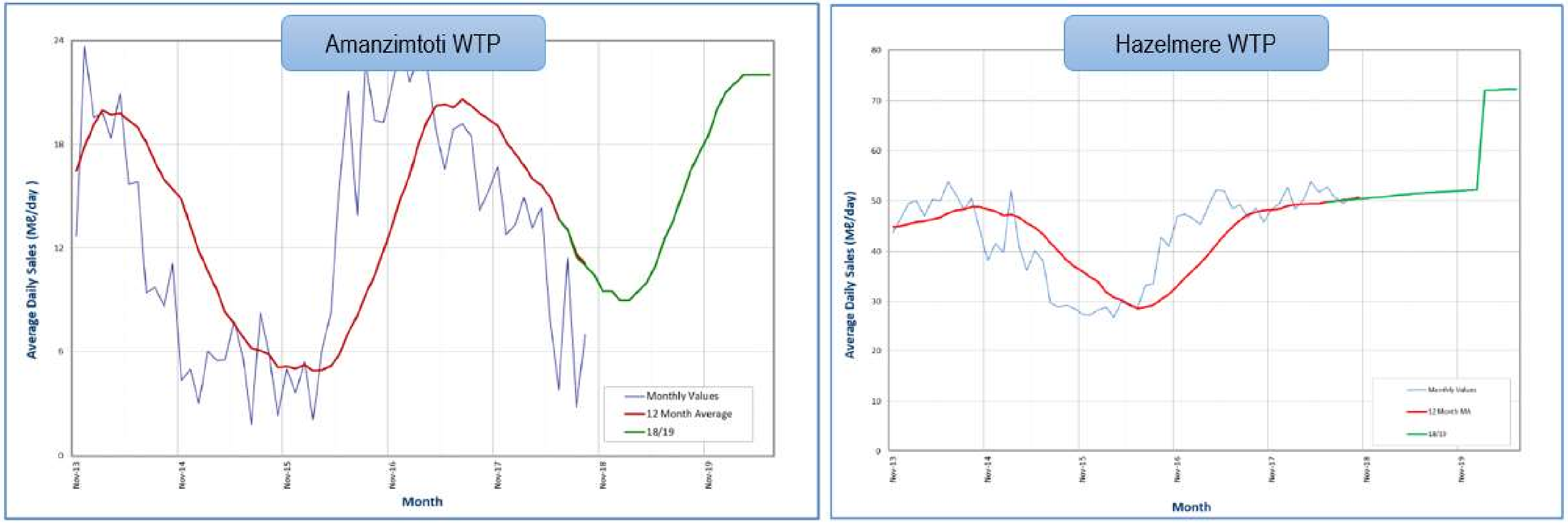


Figure B-1: Average Daily Output from WTWs [Source: UW, 2019]

The calibration of the system input volume considered the following:

i. Given the impact of the recent drought, BMC data from 2014 was used for the analysis, as demand was at this stage unaffected by system restrictions. Figure B-2 illustrates the total BMC for eThekwini over this period. While 2018 shows a return to unrestricted system demand (based on usage data in the Umgeni Water Masterplan), the EWS billing system has since changed and is still in the process of being refined. The BMC from 2014 therefore remained the most suitable dataset for use in this study.

ii. Based on the SIVs for the respective WTW supply areas, target values for the simulation start time (2020) were set. A key assumption was that SIVs have somewhat returned to pre-drought values, thereby validating the use of the 2014 dataset.

iii. Based on the water balance presented in the WSDP (EWS, 2011), real losses comprised 24% of the SIV, and apparent losses amounted to 8% of the SIV. For modelling purposes, 25% and 12.5% were adopted for real and apparent losses (respectively) such that the modelled SIV was closer to the defined target volumes.

iv. While the adopted real and apparent losses represents a NRW percentage which is higher than recently reported values (UW, 2019), it is consistent with the NRW status in 2014 (also the year selected for the BMC analysis). Furthermore, the current composition of the water balance is currently not known; as such there was preference for use of existing data (albeit from a number of years ago).

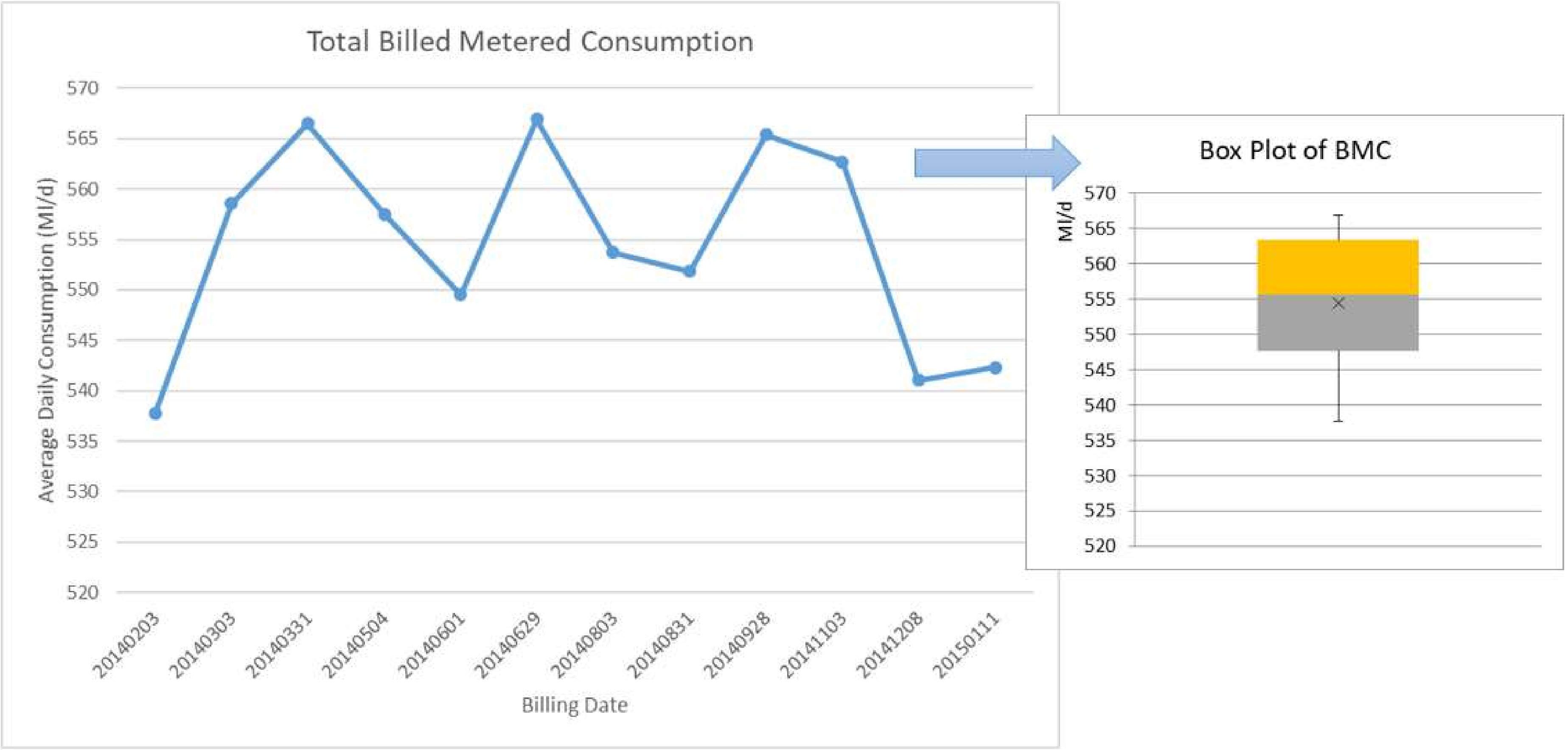


Figure B-2: Total Billed Metered Consumption for eThekwini, 2014

The below tables summarise the system input volume targets against that which was determined through the model.

Table B-1: Target vs Modelled SIVs (Including External Demands)

WTW Bulk Supply Area	SIV - with external demands		
	Target	Modelled	Percentage difference
Amanzimtoti	80	81	1.3%
Wiggins	198.6	179	-9.9%
Durban Heights	500	525	5.0%
Umlaas (Upper Mgeni)	100	95	-5.0%
Tongaat	15	10.7	-28.7%
Hazelmere	60	59	-1.7%

Table B-2: Target vs Modelled SIVs (Excluding External Demands)

WTW Bulk Supply Area	SIV - without external demands		
	Target	Modelled	Percentage Difference
Amanzimtoti	57.74	58.74	1.7%
Wiggins	198.6	179	-9.9%
Durban Heights	500	525	5.0%
Umlaas (Upper Mgeni)	100	95	-5.0%
Tongaat	15	10.7	-28.7%
Hazelmere	40.844	39.844	-2.4%

It can be seen the percentage differences between the target and modelled values are not significant – with the exception of the Tongaat supply area. While the modelled Tongaat SIV is significantly lower than the target value, compared to the other WTW supply areas, there was limited information against which to validate the Tongaat SIV. As such, the modelled value has been accepted.

Calibration of Wastewater Volumes

The eThekwini WSDP (EWS, 2011) included then-current average dry weather flows for each wastewater treatment works, as well as projected inflows up to 2030 for some key facilities where development was expected to take place. Given the drought which occurred a few years after completion of the WSDP and has had lasting effect, it was deemed unsuitable to project the 2011/12 average inflows to the simulation start time. Modelled values have instead been compared to the 2011/12 values, and where available, estimates of inflows as at 2020.

Table B-3: Target vs Modelled WWTW Inflows

WWTW	Actual (2012)	Estimated (2020)	Model
Amanzimtoti	22		30.77
Cato Ridge	0.5		0.7748

WWTW	Actual (2012)	Estimated (2020)	Model
Central	66		68
Dassenhoek	2		3.558
Fredville	2		1.03
Genazzano	1.5	2.745	2.557
Hammarsdale	7		5.245
Hillcrest	0.7		1.491
Isipingo	12		14.56
Kingsburgh	5		10.66
Kwamashu	67	75.5	61.51
Kwandengezi	1		2.572
Magabeni	0.25		0.2107
Mpumalanga	2		6.748
New Germany	1.5		6.154
None			0
Northern	54	60	75.6
Phoenix	24	40	34.61
South / Chatsworth	135		154
Tongaat	7	17.5	10.51
Umbilo	14		12.98
Umdloti	1.5	2.745	2.731
Umhlatuzana	10.5		14.43
Umkhomazi	1.5		1.264
Verulam	6	10.98	5.47

While there is large variance between some of the target and modelled values for individual treatment works, considering the cumulative result for all facilities, the modelled flow is 2.2% higher than the target flows.

Discrepancies between modelled results and the target values, especially for smaller drainage areas, may be the result of the population distribution method adopted and potential inaccuracies, especially at the boundaries of zones. The same is less noticeable for the bulk supply areas for water supply, as these areas are much larger. Other reasons for discrepancies may be due to any one or a combination of the following (*inter alia*) occurring in the sewer networks, resulting in average inflows which are different to what is expected or may be modelled: sewer blockages; sewer pumpstation breakdowns and spillages to the environment; higher or lower levels of groundwater infiltrating sewers; and illegal or informal connections to sewer pipelines.

Given the limitation (recent) available information against which to calibrate model, the small percentage difference for the cumulative wastewater flows for the study area, and the physical conditions of the networks which are unknown, the modelled values were accepted as reasonable for use in this study.

Calibration of AWBM Volumes

Figure B-3 and Figure B-4 illustrate the results of the calibration of the AWBM sub-model, where the calibration parameter is the average surface store capacity.

Given the mismatch in timescales between the AWBM sub-model (daily) and the naturalised flows from the WR2012 Study (monthly) against which the sub-model was calibrated, mean values for cumulative runoff were obtained through running a Monte Carlo analysis over a five-year period. Probabilistic inputs included the stochastic generated rainfall sequences (AWBM input) and randomised start points in the naturalised runoff timeseries (“actual runoff” input) data.

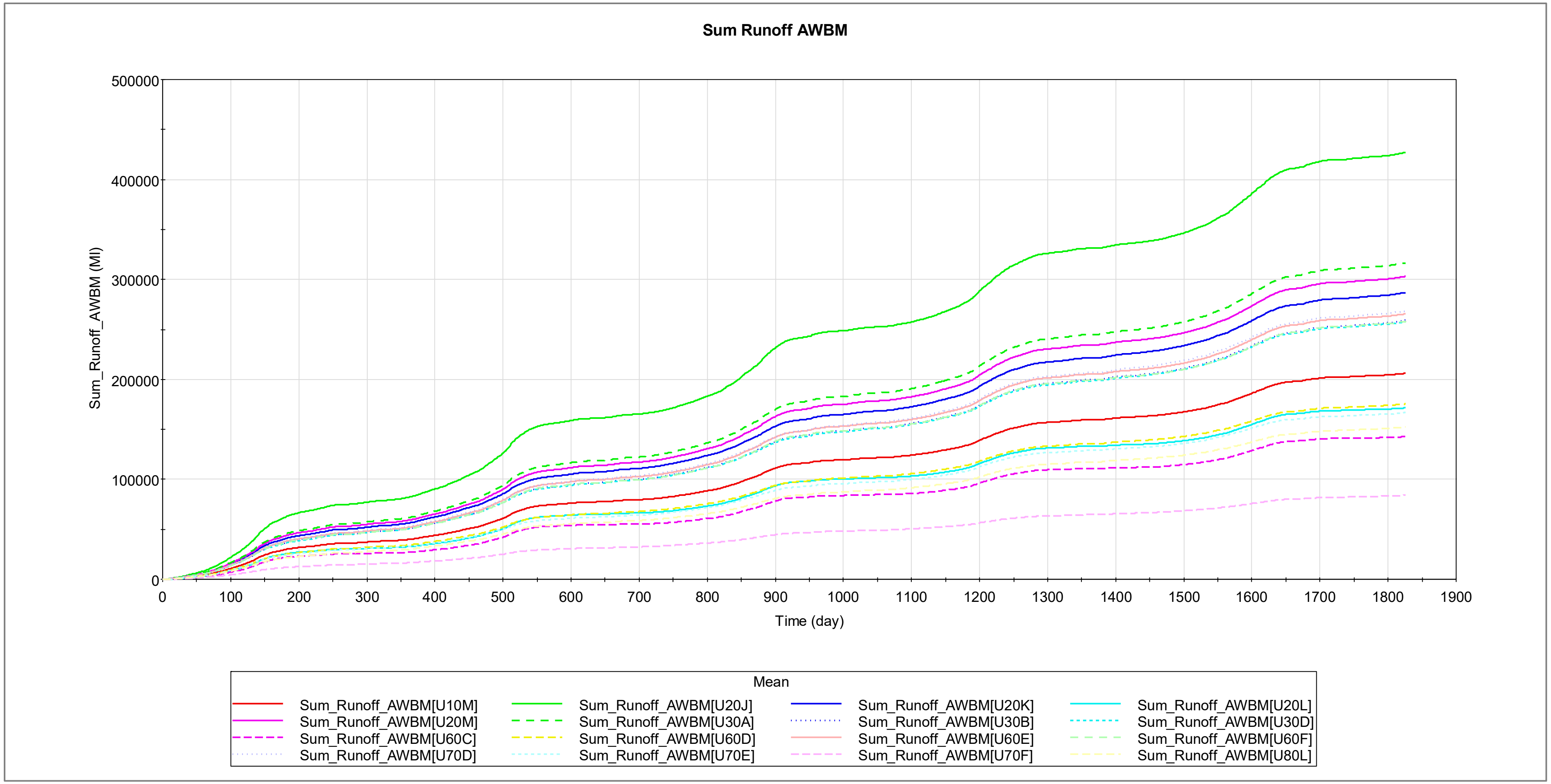


Figure B-3: Mean Simulated Cumulative Runoff (5 Year Period)

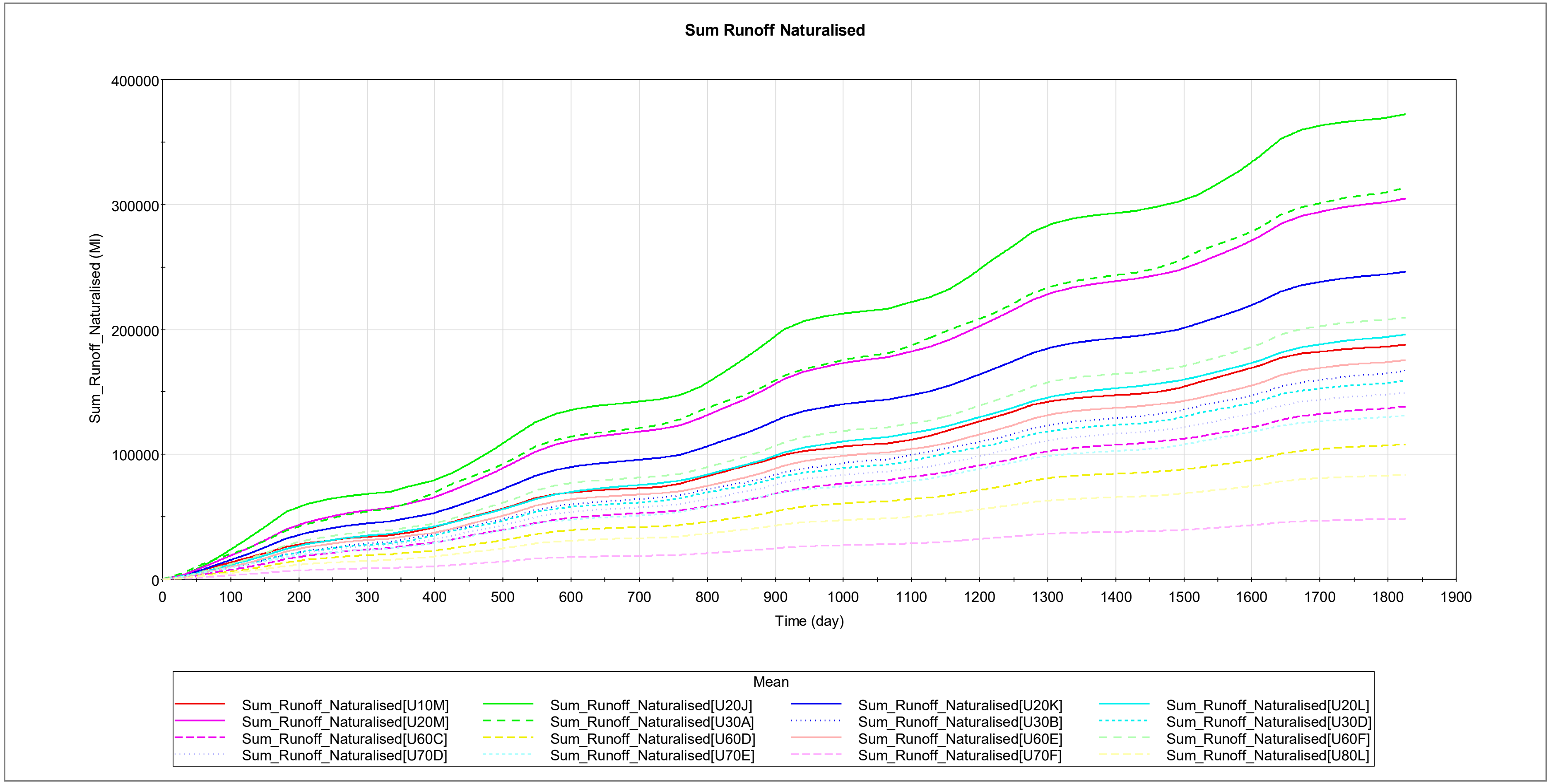


Figure B-4: Mean Cumulative Runoff of Naturalised Flows (WR2012) (5 Year Period)

Appendix C: Additional Model Results

Investigation of “Load Shift” onto Upper Mgeni System

In that the transfer of demand from the Lower Mgeni to the Upper Mgeni WSS may occur before the implementation if the uMWP, different initial load shift volumes were tested to better understand the impact on the Mgeni WSS. These volumes were tested for the baseline scenario, as this is the current trajectory on which the system would track (i.e. without any interventions).

Consistent with the commentary in the Umgeni Water Masterplan (UW, 2019), the full load shift volume of 250 Ml/d cannot be accommodated prior to uMWP. The treatment capacity of the Upper Mgeni system would be exceeded, and result in the need to restrict supply to areas upstream of eThekwini as well as within eThekwini. Midmar Dam storage is negatively impacted until such time uMWP is commissioned.

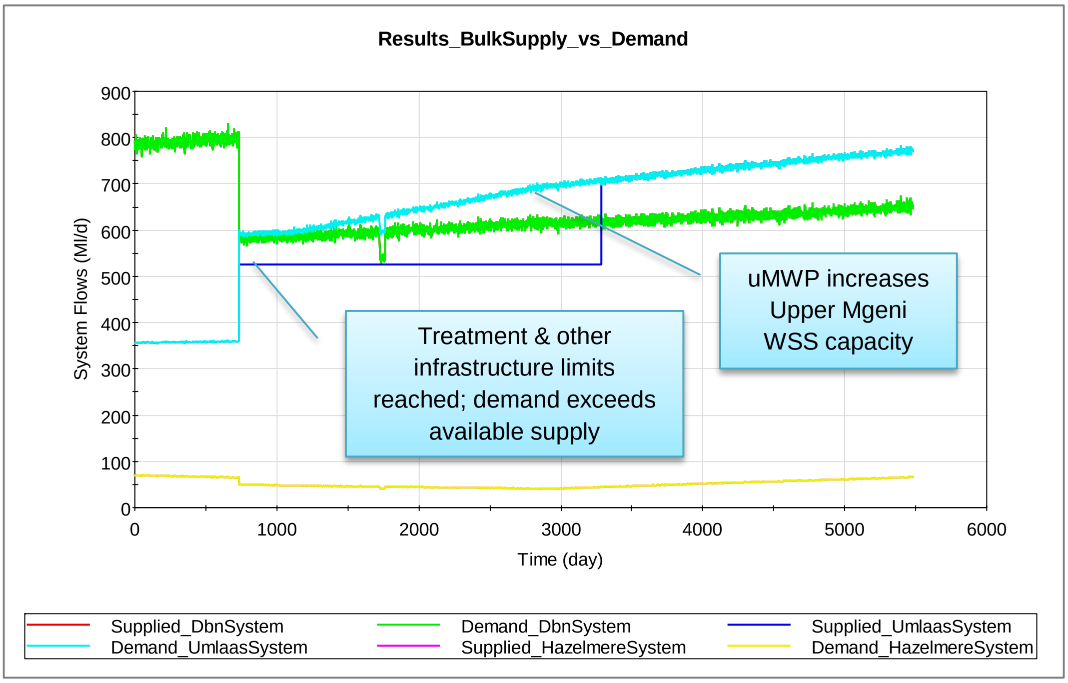


Figure C-1: Demand vs Availability for Water Supply Systems: 100% Load Shift before uMWP

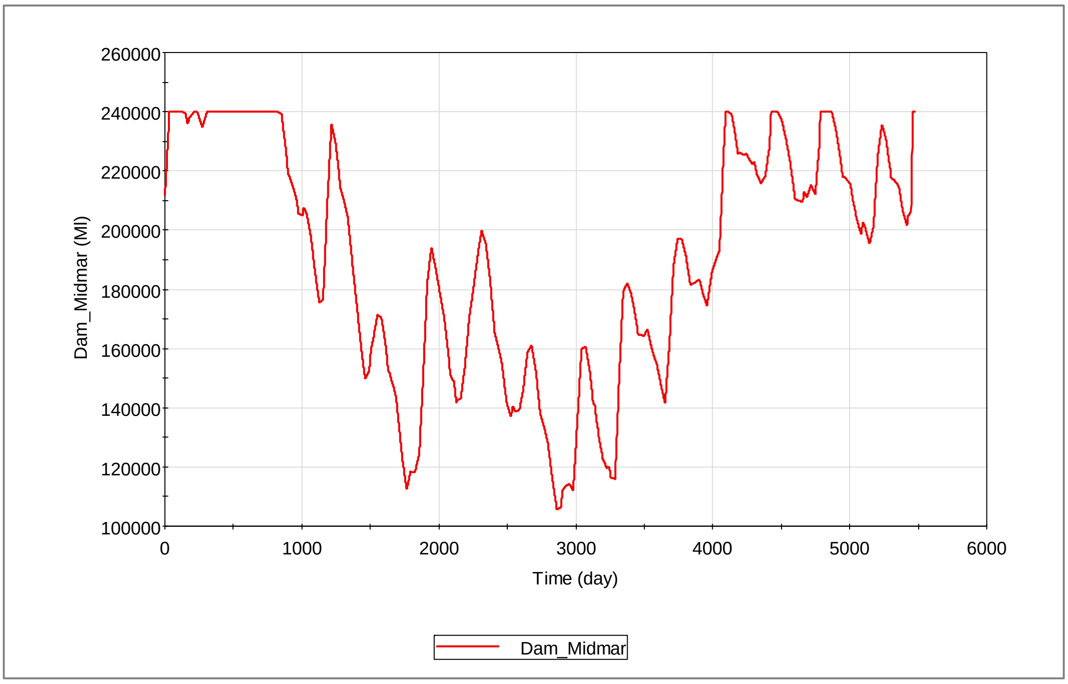


Figure C-2: Midmar Dam Storage: 100% Load Shift before uMWP

A 70% load shift prior to implementation of the uMWP sees improvement in the storage volumes of Midmar Dam, but the treatment and infrastructure capacity exceeded well in advance of uMWP.

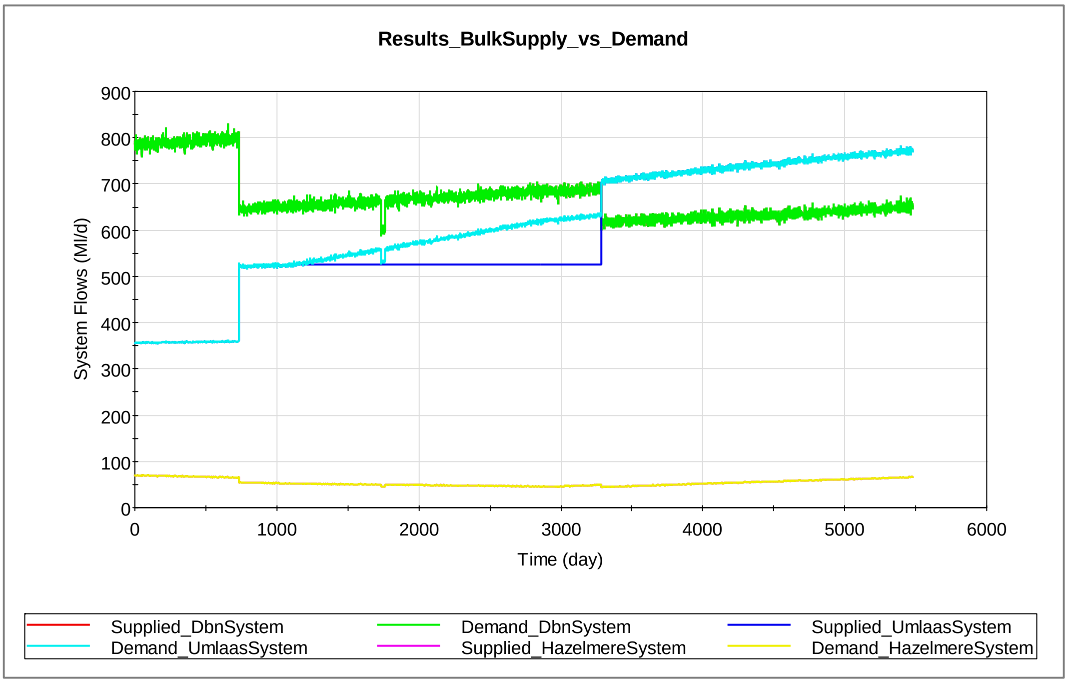


Figure C-3: Demand vs Availability for Water Supply Systems: 70% Load Shift before uMWP

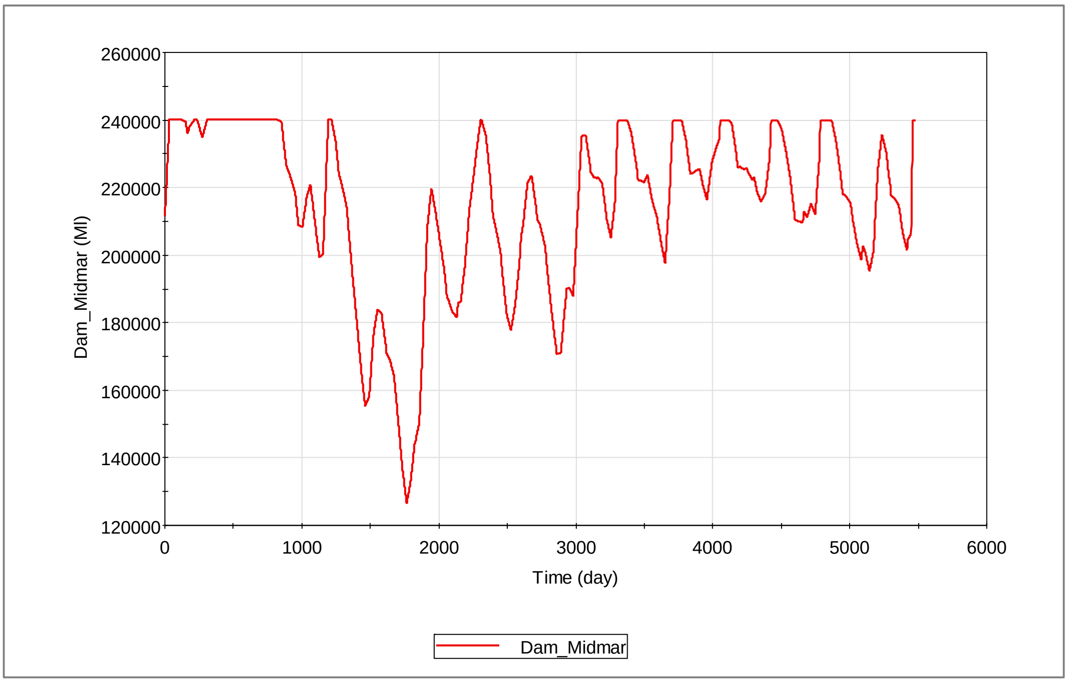


Figure C-4: Midmar Dam Storage: 70% Load Shift before uMWP

A 30% initial load shift, equivalent to some 75 Ml/d – which is within allowable limits stated in the Umgeni Water Masterplan (UW, 2019) – results in treatment capacity limits being reached shortly before uMWP is commissioned. This lower load shift has a significant positive impact on Midmar Dam storage levels.

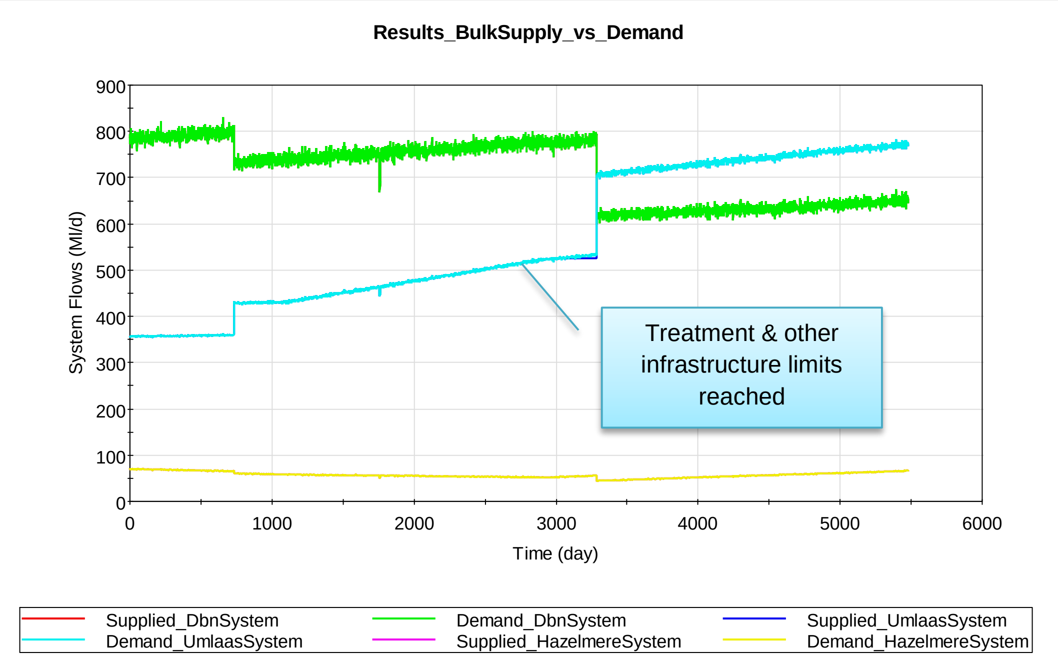


Figure C-5: Demand vs Availability for Water Supply Systems: 30% Load Shift before uMWP

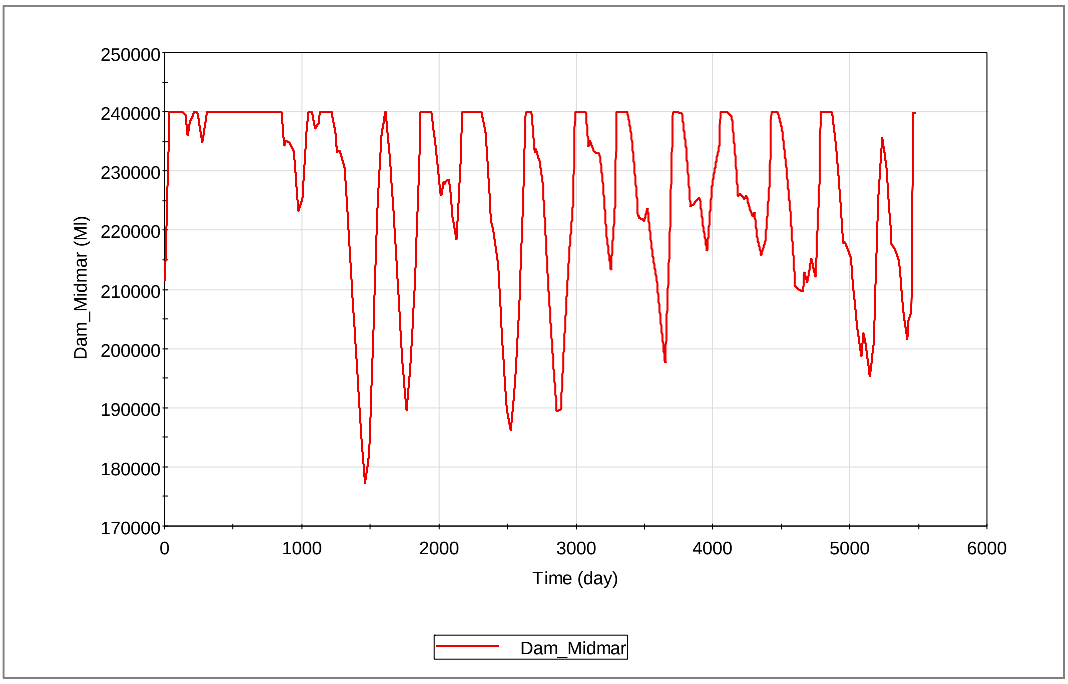


Figure C-6: Midmar Dam Storage: 30% Load Shift before uMWP

If there is no load shift prior to uMWP, the treatment capacities of neither the Upper Mgeni nor the Lower Mgeni systems are reached. There is some impact on Midmar Dam storage – which reaches a low of some 81% (versus 75% for the 30% load shift scenario).

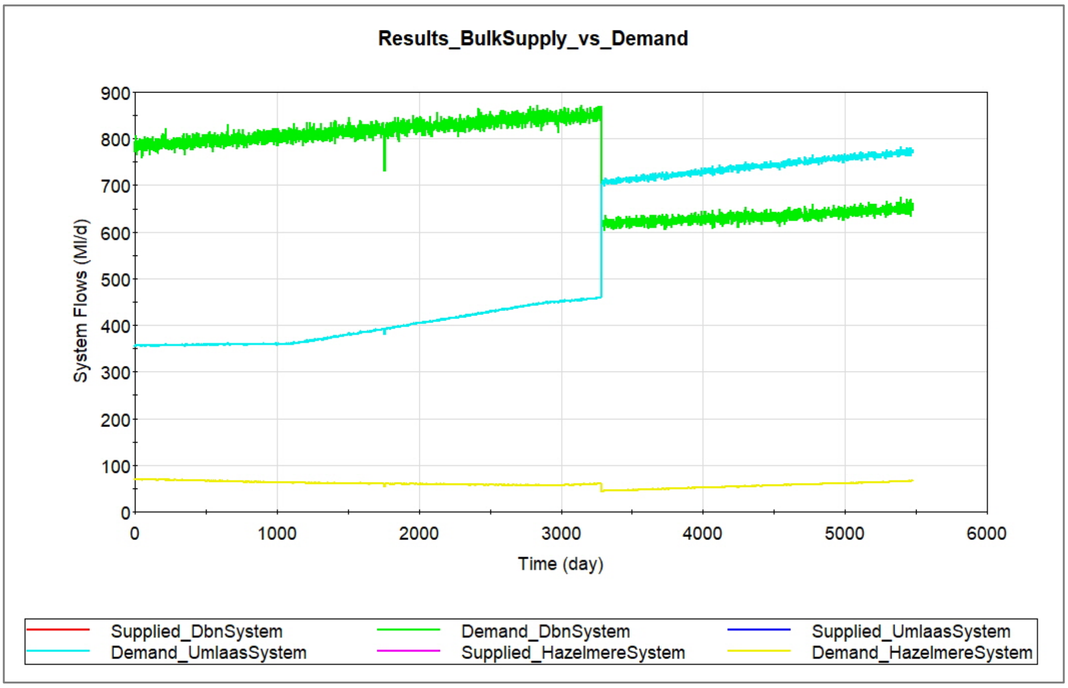


Figure C-7: Demand vs Availability for Water Supply Systems: 0% Load Shift before uMWP

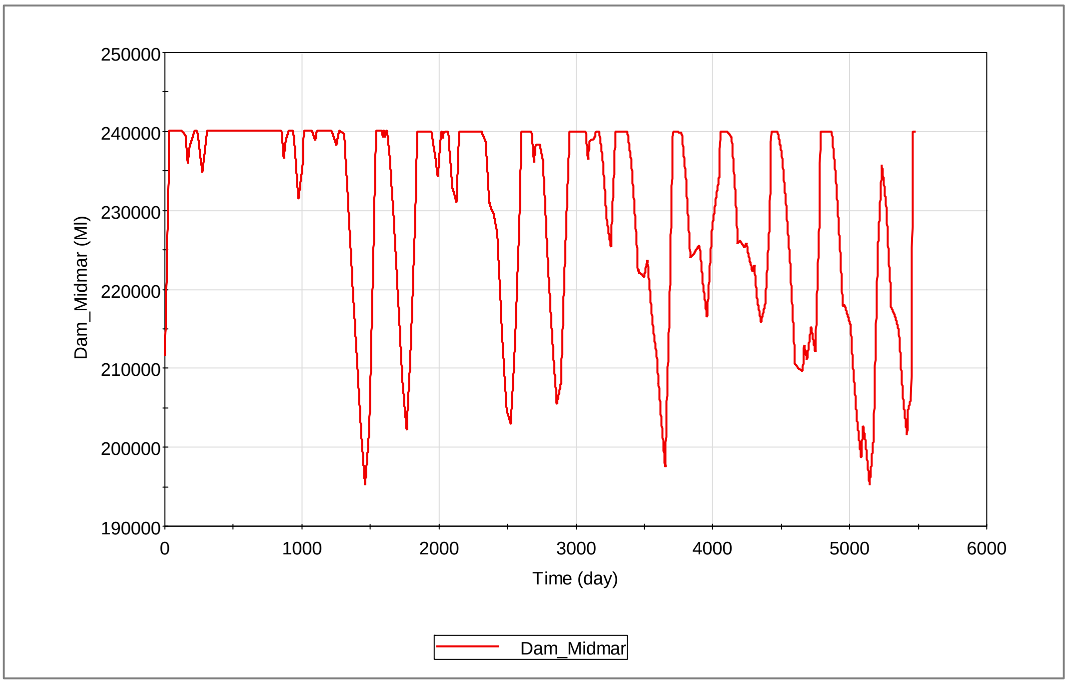
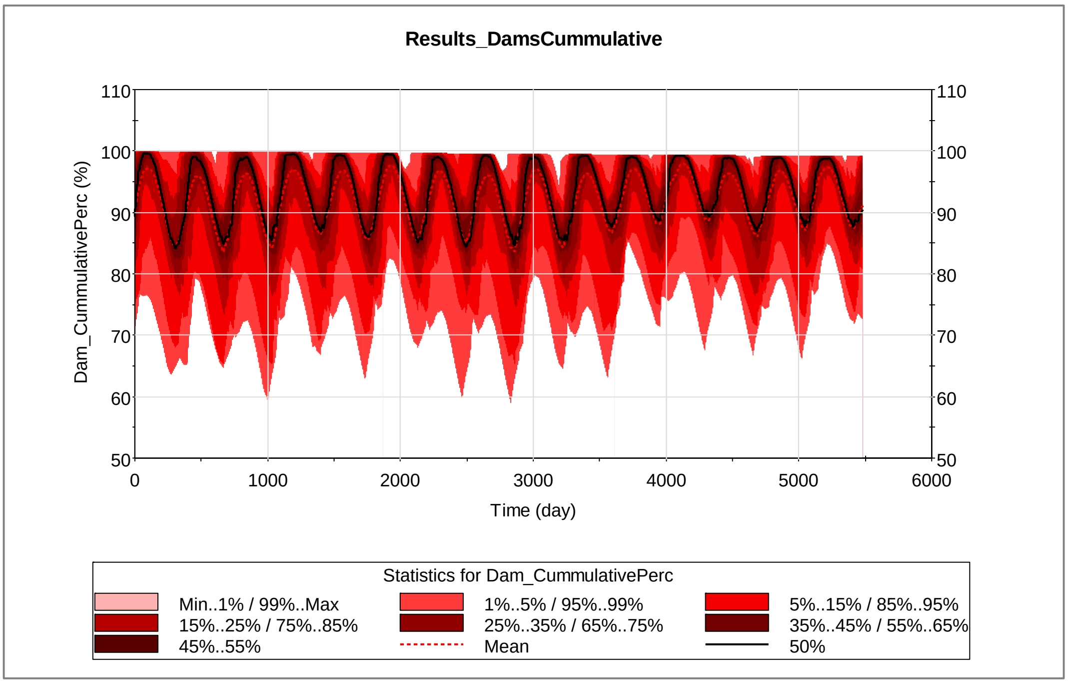
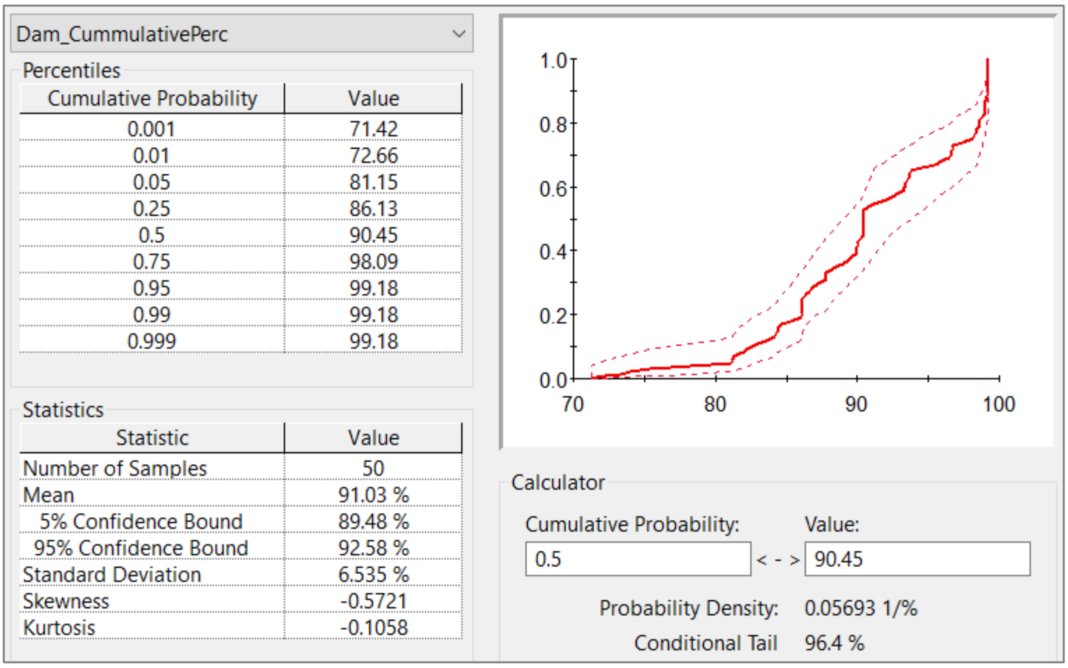


Figure C-8: Midmar Dam Storage: 0% Load Shift before uMWP

A Monte Carlo analysis for the 30% initial load shift option was run such that it could be compared to the option where no load shift is implemented prior to uMWP. The cumulative dam storage is largely similar – the 50th percentiles being 90.45% storage and 90.66% storage for the options of 30% initial load shift and 0% initial load shift respectively.





Percentiles

Cumulative Probability	Value
0.001	71.42
0.01	72.66
0.05	81.15
0.25	86.13
0.5	90.45
0.75	98.09
0.95	99.18
0.99	99.18
0.999	99.18

Statistics

Statistic	Value
Number of Samples	50
Mean	91.03 %
5% Confidence Bound	89.48 %
95% Confidence Bound	92.58 %
Standard Deviation	6.535 %
Skewness	-0.5721
Kurtosis	-0.1058

Calculator

Cumulative Probability: 0.5 < - > Value: 90.45

Probability Density: 0.05693 1/%

Conditional Tail 96.4 %

Figure C-9: Monte Carlo Analysis of Cumulative Dam Storage: 30% Load Shift before uMWP

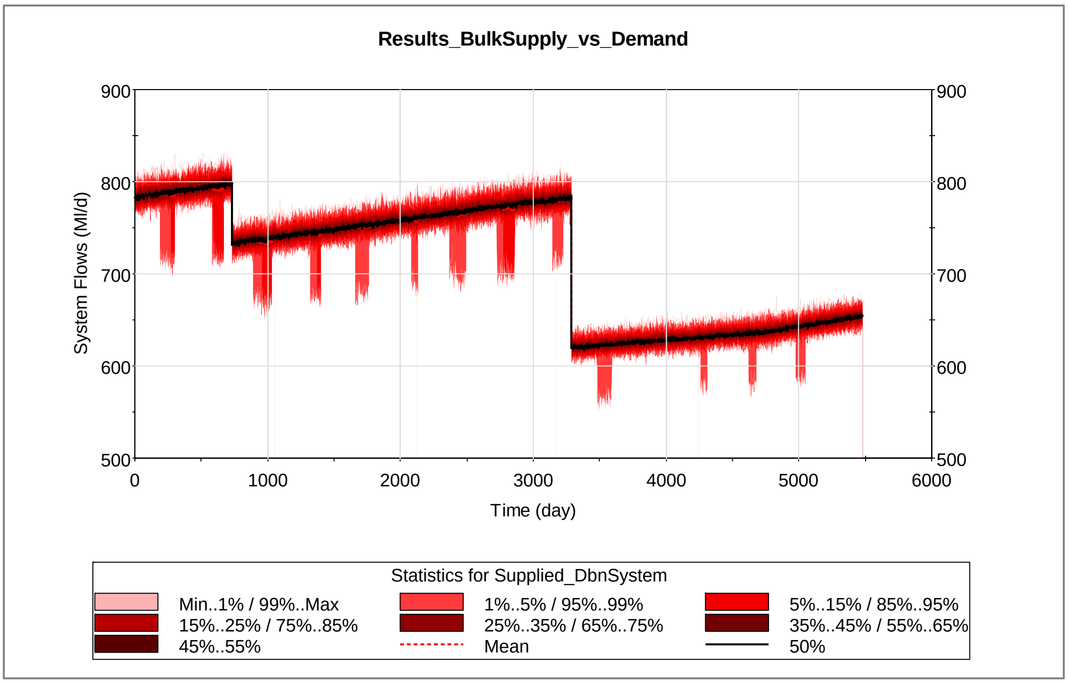


Figure C-10: Monte Carlo Analysis of Demand on Lower Mgeni System: 30% Load Shift before uMWP

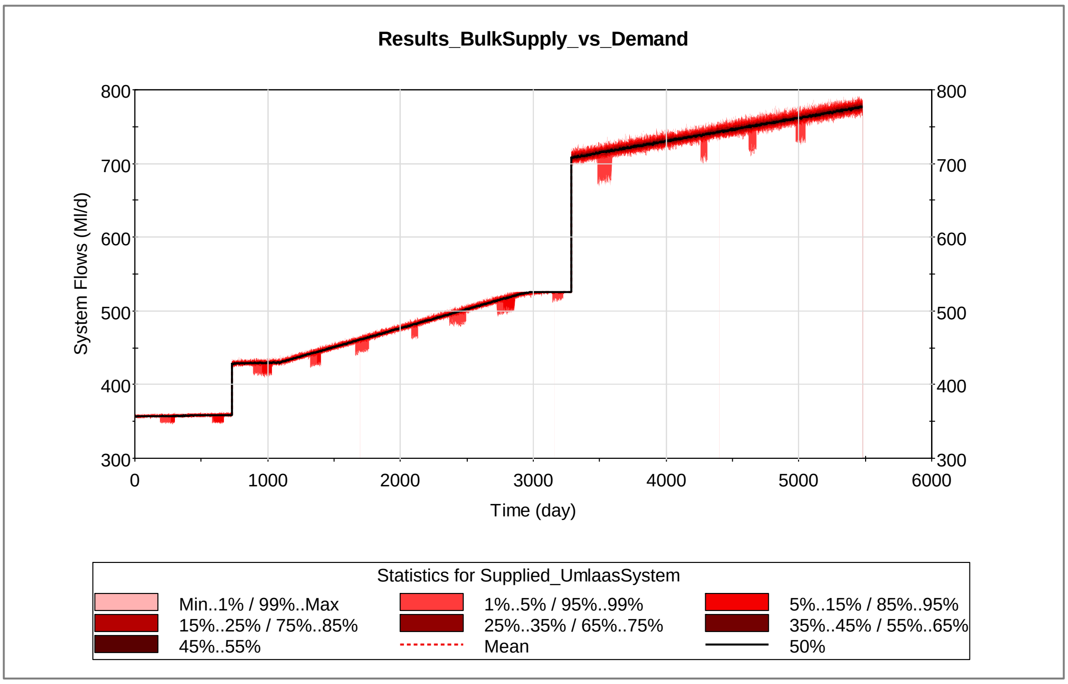


Figure C-11: Monte Carlo Analysis of Demand on Upper Mgeni System: 30% Load Shift before uMWP

If there is to be allowance for a load shift prior to the uMWP, it would appear 30% of the total volume would be optimal, though it does mean the demands in the Upper Mgeni system will require careful monitoring and management to prevent demand exceeding resource availability prior to uMWP. One of the requirements of the initial load shift, as per the Umgeni Water Masterplan (UW, 2019), reinforces this concern – the supply to the Umlaas Road sub-system (i.e. eThekwini) will likely have to be reduced over time to allow for planned growth in the areas upstream, until such time the uMWP is implemented. In that the operation of the Lower Mgeni system does not appear compromised by adopting zero load shift prior to uMWP, this is the system state adopted for the analysis of the respective interventions.

Flow Time Series Outputs for Key Scenarios

Baseline Scenario

Below are presented a series of graphs pertaining to the baseline scenario.

Figure C-12 illustrates the total projected population within eThekwini municipality and the resulting growth in total base demand (i.e. excludes real and apparent losses) across the municipality.

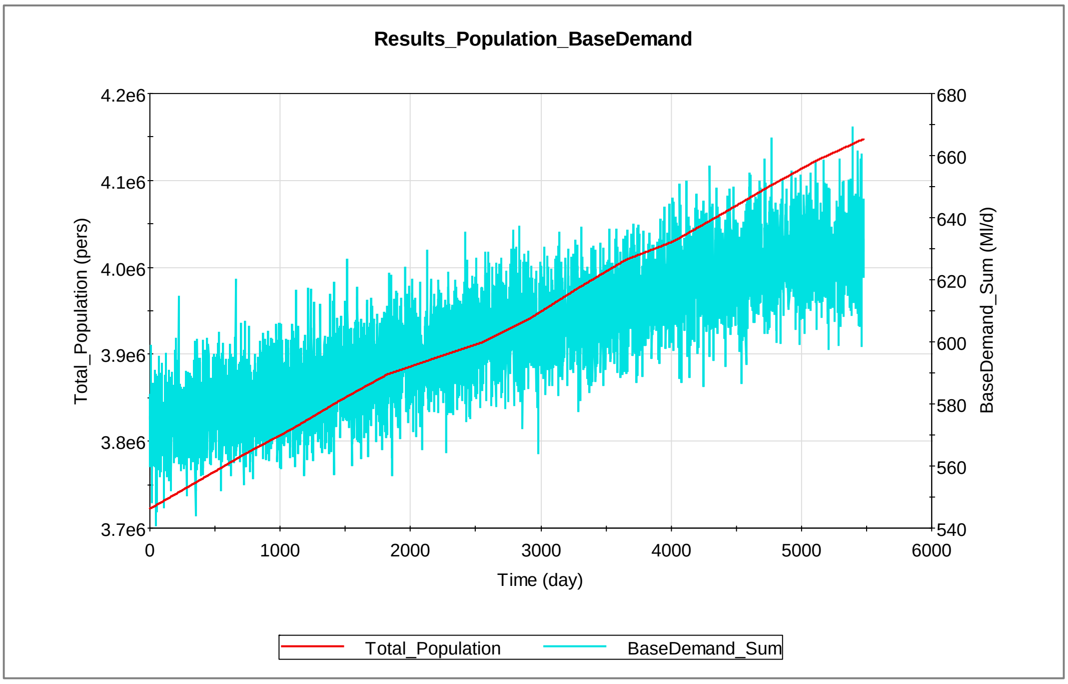


Figure C-12: Total Population for eThekwini

Figure C-13 is the resulting system input volume per defined bulk supply area, where the real and apparent losses have been included. The modelled demands are specifically for the bulk supply areas within eThekwini.

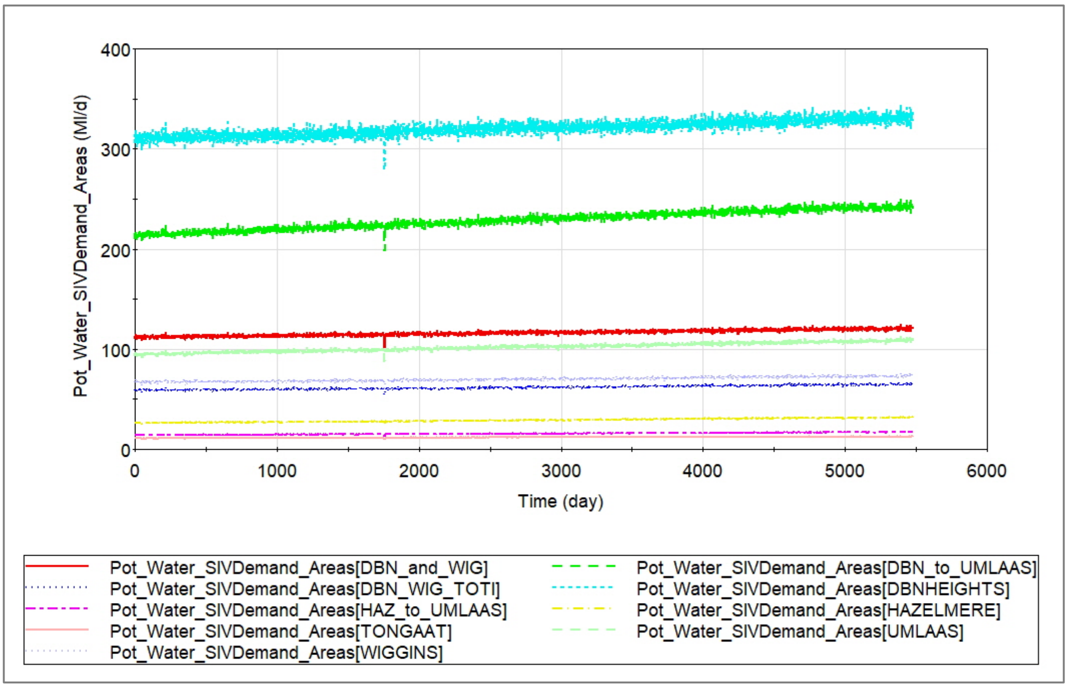
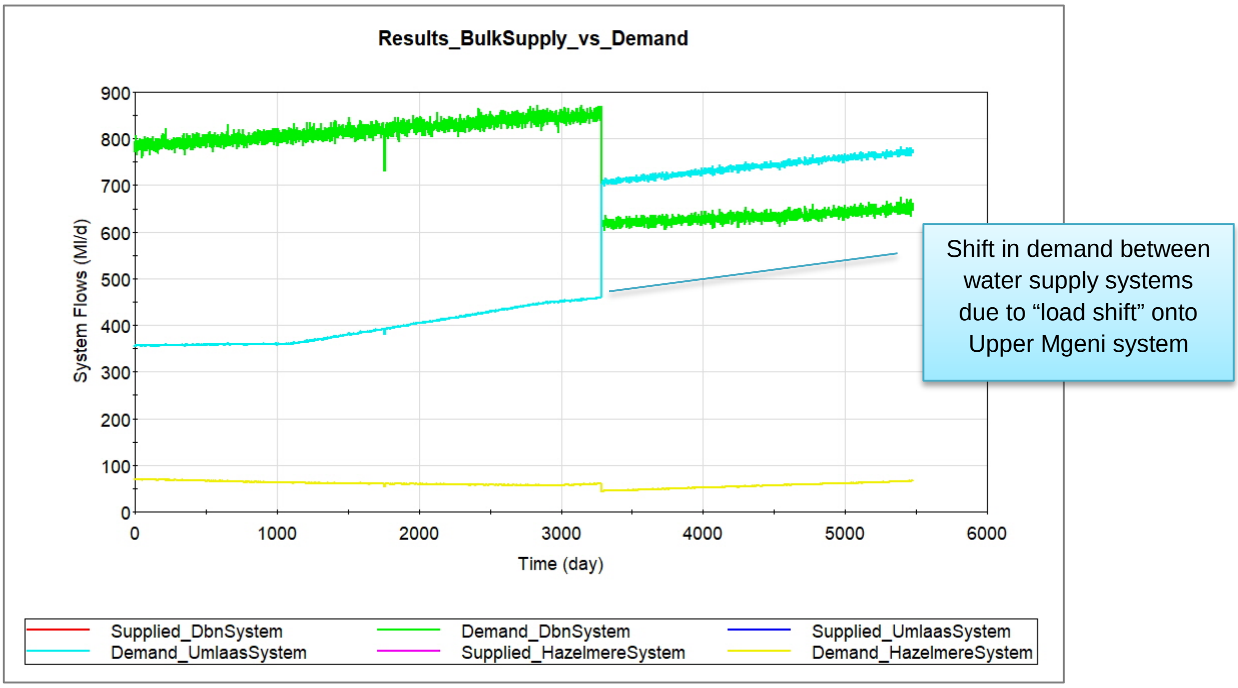


Figure C-13: Demand on Potable System per Bulk Supply Area (Baseline Scenario)

Figure C-7 aggregates the demand and available supply per major system – i.e. Upper Mgeni, Lower Mgeni, and the North Coast (Hazelmere / Tongaat).



Shift in demand between water supply systems due to “load shift” onto Upper Mgeni system

Figure C-14: Demand vs Availability for Water Supply Systems (Baseline Scenario)

Figure C-15 and Figure C-16 show the volumes of wastewater produced and the wastewater collected and conveyed to a WWTW facility (respectively). Figure C-17 illustrates the amount by which the daily treatment capacity is exceeded. This does not necessarily correspond to a wastewater facility allowing untreated effluent to overflow to the environment – facilities are generally designed to be able to absorb higher hydraulic loading to allow for within-day peak flows – but consistently exceeding the treatment capacity of a WWTW may be detrimental to the WWTW's ability to meet effluent quality standards.

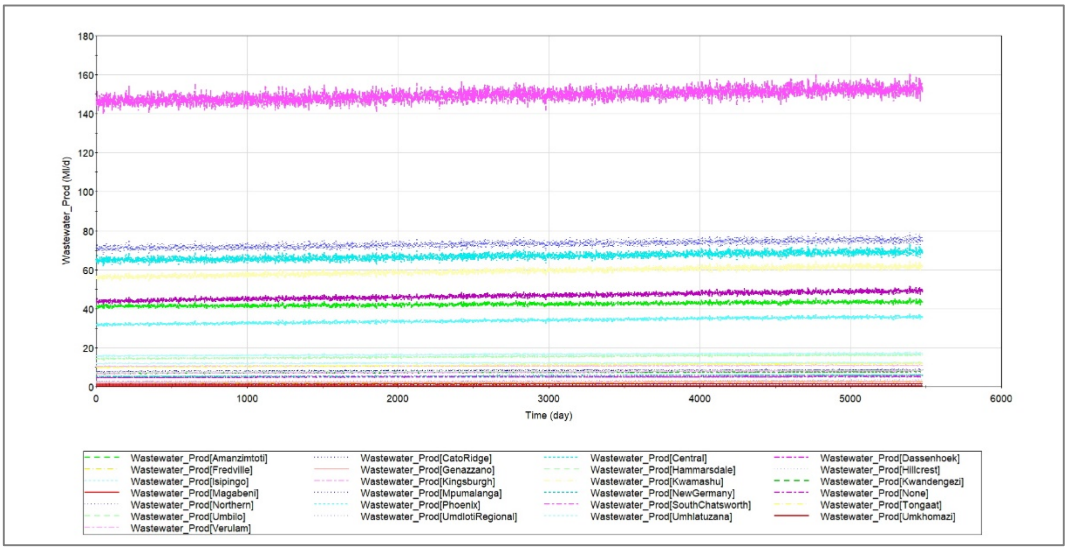


Figure C-15: Wastewater Produced per Drainage Area (Baseline Scenario)

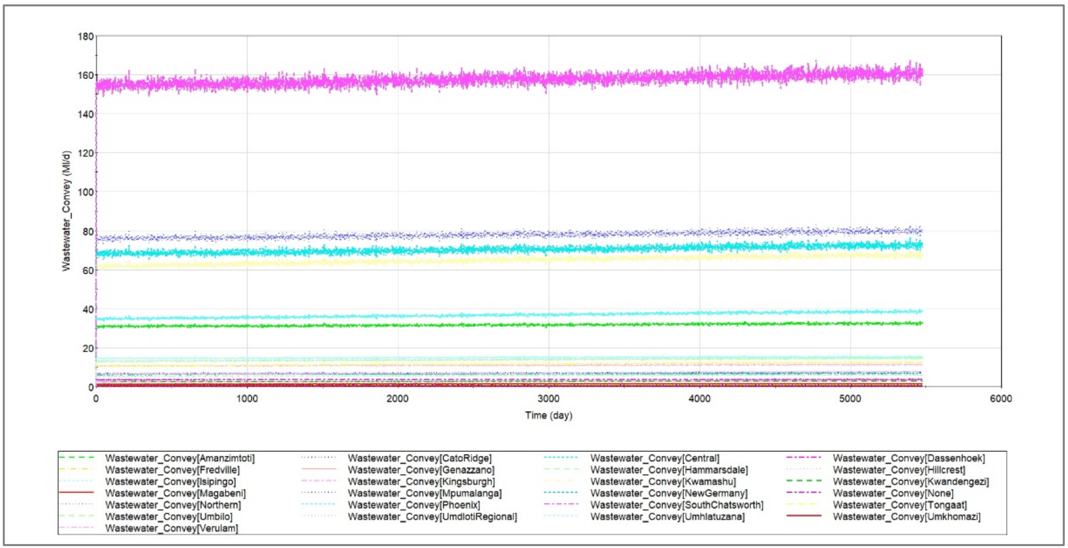


Figure C-16: Wastewater Inflow per Drainage Area (Baseline Scenario)

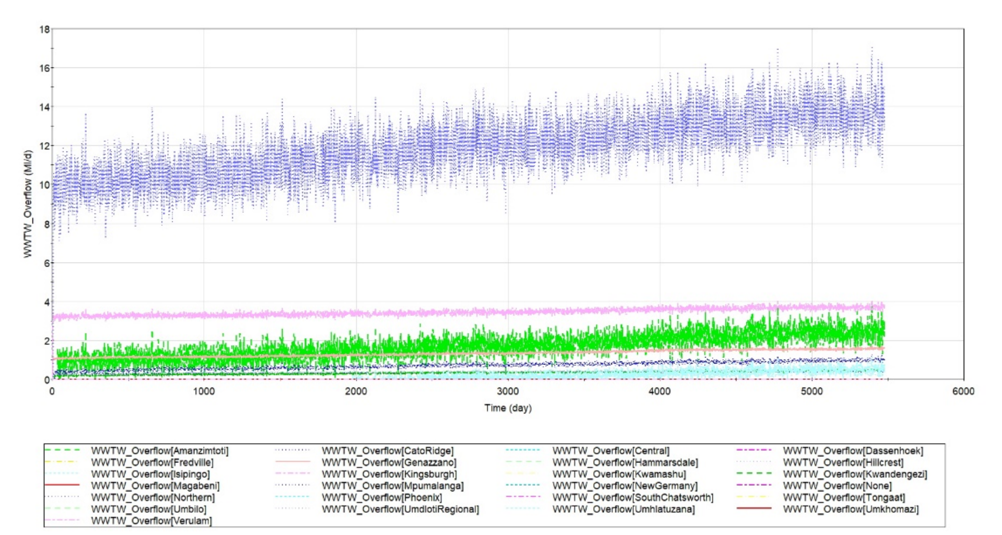


Figure C-17: Wastewater Exceedance of Treatment Capacity per Drainage Areas

System and Consumer WCWDM

Figure C-18 shows the real losses per bulk supply area, as adjusted by loss reduction measures to reach the pre-defined targets. Figure C-19 shows the reduction in base demand (i.e. BMC) as a result of consumer-focussed WCWDM interventions. The result, as shown in Figure C-20, is a levelling-off, and for some areas a decrease, in system input volume.

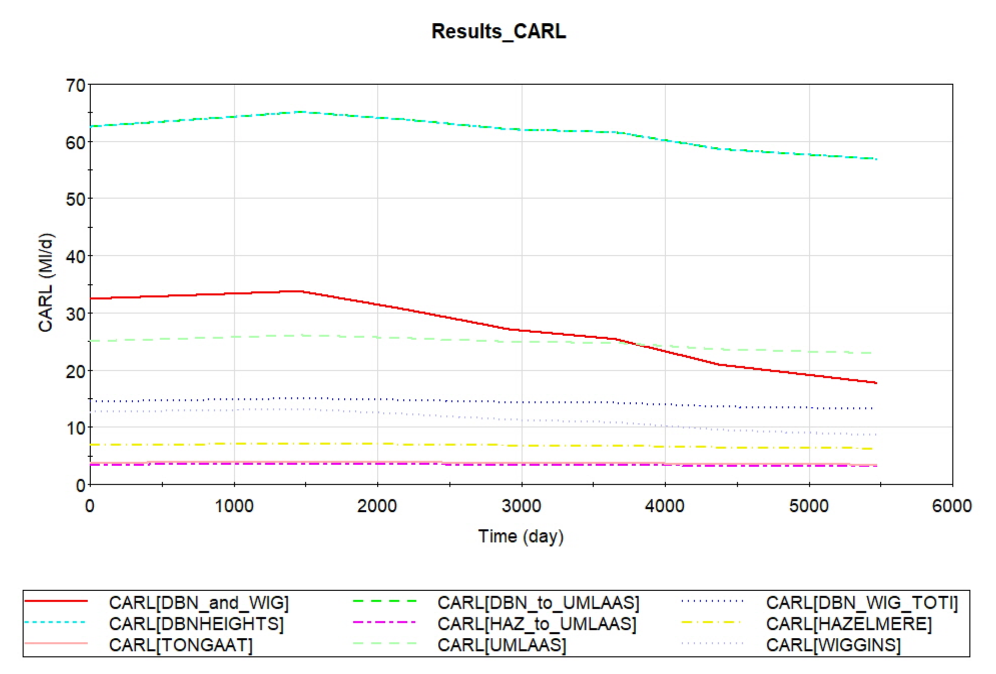


Figure C-18: Current Annual Real Losses per Bulk Supply Area

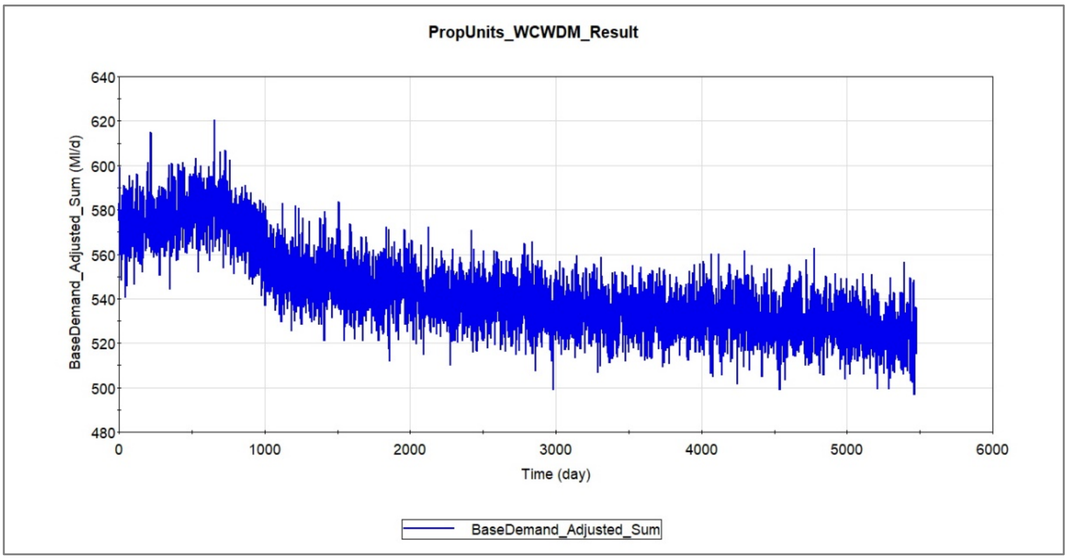


Figure C-19: Consumption Adjusted by Consumer WCWDM Measures

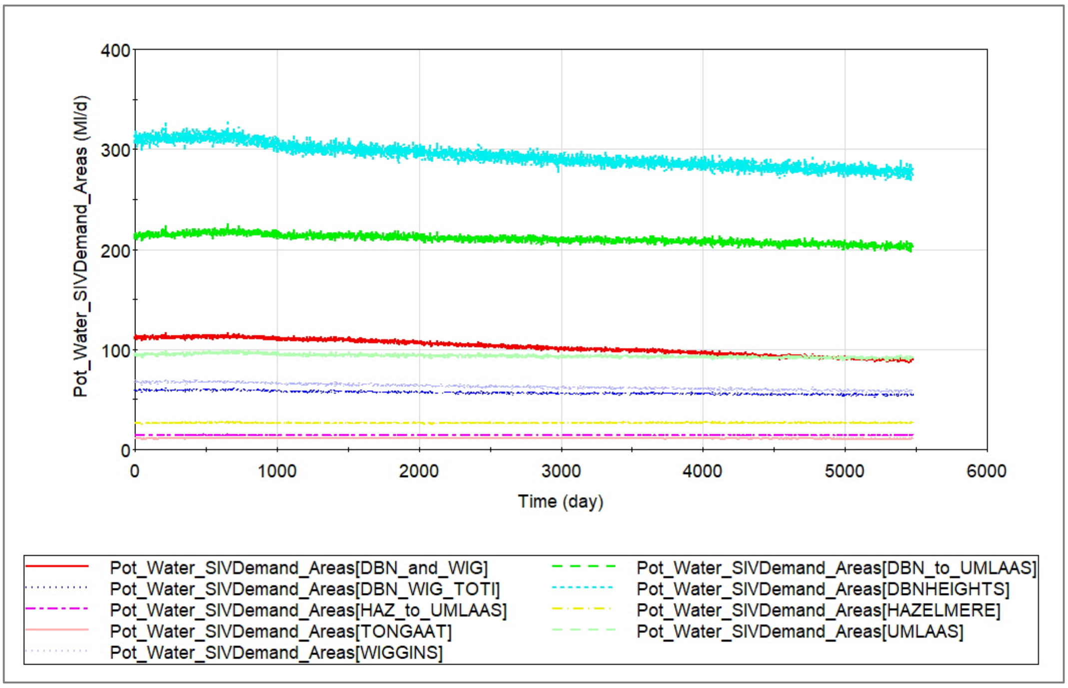


Figure C-20: Demand on Potable System per Bulk Supply Area (WCWDM Scenario)

Figure C-21 shows the resulting demand and available supply per major water supply system.

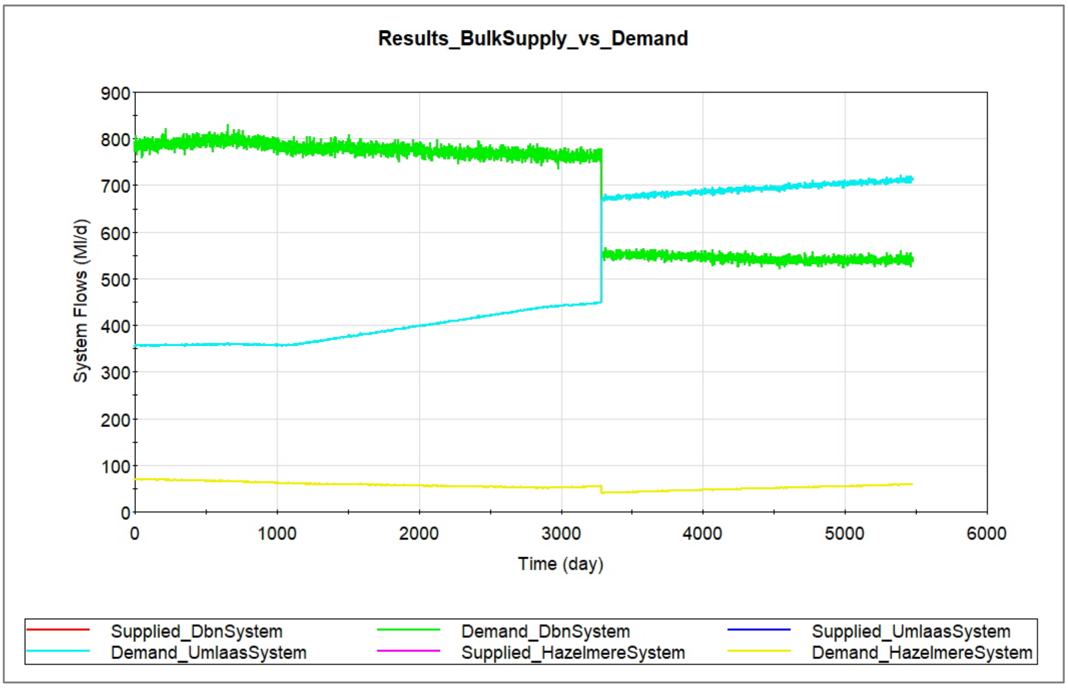


Figure C-21: Demand vs Availability for Water Supply Systems (WCWDM Scenario)

As a downstream effect of consumer-focussed WCWDM measures, the volume of wastewater produced (Figure C-22) and influent volumes to WWTW's (Figure C-23) is reduced.

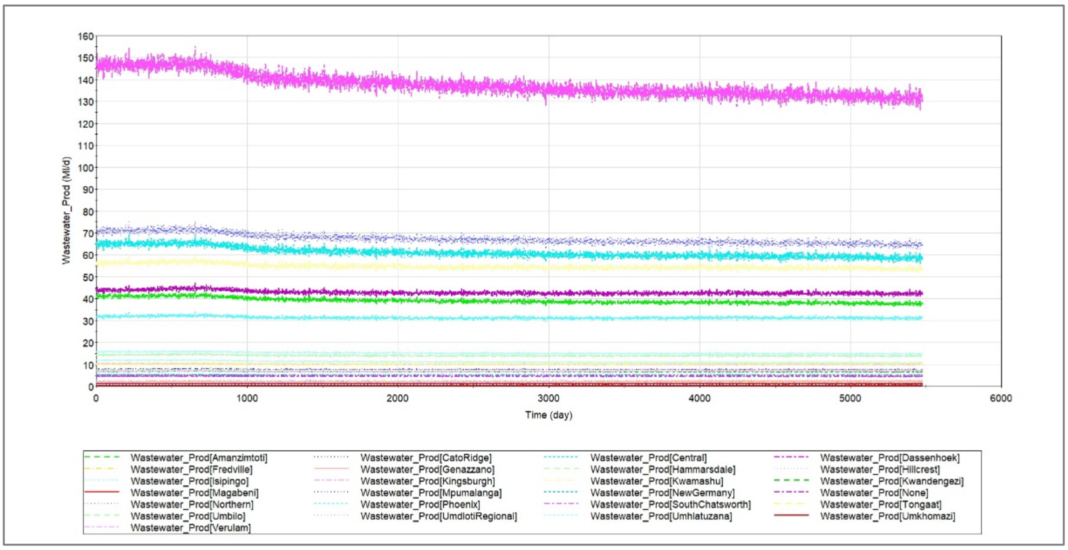


Figure C-22: Wastewater Produced per Drainage Area (WCWDM Scenario)

Figure C-23: Wastewater Inflow per Drainage Area (WCWDM Scenario)

Rainwater Harvesting with System WCWDM

Figure C-24 shows the cumulative tank outflows as a result of the available volume and the demand (as determined by the defined end-uses).

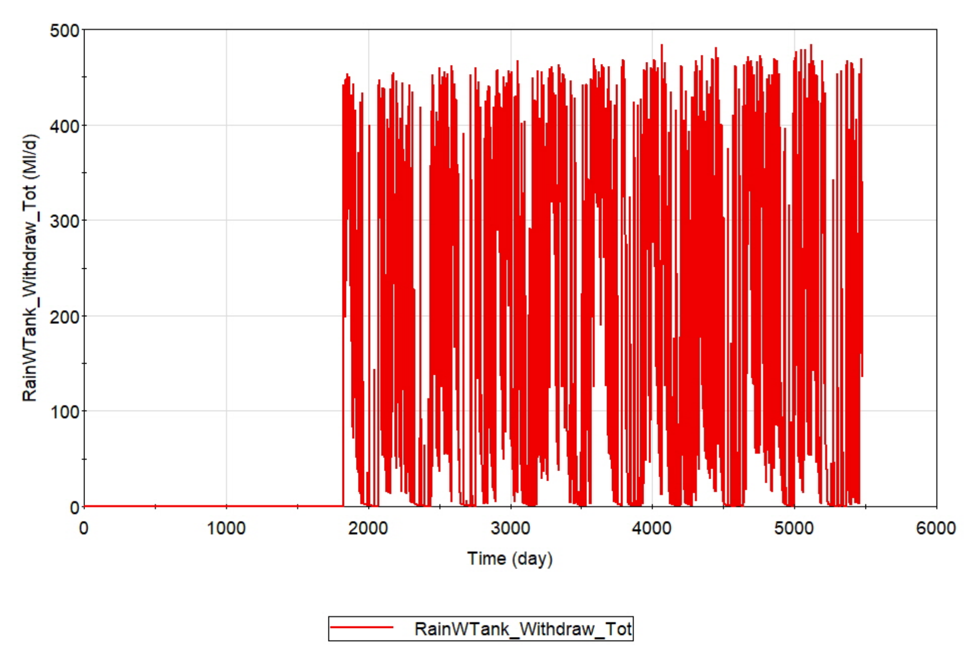


Figure C-24: Cumulative Outflows from Rainwater Tanks

The ability of the rainwater tanks to cumulatively (i.e. for the study area) attenuate rainfall is illustrated in Figure C-25, where the roof runoff represents the full volume which would either infiltrate the surrounding ground, or eventually reach urban watercourses should there be no rainwater tanks installed. The tank overflow volume is the reduced volume either infiltrating the surrounding ground, or eventually reaching urban watercourses when rainwater tanks are introduced.

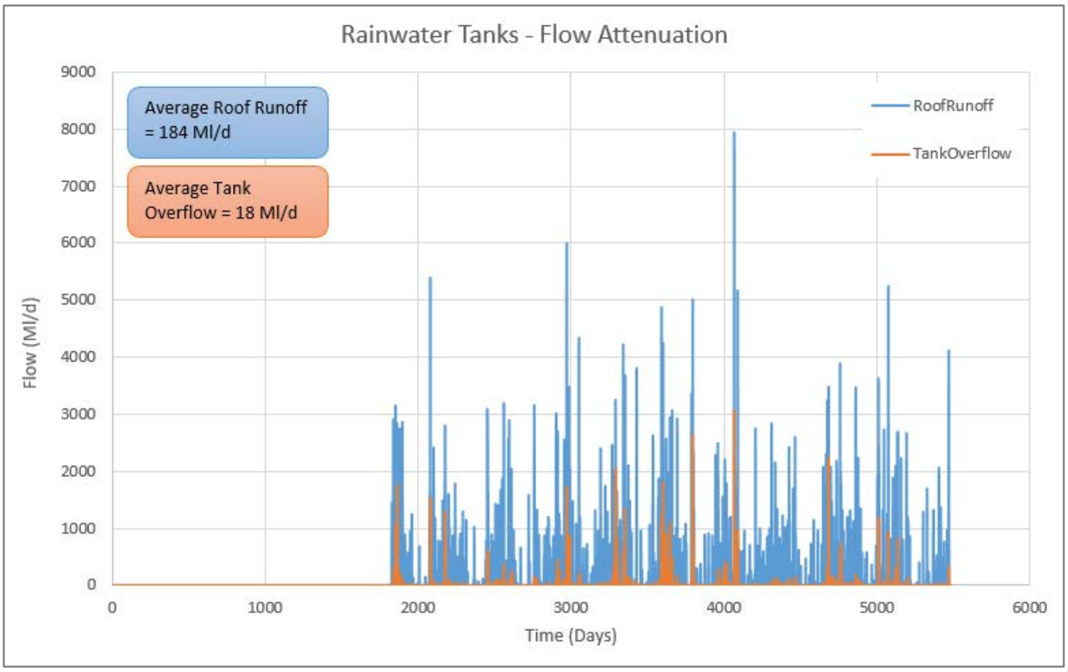


Figure C-25: Roof Runoff versus Rainwater Tank Overflows

With regard to impact on the overall water supply system, Figure C-26 shows the total demand per area, which fluctuates with rainwater tank usage. Figure C-27 illustrates the resulting demand versus available supply for the major supply systems.

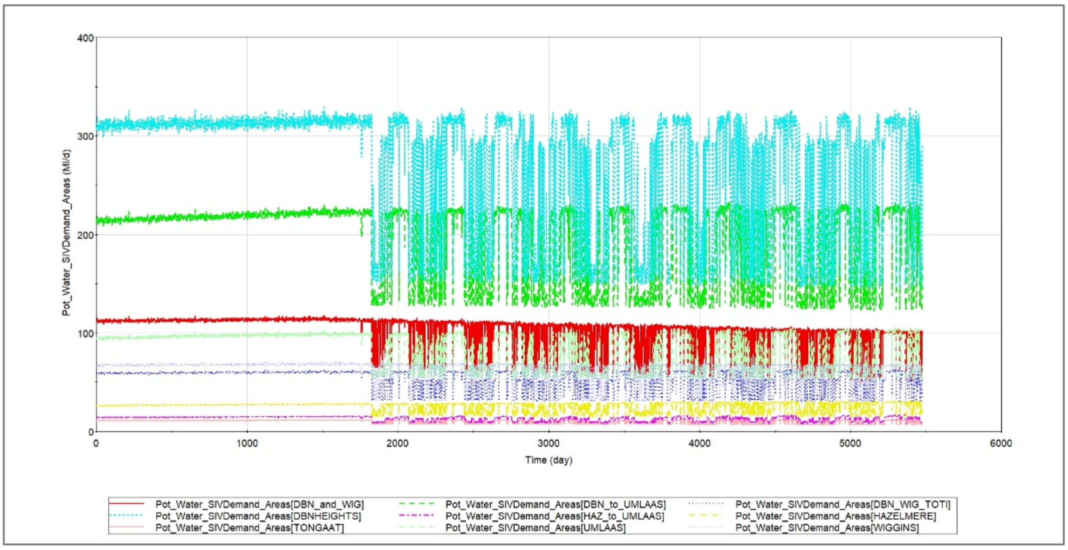


Figure C-26: Demand on Potable System per Bulk Supply Area (Rainwater Harvesting Scenario)

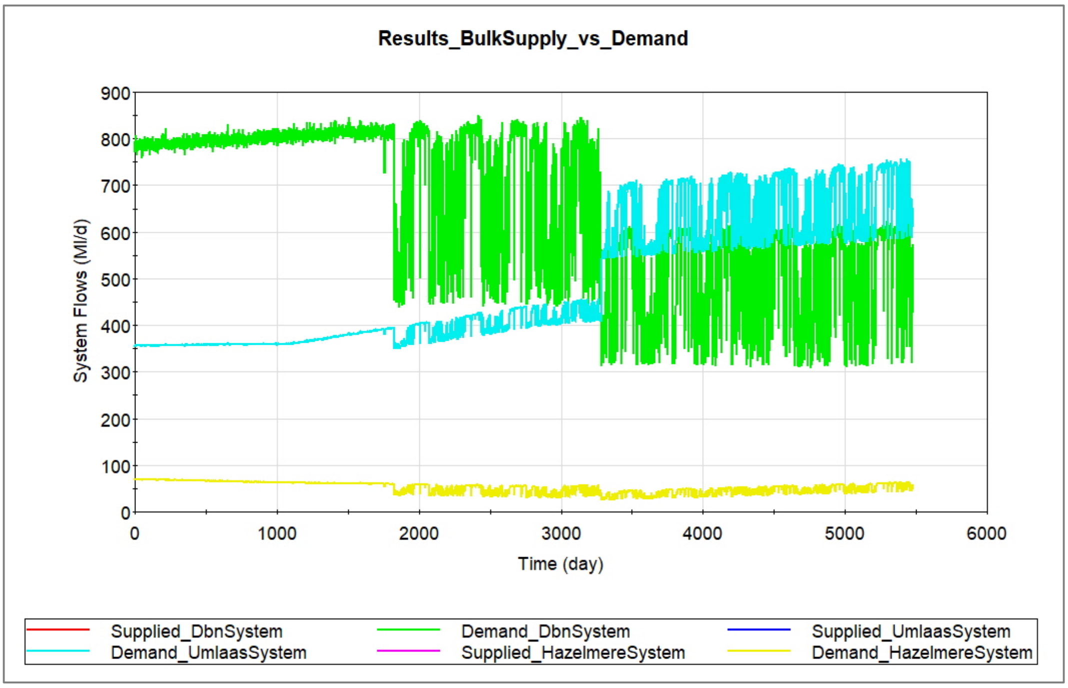


Figure C-27: Demand vs Availability for Water Supply Systems (Rainwater Harvesting Scenario)

Rainwater harvesting does not have any impact on the volumes of wastewater generated.

Greywater Reuse and WCWDM

Figure C-127 and Figure C-130 show the impact of these interventions on the total demand per bulk supply area and the demand versus availability of supply per major water supply system (respectively).

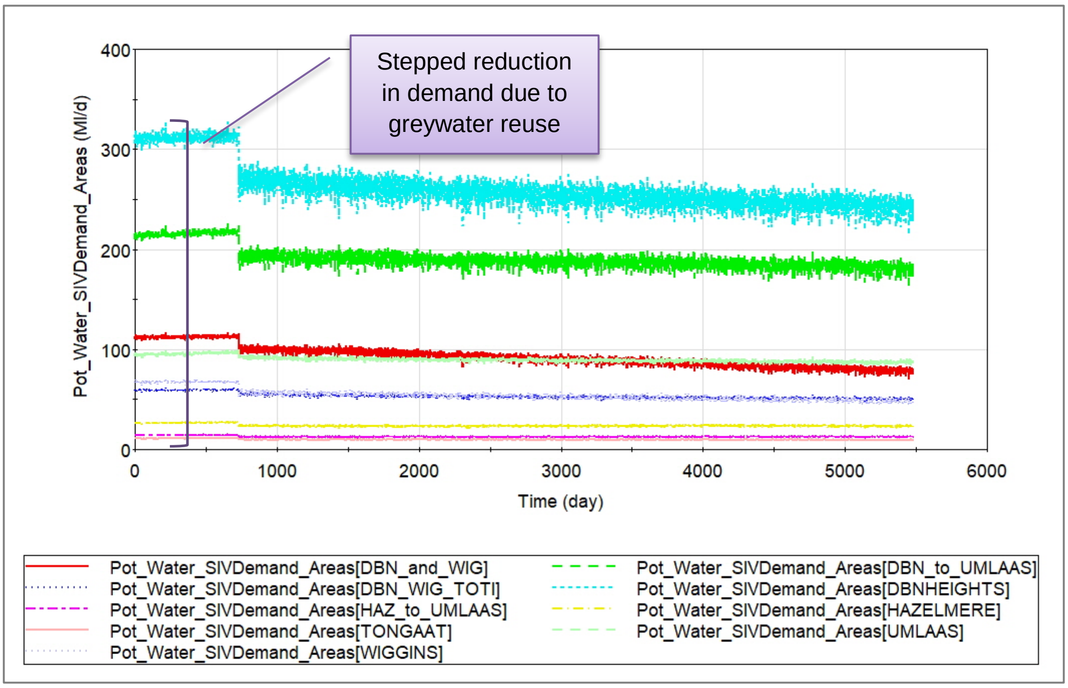


Figure C-28: Demand on Potable System per Bulk Supply Area (Greywater Reuse Scenario)

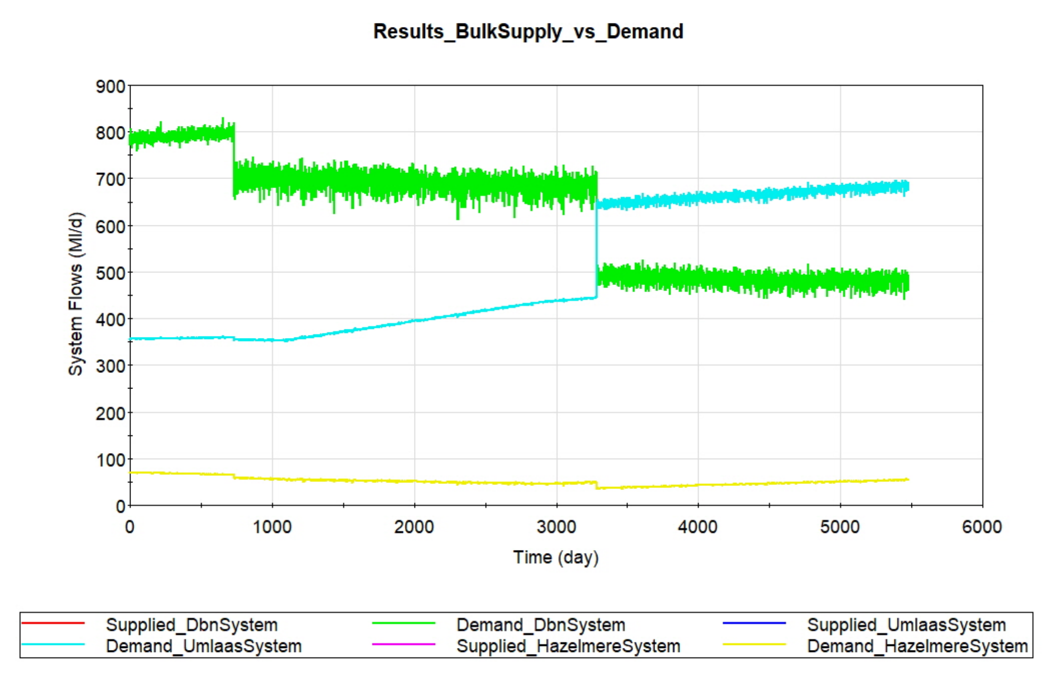


Figure C-29: Demand vs Availability for Water Supply Systems (Greywater Reuse Scenario)

The volume of wastewater produced (Figure C-30) and wastewater reaching WWTW's (Figure C-31) is reduced as a result of greywater reuse and WCWDM initiatives.

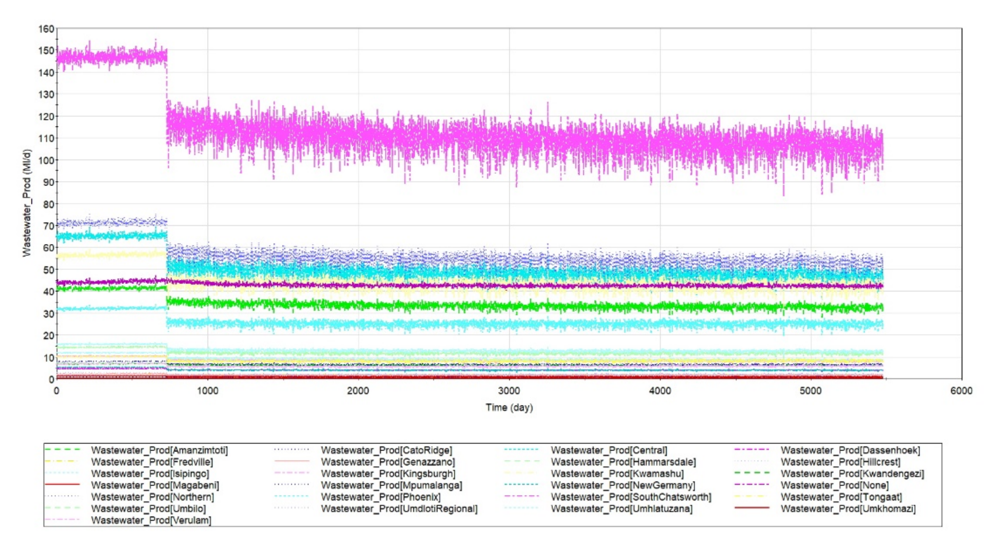


Figure C-30: Wastewater Produced per Drainage Area (Greywater Reuse Scenario)

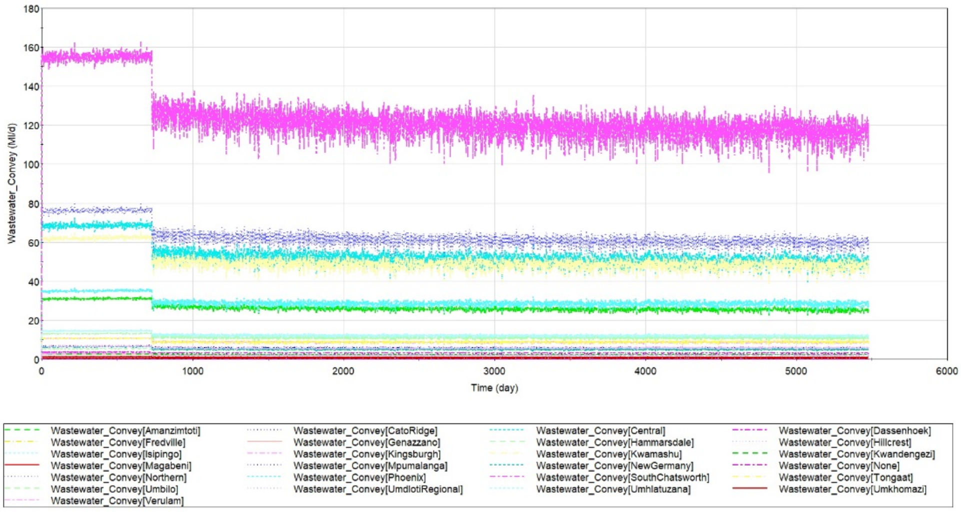


Figure C-31: Wastewater Inflow per Drainage Area (Greywater Reuse Scenario)

Wastewater Recycling with System WCWDM

Figure C-32 indicates the total volume of wastewater recycled to potable standards prior to being distributed to selected bulk supply areas, and Figure C-33 shows the total volume of wastewater recycled to non-potable standards.

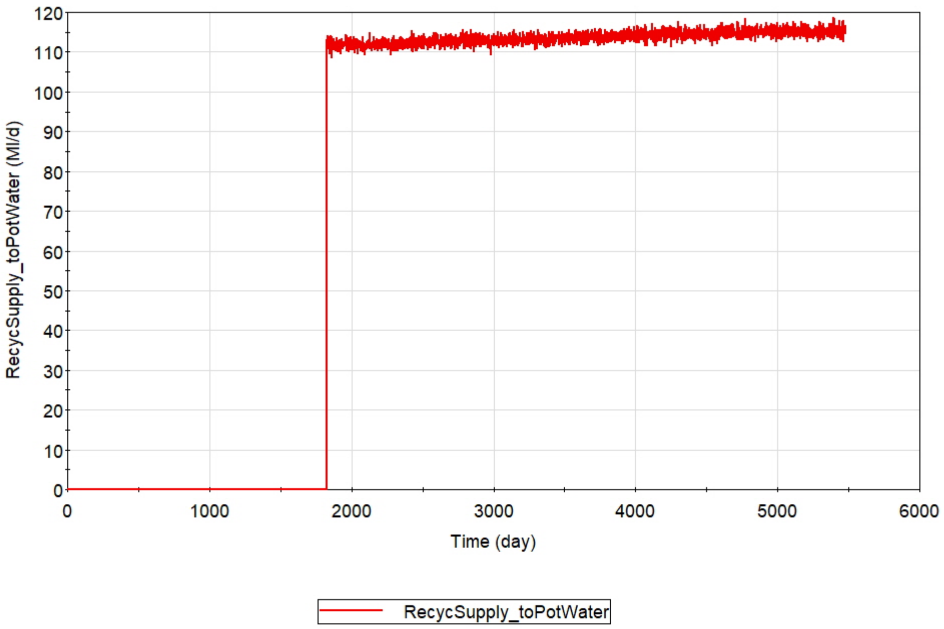


Figure C-32: Total Wastewater Recycled to Potable Standards

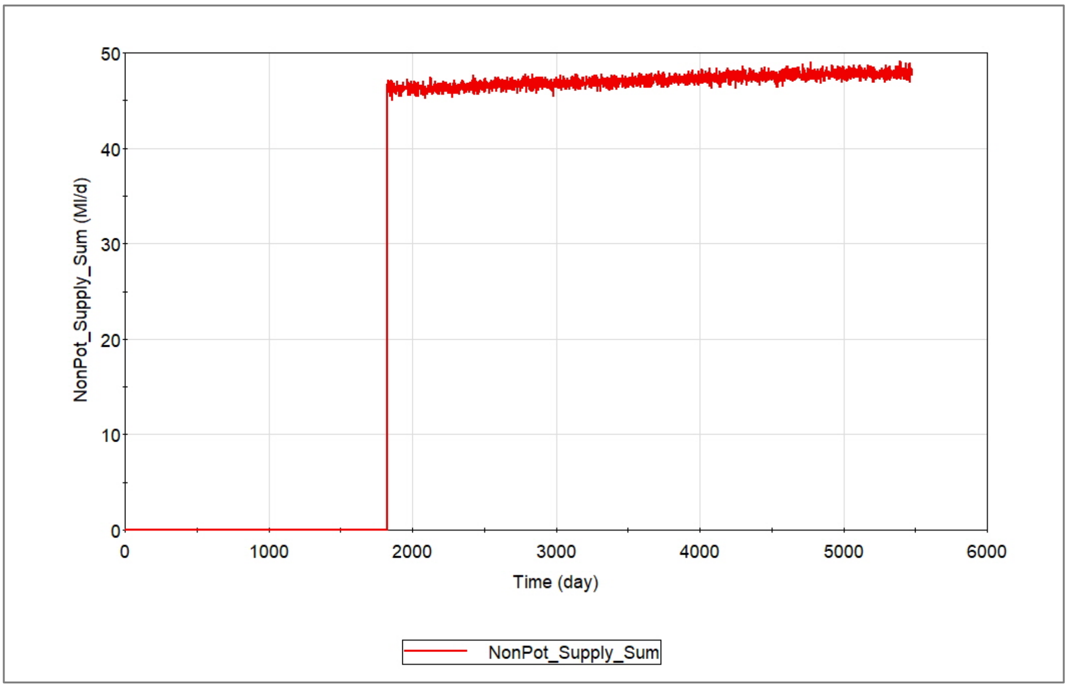


Figure C-33: Total Wastewater Recycled to Non-Potable Standards

Figure C-34 is the resulting total potable demand per bulk supply area.

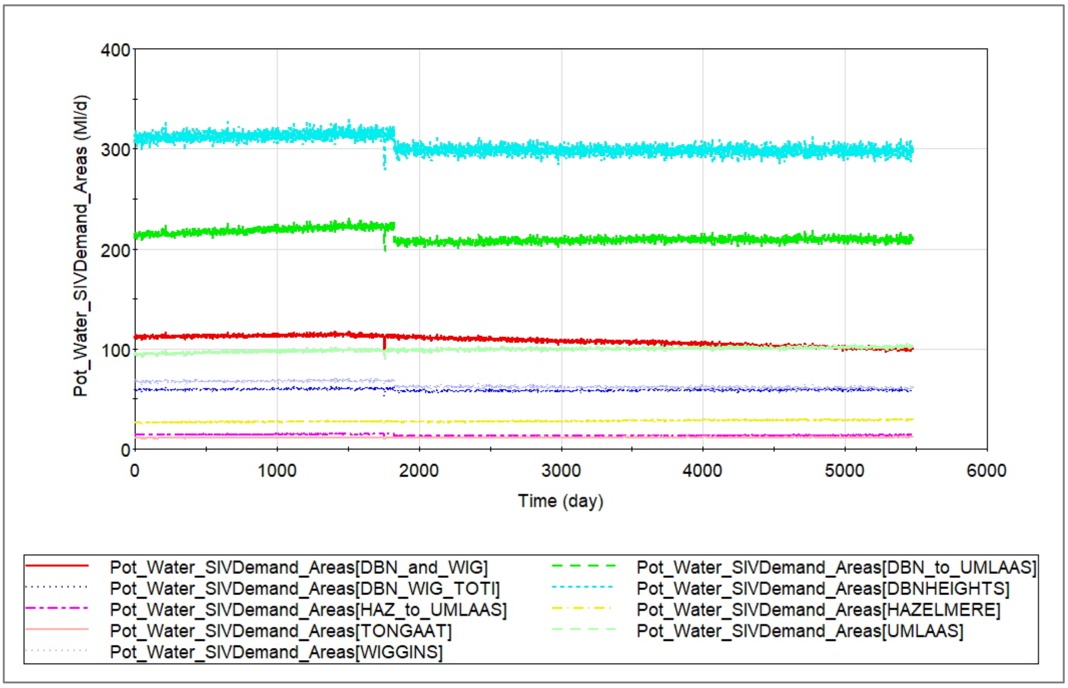


Figure C-34: Demand on Potable System per Bulk Supply Area (Wastewater Recycling Scenario)

Figure C-35 shows the resulting demand versus availability of supply per major water supply system.

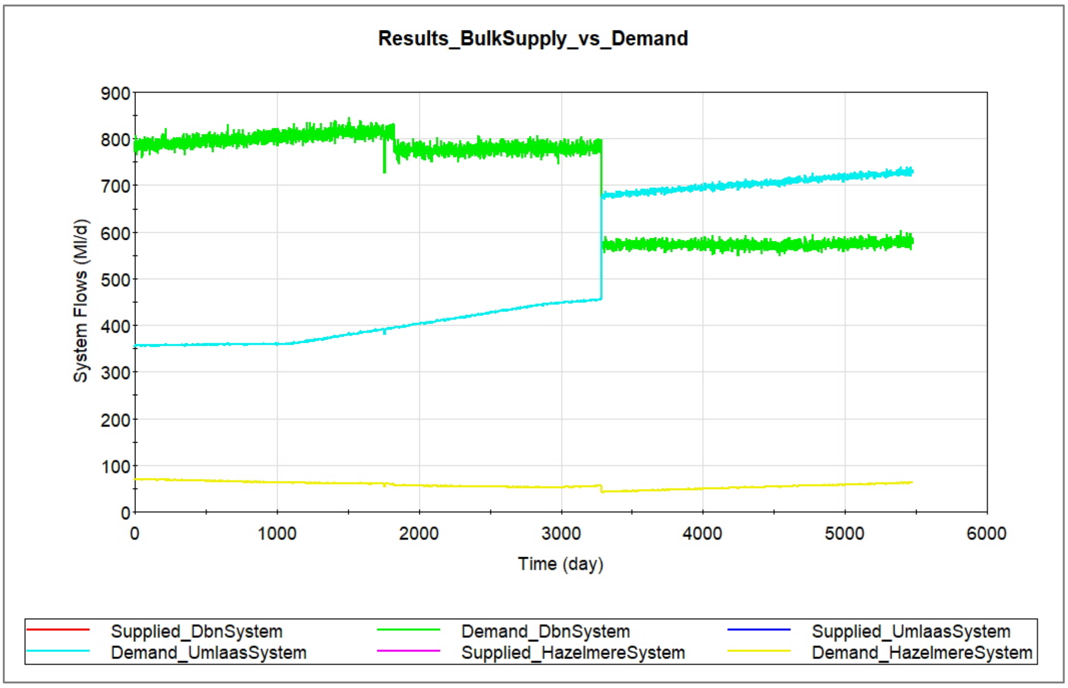


Figure C-35: Demand vs Availability for Water Supply Systems (Wastewater Recycling Scenario)

Wastewater recycling does not have any impact on the volumes of wastewater generated.

Water Quality Time Series Outputs for Key Scenarios

Model outputs pertaining to water quality for the key scenarios are illustrated below. Flow outputs for the same scenarios are to be found in Chapter 6.

Baseline

Figure C-36 shows all pollutant concentrations of wastewater influent at WWTW's. Figure C-37 shows the simulated COD concentration of influent at WWTW's; this is of particular interest for sewage treatment, as it is an indication of the "strength" of the sewage which has consequential demands on the rest of the treatment chain unit processes.

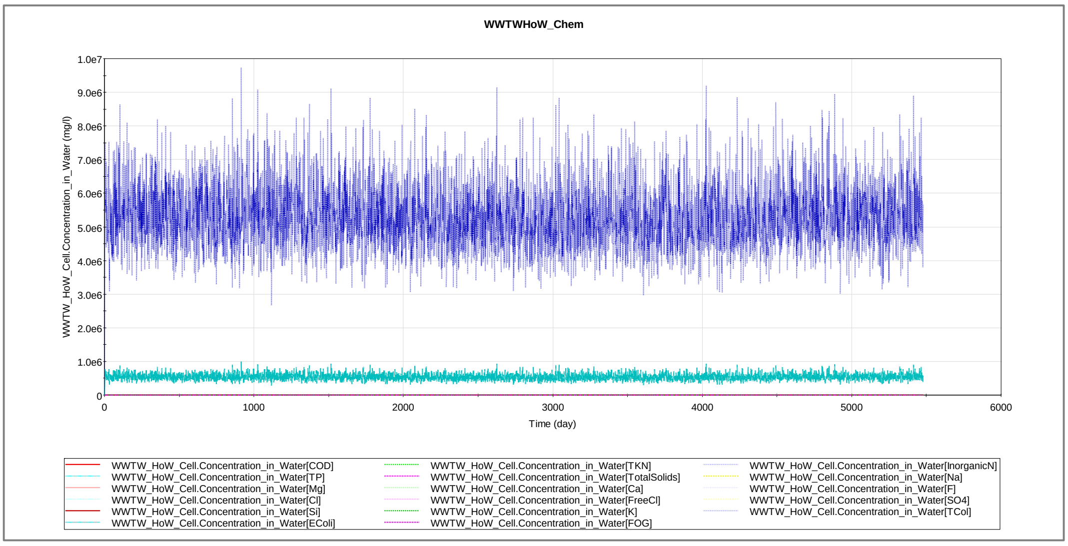


Figure C-36: Wastewater Influent Pollutant Concentrations (Baseline Scenario)

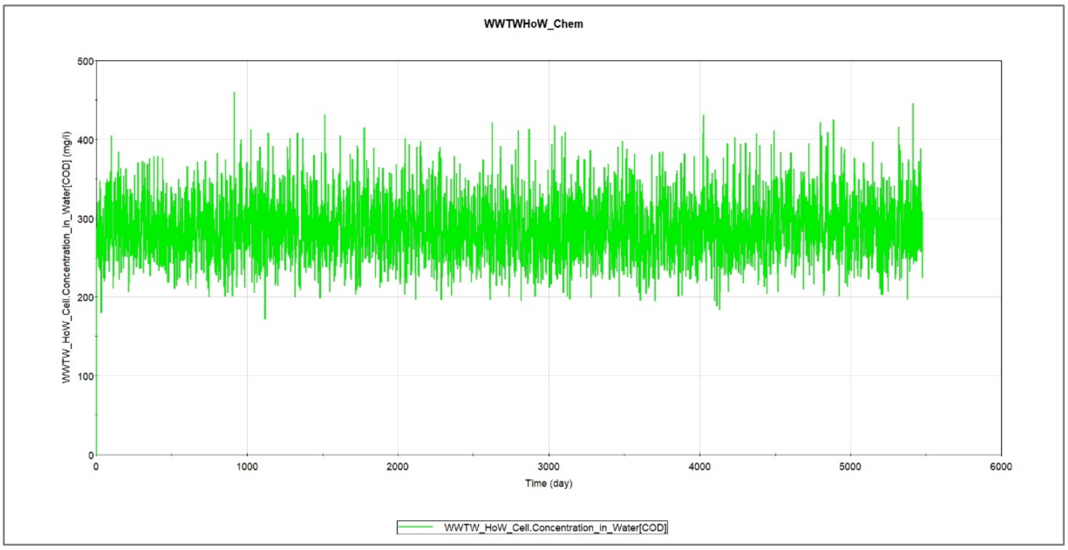


Figure C-37: Wastewater Influent COD Concentration (Baseline Scenario)

Figure C-38 presents the concentrations of all pollutants in urban waterways; the Total Coliforms and E. Coli dominate when the capacity of WWTWs is exceeded. Figure C-39 is the resulting TSS concentration in catchments as a result of build-up and wash-off behaviour in catchments.

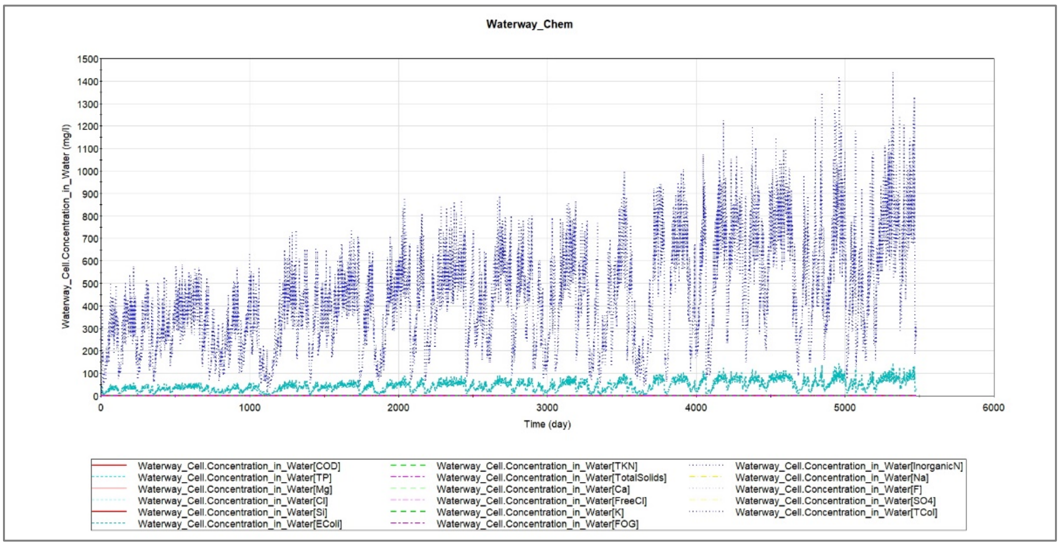


Figure C-38: Waterway Pollutant Concentrations (Baseline Scenario)

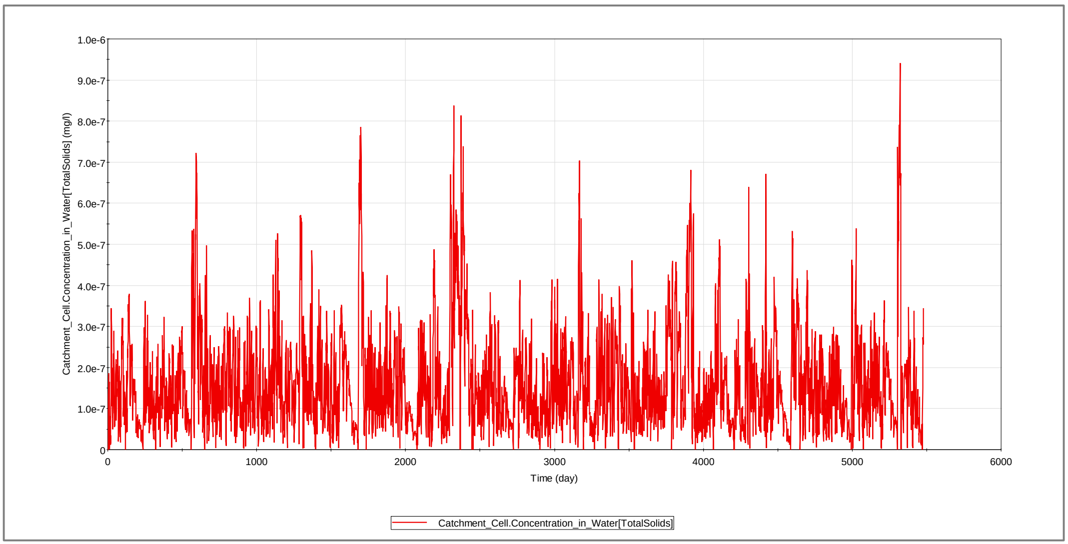


Figure C-39: Catchment TSS Concentrations (Baseline Scenario)

WCWDM

The impact of reduced wastewater flows (due to demand reductions) appears to have little impact on the influent pollutant concentrations at the start of the wastewater treatment process.

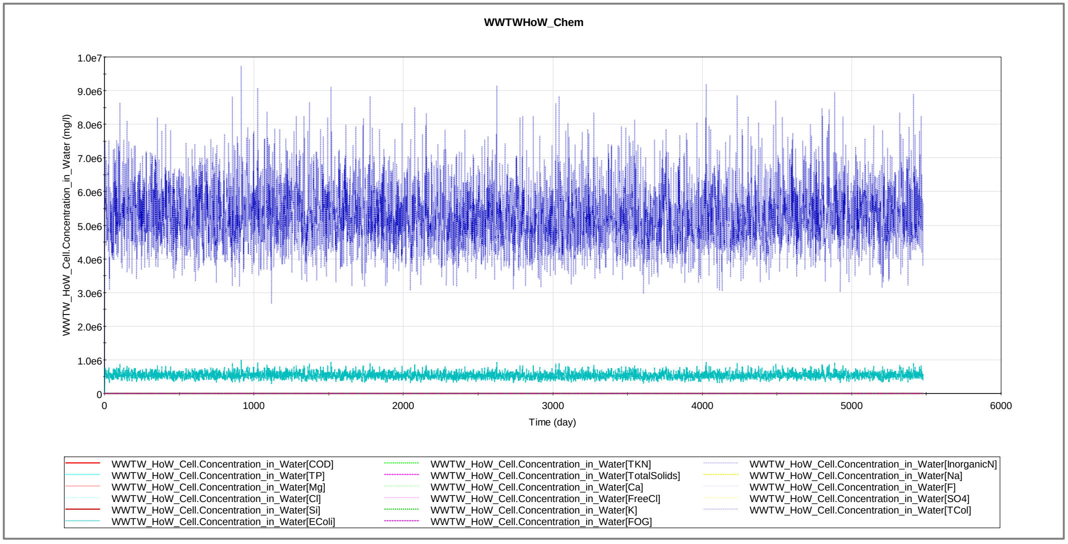


Figure C-40: Wastewater Influent Pollutant Concentrations (WCWDM Scenario)

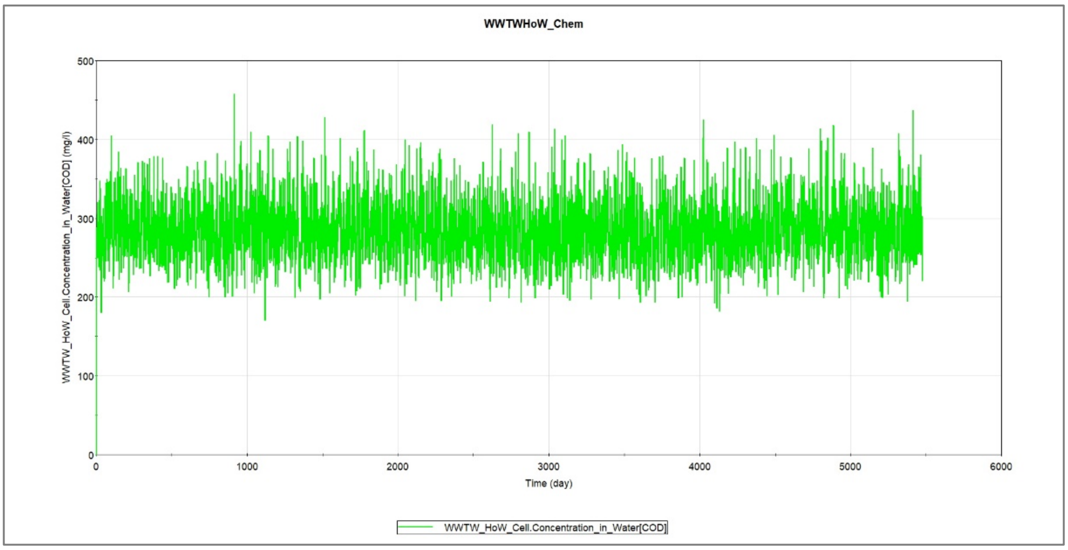


Figure C-41: Wastewater Influent COD Concentration (WCWDM Scenario)

WCWDM measures reduce the volume of wastewater requiring treatment and also the volume of possible overflows, though it appears there is little impact on the pollutant concentrations in urban waterways at the scale of the analysis.

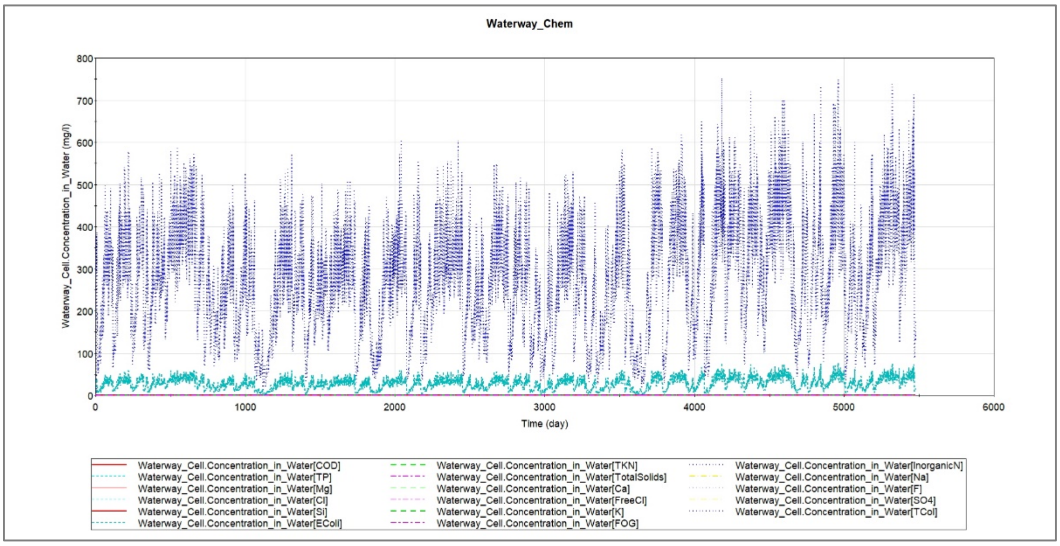


Figure C-42: Waterway Pollutant Concentrations (WCWDM Scenario)

The TSS concentration in waterways is otherwise unaffected by this particular intervention.

Rainwater Harvesting & Real Loss Reduction

In that harvested rainwater must first pass over roof area prior to being collected, there is some build-up and wash-off of pollutants; the resulting pollutant concentration – or specifically total solids – is shown in Figure C-43.

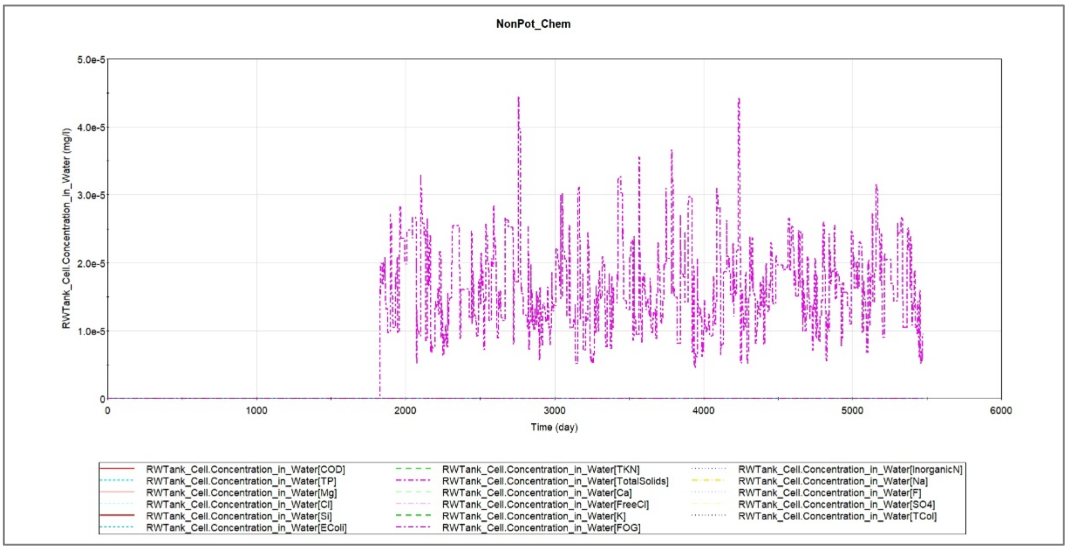


Figure C-43: Rainwater Tank TSS Concentration (Rainwater Harvesting Scenario)

Rainwater harvesting does not have any impact on the volumes of wastewater generated, though there is some reduction as a result of the real loss reduction which forms part of this scenario. There is, however, no appreciable difference in pollutant concentrations.

Figure C-44 shows the waterway pollutant concentrations. In that the cumulative roof area for rainwater harvesting activities is small compared to that of the quaternary catchments, rainwater harvesting activities do not make an appreciable reduction in the concentration of TSS in catchment areas.

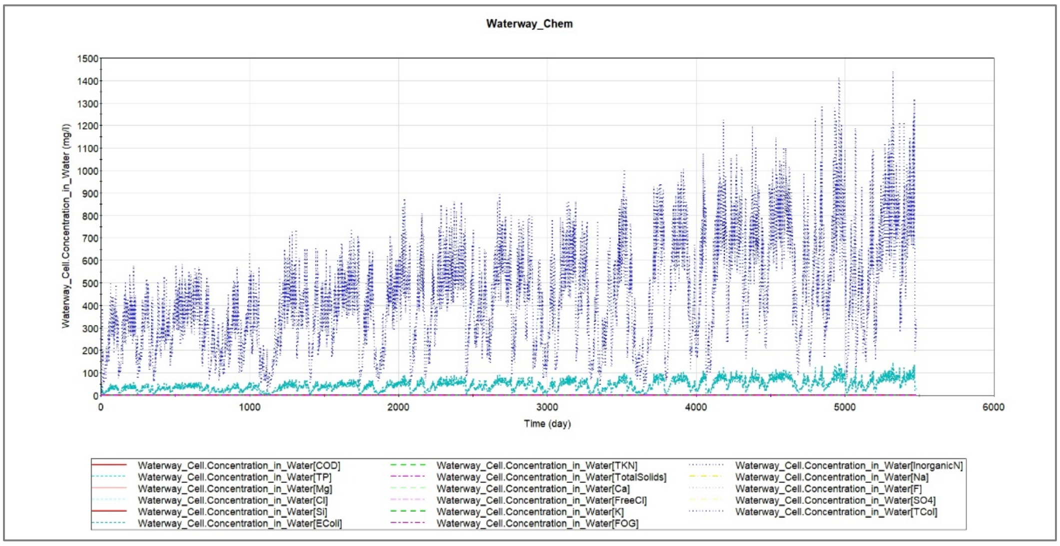


Figure C-44: Waterway Pollutant Concentrations (Rainwater Harvesting Scenario)

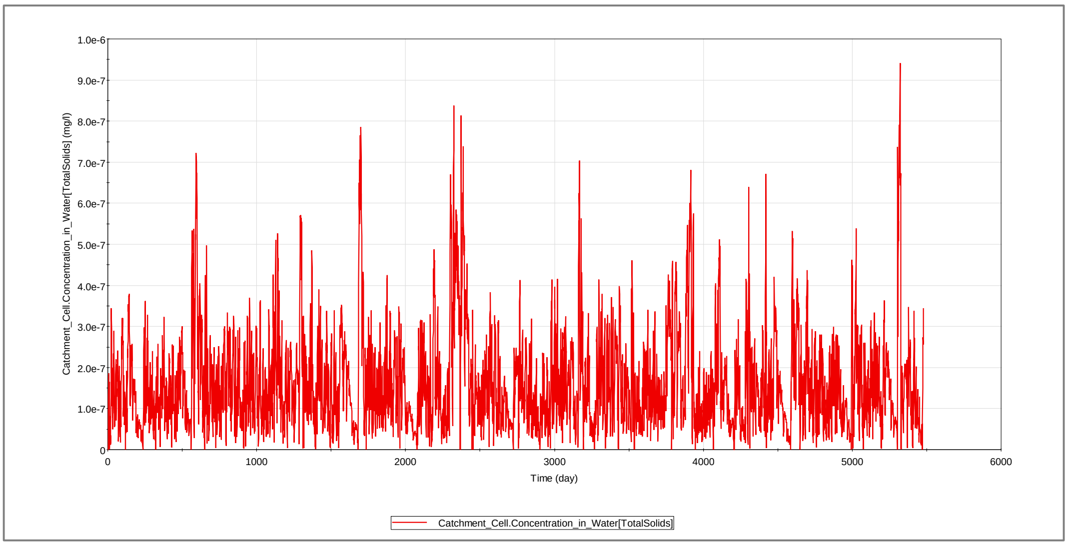


Figure C-45: Catchment TSS Concentrations (Rainwater Harvesting Scenario)

Greywater Reuse & WCWDM

The volume of wastewater produced and reaching WWTW's is reduced as a result of greywater reuse and WCWDM initiatives; there does not, however, appear to be an appreciable effect on the COD concentrations (Figure C-47).

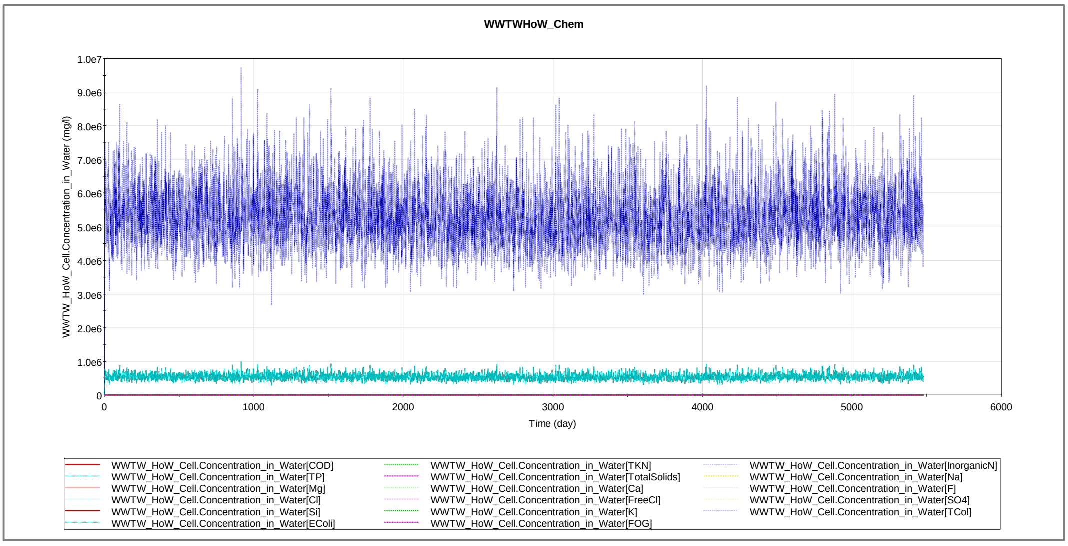


Figure C-46: Wastewater Influent Pollutant Concentrations (Greywater Reuse Scenario)

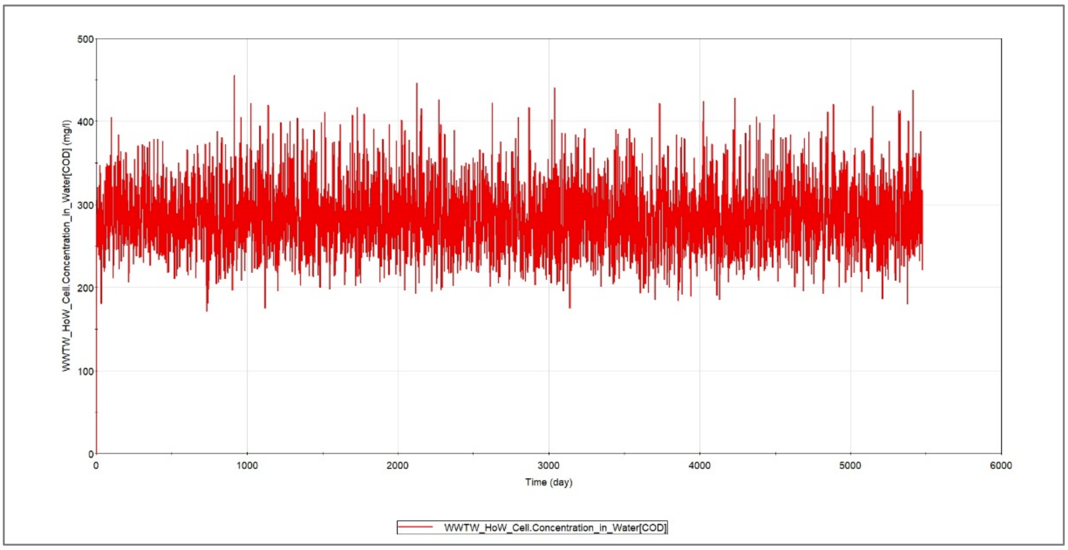


Figure C-47: Wastewater Influent COD Concentration (Greywater Reuse Scenario)

Figure C-48 and Figure C-49 illustrates the presence of pollutants in non-potable water resources (this of course assuming no treatment in reuse practices).

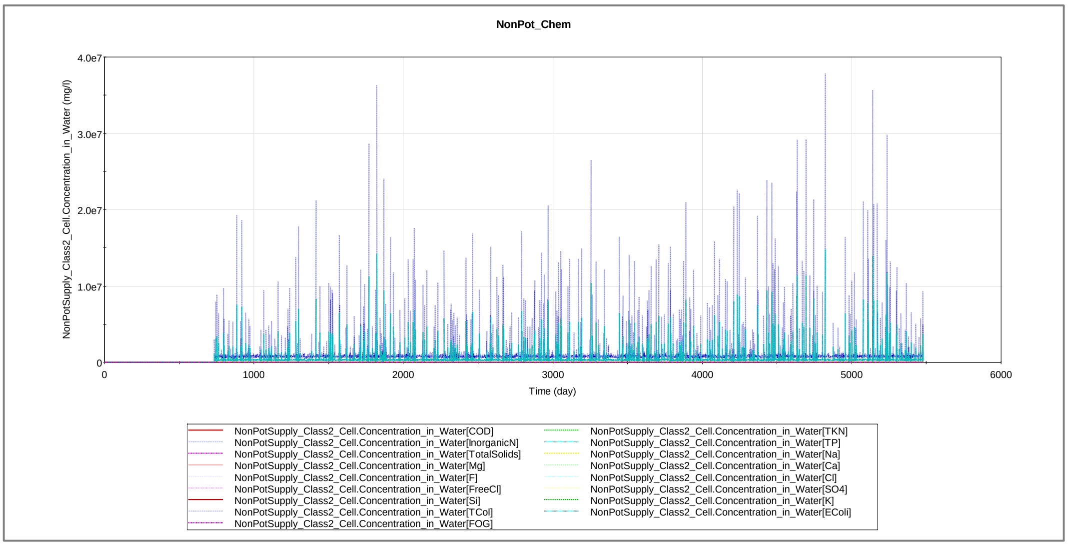


Figure C-48: Non-Potable Supply Pollutant Concentrations (Greywater Reuse Scenario)

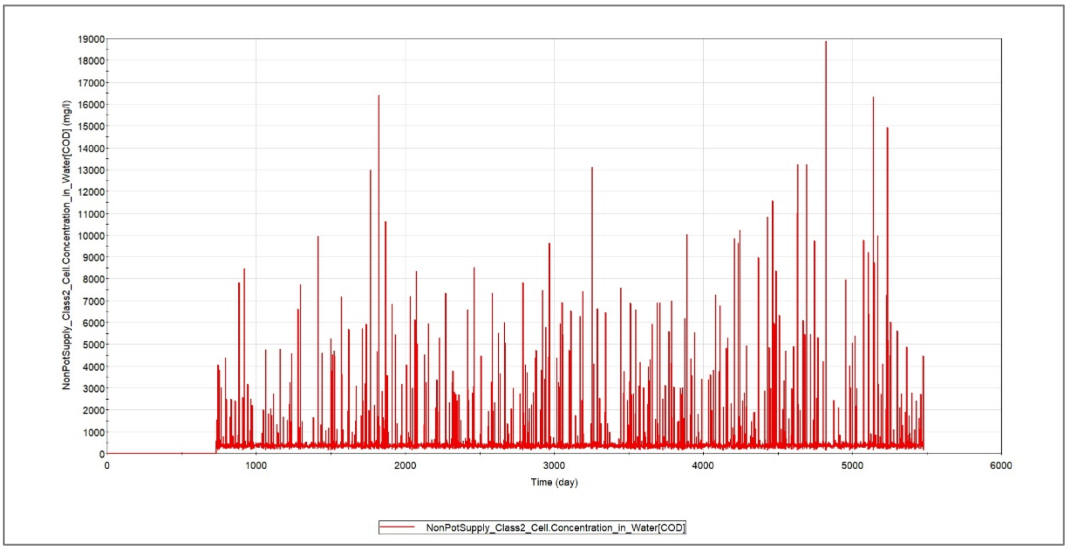


Figure C-49: Non-Potable Supply COD Concentration (Greywater Reuse Scenario)

As a result of reduced wastewater volumes, there is a large decrease in pollutant concentrations in urban waterways.

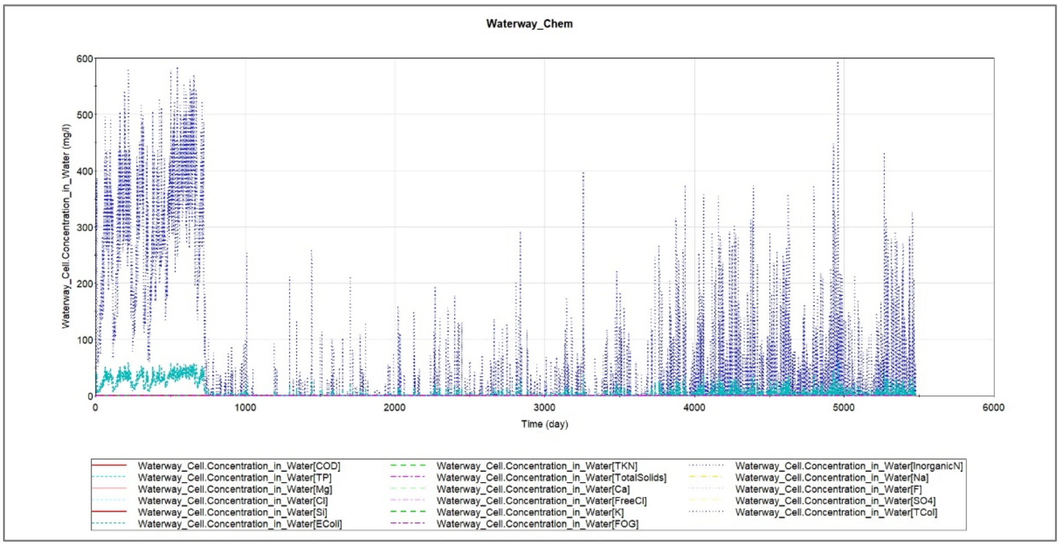


Figure C-50: Waterway Pollutant Concentrations (Greywater Reuse Scenario)

Wastewater Recycling & Real Loss Reduction

Recycling of wastewater to non-potable standards has bearing on the water quality of non-potable sources, as evidenced by Figure C-51 below.

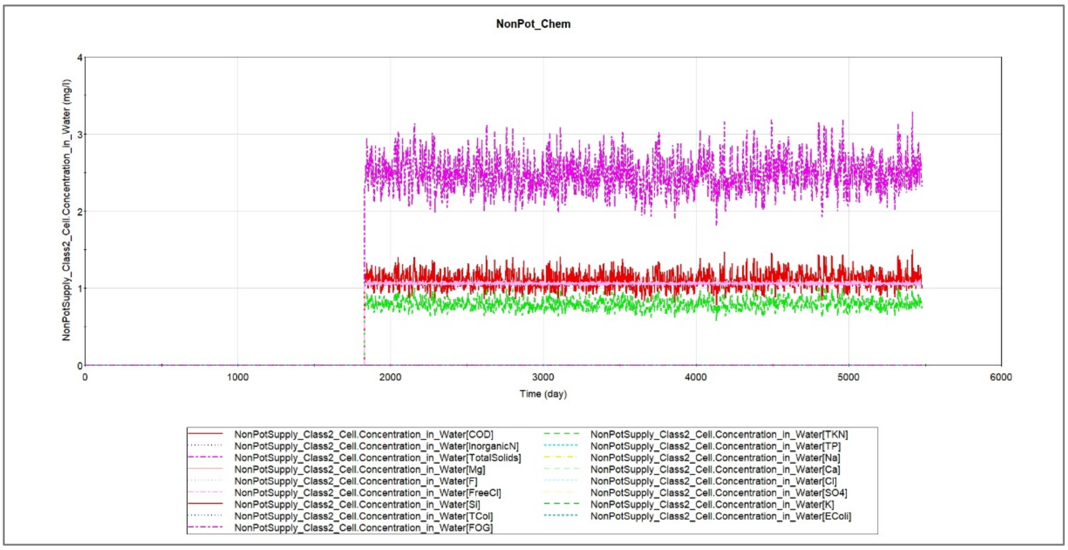


Figure C-51: Non-Potable Supply Pollutant Concentrations (Wastewater Recycling Scenario)

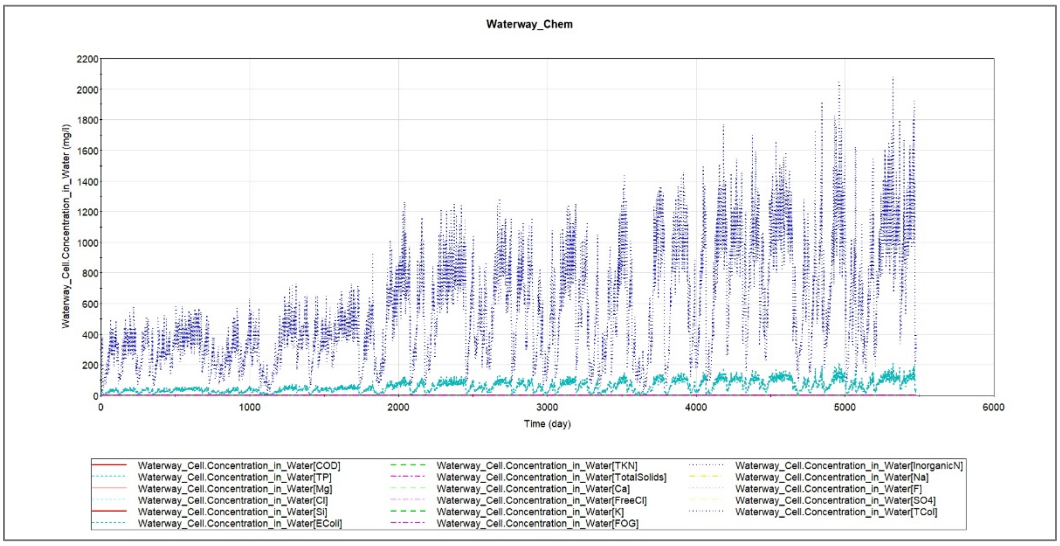


Figure C-52: Waterway Pollutant Concentrations (Wastewater Recycling Scenario)

Additional Monte Carlo Outputs for Key Scenarios

Baseline

Figure C-53 to Figure C-65 are key Monte Carlo simulation results for the baseline scenario. These performance ranges are unaffected by interventions.

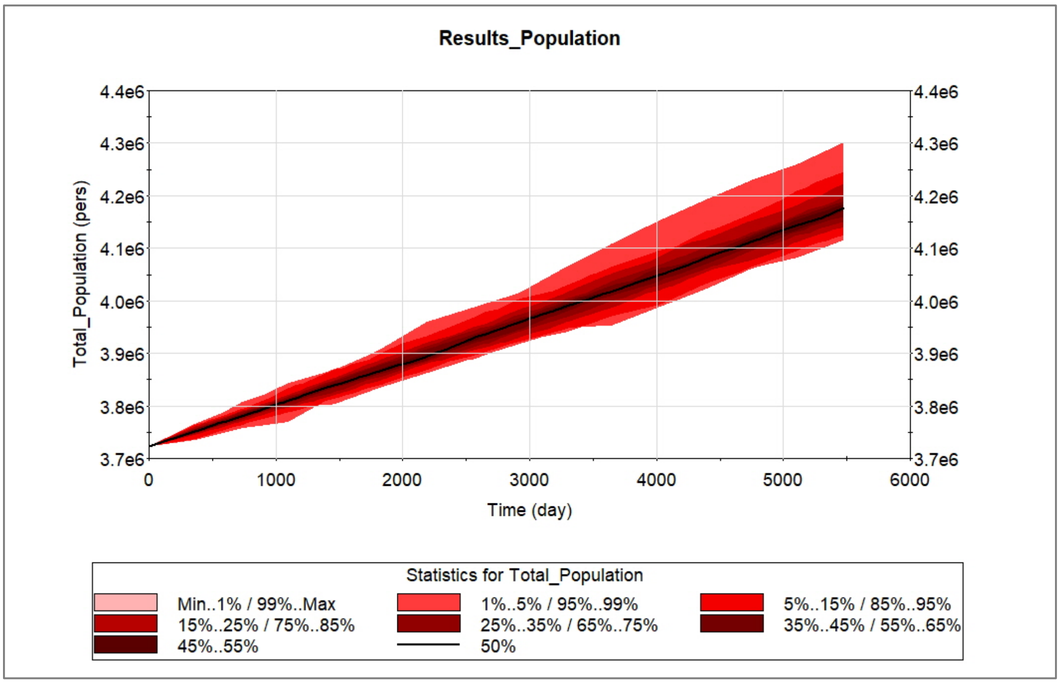


Figure C-53: Monte Carlo Analysis of Total Population (Baseline Scenario)

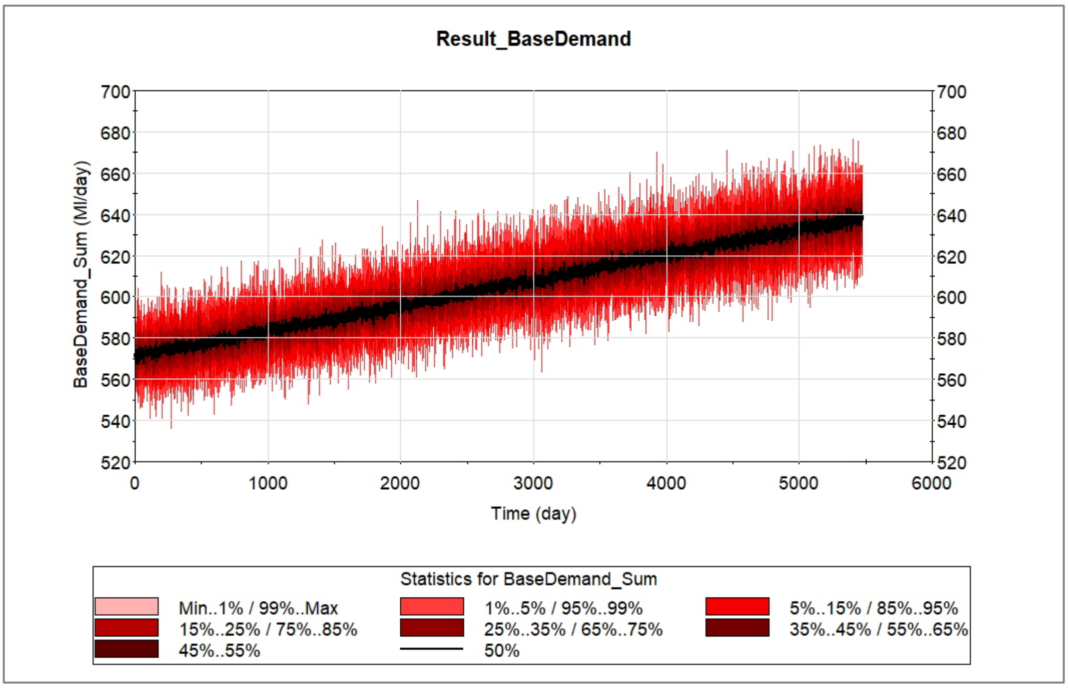


Figure C-54: Monte Carlo Analysis of Base Consumption for eThekwini (Baseline Scenario)

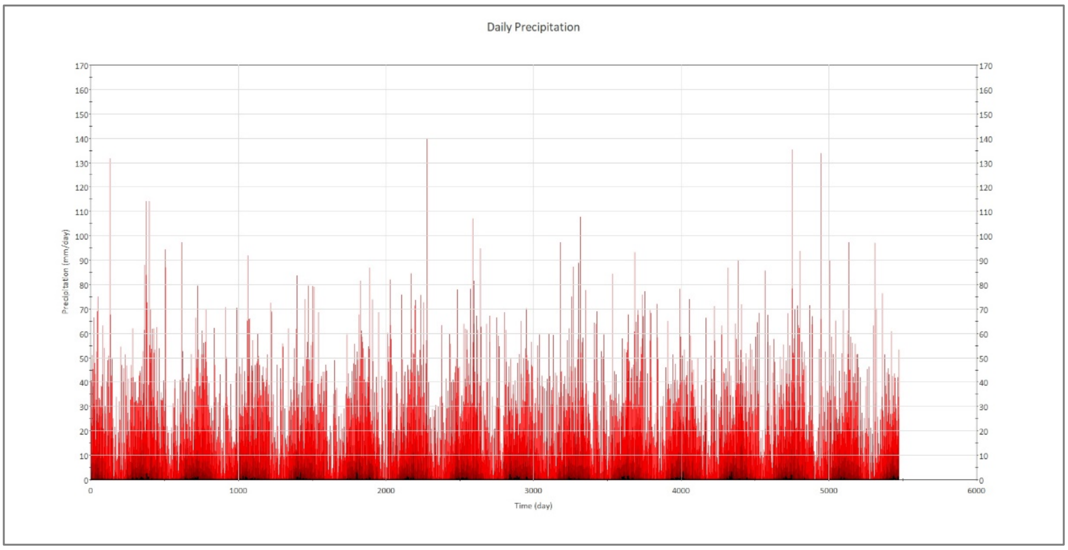


Figure C-55: Monte Carlo Analysis of Precipitation

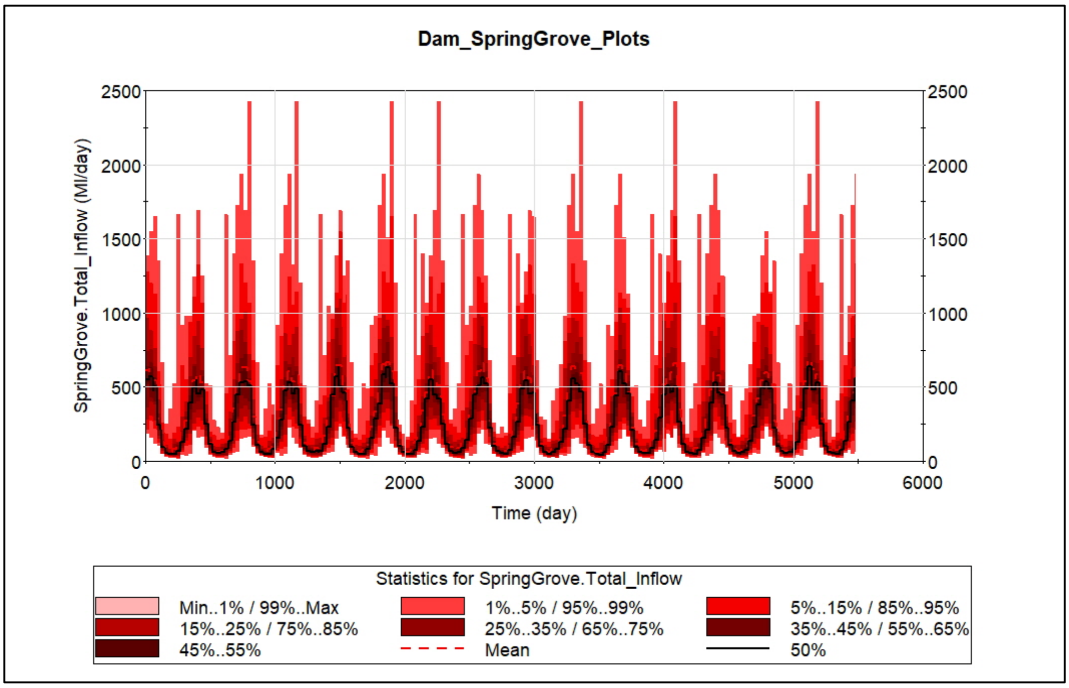


Figure C-56: Monte Carlo Analysis of Inflows to Spring Grove Dam

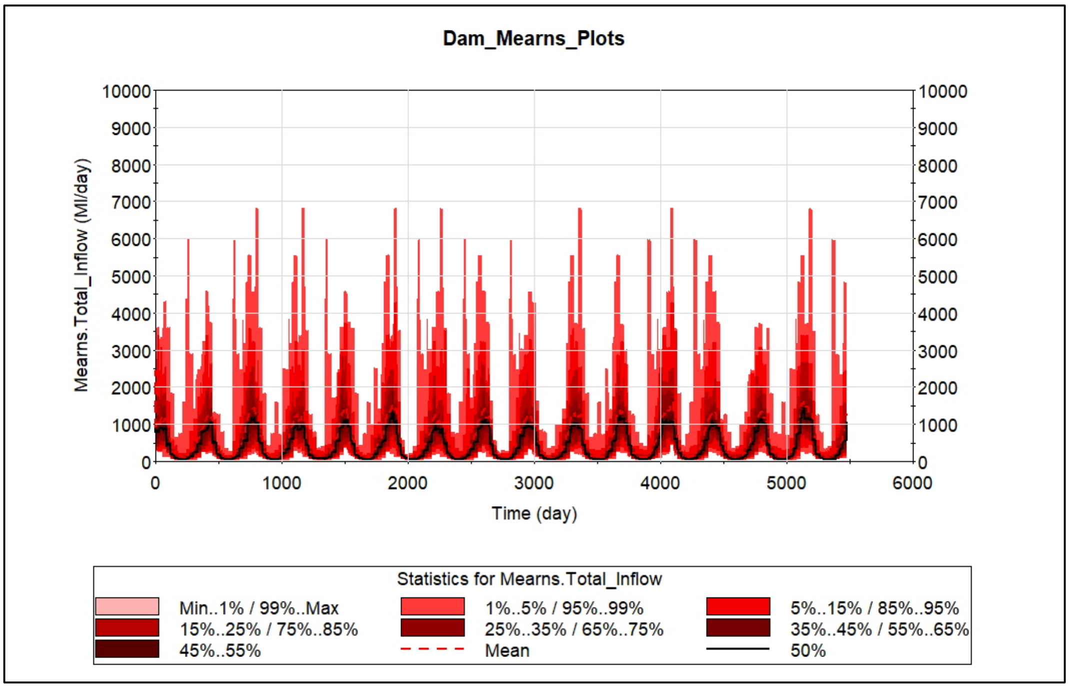


Figure C-57: Monte Carlo Analysis of Inflows to Mearns Weir

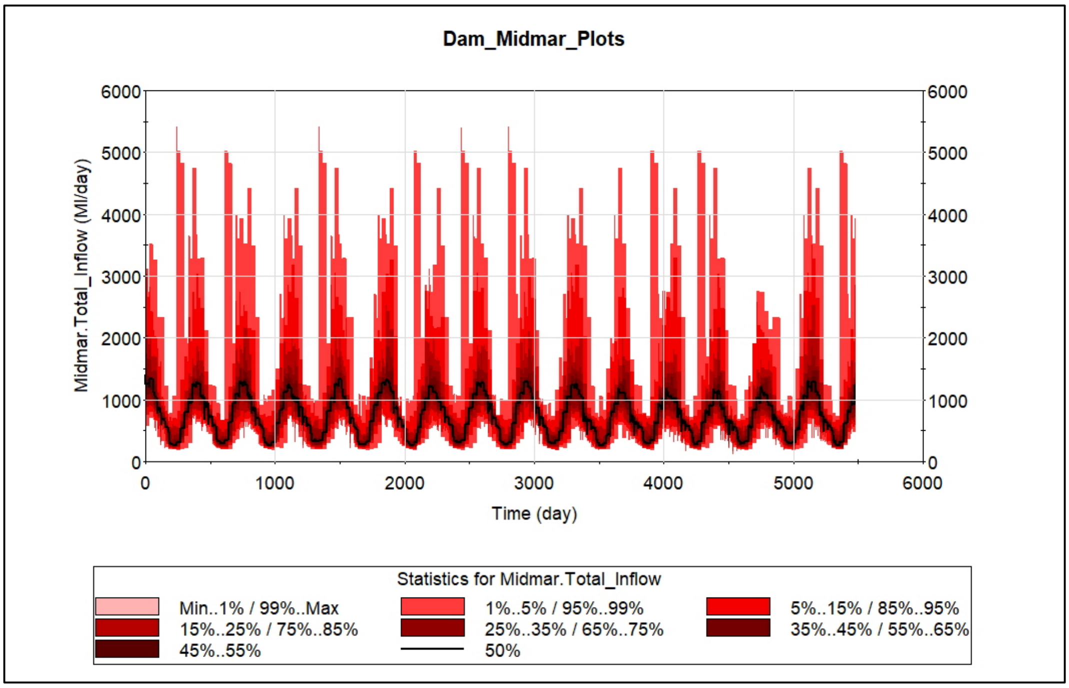


Figure C-58: Monte Carlo Analysis of Inflows to Midmar Dam

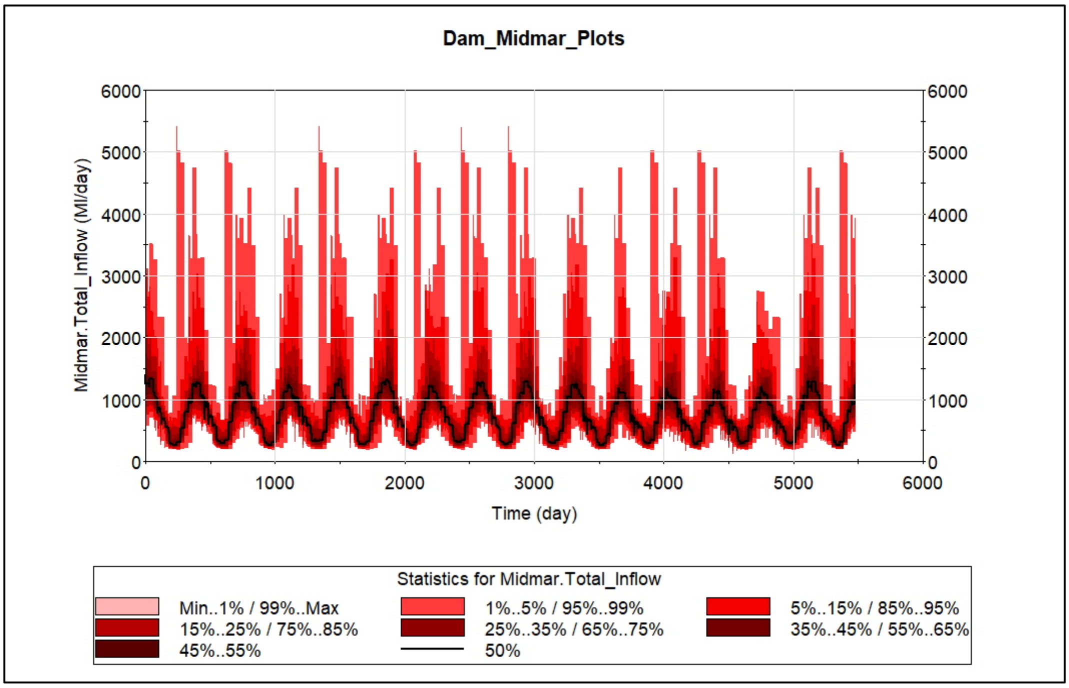


Figure C-59: Monte Carlo Analysis of Inflows to Midmar Dam

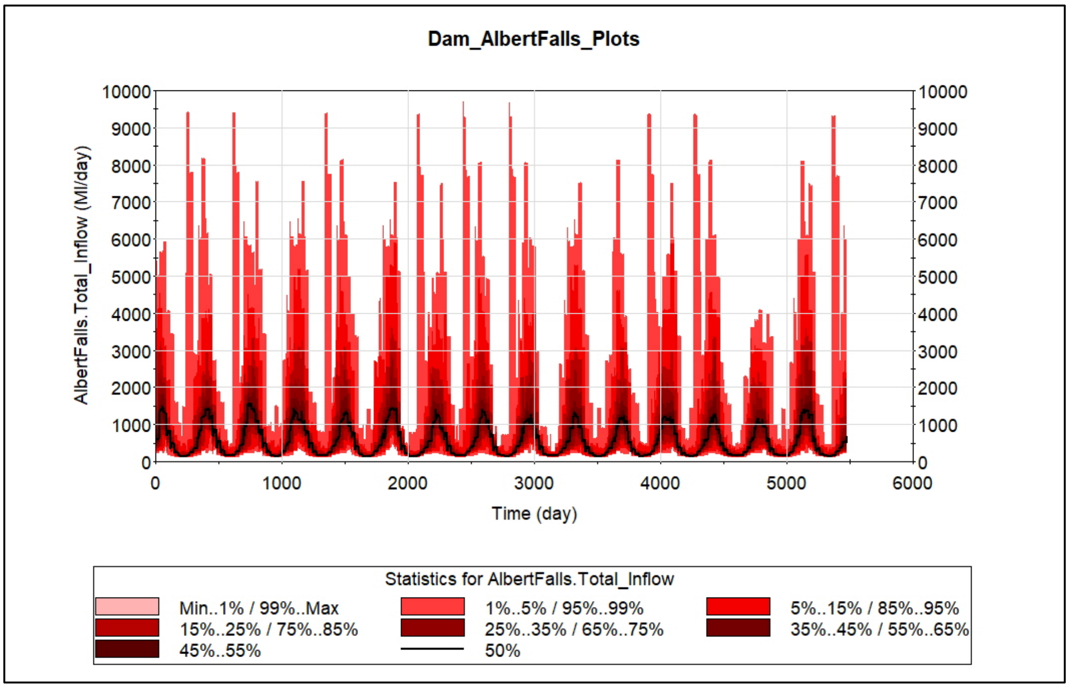


Figure C-60: Monte Carlo Analysis of Inflows to Albert Falls Dam

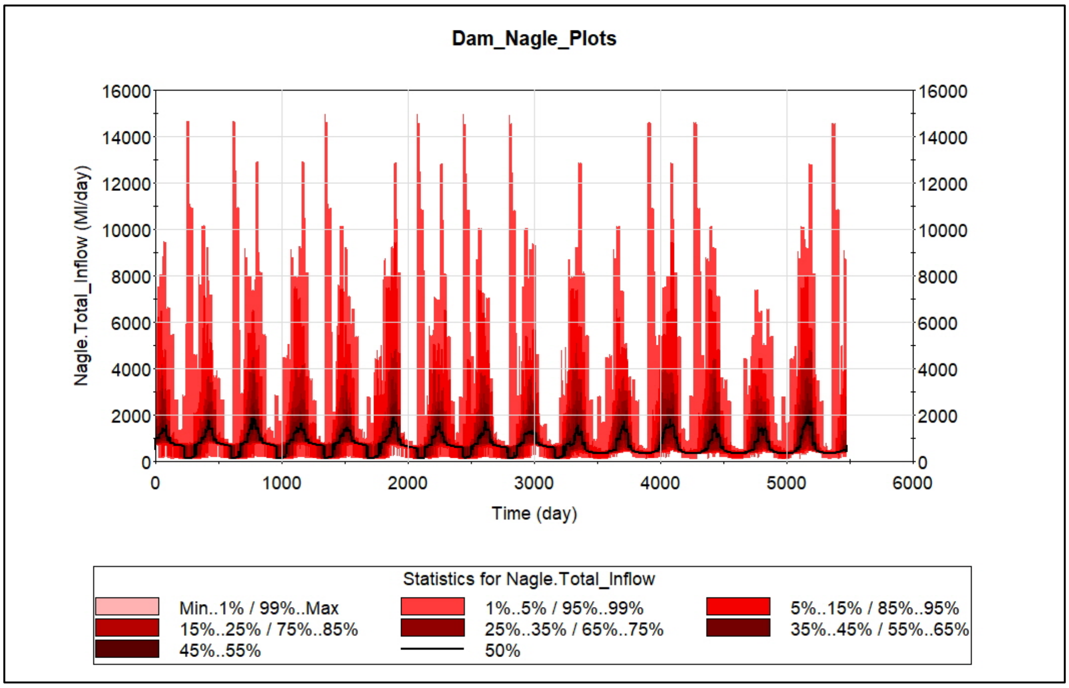


Figure C-61: Monte Carlo Analysis of Inflows to Nagle Dam

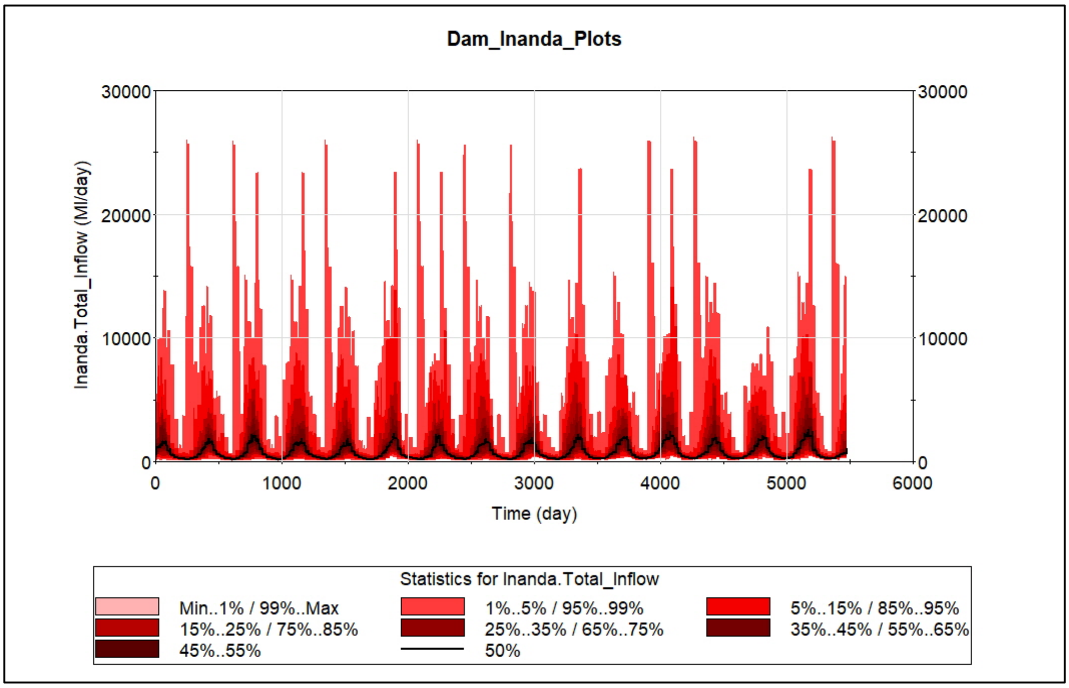


Figure C-62: Monte Carlo Analysis of Inflows to Inanda Dam

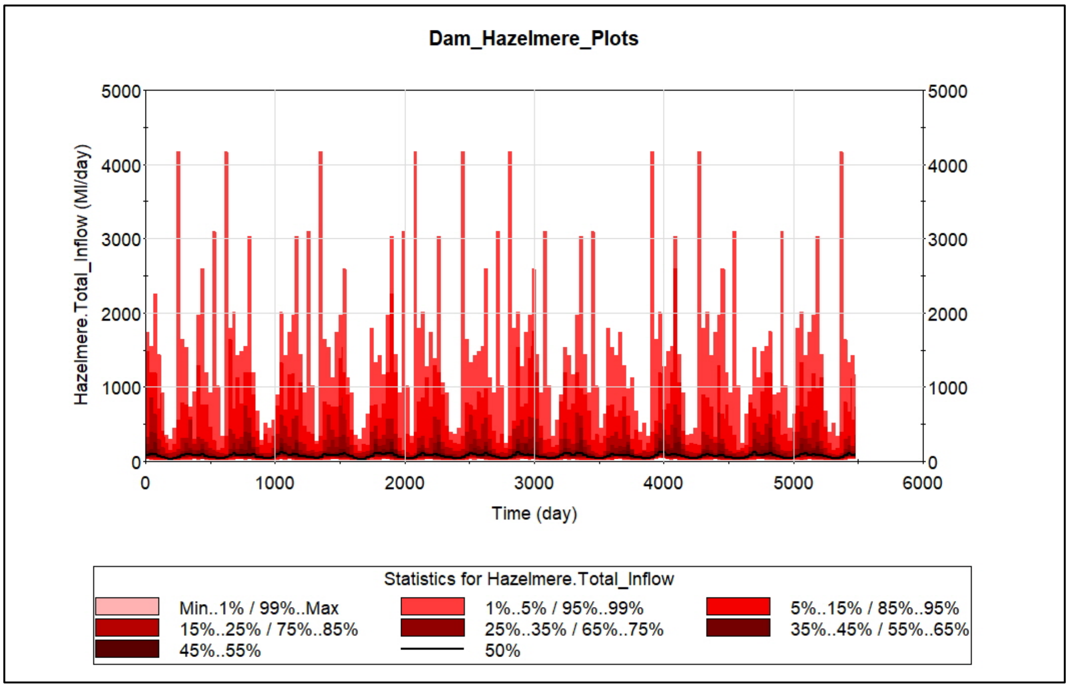


Figure C-63: Monte Carlo Analysis of Inflows to Hazelmere Dam

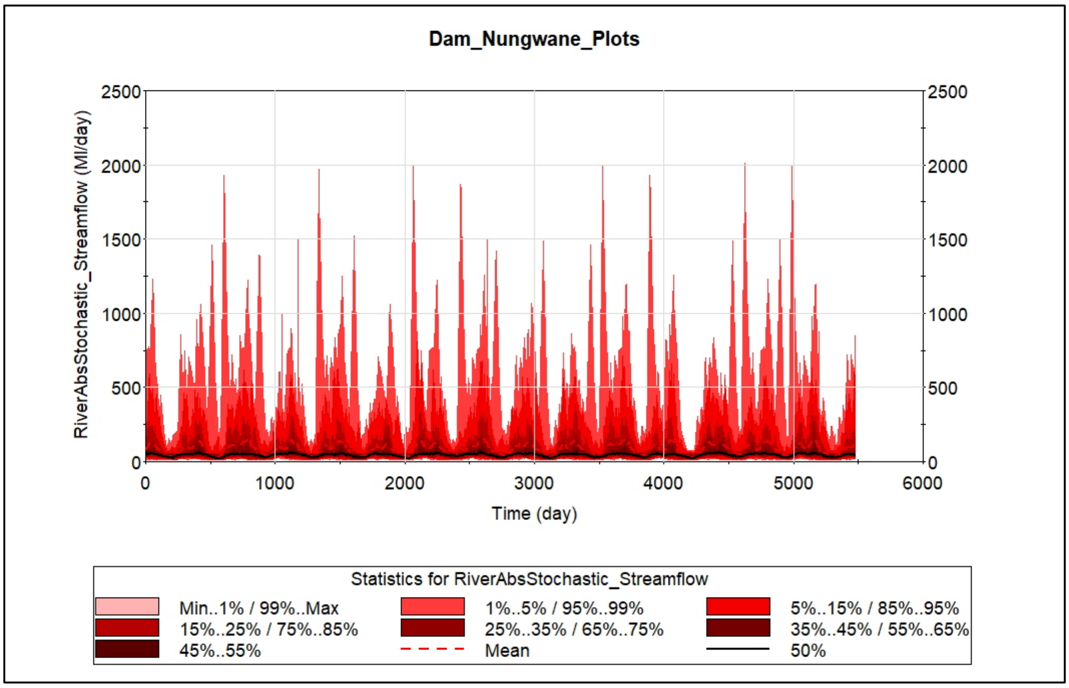


Figure C-64: Monte Carlo Analysis of Tongaat River Flows

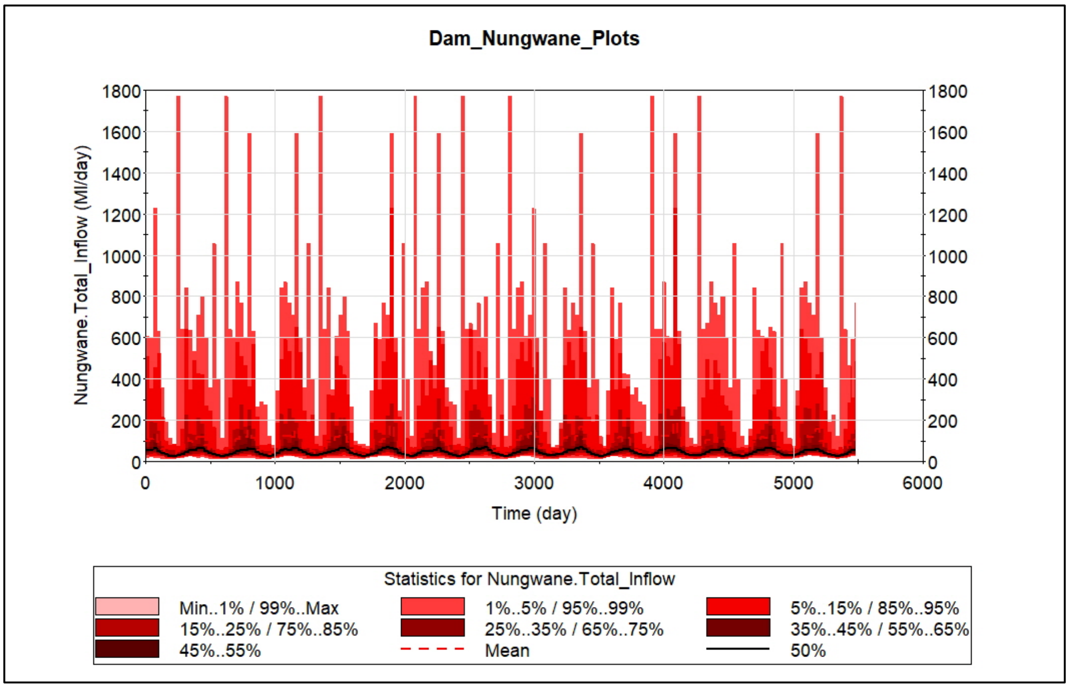


Figure C-65: Monte Carlo Analysis of Inflows to Nungwane Dam

Figure C-66 to Figure C-70 show the impact on water resources and volume of potable water supplied.

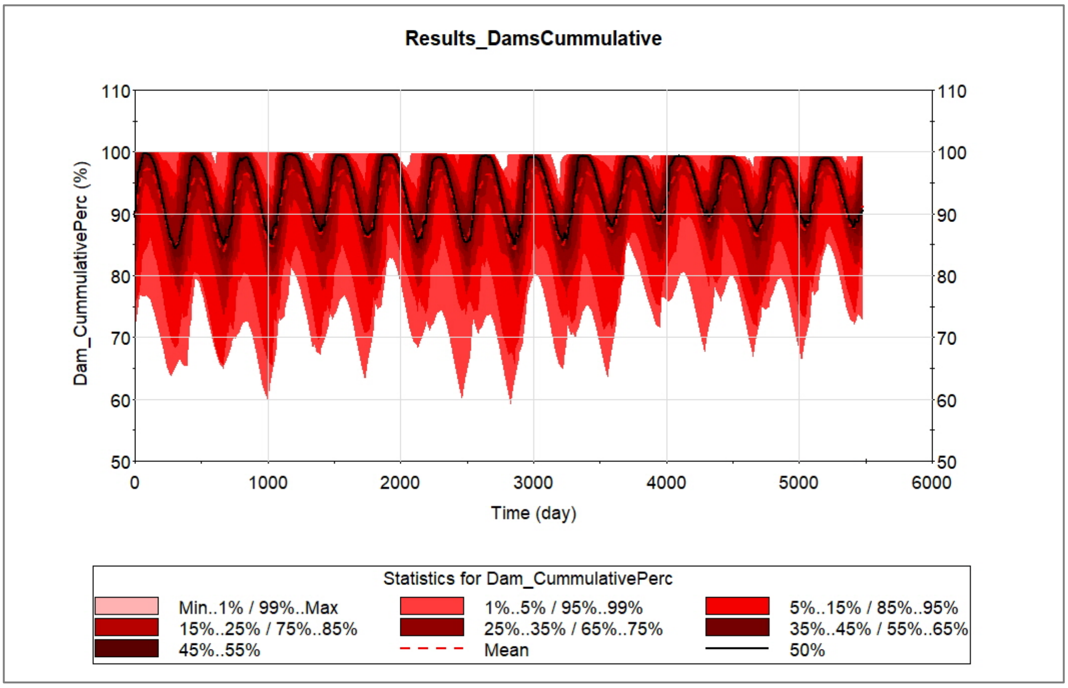


Figure C-66: Cumulative Dam Storage (Baseline Scenario)

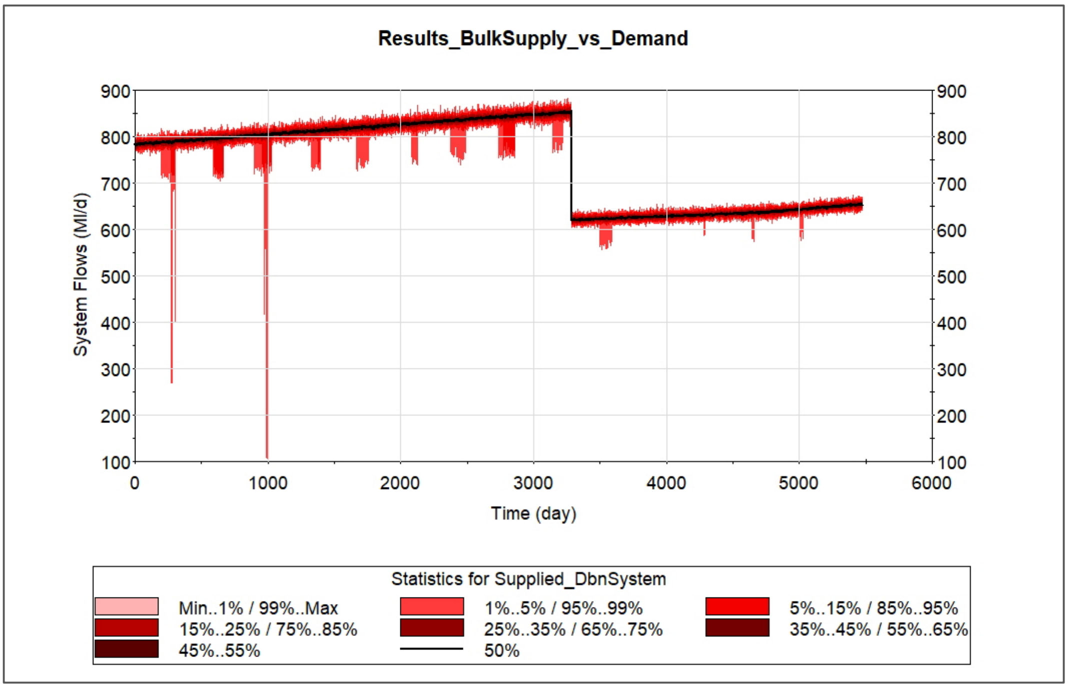


Figure C-67: Monte Carlo Analysis of Demand on Lower Mgeni System (Baseline Scenario)

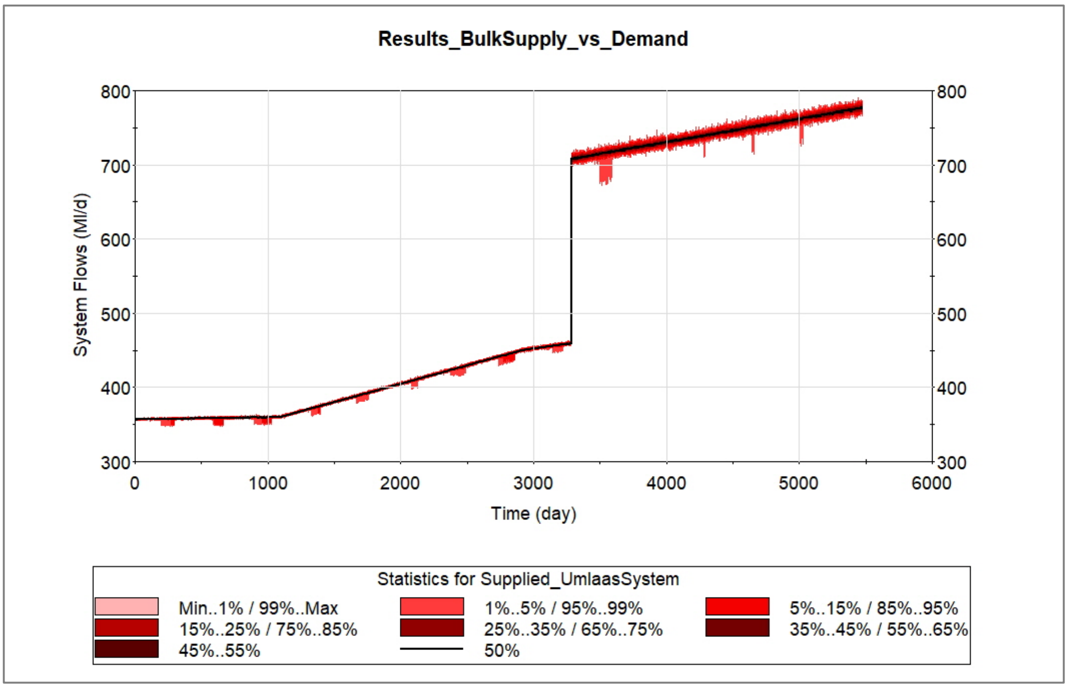


Figure C-68: Monte Carlo Analysis of Demand on Upper Mgeni System (Baseline Scenario)

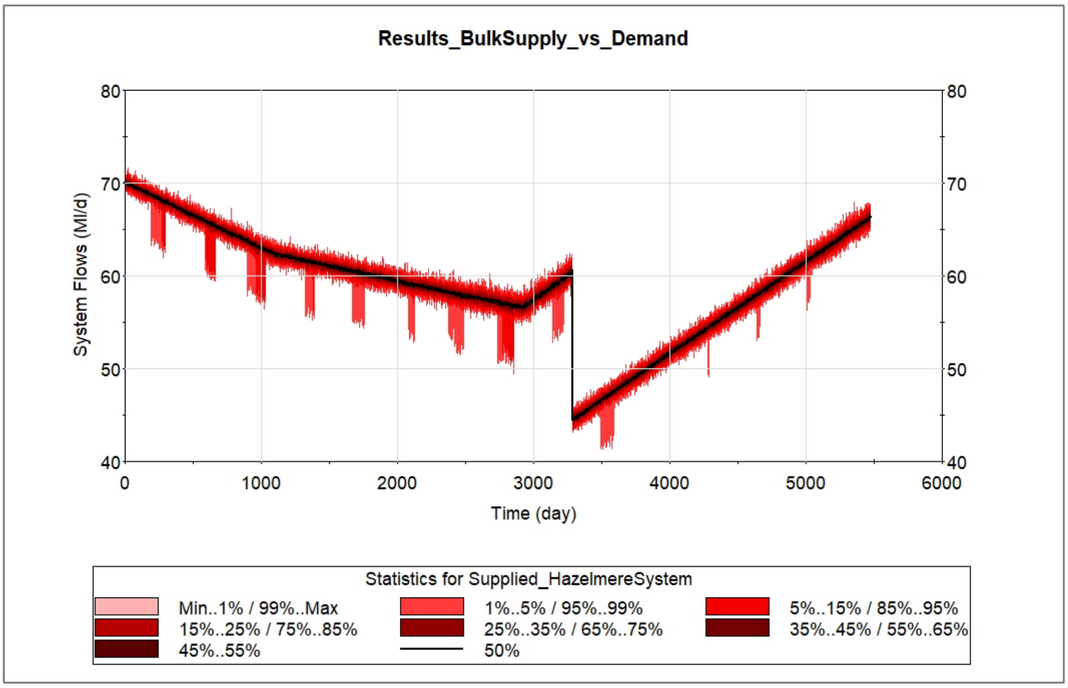


Figure C-69: Monte Carlo Analysis of Demand on Hazelmere System (Baseline Scenario)

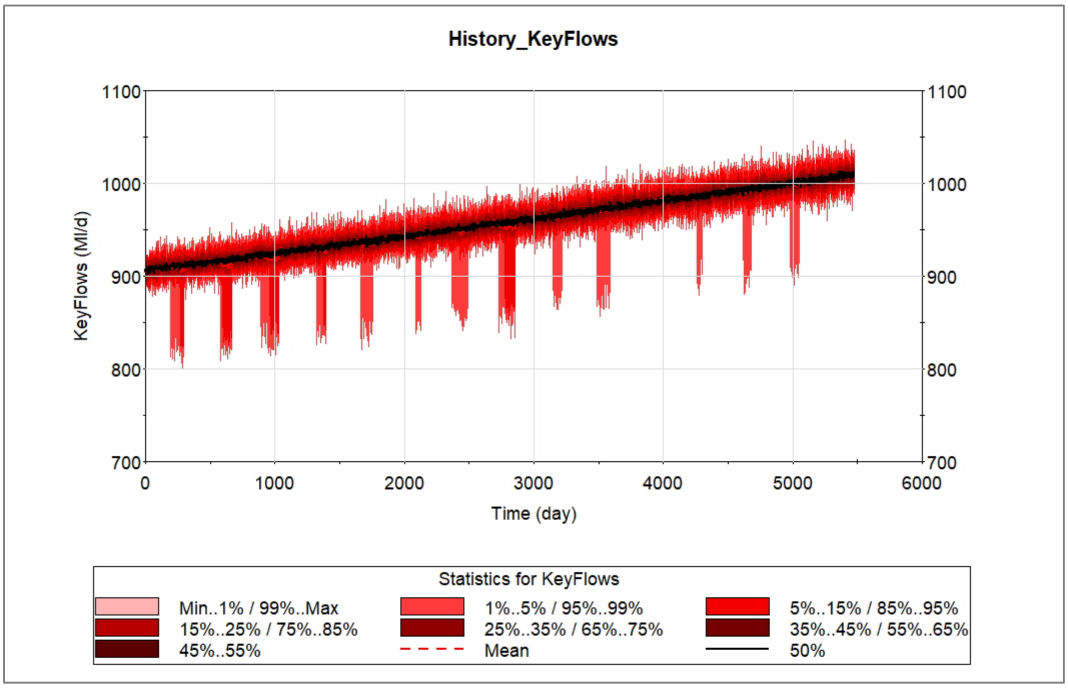


Figure C-70: Monte Carlo Analysis of Total Potable System Demand (Baseline Scenario)

WCWDM

Figure C-71 and Figure C-72 show the results of real loss reduction and consumer-focussed WCWDM measures; the probability ranges thereof ultimately impact the range in overall system performance.

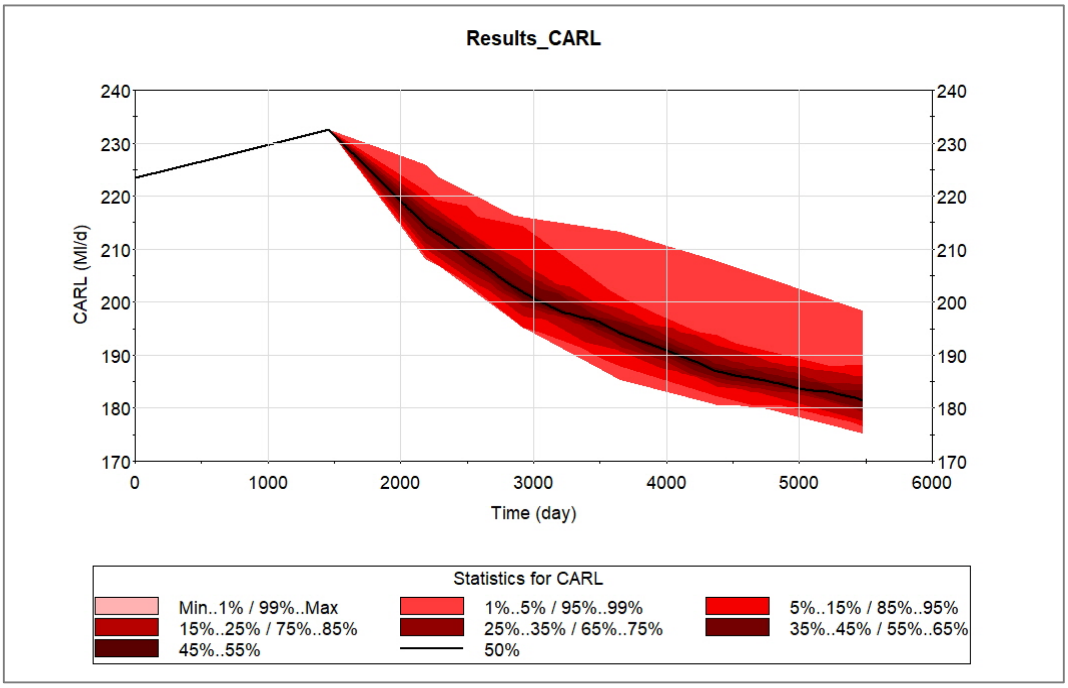


Figure C-71: Monte Carlo Analysis of Real Loss Reduction

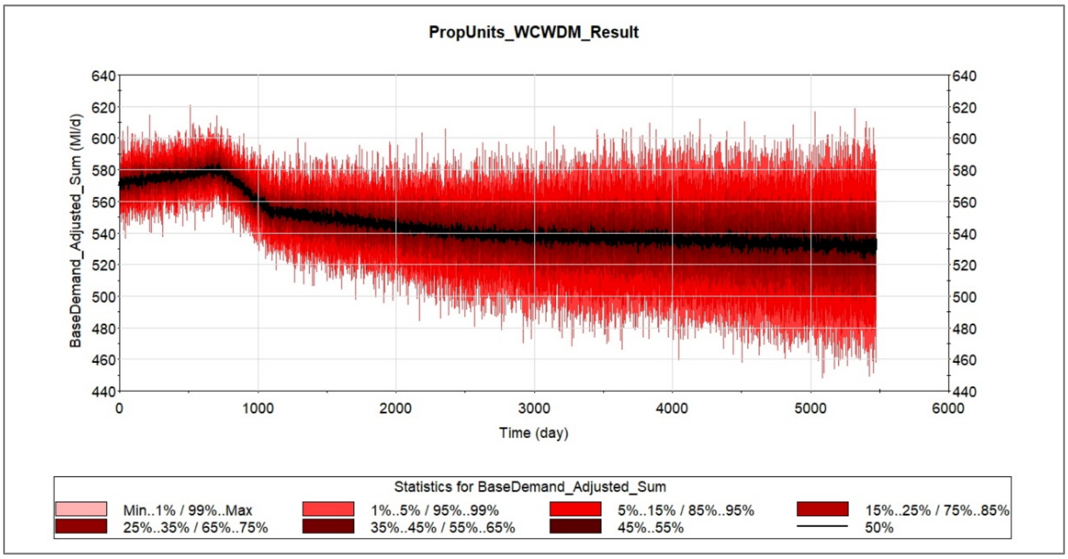


Figure C-72: Monte Carlo Analysis of Consumer-Focussed Demand Reduction

Figure C-73 to Figure C-77 show the impact on water resources and volume of potable water supplied.

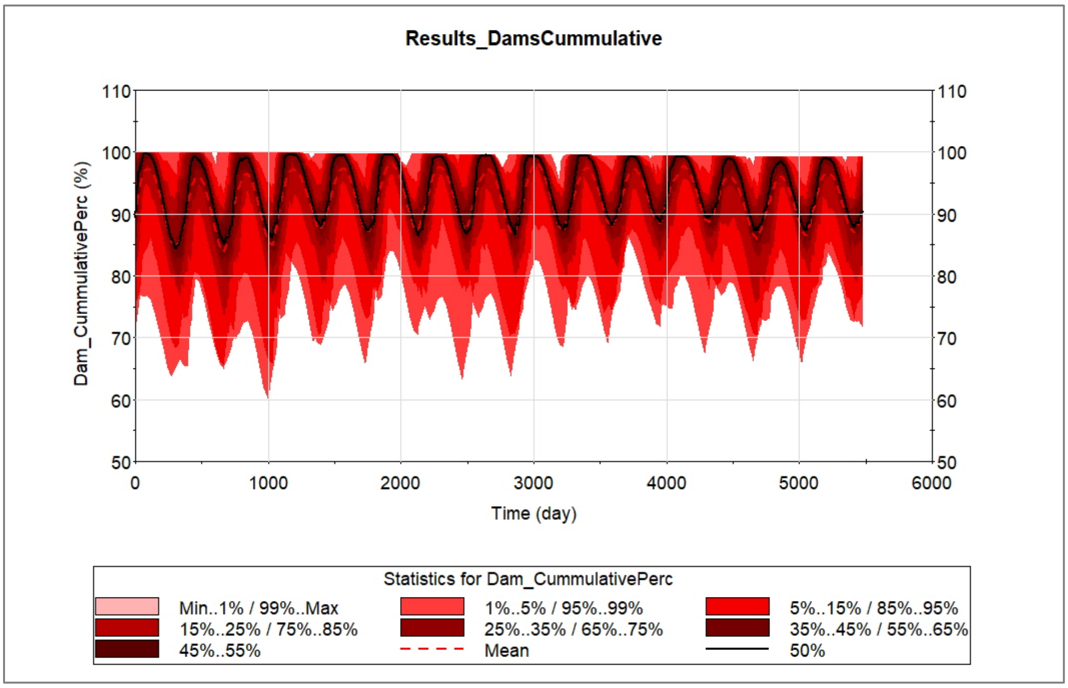


Figure C-73: Cumulative Dam Storage (WCWDM Scenario)

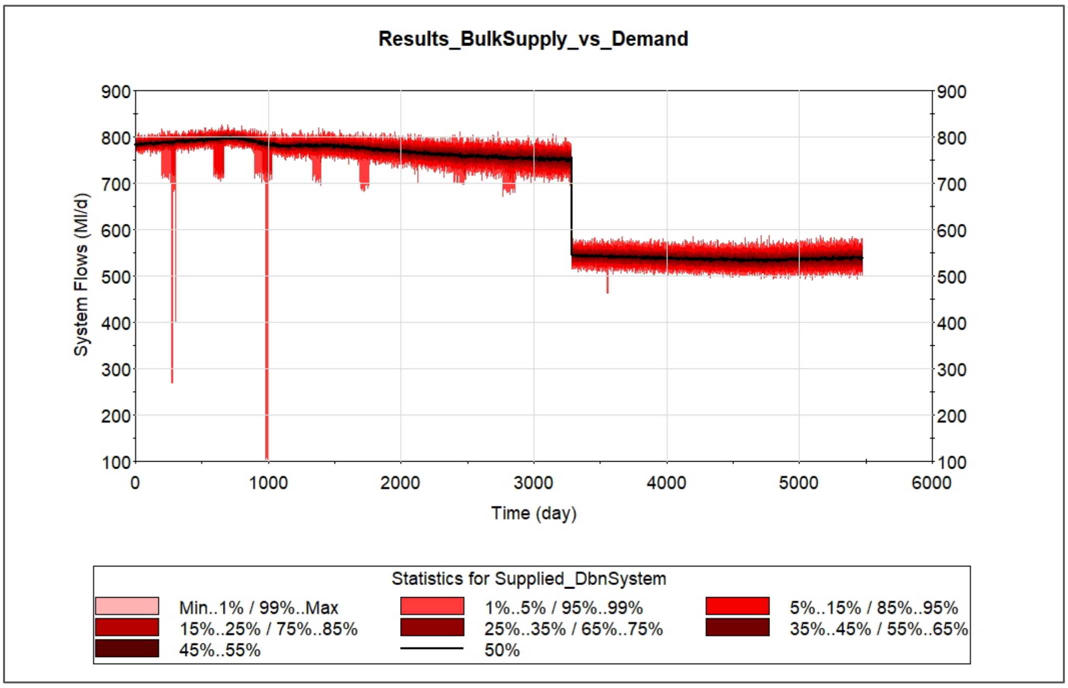


Figure C-74: Monte Carlo Analysis of Demand on Lower Mgeni System (WCWDM Scenario)

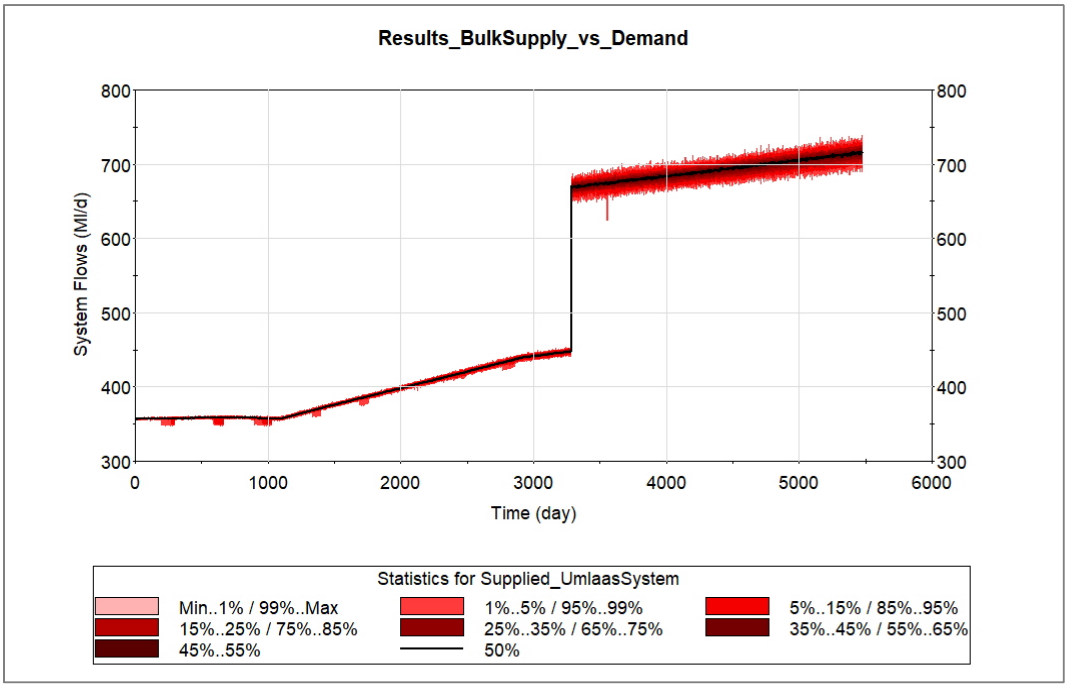


Figure C-75: Monte Carlo Analysis of Demand on Upper Mgeni System (WCWDM Scenario)

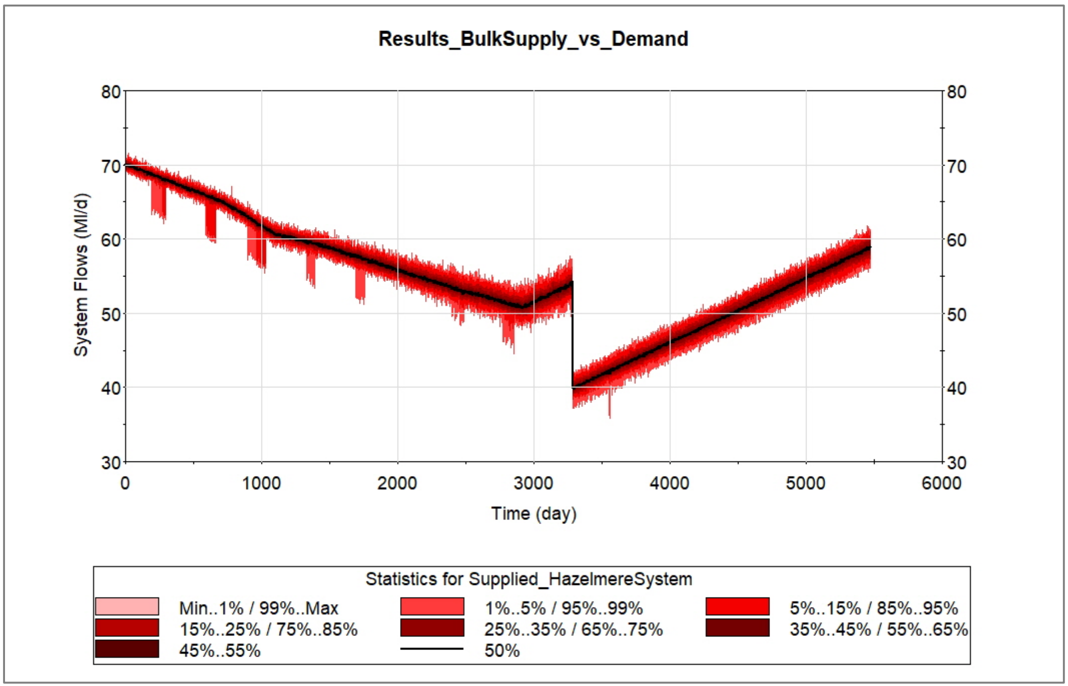


Figure C-76: Monte Carlo Analysis of Demand on Hazelmere System (WCWDM Scenario)

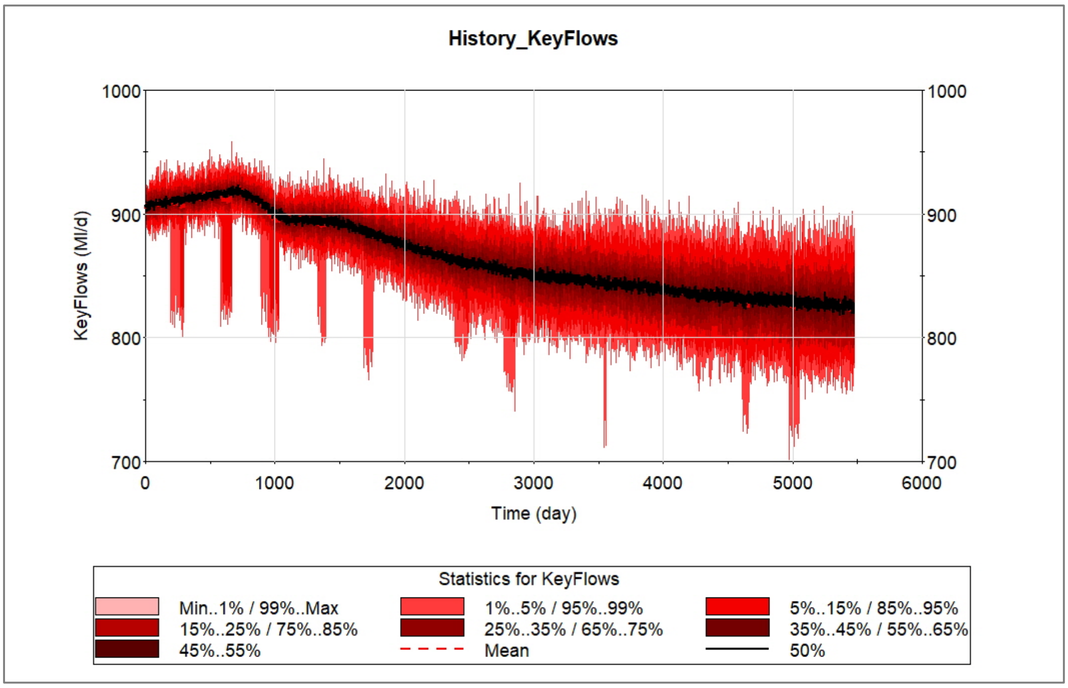


Figure C-77: Monte Carlo Analysis of Total Potable System Demand (WCWDM Scenario)

Figure C-78 and Figure C-79 show the impact on wastewater produced and treated.

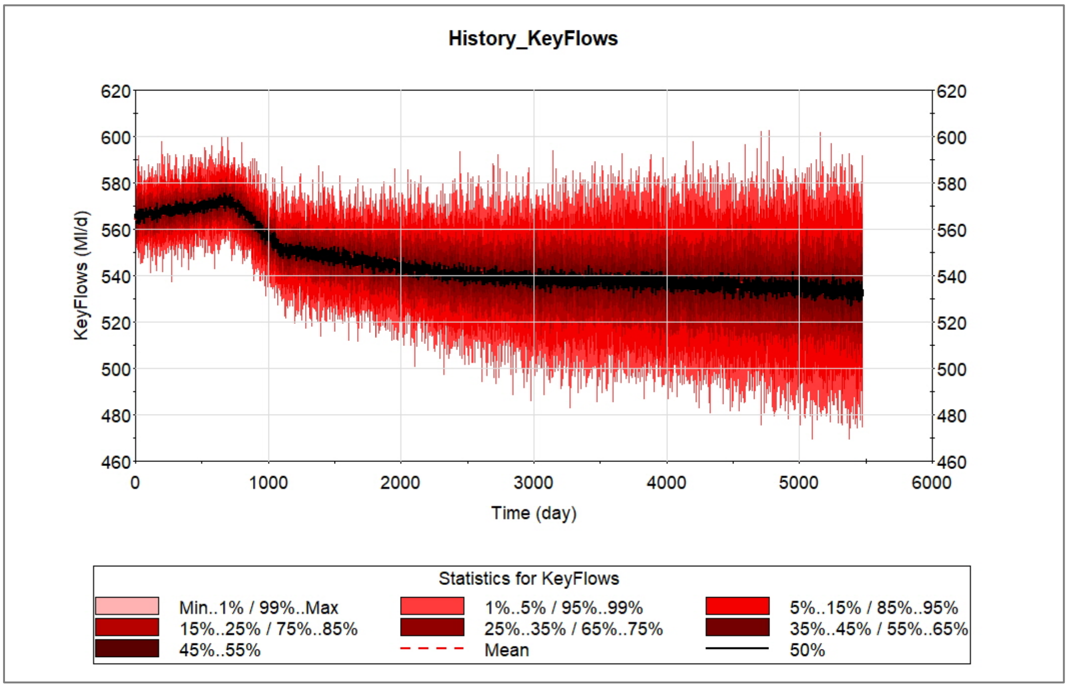


Figure C-78: Monte Carlo Analysis of Total Wastewater Produced (WCWDM Scenario)

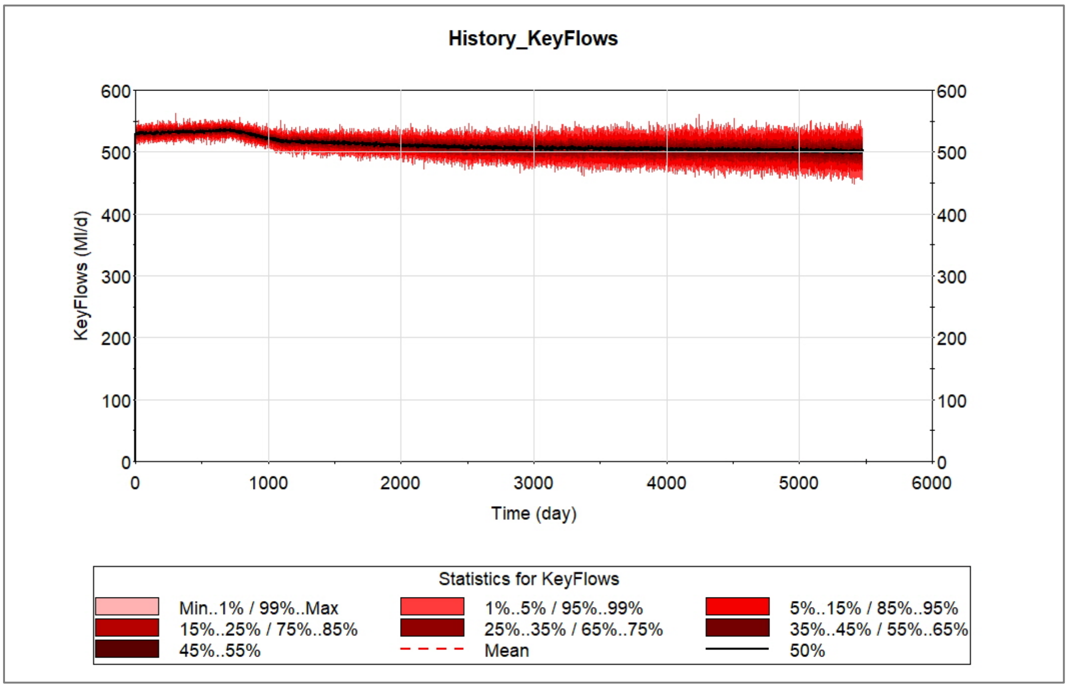


Figure C-79: Monte Carlo Analysis of Total Wastewater Treated (WCWDM Scenario)

Rainwater Harvesting & Real Loss Reduction

Figure C-80 illustrates the Monte Carlo analysis of total rainwater tank outflow volumes (i.e. volumes supplied).

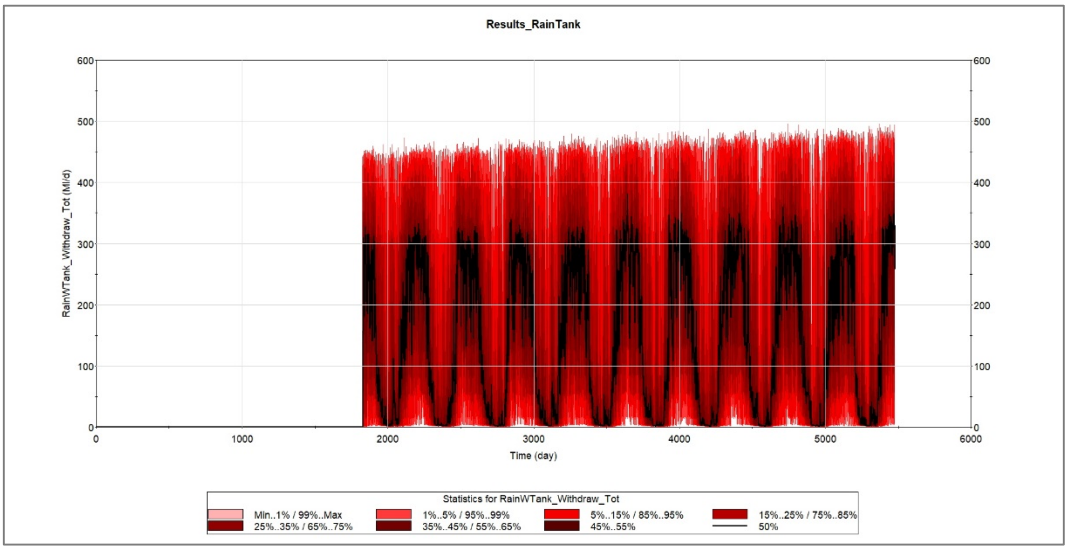


Figure C-80: Monte Carlo Analysis of Rainwater Tank Outflow Volumes

Figure C-81 to Figure C-85 show the impact on water resources and volume of potable water supplied.

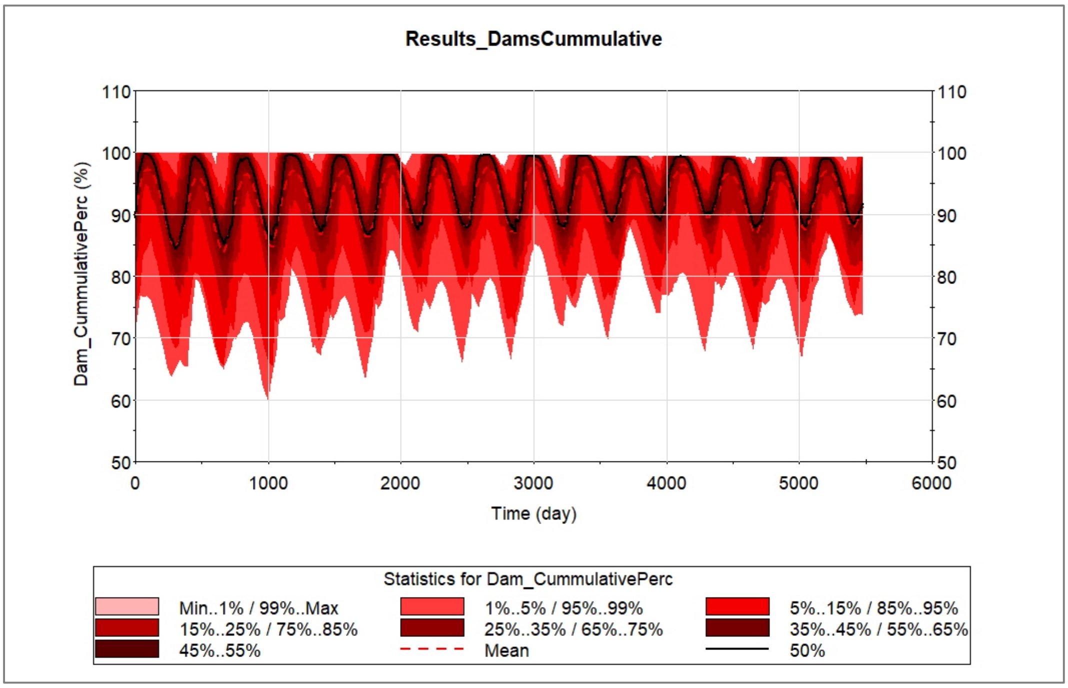


Figure C-81: Cumulative Dam Storage (Rainwater Harvesting Scenario)

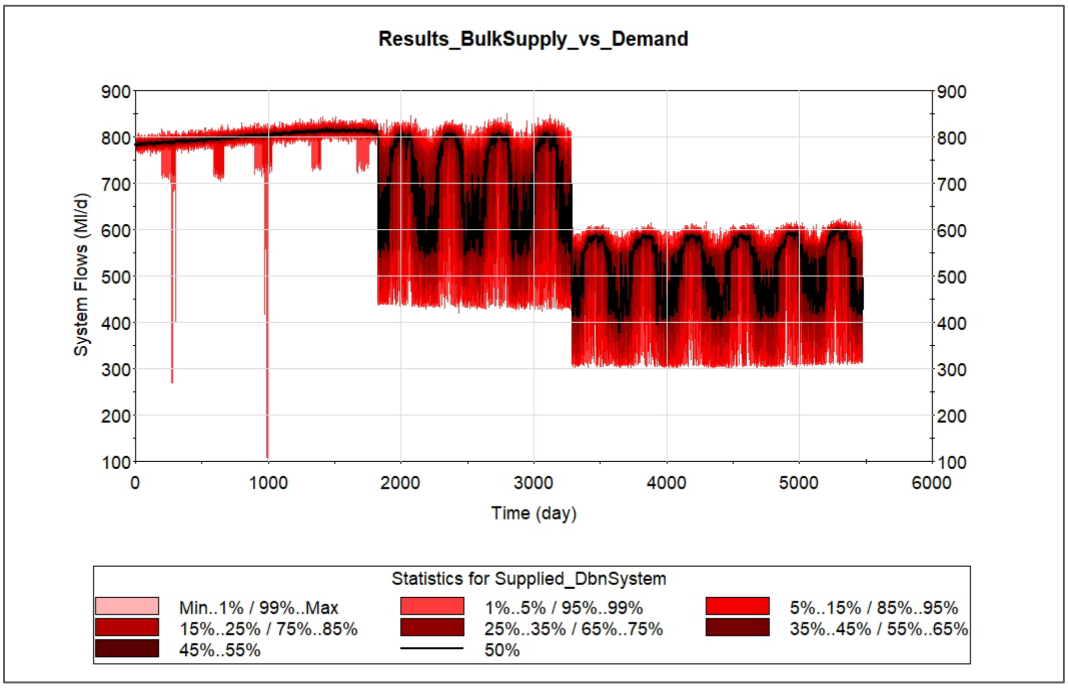


Figure C-82: Monte Carlo Analysis of Demand on Lower Mgeni System (Rainwater Harvesting Scenario)

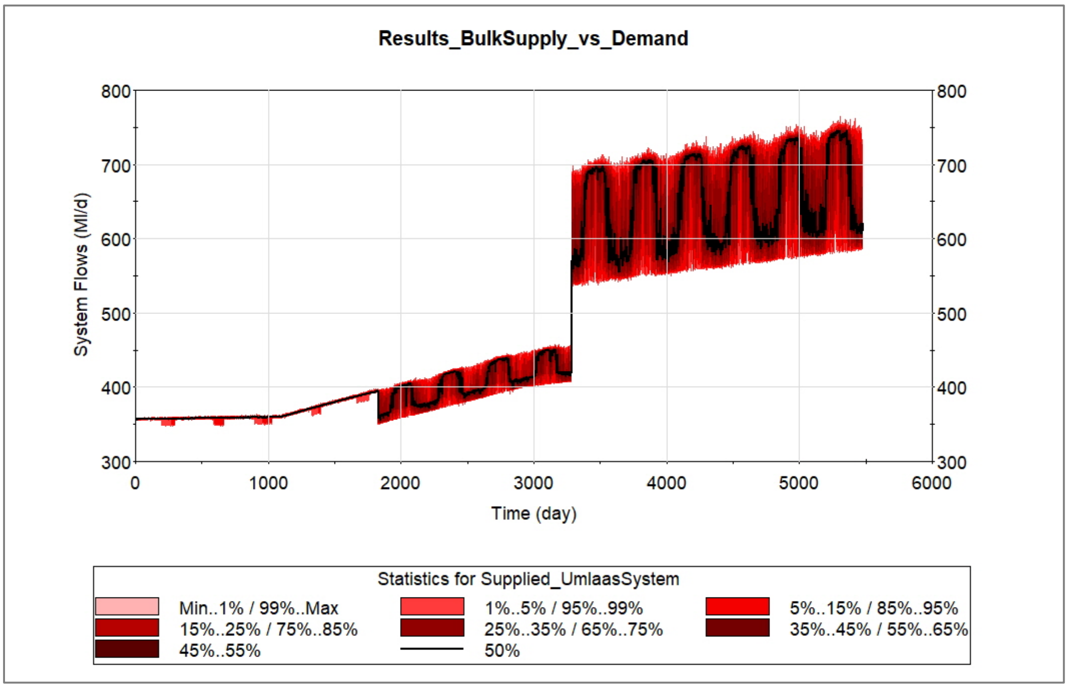


Figure C-83: Monte Carlo Analysis of Demand on Upper Mgeni System (Rainwater Harvesting Scenario)

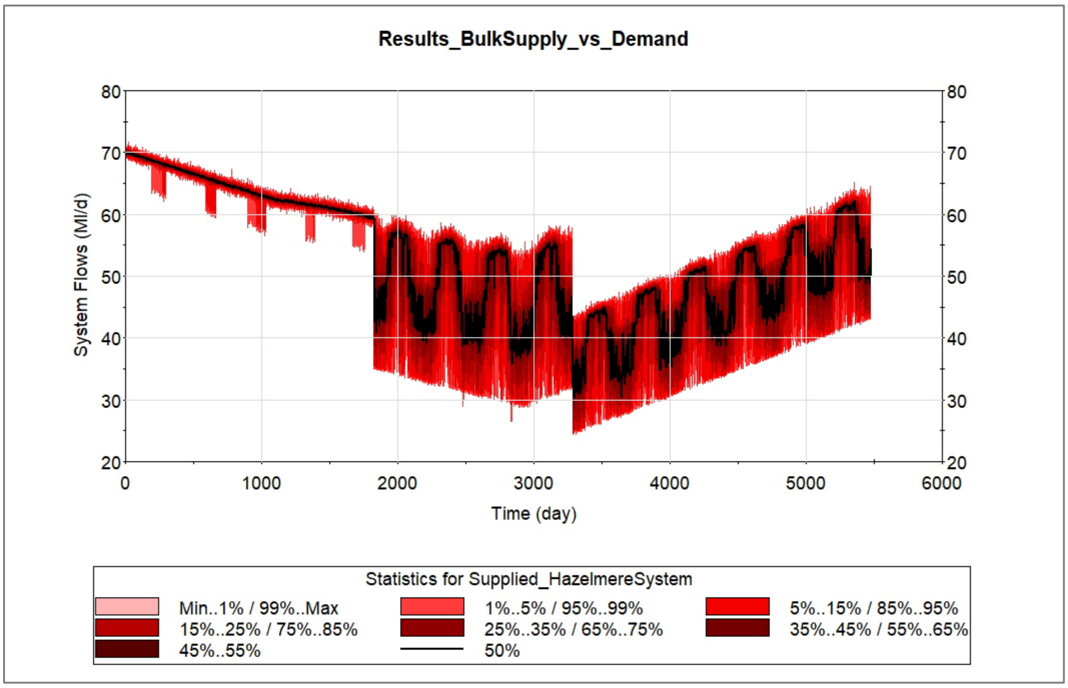


Figure C-84: Monte Carlo Analysis of Demand on Hazelmere System (Rainwater Harvesting Scenario)

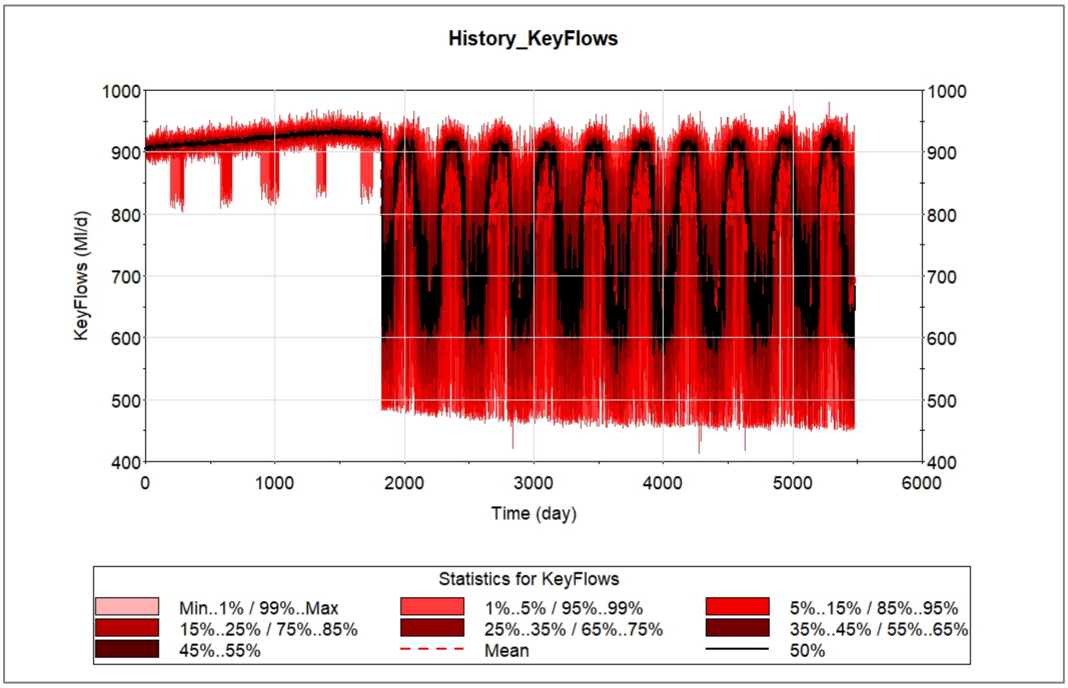


Figure C-85: Monte Carlo Analysis of Total Potable System Demand (Rainwater Harvesting Scenario)

Greywater Reuse & WCWDM

Figure C-86 indicates the range of greywater (total for all areas) which is reused.

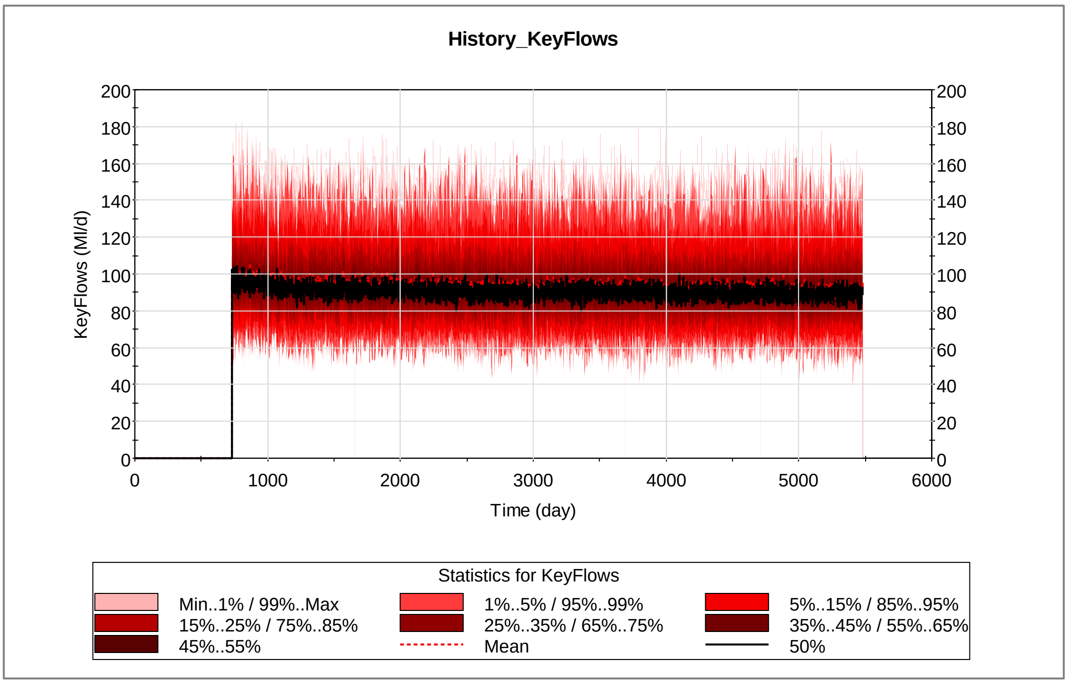


Figure C-86: Monte Carlo Analysis of Greywater Supplied

Figure C-87 to Figure C-91 show the impact on water resources and volume of potable water supplied.

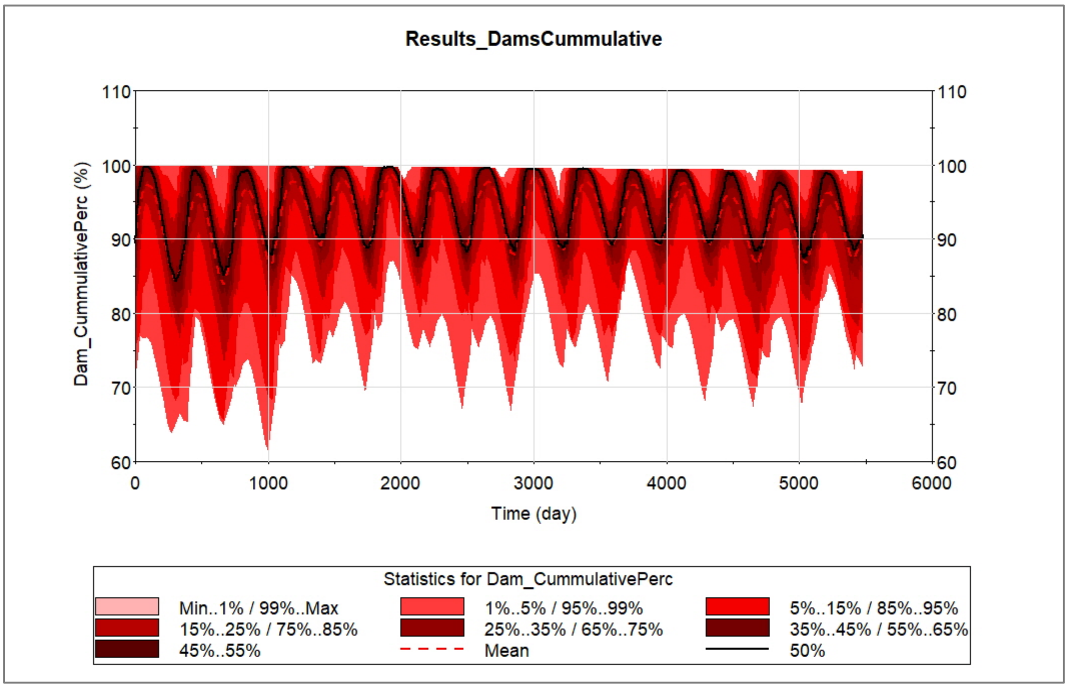


Figure C-87: Cumulative Dam Storage (Greywater Reuse Scenario)

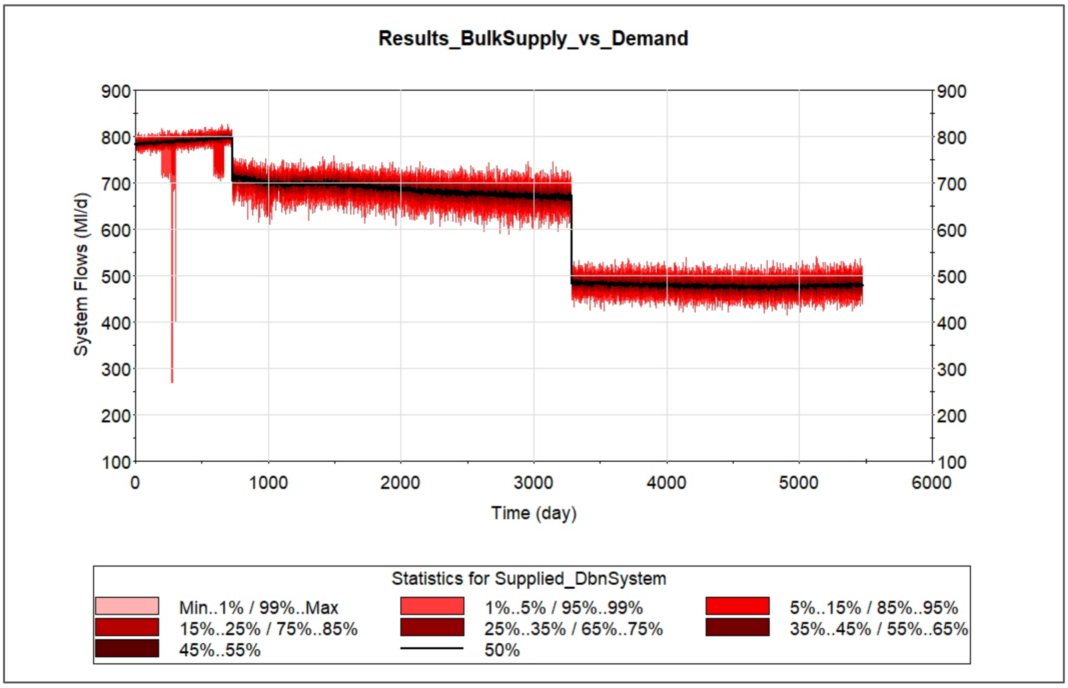


Figure C-88: Monte Carlo Analysis of Demand on Lower Mgeni System (Greywater Reuse Scenario)

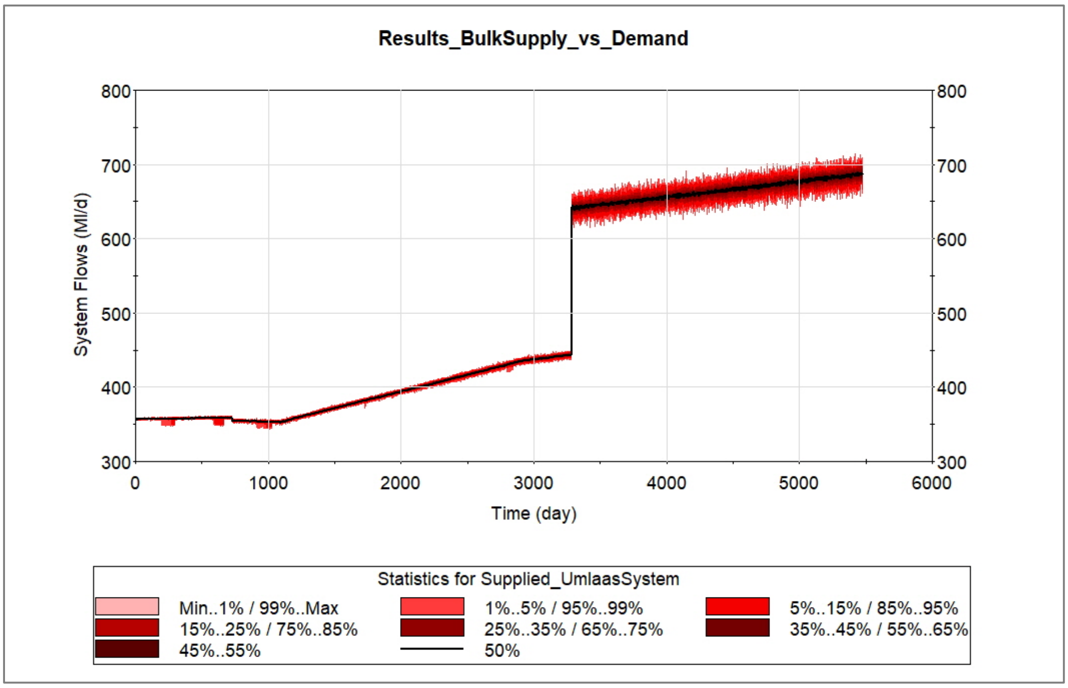


Figure C-89: Monte Carlo Analysis of Demand on Upper Mgeni System (Greywater Reuse Scenario)

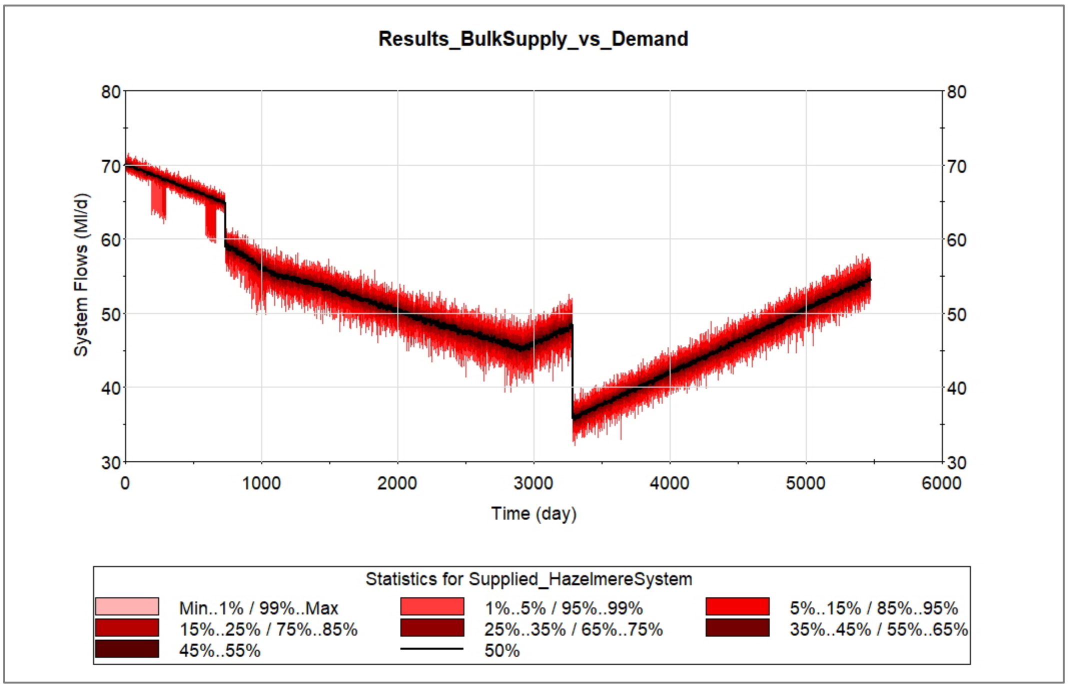


Figure C-90: Monte Carlo Analysis of Demand on Hazelmere System (Greywater Reuse Scenario)

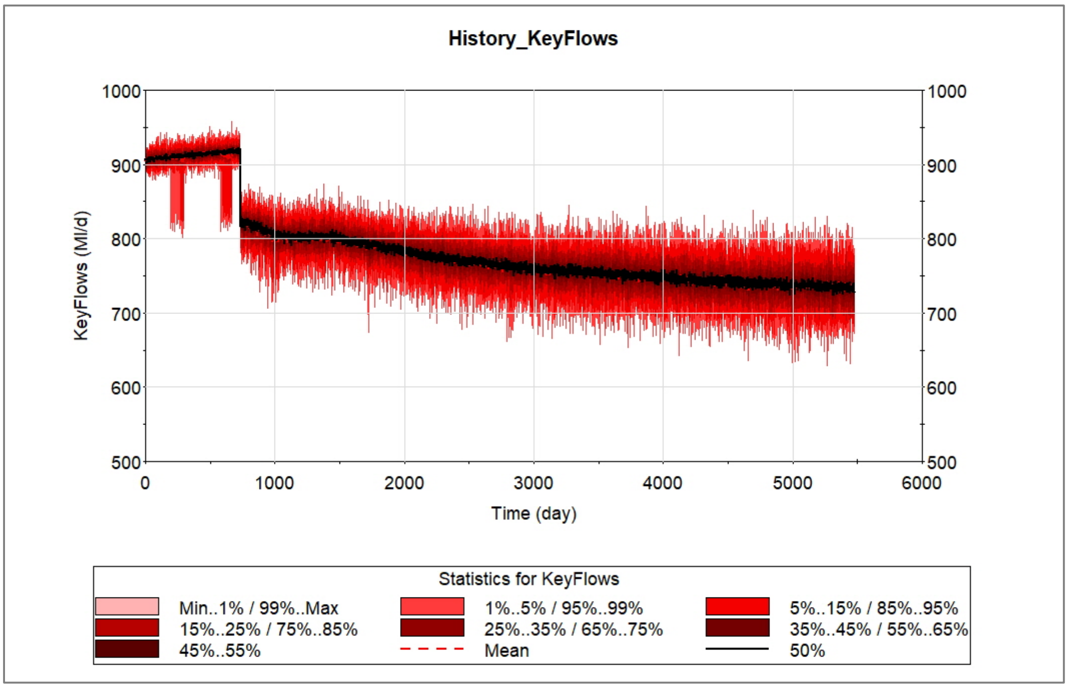


Figure C-91: Monte Carlo Analysis of Total Potable System Demand (Greywater Reuse Scenario)

Figure C-92 and Figure C-93 show the impact on wastewater produced and treated.

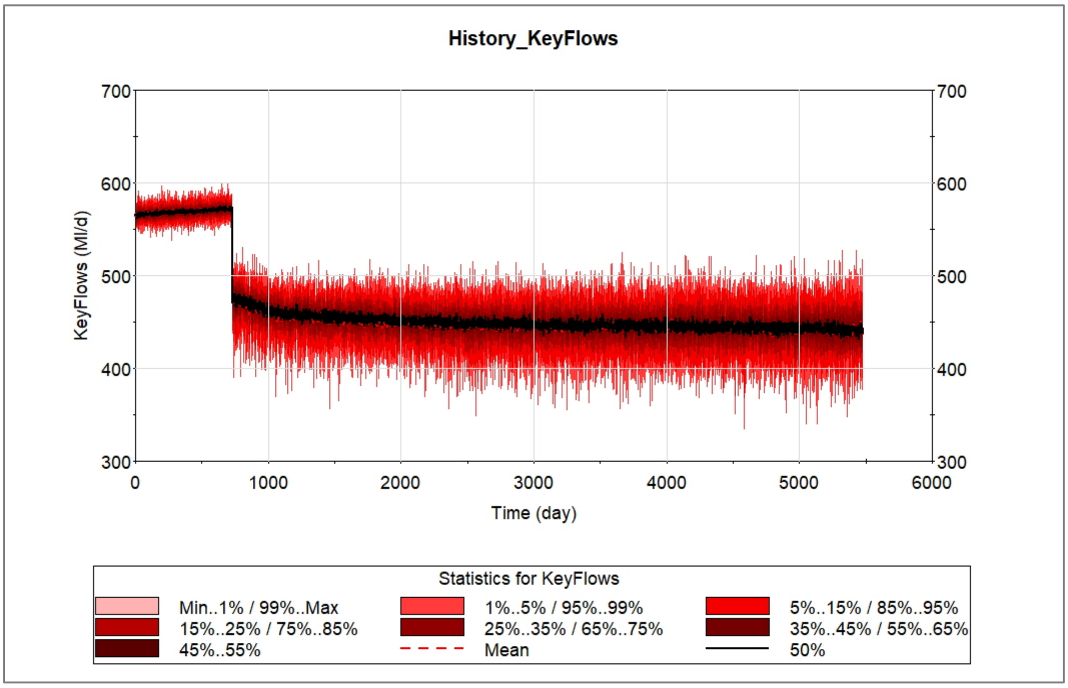


Figure C-92: Monte Carlo Analysis of Total Wastewater Produced (Greywater Reuse Scenario)

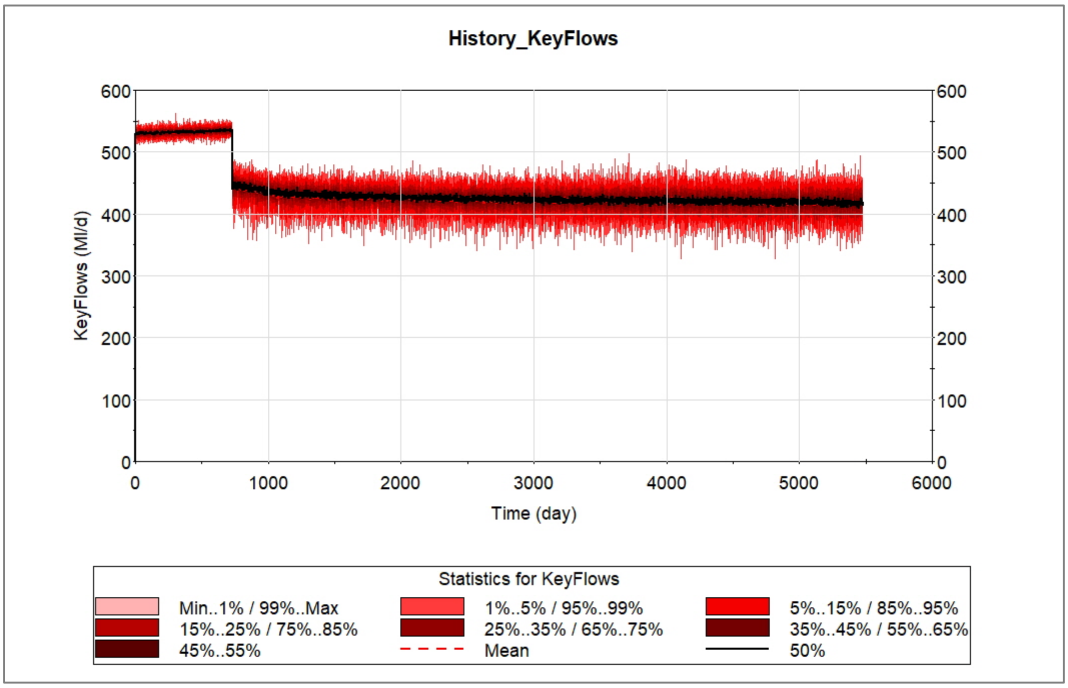


Figure C-93: Monte Carlo Analysis of Total Wastewater Treated (Greywater Reuse Scenario)

Wastewater Recycling & Real Loss Reduction

Figure C-94 and Figure C-95 indicate the range of total recycled wastewater supplied.

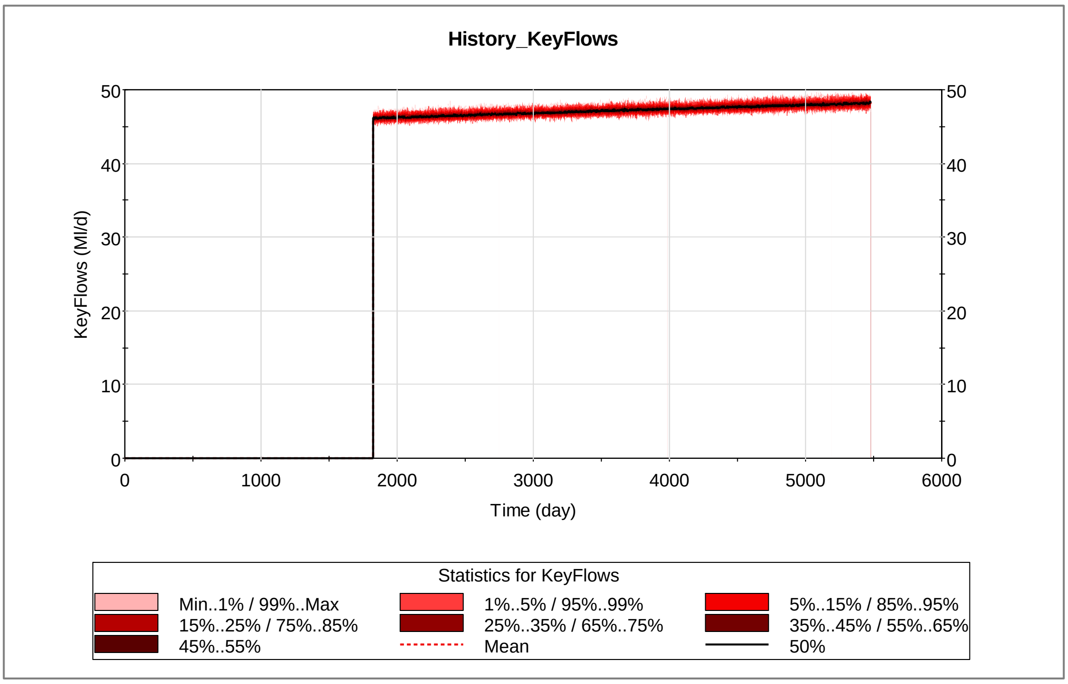


Figure C-94: Monte Carlo Analysis of Recycled Wastewater Volumes (Non-Potable Standard)

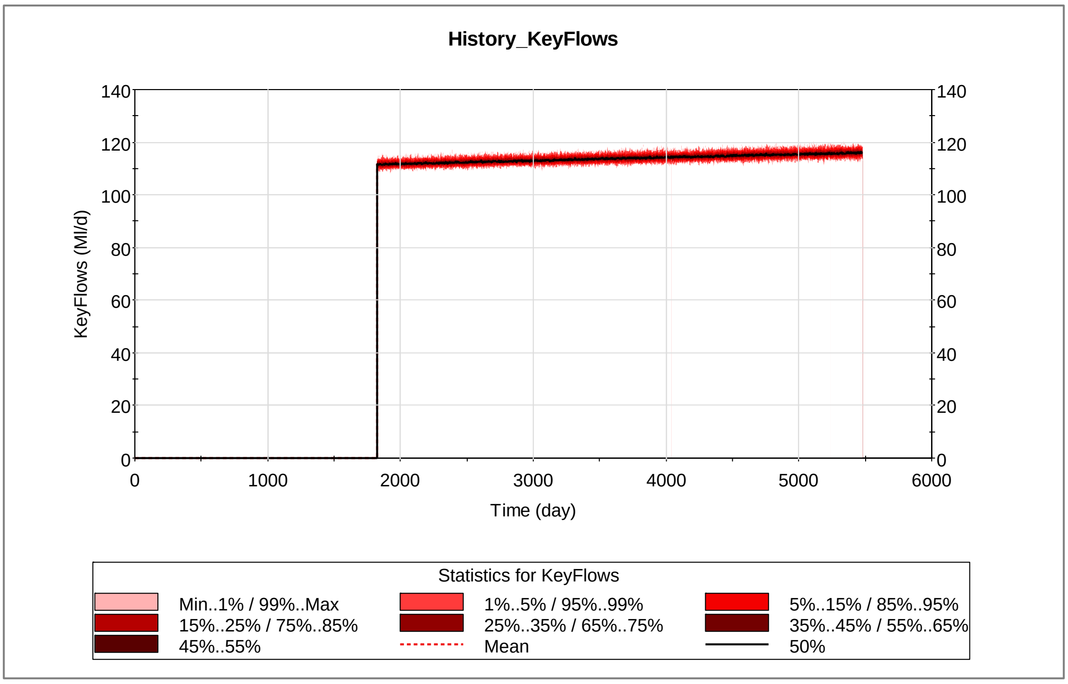


Figure C-95: Monte Carlo Analysis of Recycled Wastewater Volumes (Potable Standard)

Figure C-96 to Figure C-100 show the impact on water resources and volume of potable water supplied.

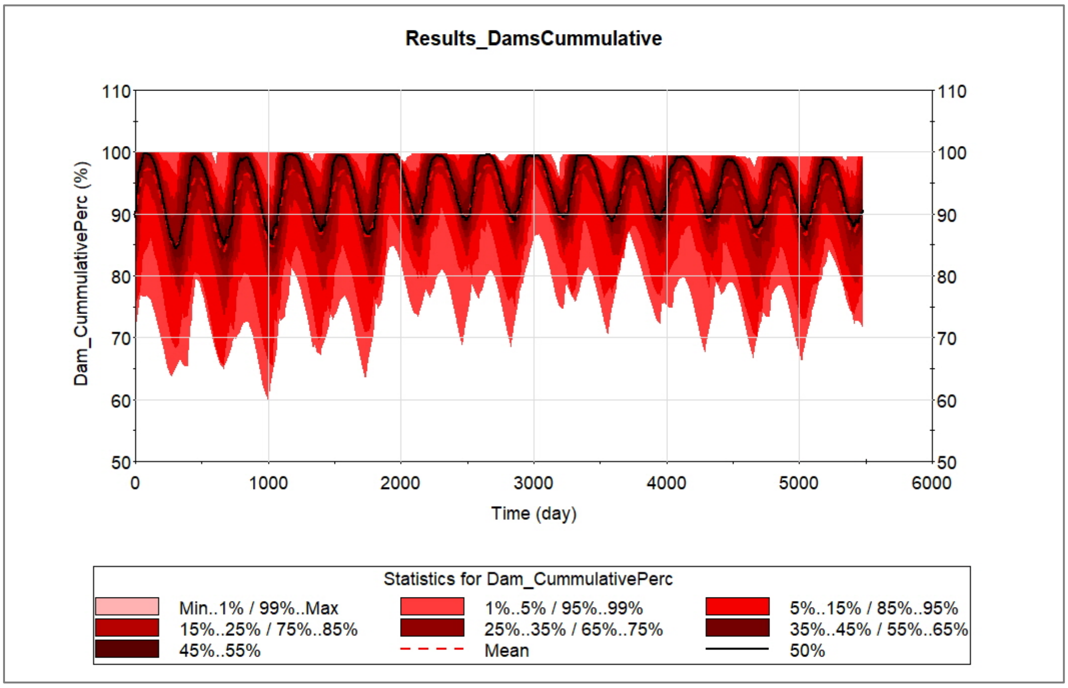


Figure C-96: Cumulative Dam Storage (Wastewater Recycling Scenario)

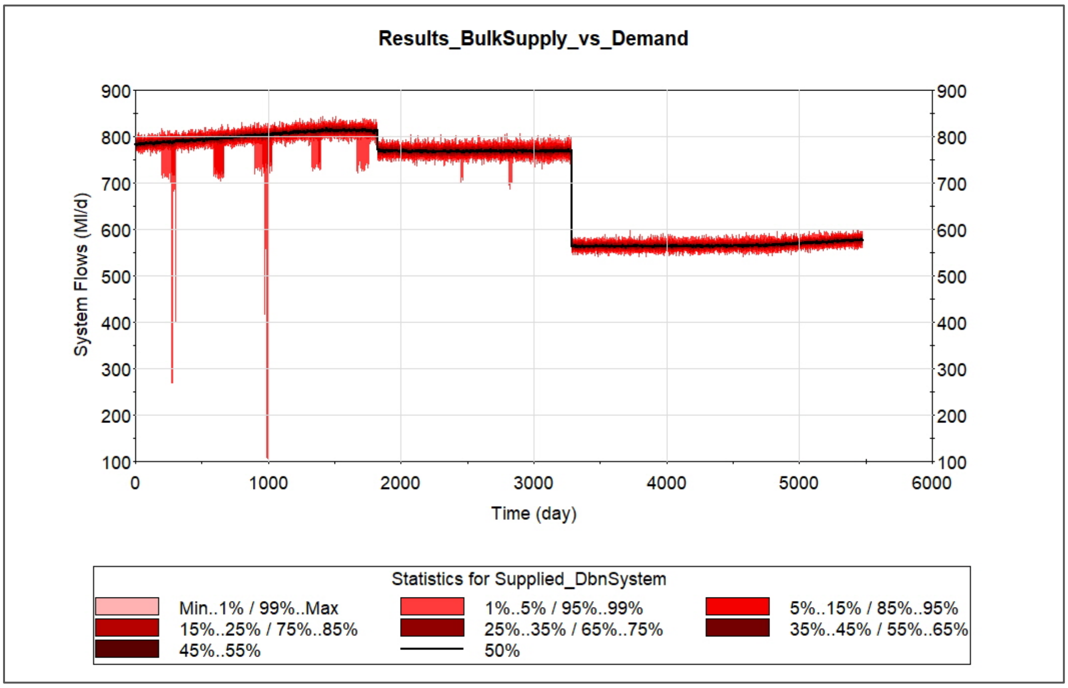


Figure C-97: Monte Carlo Analysis of Demand on Lower Mgeni System (Wastewater Recycling Scenario)

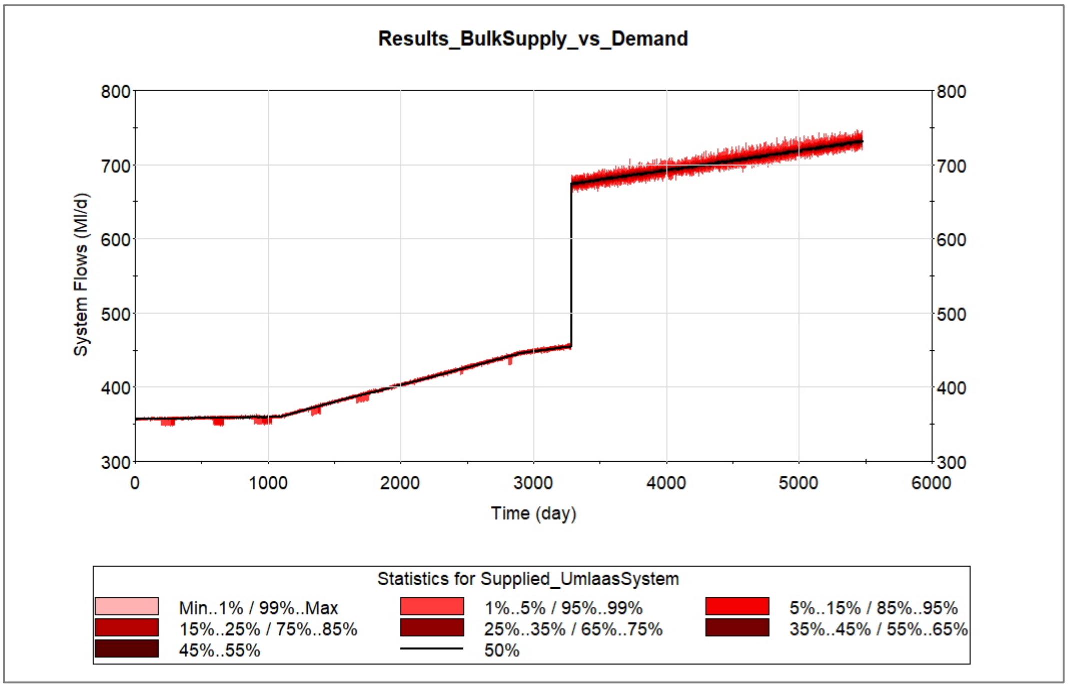


Figure C-98: Monte Carlo Analysis of Demand on Upper Mgeni System (Wastewater Recycling Scenario)

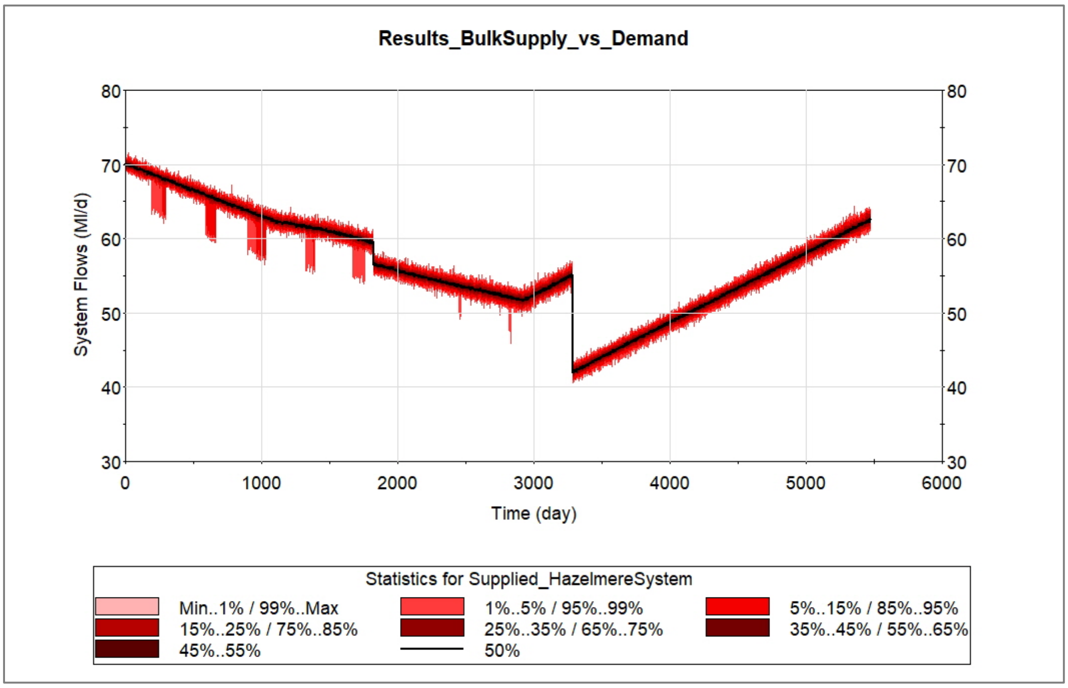


Figure C-99: Monte Carlo Analysis of Demand on Hazelmere System (Wastewater Recycling Scenario)

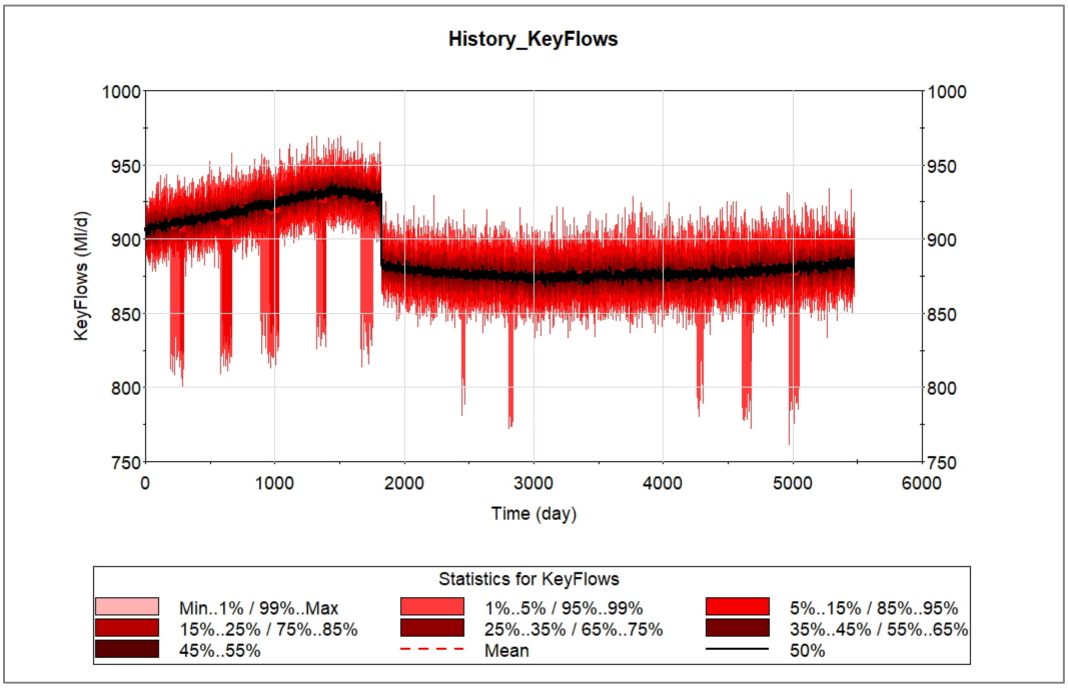


Figure C-100: Monte Carlo Analysis of Total Potable System Demand (Wastewater Recycling Scenario)

Performance Indicator Outputs for Key Scenarios

The growth in the potable water (Figure C-101) and wastewater (Figure C-102) conveyed is shown for each scenario; the growth over the simulation period is compared to the average over the first year.

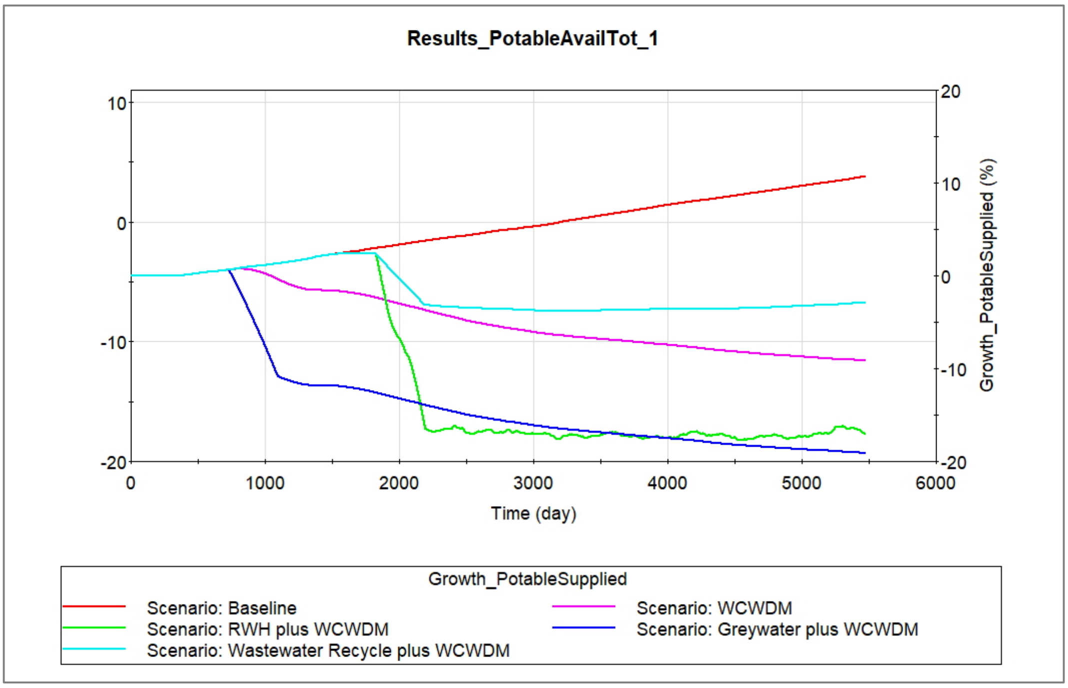


Figure C-101: Growth in Potable Water Demand, Performance across Scenarios

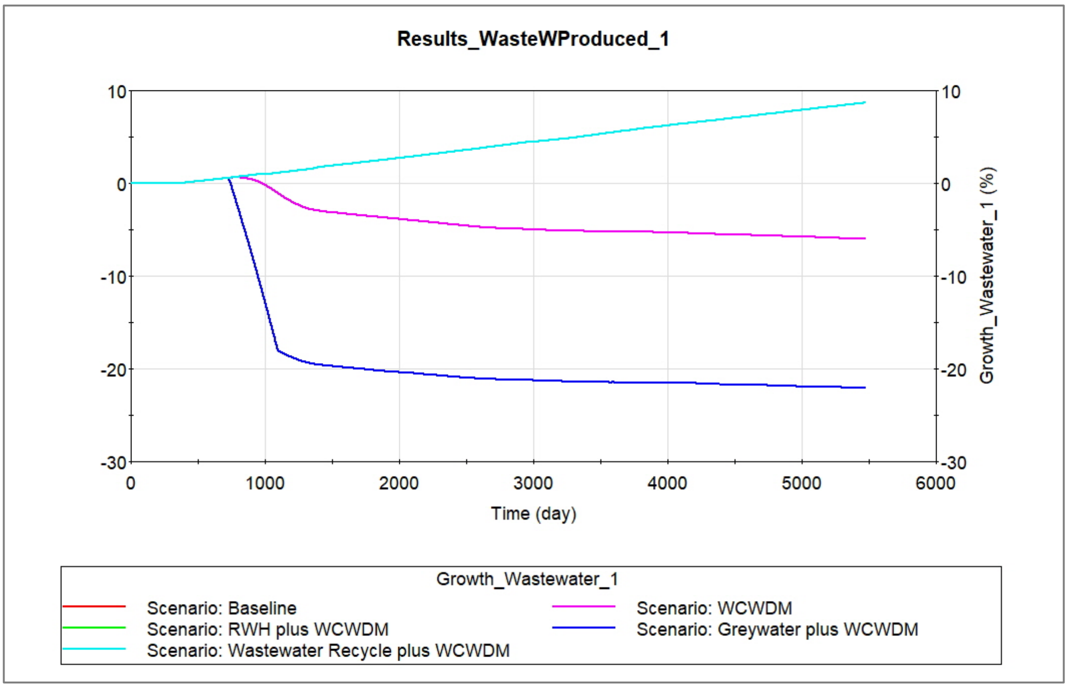
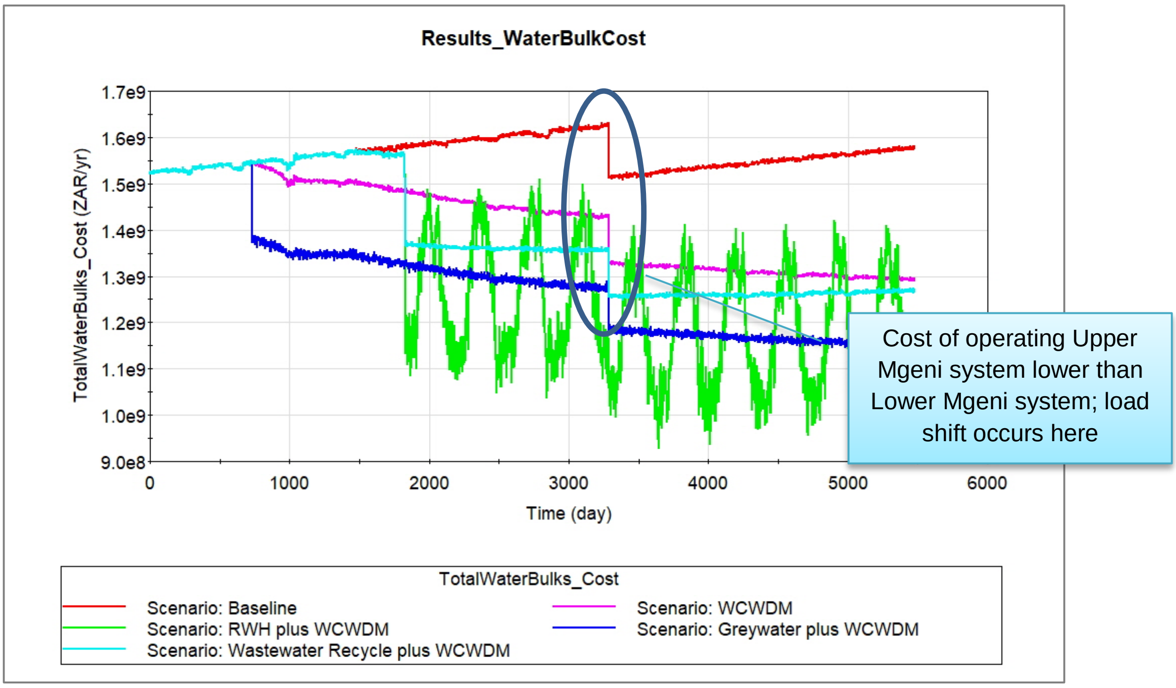


Figure C-102: Growth in Wastewater Flows, Performance across Scenarios

Given the changes to volumes of potable water supplied and wastewater generated, there are implications for the operational cost and energy associated with service provision. This is, however, offset with the operational cost and energy requirements of the respective interventions. The subsequent set of figures breaks down the cost and energy utilisation for bulk service provision and the alternative water supply options.



Cost of operating Upper Mgeni system lower than Lower Mgeni system; load shift occurs here

Note: The cost of operating the Upper Mgeni system is lower than that of the Lower Mgeni system; as a result, when the load shift operation occurs when uMWP is implemented, there is a drop in overall operating costs.

Figure C-103: Cost of Bulk Water Supply

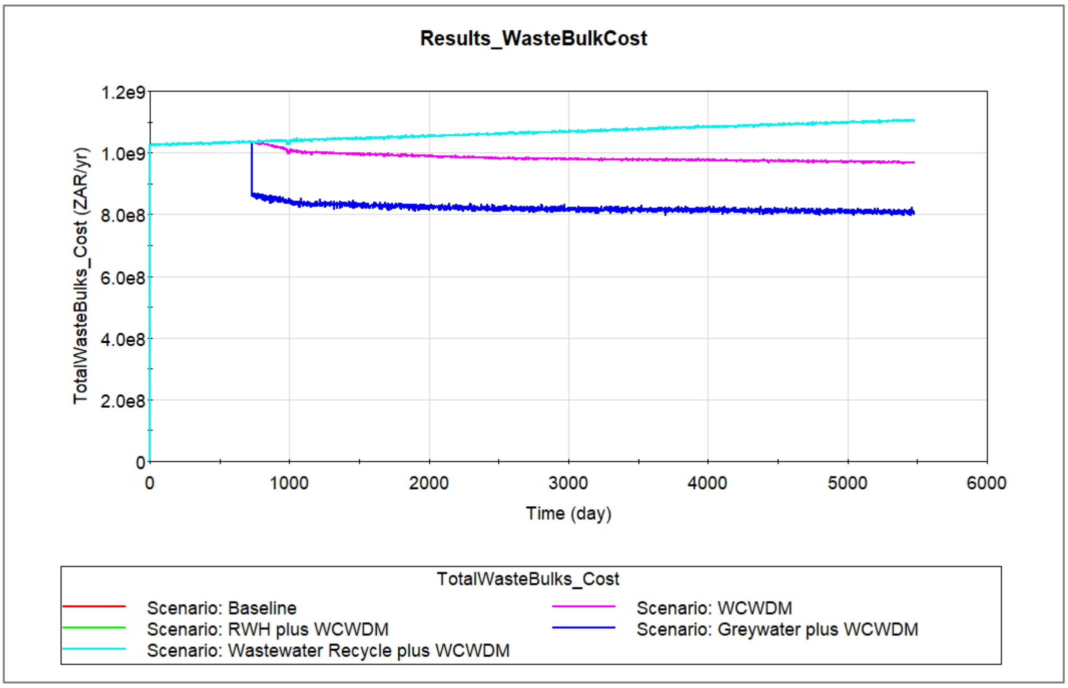


Figure C-104: Cost of Bulk Sanitation Services

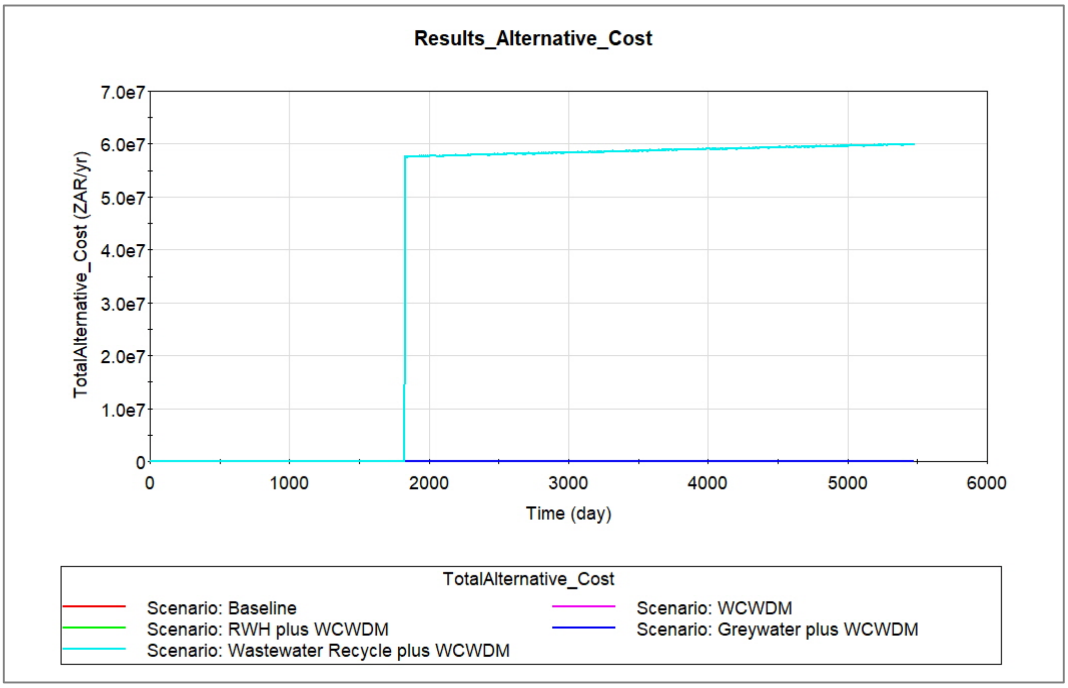


Figure C-105: Cost of Alternative Water Supply

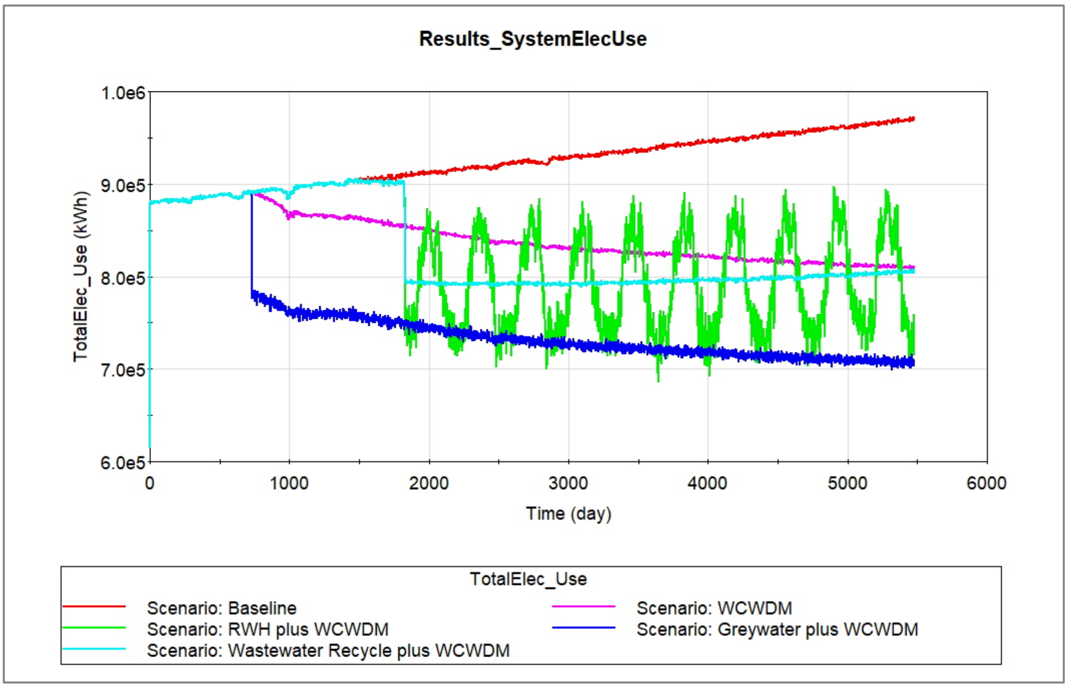


Figure C-106: Electricity Use of Bulk Water & Sanitation Services

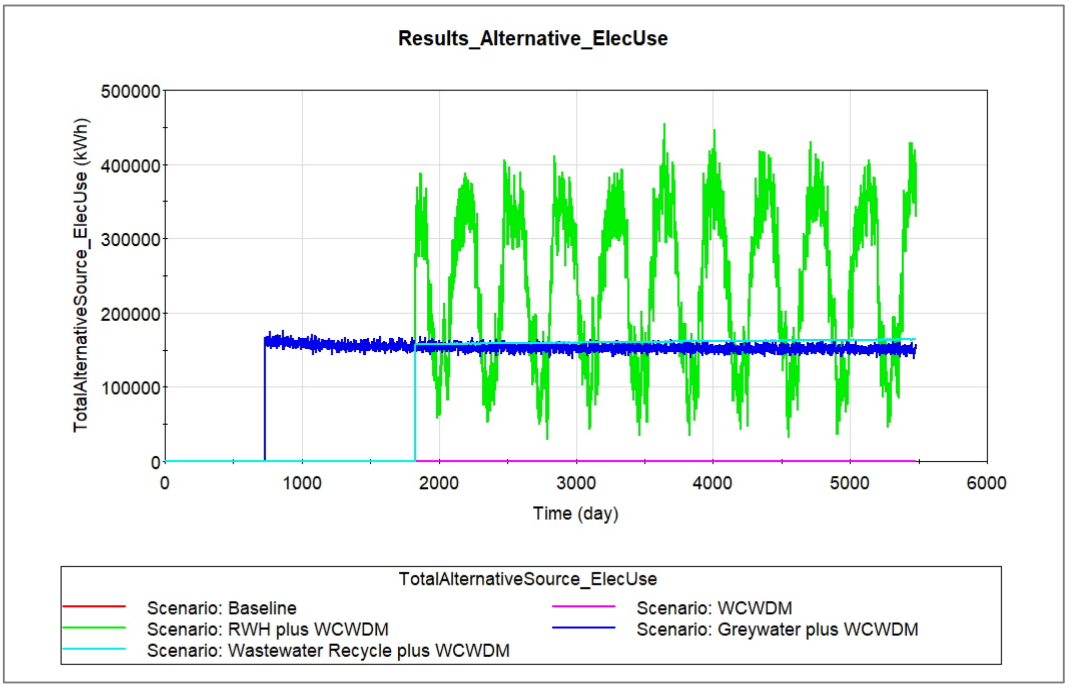


Figure C-107: Electricity Use for Alternative Water Supply

It must be noted that the operational costs presented herein are from the perspective of the municipality; as such, the operating cost of rainwater harvesting and greywater reuse is assumed to be carried by the consumer. On the other hand, energy utilisation is considered for both the municipality and the end-user to obtain the total energy consumption associated with the system. Capital expenditure associated with the bulk infrastructure and interventions is expressly excluded from this analysis.

The net impact on the overall cost and energy requirements of service provision – the combined result of bulk service provision and alternative water supplies – is shown in Figure C-108 to Figure C-109.

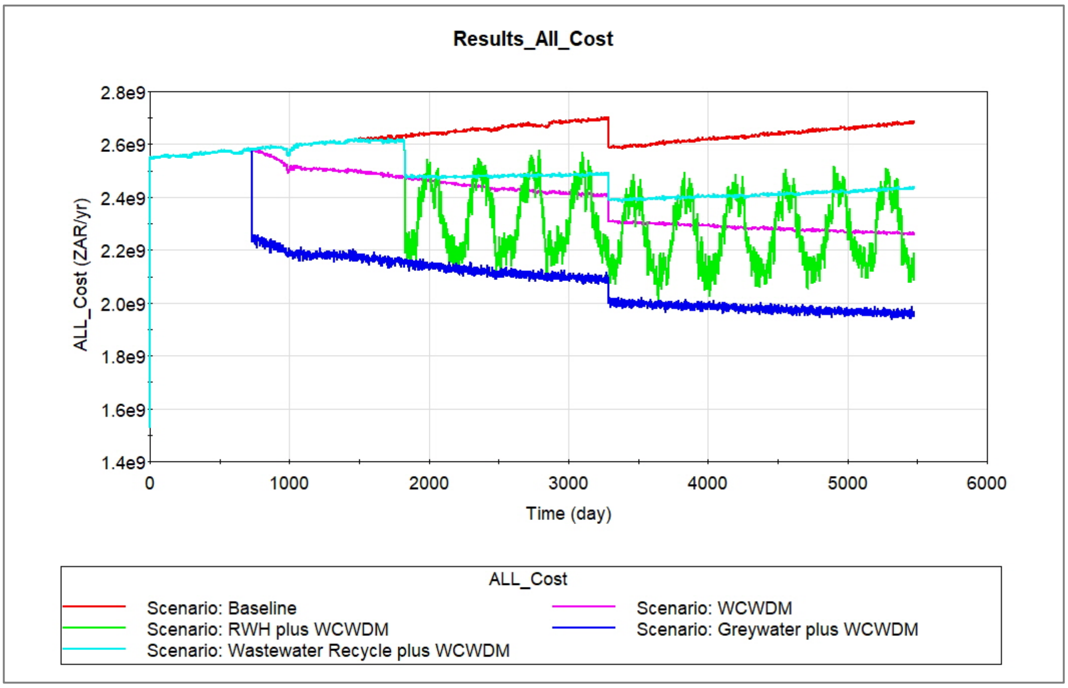


Figure C-108: Total Cost of Bulk Water & Sanitation Services & Alternative Water Sources, Performance across Scenarios

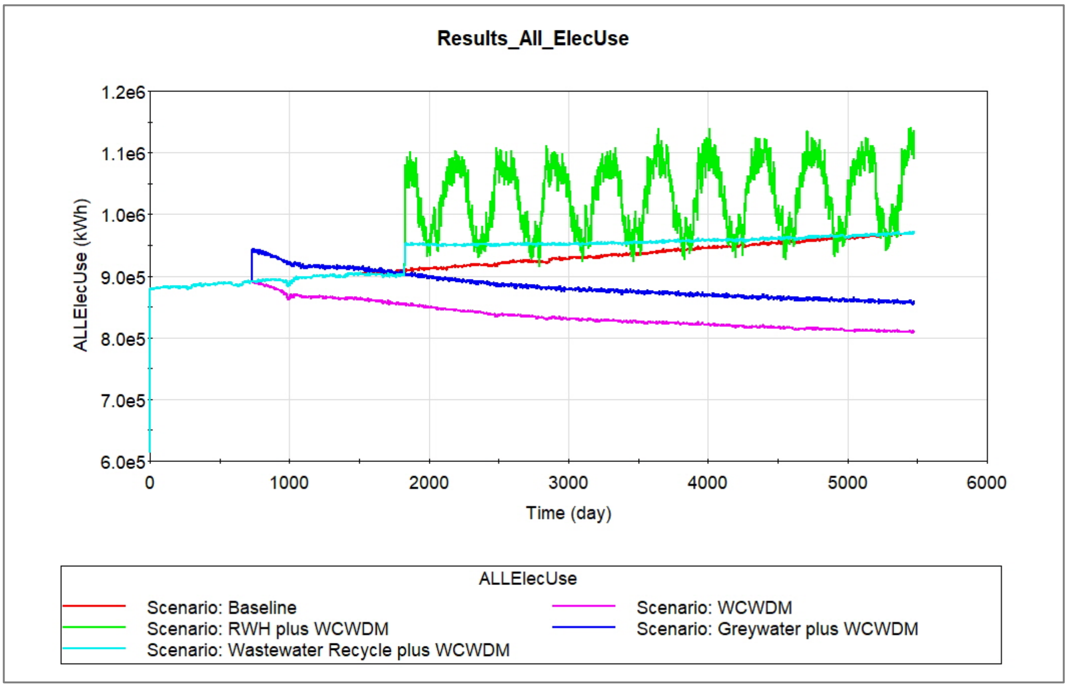


Figure C-109: Total Electricity Use of Bulk Water & Sanitation Services & Alternative Water Sources, Performance across Scenarios

Figure C-110 shows the growth in the total cost of service provision; Figure C-111 shows the growth in the total energy utilisation associated with service provision.

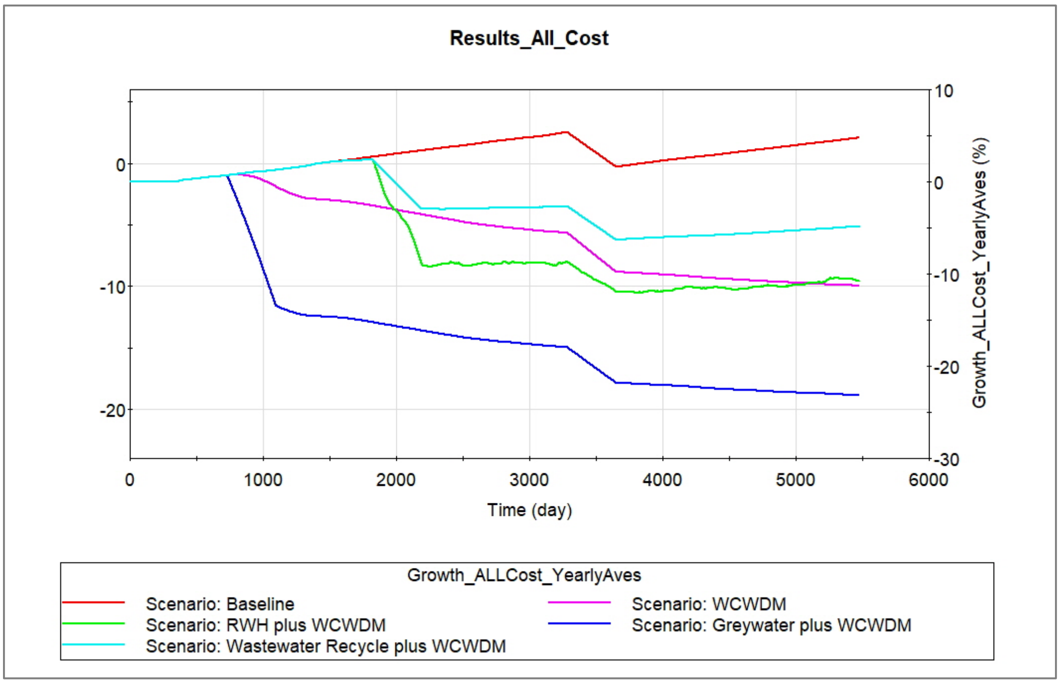


Figure C-110: Growth in Cost of Bulk Water & Sanitation Services & Alternative Water Sources, Performance across Scenarios

While there are energy increases associated with rainwater harvesting and greywater reuse as a result of possibly needing to pump water from storage locations to the rest of the property, the actual energy use here would depend on the system configuration for individual consumers. In some cases, where rainwater or greywater are supplied to end-uses under gravity or by manual means, there would be no energy consumption. The energy utilisation for these scenarios should therefore be viewed as the upper envelope of such.

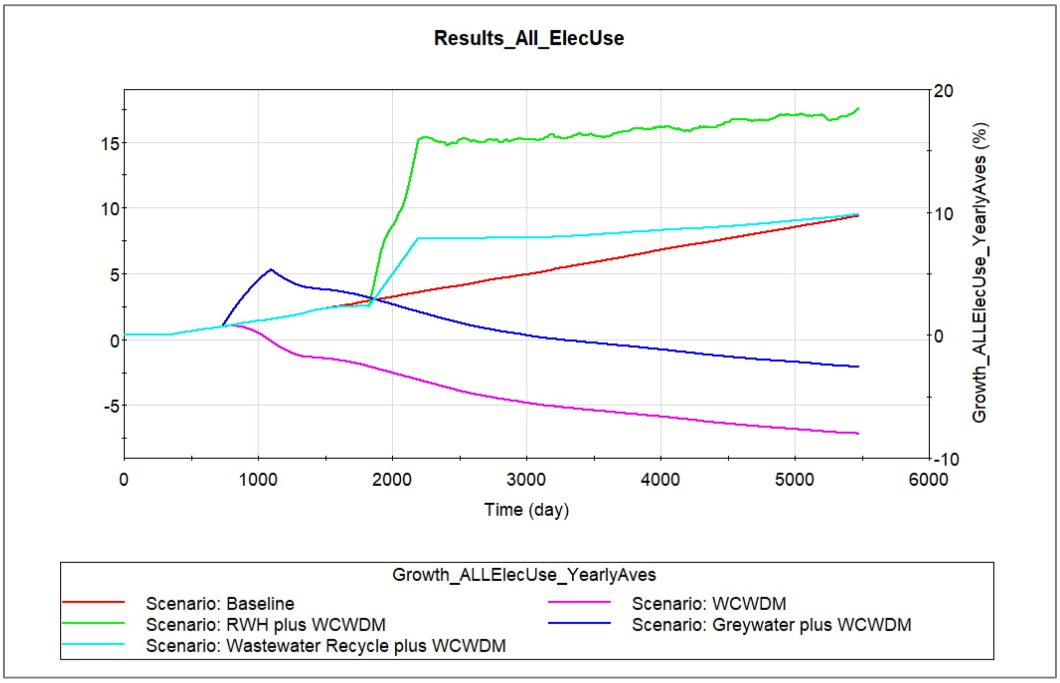


Figure C-111: Growth in Electricity Use of Bulk Water & Sanitation Services & Alternative Water Sources, Performance across Scenarios

The energy use per capita (Figure C-112) is a useful measure of resource efficiency (along with the potable water supplied per capita as shown in Chapter 6).

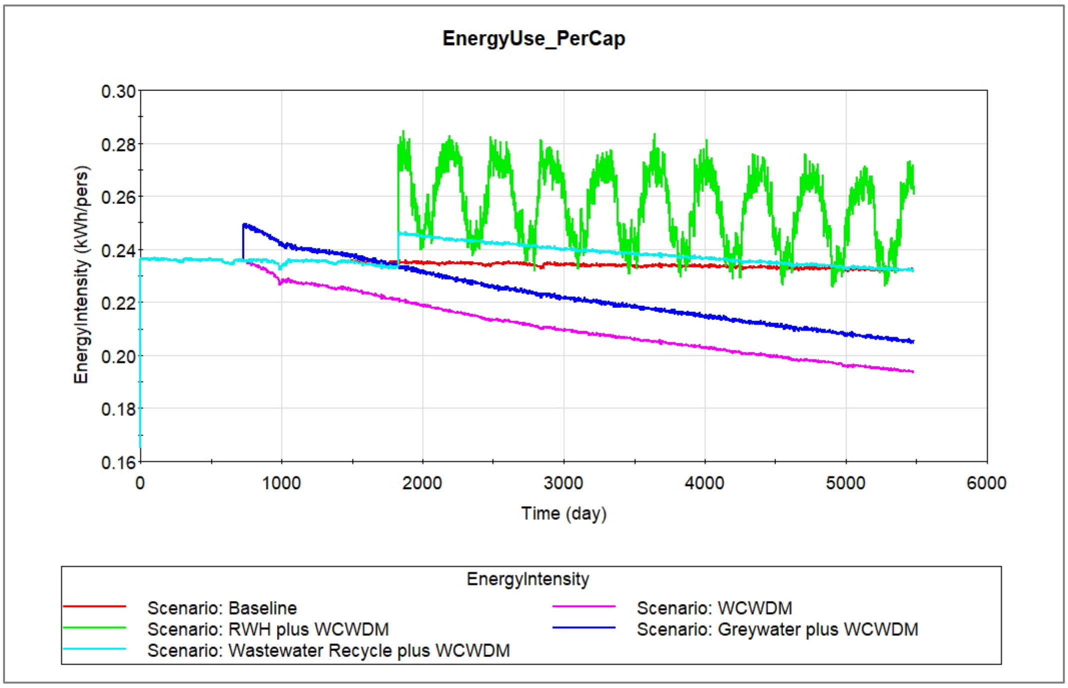


Figure C-112: Energy Use per Capita

Further measures of resource efficiency are the internal harvesting and internal recycling ratios, shown in Figure C-113 and Figure C-114 (respectively).

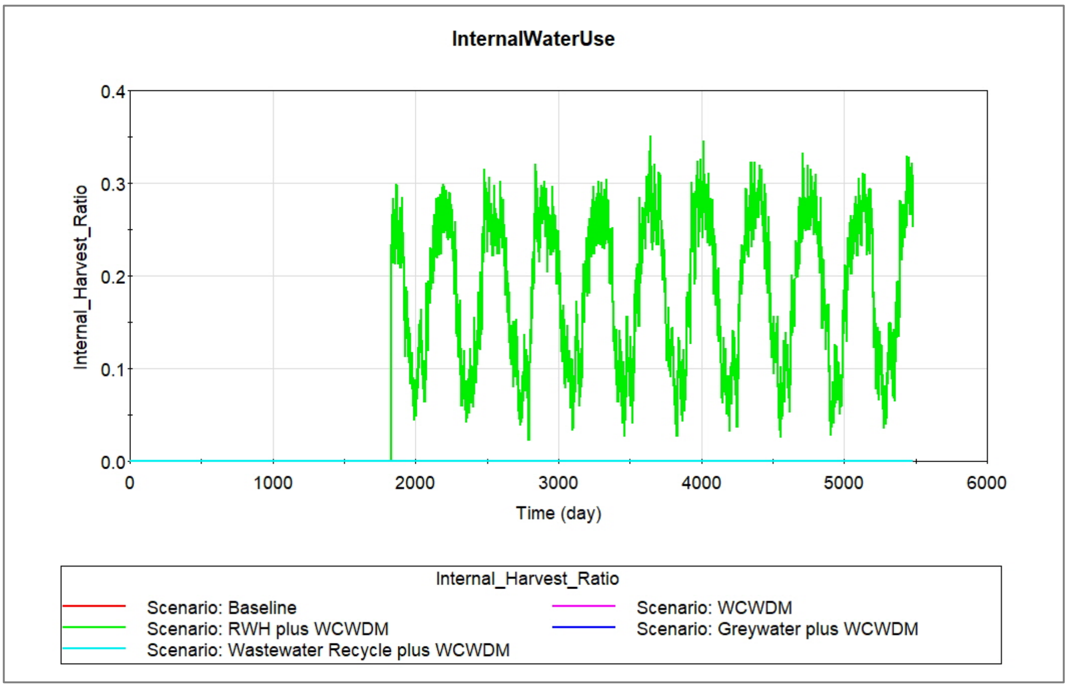


Figure C-113: Internal Harvesting Ratios

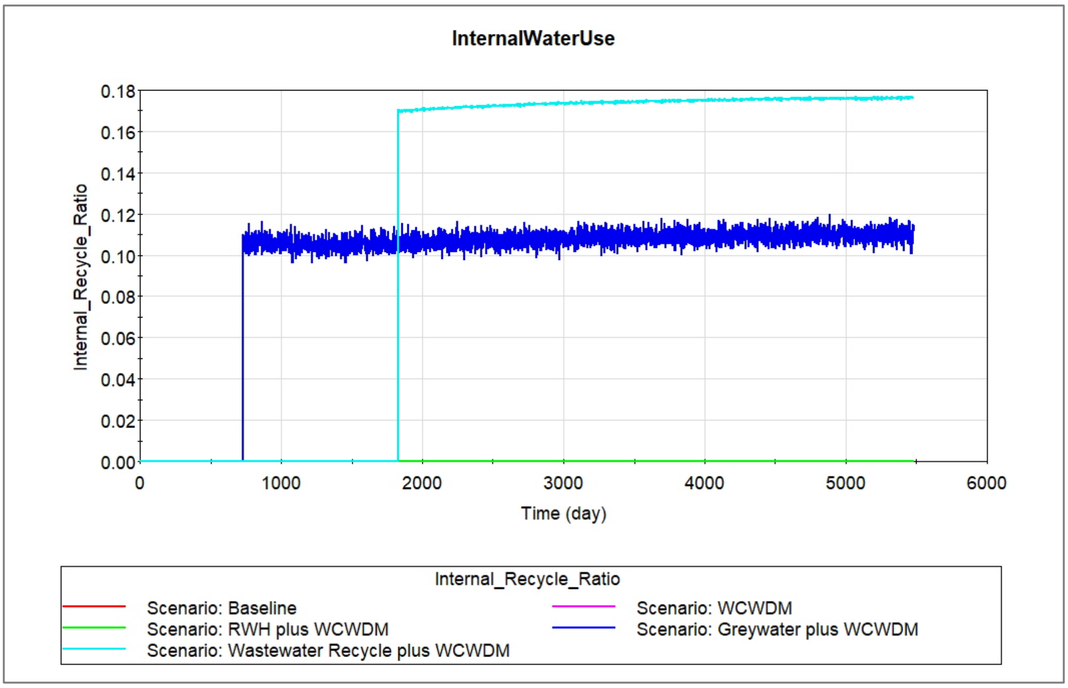


Figure C-114: Internal Recycling Ratios

Criteria Scores for Key Scenarios

Figure C-115 to Figure C-118 show the resulting scores for each scenario for each of the defined criteria – environmental, economic, risk, and functionality.

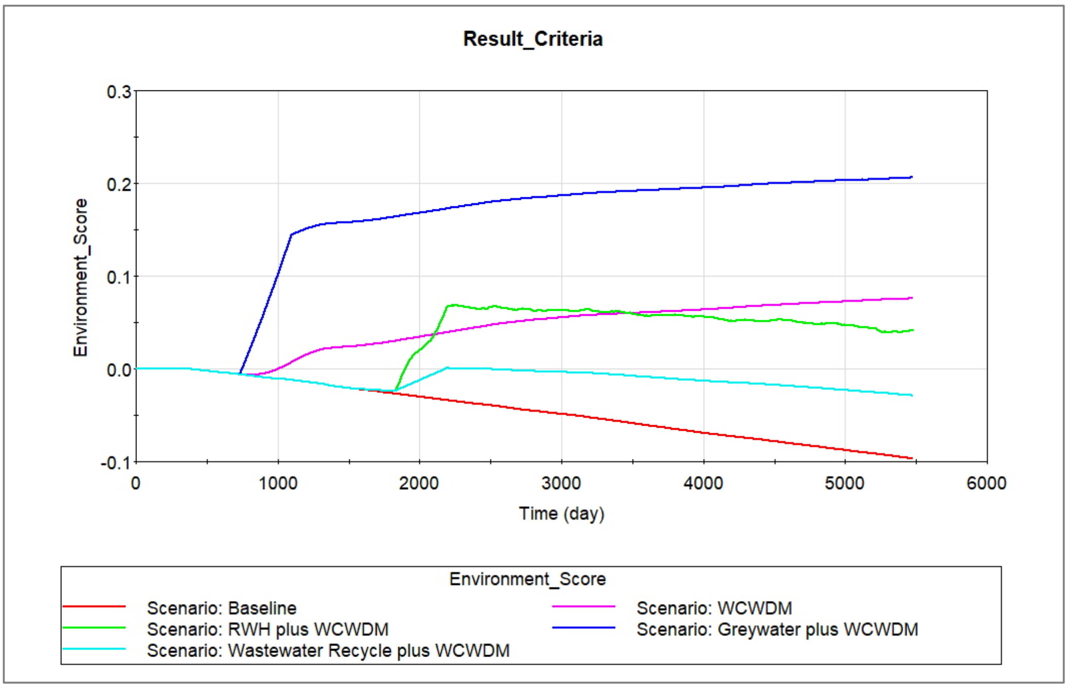


Figure C-115: Environmental Scores

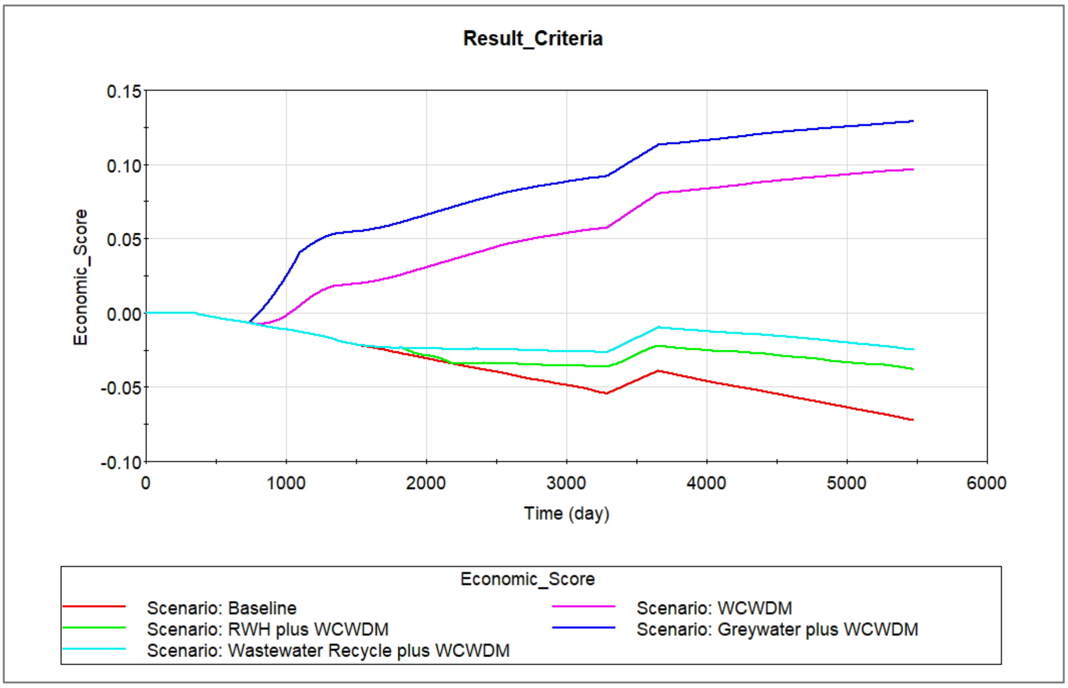


Figure C-116: Economic Scores

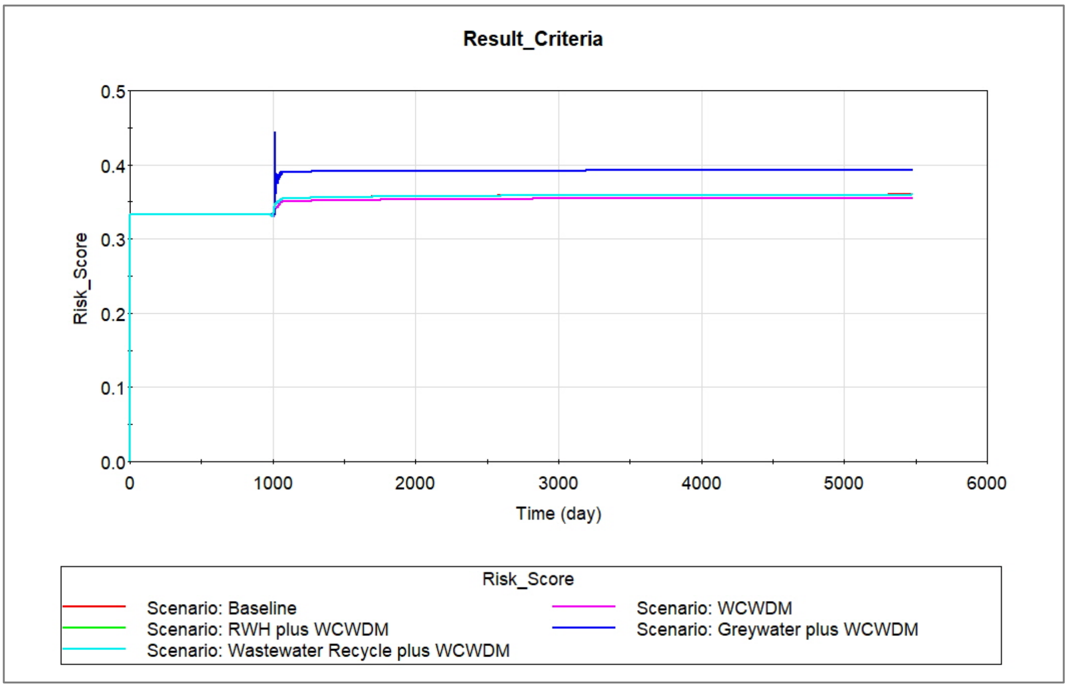


Figure C-117: Risk Scores

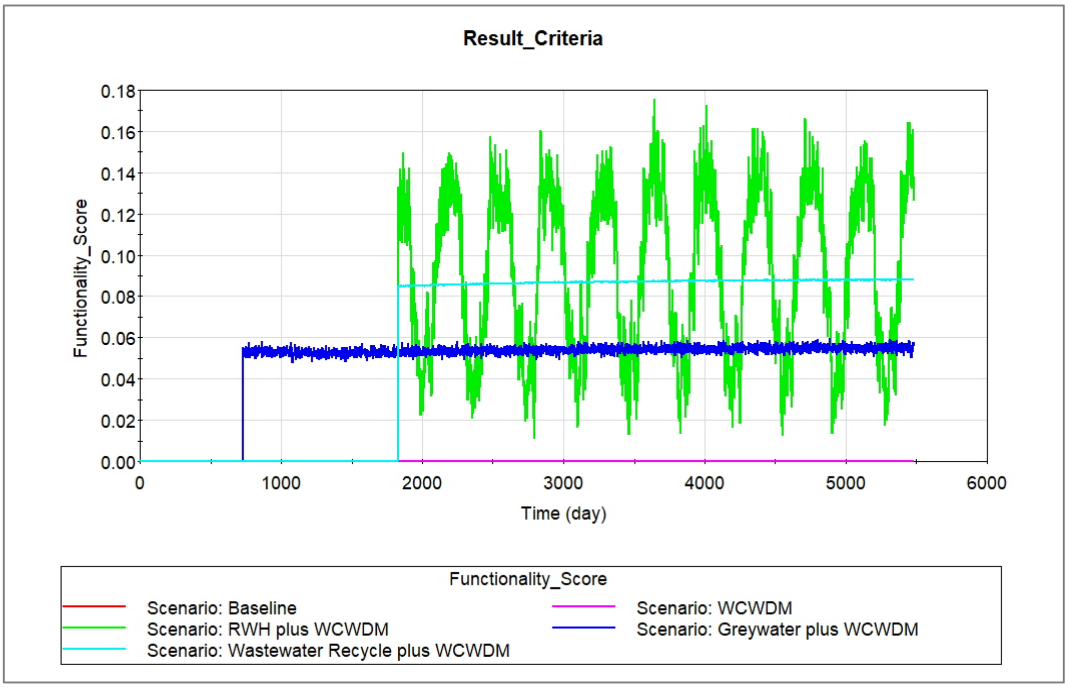
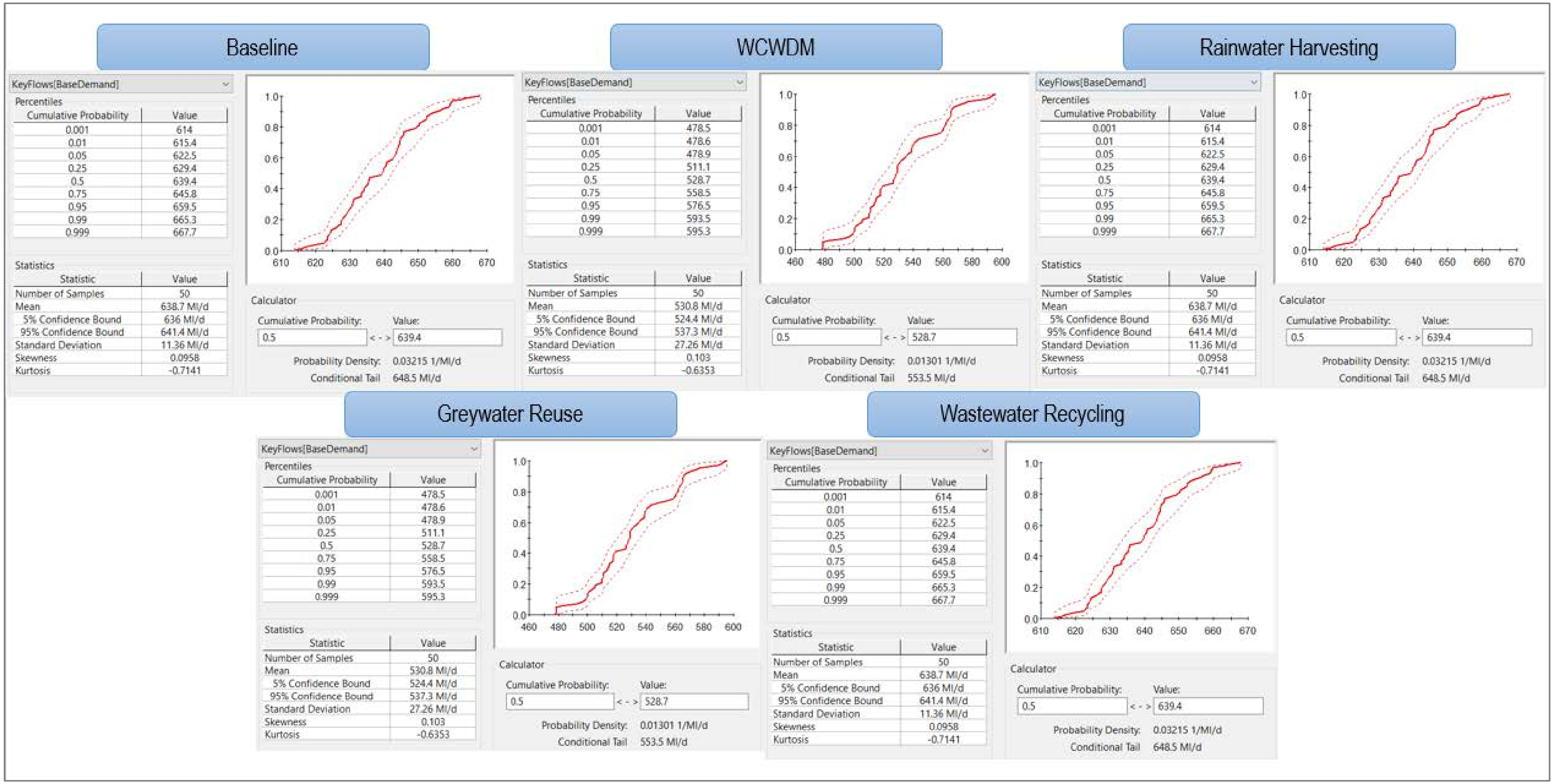


Figure C-118: Functionality Scores

Cumulative Frequency Diagrams for Key Scenarios

Cumulative frequency diagrams are a convenient means of summarising the ranges of values occurring over the entire simulation period. The flow diagrams presented in Chapter 6 are based on the 50th percentile values presented here.



Baseline

KeyFlows[BaseDemand]

Percentiles

Cumulative Probability	Value
0.001	614
0.01	615.4
0.05	622.5
0.25	629.4
0.5	639.4
0.75	645.8
0.95	659.5
0.99	665.3
0.999	667.7

Statistics

Statistic	Value
Number of Samples	50
Mean	638.7 Ml/d
5% Confidence Bound	636 Ml/d
95% Confidence Bound	641.4 Ml/d
Standard Deviation	11.36 Ml/d
Skewness	0.0958
Kurtosis	-0.7141

Calculator

Cumulative Probability: 0.5 < - > Value: 639.4

Probability Density: 0.03215 1/Ml/d

Conditional Tail 648.5 Ml/d

WCWDM

KeyFlows[BaseDemand]

Percentiles

Cumulative Probability	Value
0.001	478.5
0.01	478.6
0.05	478.9
0.25	511.1
0.5	528.7
0.75	558.5
0.95	576.5
0.99	593.5
0.999	595.3

Statistics

Statistic	Value
Number of Samples	50
Mean	530.8 Ml/d
5% Confidence Bound	524.4 Ml/d
95% Confidence Bound	537.3 Ml/d
Standard Deviation	27.26 Ml/d
Skewness	0.103
Kurtosis	-0.6353

Calculator

Cumulative Probability: 0.5 < - > Value: 528.7

Probability Density: 0.01301 1/Ml/d

Conditional Tail 553.5 Ml/d

Rainwater Harvesting

KeyFlows[BaseDemand]

Percentiles

Cumulative Probability	Value
0.001	614
0.01	615.4
0.05	622.5
0.25	629.4
0.5	639.4
0.75	645.8
0.95	659.5
0.99	665.3
0.999	667.7

Statistics

Statistic	Value
Number of Samples	50
Mean	638.7 Ml/d
5% Confidence Bound	636 Ml/d
95% Confidence Bound	641.4 Ml/d
Standard Deviation	11.36 Ml/d
Skewness	0.0958
Kurtosis	-0.7141

Calculator

Cumulative Probability: 0.5 < - > Value: 639.4

Probability Density: 0.03215 1/Ml/d

Conditional Tail 648.5 Ml/d

Greywater Reuse

KeyFlows[BaseDemand]

Percentiles

Cumulative Probability	Value
0.001	478.5
0.01	478.6
0.05	478.9
0.25	511.1
0.5	528.7
0.75	558.5
0.95	576.5
0.99	593.5
0.999	595.3

Statistics

Statistic	Value
Number of Samples	50
Mean	530.8 Ml/d
5% Confidence Bound	524.4 Ml/d
95% Confidence Bound	537.3 Ml/d
Standard Deviation	27.26 Ml/d
Skewness	0.103
Kurtosis	-0.6353

Calculator

Cumulative Probability: 0.5 < - > Value: 528.7

Probability Density: 0.01301 1/Ml/d

Conditional Tail 553.5 Ml/d

Wastewater Recycling

KeyFlows[BaseDemand]

Percentiles

Cumulative Probability	Value
0.001	614
0.01	615.4
0.05	622.5
0.25	629.4
0.5	639.4
0.75	645.8
0.95	659.5
0.99	665.3
0.999	667.7

Statistics

Statistic	Value
Number of Samples	50
Mean	638.7 Ml/d
5% Confidence Bound	636 Ml/d
95% Confidence Bound	641.4 Ml/d
Standard Deviation	11.36 Ml/d
Skewness	0.0958
Kurtosis	-0.7141

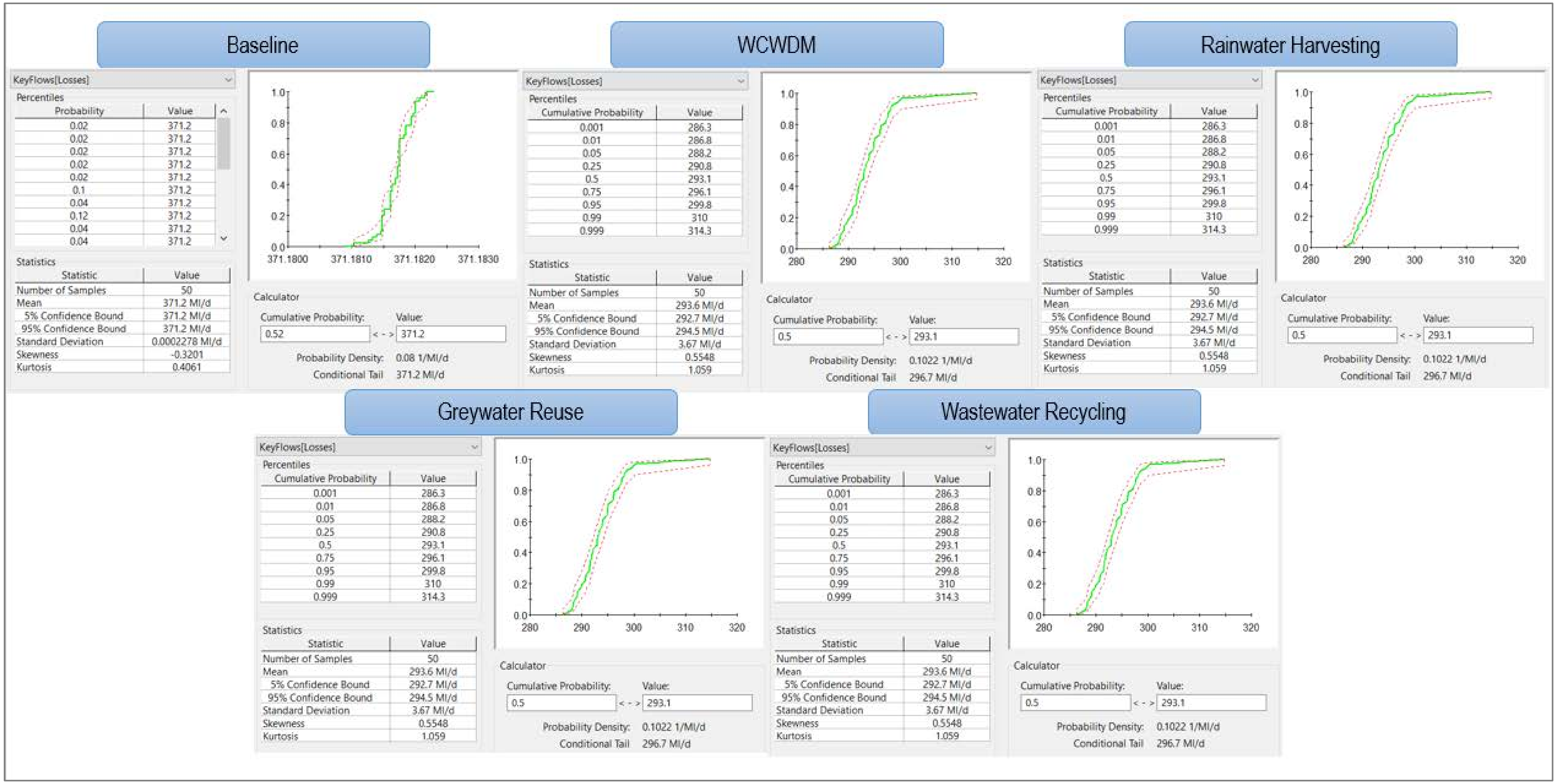
Calculator

Cumulative Probability: 0.5 < - > Value: 639.4

Probability Density: 0.03215 1/Ml/d

Conditional Tail 648.5 Ml/d

Figure C-119: Cumulative Frequency Diagrams for Base Demand – All Scenarios



Baseline

KeyFlows[Losses]

Percentiles

Probability	Value
0.02	371.2
0.02	371.2
0.02	371.2
0.02	371.2
0.02	371.2
0.1	371.2
0.04	371.2
0.12	371.2
0.04	371.2
0.04	371.2

Statistics

Statistic	Value
Number of Samples	50
Mean	371.2 Ml/d
5% Confidence Bound	371.2 Ml/d
95% Confidence Bound	371.2 Ml/d
Standard Deviation	0.0002278 Ml/d
Skewness	-0.3201
Kurtosis	0.4061

Calculator

Cumulative Probability: 0.52 < - > Value: 371.2

Probability Density: 0.08 1/Ml/d

Conditional Tail 371.2 Ml/d

WCWDM

KeyFlows[Losses]

Percentiles

Cumulative Probability	Value
0.001	286.3
0.01	286.8
0.05	288.2
0.25	290.8
0.5	293.1
0.75	296.1
0.95	299.8
0.99	310
0.999	314.3

Statistics

Statistic	Value
Number of Samples	50
Mean	293.6 Ml/d
5% Confidence Bound	292.7 Ml/d
95% Confidence Bound	294.5 Ml/d
Standard Deviation	3.67 Ml/d
Skewness	0.5548
Kurtosis	1.059

Calculator

Cumulative Probability: 0.5 < - > Value: 293.1

Probability Density: 0.1022 1/Ml/d

Conditional Tail 296.7 Ml/d

Rainwater Harvesting

KeyFlows[Losses]

Percentiles

Cumulative Probability	Value
0.001	286.3
0.01	286.8
0.05	288.2
0.25	290.8
0.5	293.1
0.75	296.1
0.95	299.8
0.99	310
0.999	314.3

Statistics

Statistic	Value
Number of Samples	50
Mean	293.6 Ml/d
5% Confidence Bound	292.7 Ml/d
95% Confidence Bound	294.5 Ml/d
Standard Deviation	3.67 Ml/d
Skewness	0.5548
Kurtosis	1.059

Calculator

Cumulative Probability: 0.5 < - > Value: 293.1

Probability Density: 0.1022 1/Ml/d

Conditional Tail 296.7 Ml/d

Greywater Reuse

KeyFlows[Losses]

Percentiles

Cumulative Probability	Value
0.001	286.3
0.01	286.8
0.05	288.2
0.25	290.8
0.5	293.1
0.75	296.1
0.95	299.8
0.99	310
0.999	314.3

Statistics

Statistic	Value
Number of Samples	50
Mean	293.6 Ml/d
5% Confidence Bound	292.7 Ml/d
95% Confidence Bound	294.5 Ml/d
Standard Deviation	3.67 Ml/d
Skewness	0.5548
Kurtosis	1.059

Calculator

Cumulative Probability: 0.5 < - > Value: 293.1

Probability Density: 0.1022 1/Ml/d

Conditional Tail 296.7 Ml/d

Wastewater Recycling

KeyFlows[Losses]

Percentiles

Cumulative Probability	Value
0.001	286.3
0.01	286.8
0.05	288.2
0.25	290.8
0.5	293.1
0.75	296.1
0.95	299.8
0.99	310
0.999	314.3

Statistics

Statistic	Value
Number of Samples	50
Mean	293.6 Ml/d
5% Confidence Bound	292.7 Ml/d
95% Confidence Bound	294.5 Ml/d
Standard Deviation	3.67 Ml/d
Skewness	0.5548
Kurtosis	1.059

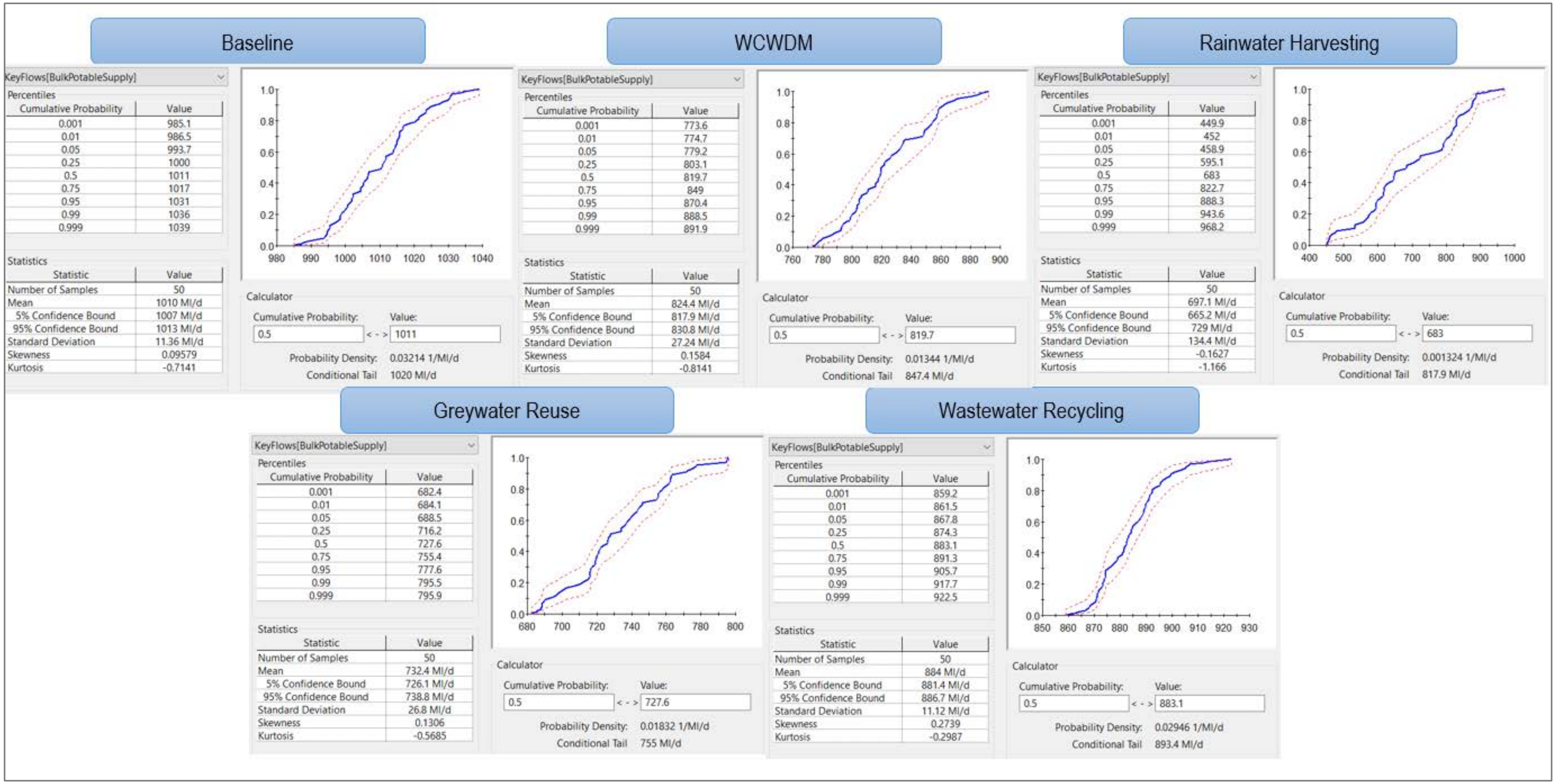
Calculator

Cumulative Probability: 0.5 < - > Value: 293.1

Probability Density: 0.1022 1/Ml/d

Conditional Tail 296.7 Ml/d

Figure C-120: Cumulative Frequency Diagrams for Losses – All Scenarios



Baseline

KeyFlows[BulkPotableSupply]

Percentiles

Cumulative Probability	Value
0.001	985.1
0.01	986.5
0.05	993.7
0.25	1000
0.5	1011
0.75	1017
0.95	1031
0.99	1036
0.999	1039

Statistics

Statistic	Value
Number of Samples	50
Mean	1010 Ml/d
5% Confidence Bound	1007 Ml/d
95% Confidence Bound	1013 Ml/d
Standard Deviation	11.36 Ml/d
Skewness	0.09579
Kurtosis	-0.7141

Calculator

Cumulative Probability: 0.5 < - > Value: 1011

Probability Density: 0.03214 1/Ml/d

Conditional Tail 1020 Ml/d

WCWDM

KeyFlows[BulkPotableSupply]

Percentiles

Cumulative Probability	Value
0.001	773.6
0.01	774.7
0.05	779.2
0.25	803.1
0.5	819.7
0.75	849
0.95	870.4
0.99	888.5
0.999	891.9

Statistics

Statistic	Value
Number of Samples	50
Mean	824.4 Ml/d
5% Confidence Bound	817.9 Ml/d
95% Confidence Bound	830.8 Ml/d
Standard Deviation	27.24 Ml/d
Skewness	0.1584
Kurtosis	-0.8141

Calculator

Cumulative Probability: 0.5 < - > Value: 819.7

Probability Density: 0.01344 1/Ml/d

Conditional Tail 847.4 Ml/d

Rainwater Harvesting

KeyFlows[BulkPotableSupply]

Percentiles

Cumulative Probability	Value
0.001	449.9
0.01	452
0.05	458.9
0.25	595.1
0.5	683
0.75	822.7
0.95	888.3
0.99	943.6
0.999	968.2

Statistics

Statistic	Value
Number of Samples	50
Mean	697.1 Ml/d
5% Confidence Bound	665.2 Ml/d
95% Confidence Bound	729 Ml/d
Standard Deviation	134.4 Ml/d
Skewness	-0.1627
Kurtosis	-1.166

Calculator

Cumulative Probability: 0.5 < - > Value: 683

Probability Density: 0.001324 1/Ml/d

Conditional Tail 817.9 Ml/d

Greywater Reuse

KeyFlows[BulkPotableSupply]

Percentiles

Cumulative Probability	Value
0.001	682.4
0.01	684.1
0.05	688.5
0.25	716.2
0.5	727.6
0.75	755.4
0.95	777.6
0.99	795.5
0.999	795.9

Statistics

Statistic	Value
Number of Samples	50
Mean	732.4 Ml/d
5% Confidence Bound	726.1 Ml/d
95% Confidence Bound	738.8 Ml/d
Standard Deviation	26.8 Ml/d
Skewness	0.1306
Kurtosis	-0.5685

Calculator

Cumulative Probability: 0.5 < - > Value: 727.6

Probability Density: 0.01832 1/Ml/d

Conditional Tail 755 Ml/d

Wastewater Recycling

KeyFlows[BulkPotableSupply]

Percentiles

Cumulative Probability	Value
0.001	859.2
0.01	861.5
0.05	867.8
0.25	874.3
0.5	883.1
0.75	891.3
0.95	905.7
0.99	917.7
0.999	922.5

Statistics

Statistic	Value
Number of Samples	50
Mean	884 Ml/d
5% Confidence Bound	881.4 Ml/d
95% Confidence Bound	886.7 Ml/d
Standard Deviation	11.12 Ml/d
Skewness	0.2739
Kurtosis	-0.2987

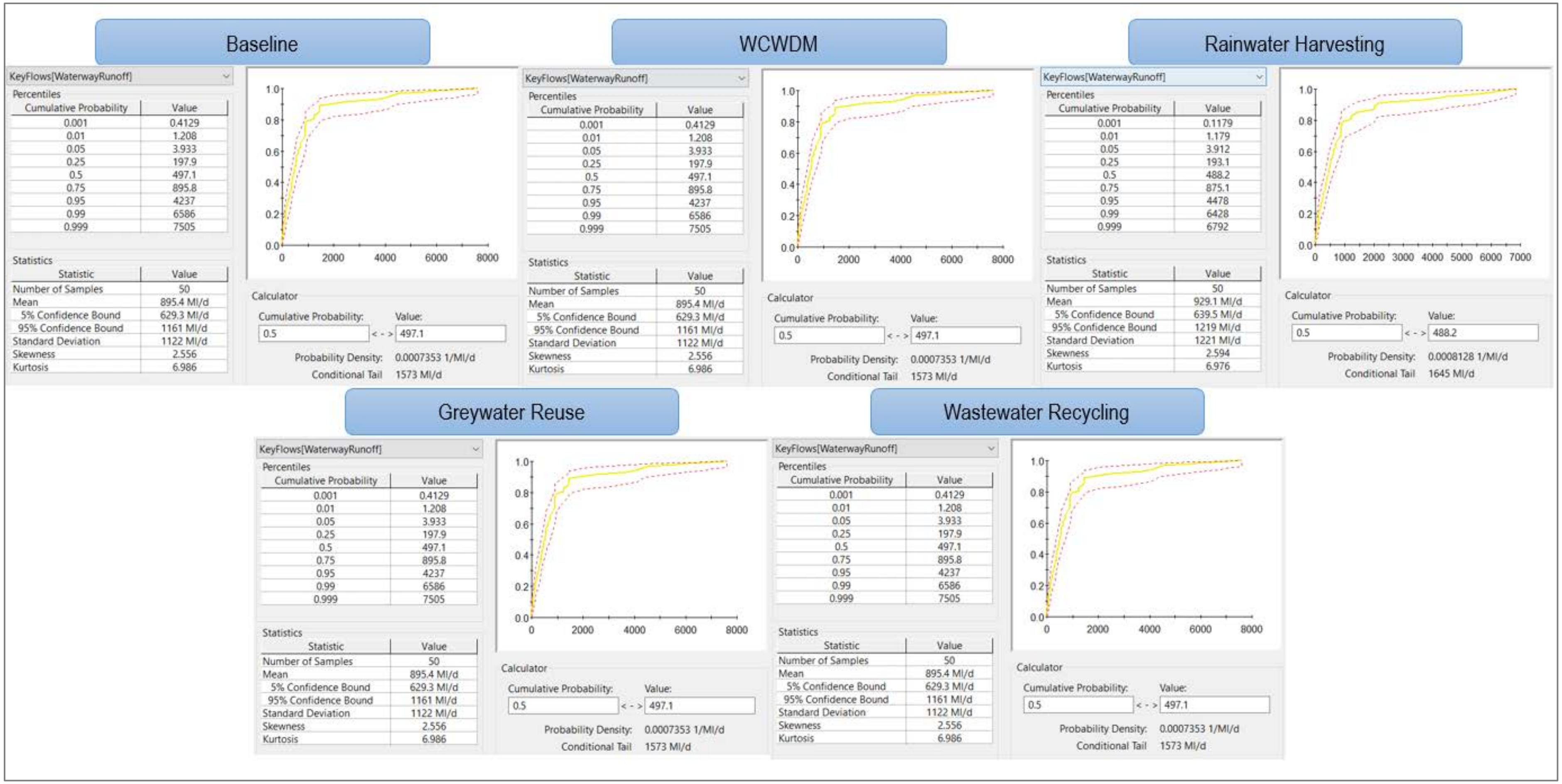
Calculator

Cumulative Probability: 0.5 < - > Value: 883.1

Probability Density: 0.02946 1/Ml/d

Conditional Tail 893.4 Ml/d

Figure C-121: Cumulative Frequency Diagrams for Bulk Potable Supply – All Scenarios



Baseline

KeyFlows[WaterwayRunoff]

Percentiles

Cumulative Probability	Value
0.001	0.4129
0.01	1.208
0.05	3.933
0.25	197.9
0.5	497.1
0.75	895.8
0.95	4237
0.99	6586
0.999	7505

Statistics

Statistic	Value
Number of Samples	50
Mean	895.4 Ml/d
5% Confidence Bound	629.3 Ml/d
95% Confidence Bound	1161 Ml/d
Standard Deviation	1122 Ml/d
Skewness	2.556
Kurtosis	6.986

Calculator

Cumulative Probability: 0.5 < - > Value: 497.1

Probability Density: 0.0007353 1/Ml/d

Conditional Tail 1573 Ml/d

WCWDM

KeyFlows[WaterwayRunoff]

Percentiles

Cumulative Probability	Value
0.001	0.4129
0.01	1.208
0.05	3.933
0.25	197.9
0.5	497.1
0.75	895.8
0.95	4237
0.99	6586
0.999	7505

Statistics

Statistic	Value
Number of Samples	50
Mean	895.4 Ml/d
5% Confidence Bound	629.3 Ml/d
95% Confidence Bound	1161 Ml/d
Standard Deviation	1122 Ml/d
Skewness	2.556
Kurtosis	6.986

Calculator

Cumulative Probability: 0.5 < - > Value: 497.1

Probability Density: 0.0007353 1/Ml/d

Conditional Tail 1573 Ml/d

Rainwater Harvesting

KeyFlows[WaterwayRunoff]

Percentiles

Cumulative Probability	Value
0.001	0.1179
0.01	1.179
0.05	3.912
0.25	193.1
0.5	488.2
0.75	875.1
0.95	4478
0.99	6428
0.999	6792

Statistics

Statistic	Value
Number of Samples	50
Mean	929.1 Ml/d
5% Confidence Bound	639.5 Ml/d
95% Confidence Bound	1219 Ml/d
Standard Deviation	1221 Ml/d
Skewness	2.594
Kurtosis	6.976

Calculator

Cumulative Probability: 0.5 < - > Value: 488.2

Probability Density: 0.0008128 1/Ml/d

Conditional Tail 1645 Ml/d

Greywater Reuse

KeyFlows[WaterwayRunoff]

Percentiles

Cumulative Probability	Value
0.001	0.4129
0.01	1.208
0.05	3.933
0.25	197.9
0.5	497.1
0.75	895.8
0.95	4237
0.99	6586
0.999	7505

Statistics

Statistic	Value
Number of Samples	50
Mean	895.4 Ml/d
5% Confidence Bound	629.3 Ml/d
95% Confidence Bound	1161 Ml/d
Standard Deviation	1122 Ml/d
Skewness	2.556
Kurtosis	6.986

Calculator

Cumulative Probability: 0.5 < - > Value: 497.1

Probability Density: 0.0007353 1/Ml/d

Conditional Tail 1573 Ml/d

Wastewater Recycling

KeyFlows[WaterwayRunoff]

Percentiles

Cumulative Probability	Value
0.001	0.4129
0.01	1.208
0.05	3.933
0.25	197.9
0.5	497.1
0.75	895.8
0.95	4237
0.99	6586
0.999	7505

Statistics

Statistic	Value
Number of Samples	50
Mean	895.4 Ml/d
5% Confidence Bound	629.3 Ml/d
95% Confidence Bound	1161 Ml/d
Standard Deviation	1122 Ml/d
Skewness	2.556
Kurtosis	6.986

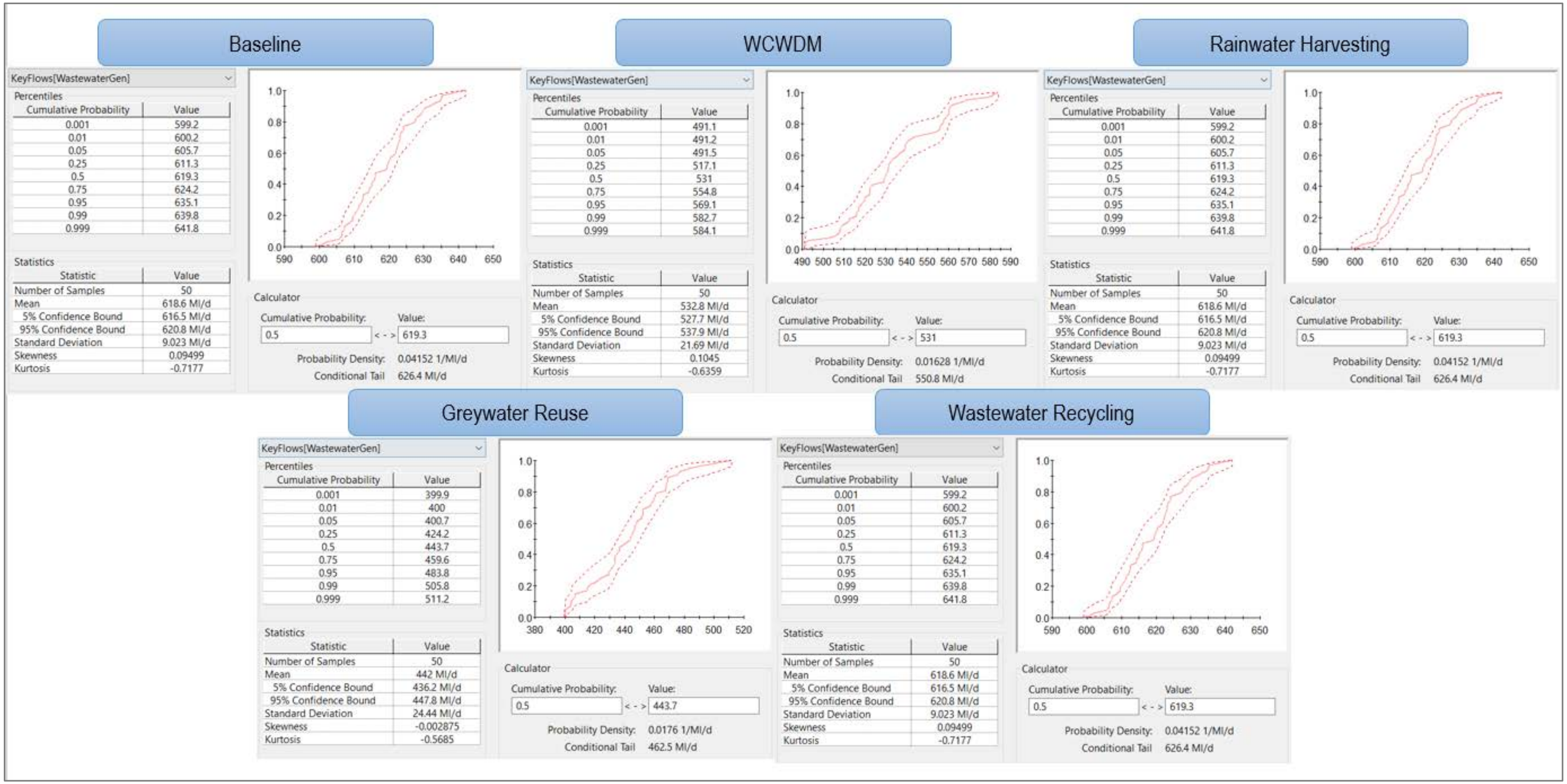
Calculator

Cumulative Probability: 0.5 < - > Value: 497.1

Probability Density: 0.0007353 1/Ml/d

Conditional Tail 1573 Ml/d

Figure C-122: Cumulative Frequency Diagrams for Waterway Runoff – All Scenarios



Baseline

KeyFlows[WastewaterGen]

Percentiles

Cumulative Probability	Value
0.001	599.2
0.01	600.2
0.05	605.7
0.25	611.3
0.5	619.3
0.75	624.2
0.95	635.1
0.99	639.8
0.999	641.8

Statistics

Statistic	Value
Number of Samples	50
Mean	618.6 Ml/d
5% Confidence Bound	616.5 Ml/d
95% Confidence Bound	620.8 Ml/d
Standard Deviation	9.023 Ml/d
Skewness	0.09499
Kurtosis	-0.7177

Calculator

Cumulative Probability: 0.5 < - > Value: 619.3

Probability Density: 0.04152 1/Ml/d

Conditional Tail 626.4 Ml/d

WCWDM

KeyFlows[WastewaterGen]

Percentiles

Cumulative Probability	Value
0.001	491.1
0.01	491.2
0.05	491.5
0.25	517.1
0.5	531
0.75	554.8
0.95	569.1
0.99	582.7
0.999	584.1

Statistics

Statistic	Value
Number of Samples	50
Mean	532.8 Ml/d
5% Confidence Bound	527.7 Ml/d
95% Confidence Bound	537.9 Ml/d
Standard Deviation	21.69 Ml/d
Skewness	0.1045
Kurtosis	-0.6359

Calculator

Cumulative Probability: 0.5 < - > Value: 531

Probability Density: 0.01628 1/Ml/d

Conditional Tail 550.8 Ml/d

Rainwater Harvesting

KeyFlows[WastewaterGen]

Percentiles

Cumulative Probability	Value
0.001	599.2
0.01	600.2
0.05	605.7
0.25	611.3
0.5	619.3
0.75	624.2
0.95	635.1
0.99	639.8
0.999	641.8

Statistics

Statistic	Value
Number of Samples	50
Mean	618.6 Ml/d
5% Confidence Bound	616.5 Ml/d
95% Confidence Bound	620.8 Ml/d
Standard Deviation	9.023 Ml/d
Skewness	0.09499
Kurtosis	-0.7177

Calculator

Cumulative Probability: 0.5 < - > Value: 619.3

Probability Density: 0.04152 1/Ml/d

Conditional Tail 626.4 Ml/d

Greywater Reuse

KeyFlows[WastewaterGen]

Percentiles

Cumulative Probability	Value
0.001	399.9
0.01	400
0.05	400.7
0.25	424.2
0.5	443.7
0.75	459.6
0.95	483.8
0.99	505.8
0.999	511.2

Statistics

Statistic	Value
Number of Samples	50
Mean	442 Ml/d
5% Confidence Bound	436.2 Ml/d
95% Confidence Bound	447.8 Ml/d
Standard Deviation	24.44 Ml/d
Skewness	-0.002875
Kurtosis	-0.5685

Calculator

Cumulative Probability: 0.5 < - > Value: 443.7

Probability Density: 0.0176 1/Ml/d

Conditional Tail 462.5 Ml/d

Wastewater Recycling

KeyFlows[WastewaterGen]

Percentiles

Cumulative Probability	Value
0.001	599.2
0.01	600.2
0.05	605.7
0.25	611.3
0.5	619.3
0.75	624.2
0.95	635.1
0.99	639.8
0.999	641.8

Statistics

Statistic	Value
Number of Samples	50
Mean	618.6 Ml/d
5% Confidence Bound	616.5 Ml/d
95% Confidence Bound	620.8 Ml/d
Standard Deviation	9.023 Ml/d
Skewness	0.09499
Kurtosis	-0.7177

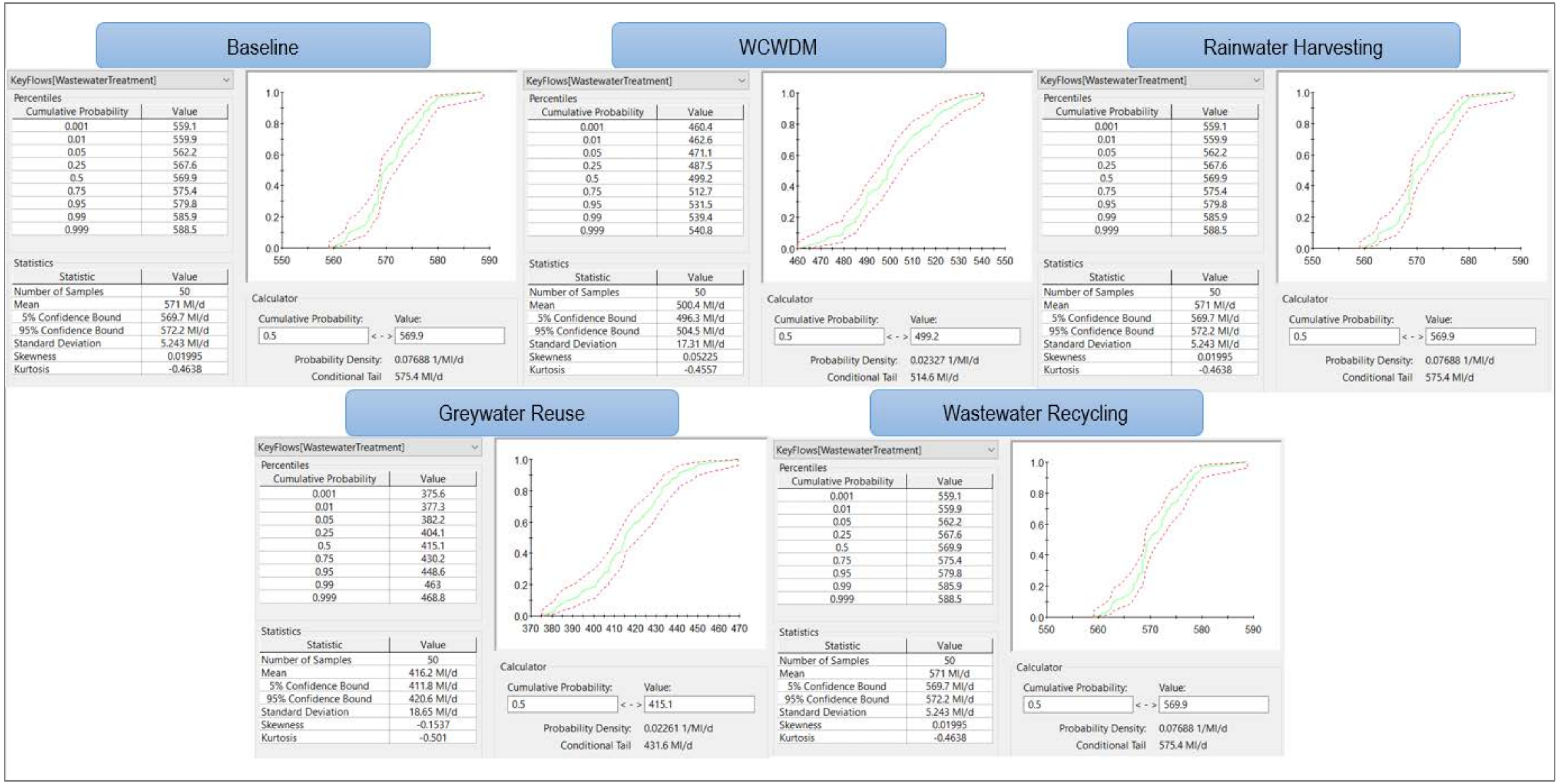
Calculator

Cumulative Probability: 0.5 < - > Value: 619.3

Probability Density: 0.04152 1/Ml/d

Conditional Tail 626.4 Ml/d

Figure C-123: Cumulative Frequency Diagrams for Generated Wastewater – All Scenarios



Baseline

KeyFlows[WastewaterTreatment]

Percentiles

Cumulative Probability	Value
0.001	559.1
0.01	559.9
0.05	562.2
0.25	567.6
0.5	569.9
0.75	575.4
0.95	579.8
0.99	585.9
0.999	588.5

Statistics

Statistic	Value
Number of Samples	50
Mean	571 Ml/d
5% Confidence Bound	569.7 Ml/d
95% Confidence Bound	572.2 Ml/d
Standard Deviation	5.243 Ml/d
Skewness	0.01995
Kurtosis	-0.4638

Calculator

Cumulative Probability: 0.5 < - > Value: 569.9

Probability Density: 0.07688 1/Ml/d

Conditional Tail 575.4 Ml/d

WCWDM

KeyFlows[WastewaterTreatment]

Percentiles

Cumulative Probability	Value
0.001	460.4
0.01	462.6
0.05	471.1
0.25	487.5
0.5	499.2
0.75	512.7
0.95	531.5
0.99	539.4
0.999	540.8

Statistics

Statistic	Value
Number of Samples	50
Mean	500.4 Ml/d
5% Confidence Bound	496.3 Ml/d
95% Confidence Bound	504.5 Ml/d
Standard Deviation	17.31 Ml/d
Skewness	0.05225
Kurtosis	-0.4557

Calculator

Cumulative Probability: 0.5 < - > Value: 499.2

Probability Density: 0.02327 1/Ml/d

Conditional Tail 514.6 Ml/d

Rainwater Harvesting

KeyFlows[WastewaterTreatment]

Percentiles

Cumulative Probability	Value
0.001	559.1
0.01	559.9
0.05	562.2
0.25	567.6
0.5	569.9
0.75	575.4
0.95	579.8
0.99	585.9
0.999	588.5

Statistics

Statistic	Value
Number of Samples	50
Mean	571 Ml/d
5% Confidence Bound	569.7 Ml/d
95% Confidence Bound	572.2 Ml/d
Standard Deviation	5.243 Ml/d
Skewness	0.01995
Kurtosis	-0.4638

Calculator

Cumulative Probability: 0.5 < - > Value: 569.9

Probability Density: 0.07688 1/Ml/d

Conditional Tail 575.4 Ml/d

Greywater Reuse

KeyFlows[WastewaterTreatment]

Percentiles

Cumulative Probability	Value
0.001	375.6
0.01	377.3
0.05	382.2
0.25	404.1
0.5	415.1
0.75	430.2
0.95	448.6
0.99	463
0.999	468.8

Statistics

Statistic	Value
Number of Samples	50
Mean	416.2 Ml/d
5% Confidence Bound	411.8 Ml/d
95% Confidence Bound	420.6 Ml/d
Standard Deviation	18.65 Ml/d
Skewness	-0.1537
Kurtosis	-0.501

Calculator

Cumulative Probability: 0.5 < - > Value: 415.1

Probability Density: 0.02261 1/Ml/d

Conditional Tail 431.6 Ml/d

Wastewater Recycling

KeyFlows[WastewaterTreatment]

Percentiles

Cumulative Probability	Value
0.001	559.1
0.01	559.9
0.05	562.2
0.25	567.6
0.5	569.9
0.75	575.4
0.95	579.8
0.99	585.9
0.999	588.5

Statistics

Statistic	Value
Number of Samples	50
Mean	571 Ml/d
5% Confidence Bound	569.7 Ml/d
95% Confidence Bound	572.2 Ml/d
Standard Deviation	5.243 Ml/d
Skewness	0.01995
Kurtosis	-0.4638

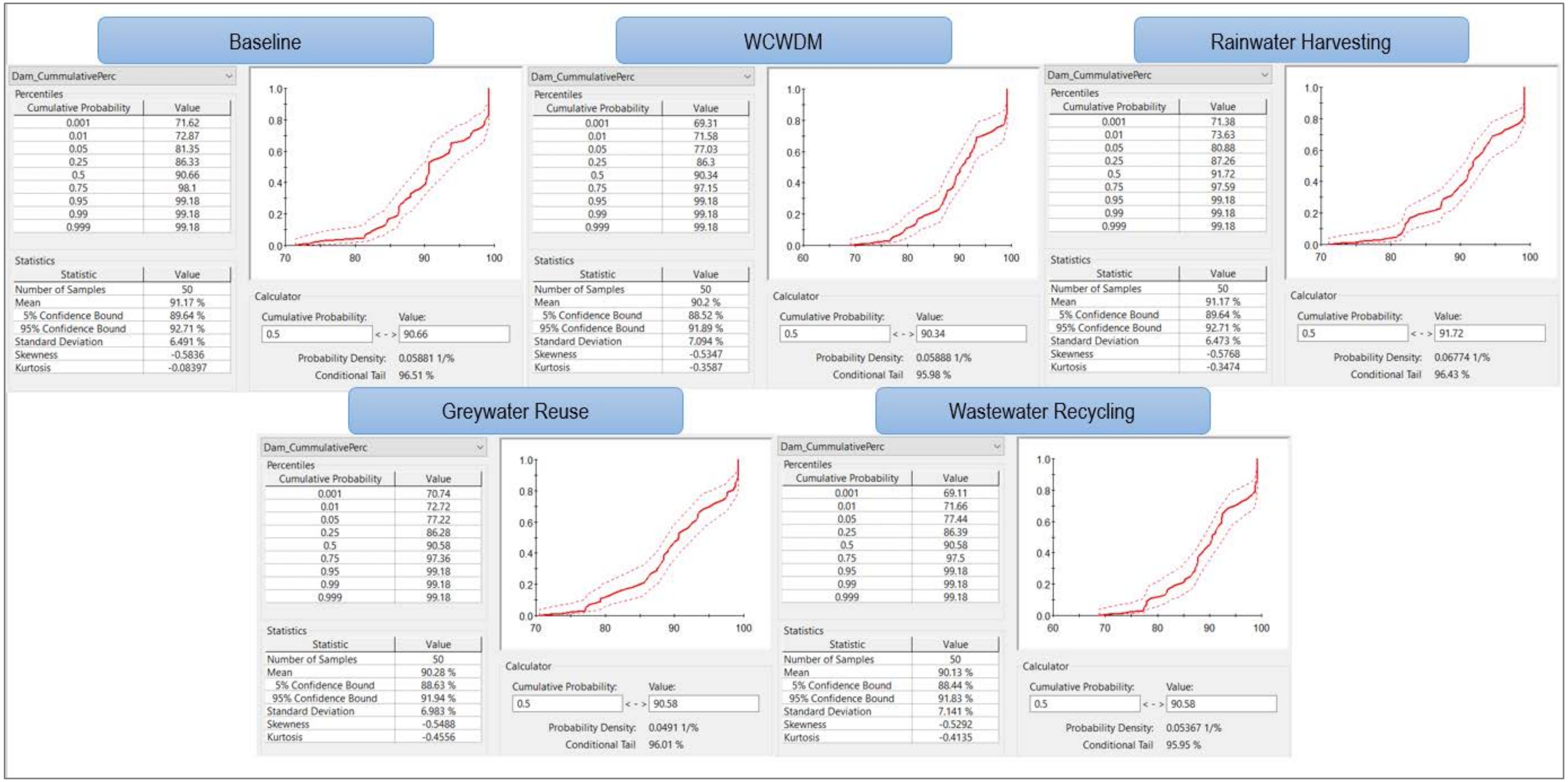
Calculator

Cumulative Probability: 0.5 < - > Value: 569.9

Probability Density: 0.07688 1/Ml/d

Conditional Tail 575.4 Ml/d

Figure C-124: Cumulative Frequency Diagrams for Treated Wastewater – All Scenarios



Baseline

Dam_CummulativePerc

Percentiles

Cumulative Probability	Value
0.001	71.62
0.01	72.87
0.05	81.35
0.25	86.33
0.5	90.66
0.75	98.1
0.95	99.18
0.99	99.18
0.999	99.18

Statistics

Statistic	Value
Number of Samples	50
Mean	91.17 %
5% Confidence Bound	89.64 %
95% Confidence Bound	92.71 %
Standard Deviation	6.491 %
Skewness	-0.5836
Kurtosis	-0.08397

Calculator

Cumulative Probability: 0.5 < - > Value: 90.66

Probability Density: 0.05881 1/%

Conditional Tail 96.51 %

WCWDM

Dam_CummulativePerc

Percentiles

Cumulative Probability	Value
0.001	69.31
0.01	71.58
0.05	77.03
0.25	86.3
0.5	90.34
0.75	97.15
0.95	99.18
0.99	99.18
0.999	99.18

Statistics

Statistic	Value
Number of Samples	50
Mean	90.2 %
5% Confidence Bound	88.52 %
95% Confidence Bound	91.89 %
Standard Deviation	7.094 %
Skewness	-0.5347
Kurtosis	-0.3587

Calculator

Cumulative Probability: 0.5 < - > Value: 90.34

Probability Density: 0.05888 1/%

Conditional Tail 95.98 %

Rainwater Harvesting

Dam_CummulativePerc

Percentiles

Cumulative Probability	Value
0.001	71.38
0.01	73.63
0.05	80.88
0.25	87.26
0.5	91.72
0.75	97.59
0.95	99.18
0.99	99.18
0.999	99.18

Statistics

Statistic	Value
Number of Samples	50
Mean	91.17 %
5% Confidence Bound	89.64 %
95% Confidence Bound	92.71 %
Standard Deviation	6.473 %
Skewness	-0.5768
Kurtosis	-0.3474

Calculator

Cumulative Probability: 0.5 < - > Value: 91.72

Probability Density: 0.06774 1/%

Conditional Tail 96.43 %

Greywater Reuse

Dam_CummulativePerc

Percentiles

Cumulative Probability	Value
0.001	70.74
0.01	72.72
0.05	77.22
0.25	86.28
0.5	90.58
0.75	97.36
0.95	99.18
0.99	99.18
0.999	99.18

Statistics

Statistic	Value
Number of Samples	50
Mean	90.28 %
5% Confidence Bound	88.63 %
95% Confidence Bound	91.94 %
Standard Deviation	6.983 %
Skewness	-0.5488
Kurtosis	-0.4556

Calculator

Cumulative Probability: 0.5 < - > Value: 90.58

Probability Density: 0.0491 1/%

Conditional Tail 96.01 %

Wastewater Recycling

Dam_CummulativePerc

Percentiles

Cumulative Probability	Value
0.001	69.11
0.01	71.66
0.05	77.44
0.25	86.39
0.5	90.58
0.75	97.5
0.95	99.18
0.99	99.18
0.999	99.18

Statistics

Statistic	Value
Number of Samples	50
Mean	90.13 %
5% Confidence Bound	88.44 %
95% Confidence Bound	91.83 %
Standard Deviation	7.141 %
Skewness	-0.5292
Kurtosis	-0.4135

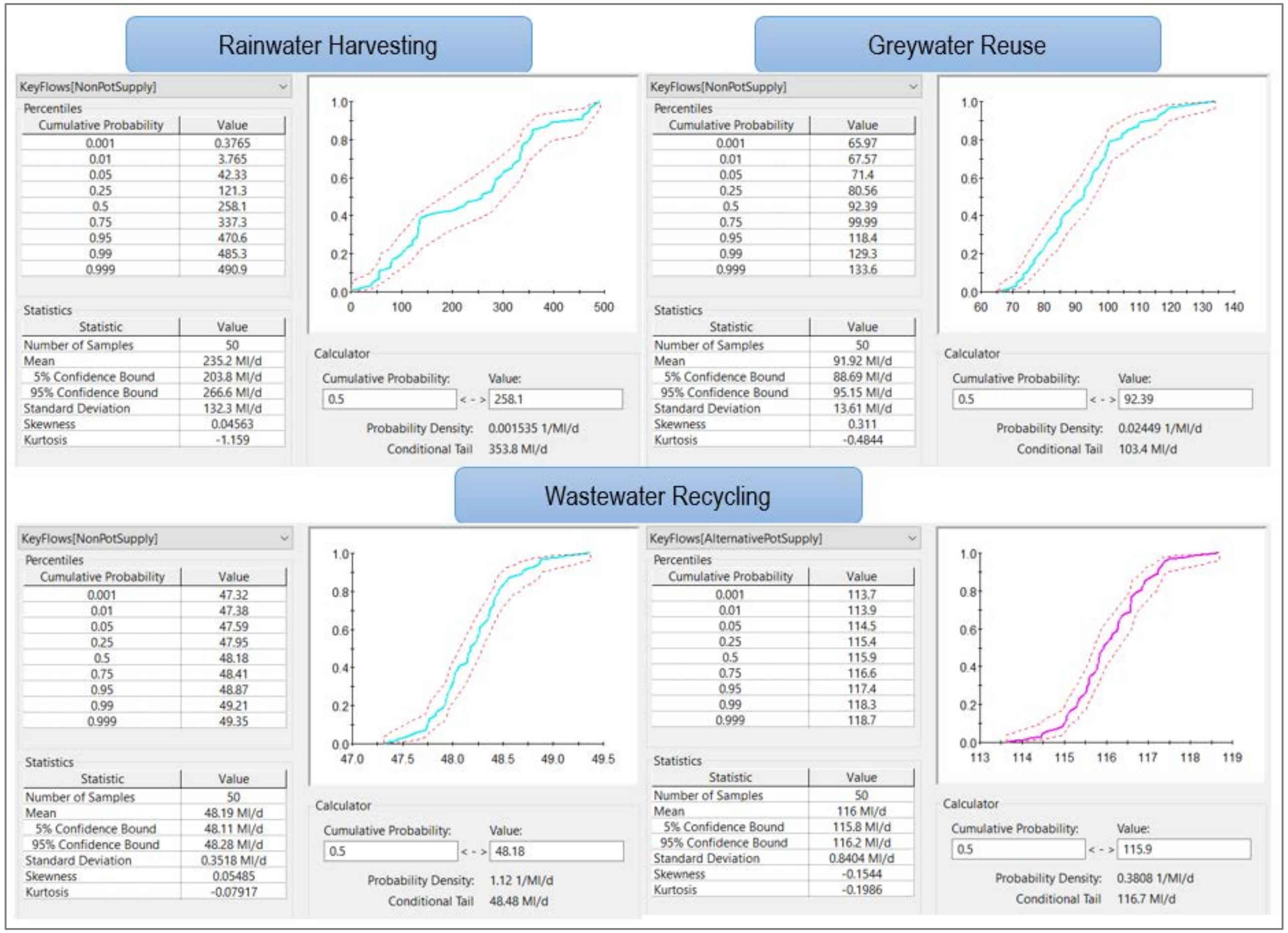
Calculator

Cumulative Probability: 0.5 < - > Value: 90.58

Probability Density: 0.05367 1/%

Conditional Tail 95.95 %

Figure C-125: Cumulative Frequency Diagrams for Total Dam Storage – All Scenarios



Rainwater Harvesting

KeyFlows[NonPotSupply]

Percentiles

Cumulative Probability	Value
0.001	0.3765
0.01	3.765
0.05	42.33
0.25	121.3
0.5	258.1
0.75	337.3
0.95	470.6
0.99	485.3
0.999	490.9

Statistics

Statistic	Value
Number of Samples	50
Mean	235.2 Ml/d
5% Confidence Bound	203.8 Ml/d
95% Confidence Bound	266.6 Ml/d
Standard Deviation	132.3 Ml/d
Skewness	0.04563
Kurtosis	-1.159

Calculator

Cumulative Probability: 0.5 < - > Value: 258.1

Probability Density: 0.001535 1/Ml/d

Conditional Tail 353.8 Ml/d

Greywater Reuse

KeyFlows[NonPotSupply]

Percentiles

Cumulative Probability	Value
0.001	65.97
0.01	67.57
0.05	71.4
0.25	80.56
0.5	92.39
0.75	99.99
0.95	118.4
0.99	129.3
0.999	133.6

Statistics

Statistic	Value
Number of Samples	50
Mean	91.92 Ml/d
5% Confidence Bound	88.69 Ml/d
95% Confidence Bound	95.15 Ml/d
Standard Deviation	13.61 Ml/d
Skewness	0.311
Kurtosis	-0.4844

Calculator

Cumulative Probability: 0.5 < - > Value: 92.39

Probability Density: 0.02449 1/Ml/d

Conditional Tail 103.4 Ml/d

Wastewater Recycling

KeyFlows[NonPotSupply]

Percentiles

Cumulative Probability	Value
0.001	47.32
0.01	47.38
0.05	47.59
0.25	47.95
0.5	48.18
0.75	48.41
0.95	48.87
0.99	49.21
0.999	49.35

Statistics

Statistic	Value
Number of Samples	50
Mean	48.19 Ml/d
5% Confidence Bound	48.11 Ml/d
95% Confidence Bound	48.28 Ml/d
Standard Deviation	0.3518 Ml/d
Skewness	0.05485
Kurtosis	-0.07917

Calculator

Cumulative Probability: 0.5 < - > Value: 48.18

Probability Density: 1.12 1/Ml/d

Conditional Tail 48.48 Ml/d

KeyFlows[AlternativePotSupply]

Percentiles

Cumulative Probability	Value
0.001	113.7
0.01	113.9
0.05	114.5
0.25	115.4
0.5	115.9
0.75	116.6
0.95	117.4
0.99	118.3
0.999	118.7

Statistics

Statistic	Value
Number of Samples	50
Mean	116 Ml/d
5% Confidence Bound	115.8 Ml/d
95% Confidence Bound	116.2 Ml/d
Standard Deviation	0.8404 Ml/d
Skewness	-0.1544
Kurtosis	-0.1986

Calculator

Cumulative Probability: 0.5 < - > Value: 115.9

Probability Density: 0.3808 1/Ml/d

Conditional Tail 116.7 Ml/d

Figure C-126: Cumulative Frequency Diagrams for Non Potable & Alternative Potable Supply – All Scenarios

All Time Series Outputs for Additional Interventions

Stormwater Harvesting & Real Loss Reduction

Model outputs for stormwater harvesting are summarised in the below series of figures.

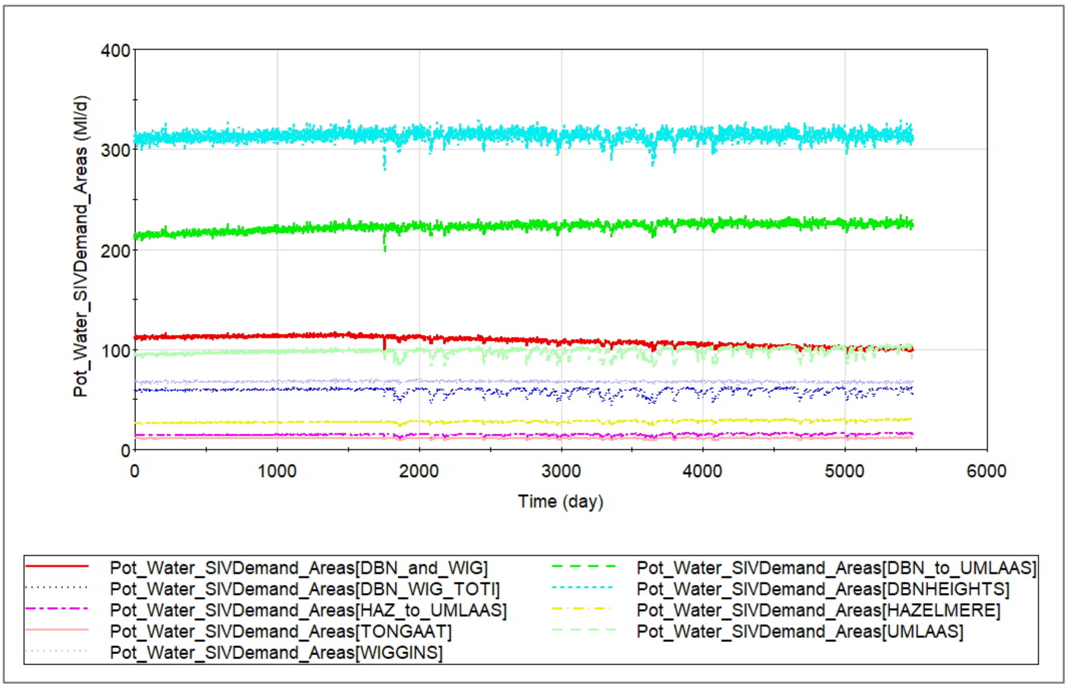


Figure C-127: Demand on Potable System per Bulk Supply Area (Stormwater Harvesting Scenario)

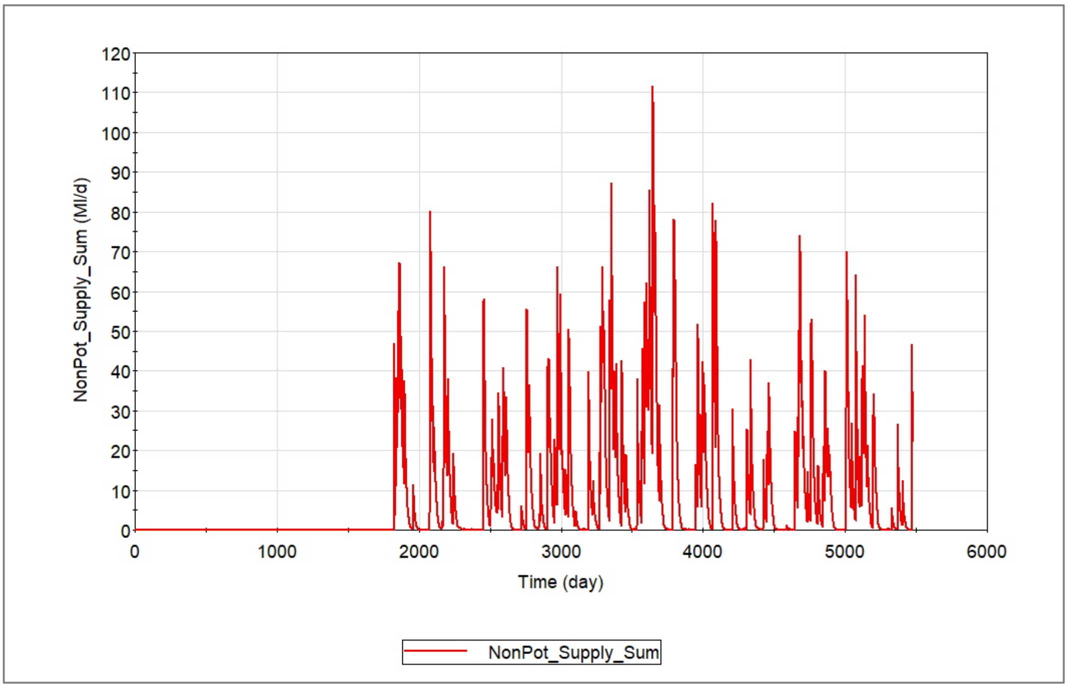


Figure C-128: Cumulative Outflows from Stormwater Harvesting Facilities

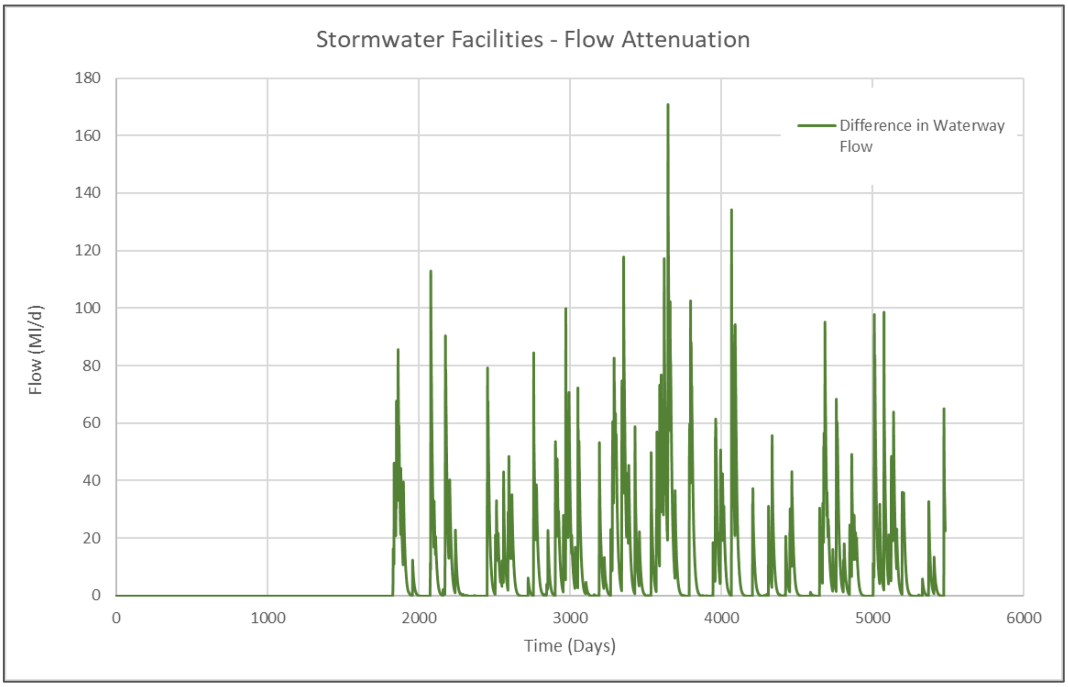


Figure C-129: Difference in Waterway Flows as a Result of Stormwater Harvesting

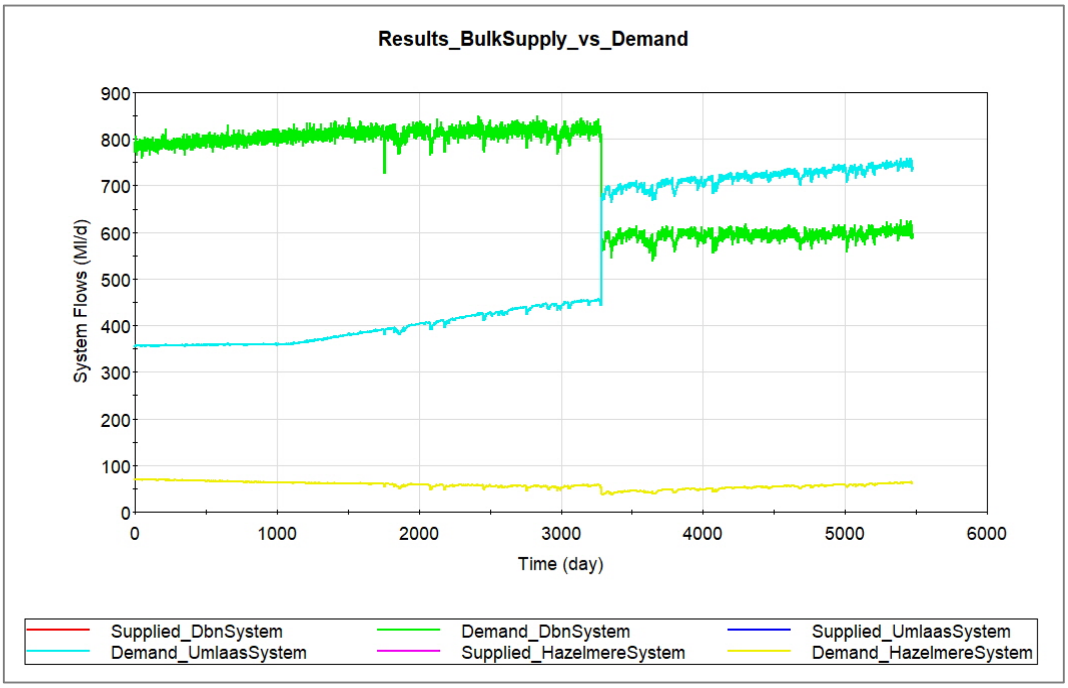


Figure C-130: Demand vs Availability for Water Supply Systems (Stormwater Harvesting Scenario)

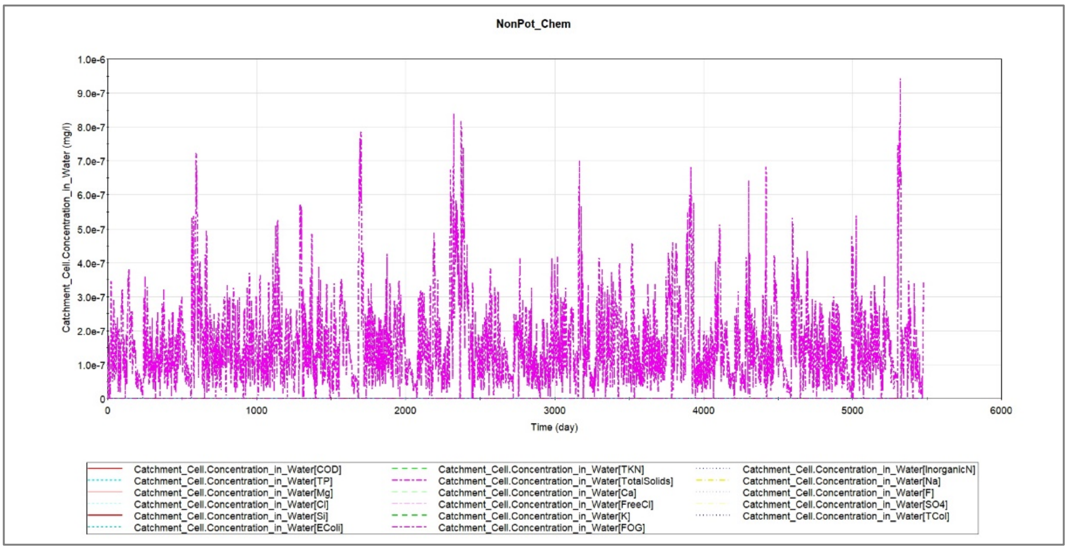


Figure C-131: Catchment TSS Concentrations (Stormwater Harvesting Scenario)

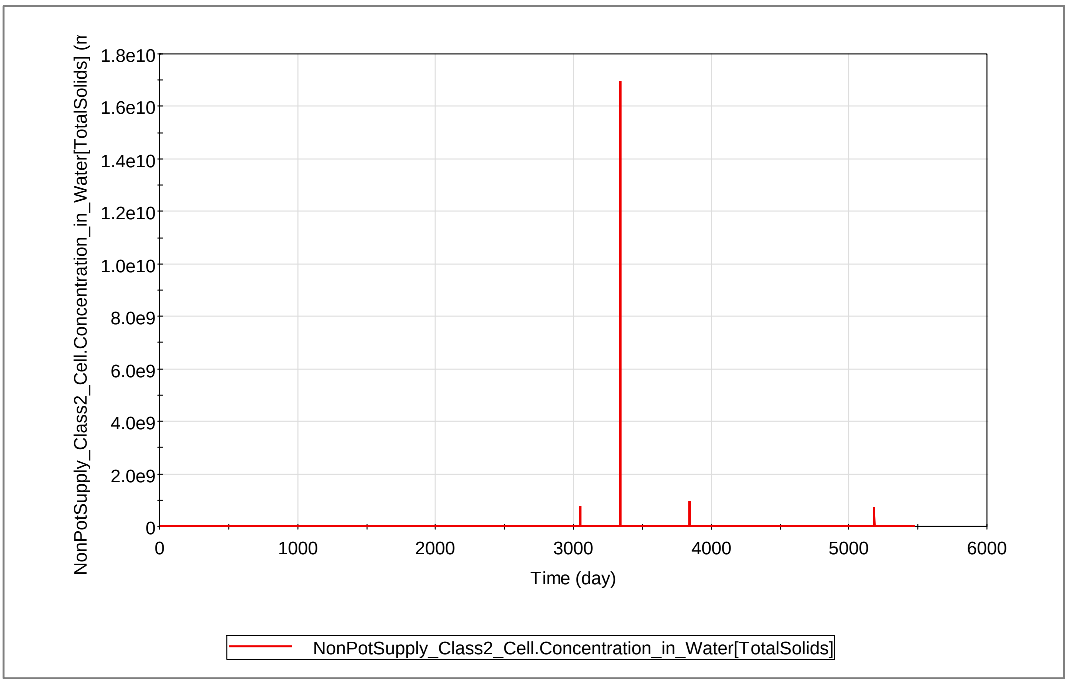


Figure C-132: Stormwater Harvesting Supply TSS Concentrations

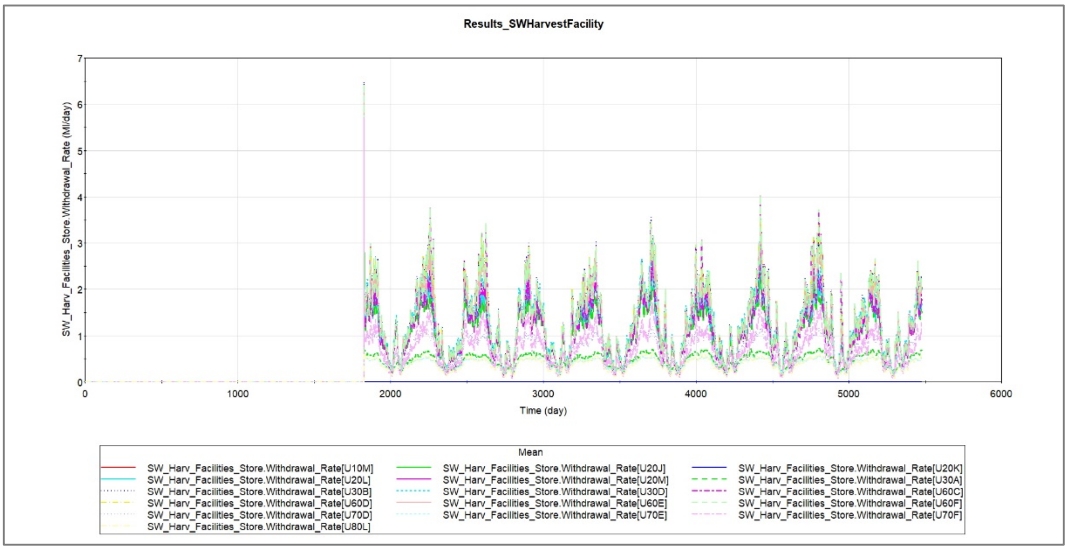


Figure C-133: Monte Carlo Analysis of Stormwater Harvesting Facility Mean Outflows per Catchment

Figure C-134 to Figure C-138 show the impact on water resources and volume of potable water supplied.

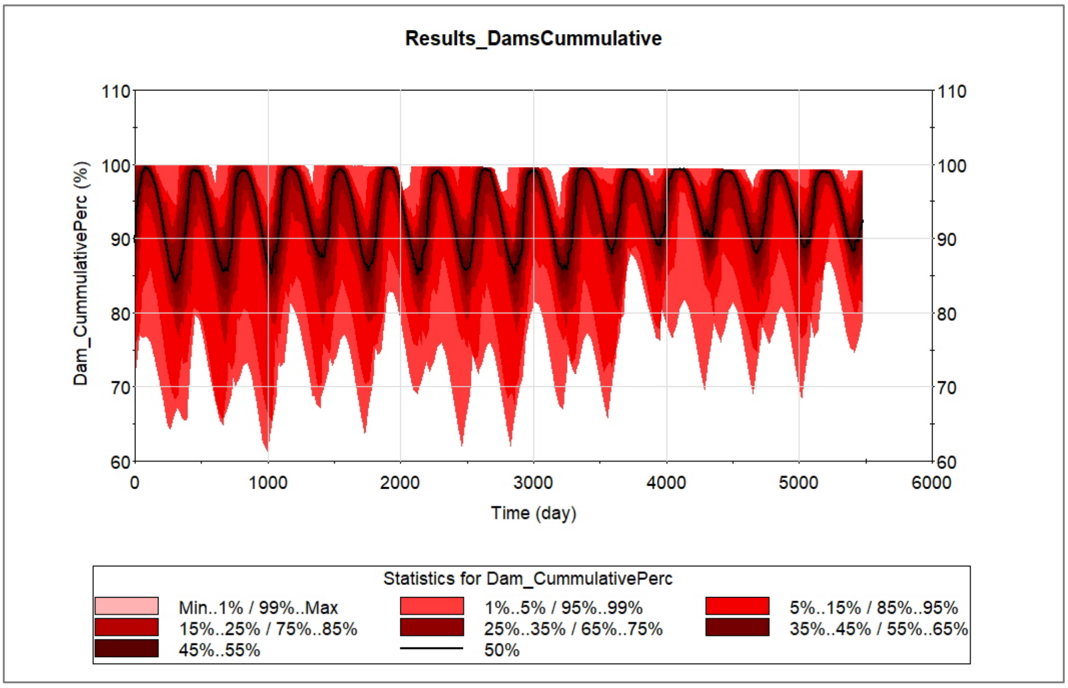


Figure C-134: Cumulative Dam Storage (Stormwater Harvesting Scenario)

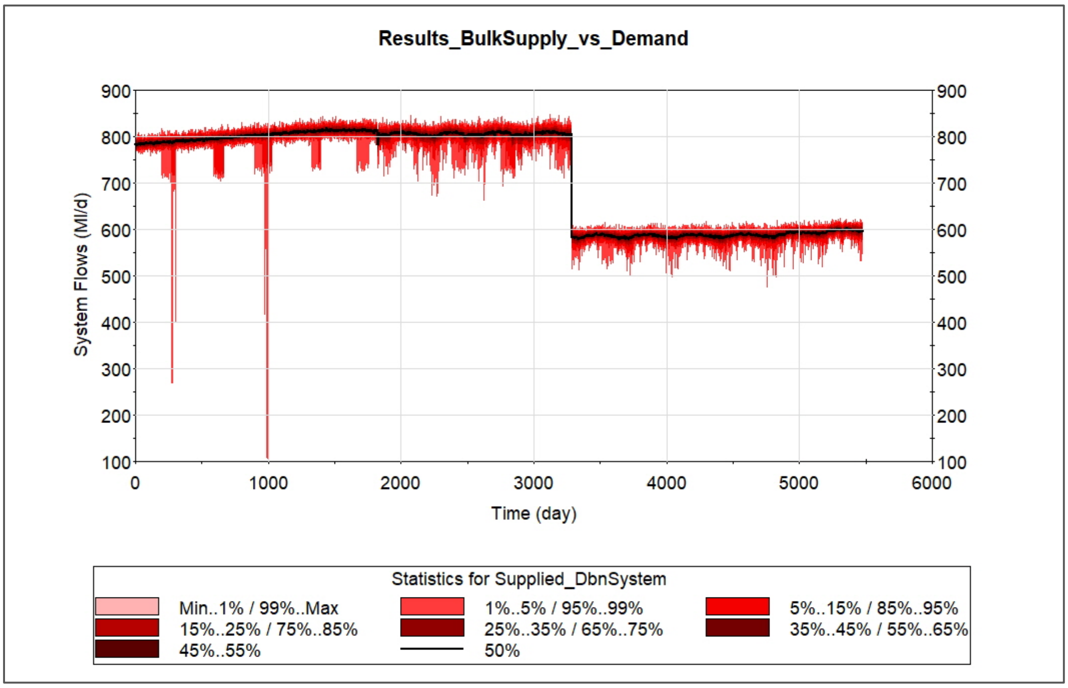


Figure C-135: Monte Carlo Analysis of Demand on Lower Mgeni System (Stormwater Harvesting Scenario)

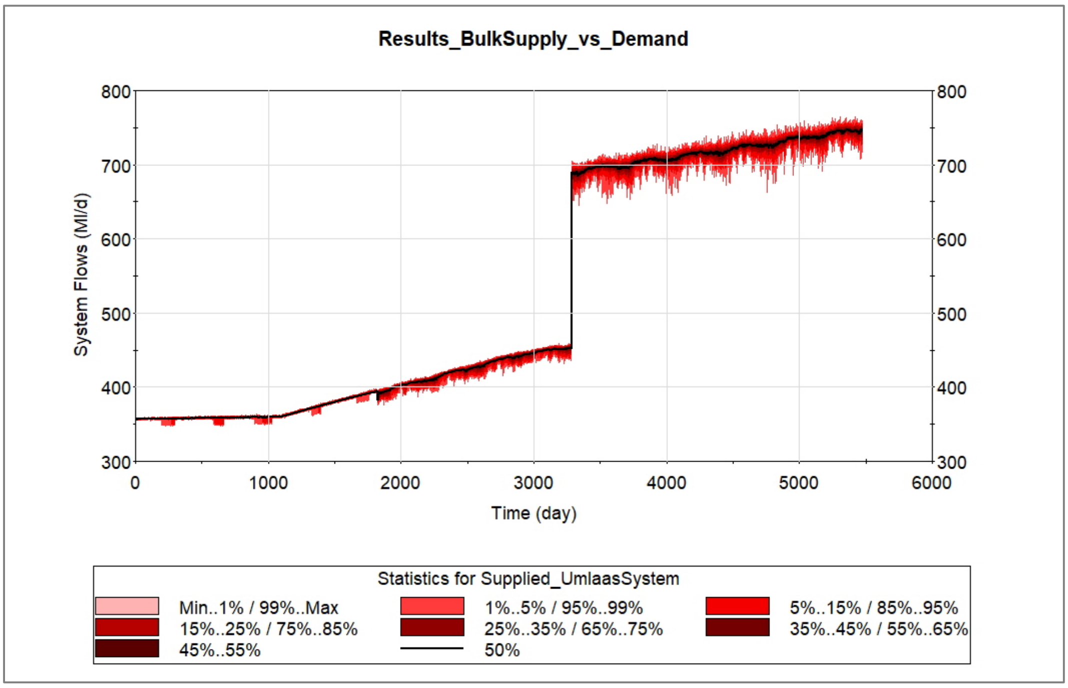


Figure C-136: Monte Carlo Analysis of Demand on Upper Mgeni System (Stormwater Harvesting Scenario)

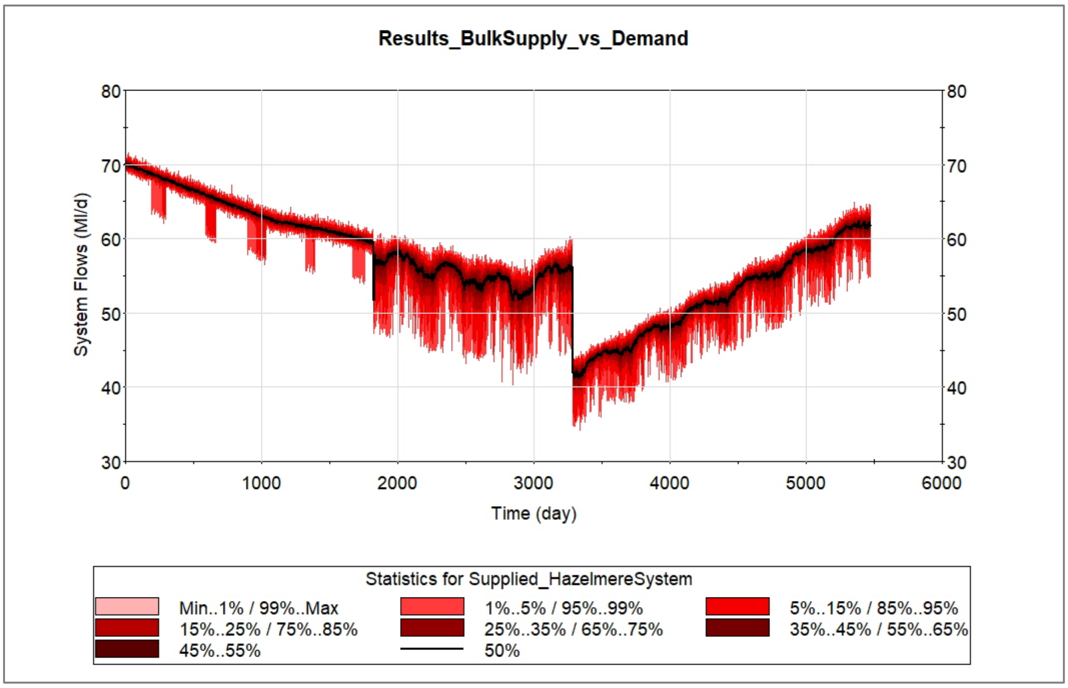


Figure C-137: Monte Carlo Analysis of Demand on Hazelmere System (Stormwater Harvesting Scenario)

Groundwater & Real Loss Reduction

Model outputs for groundwater use are summarised in the below series of figures.

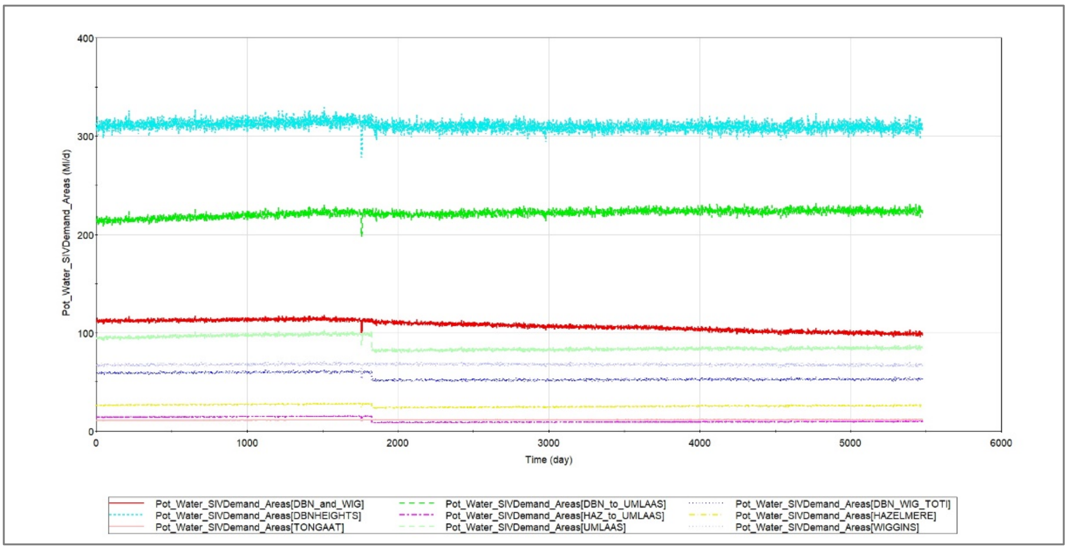


Figure C-138: Demand on Potable System per Bulk Supply Area (Groundwater Scenario)

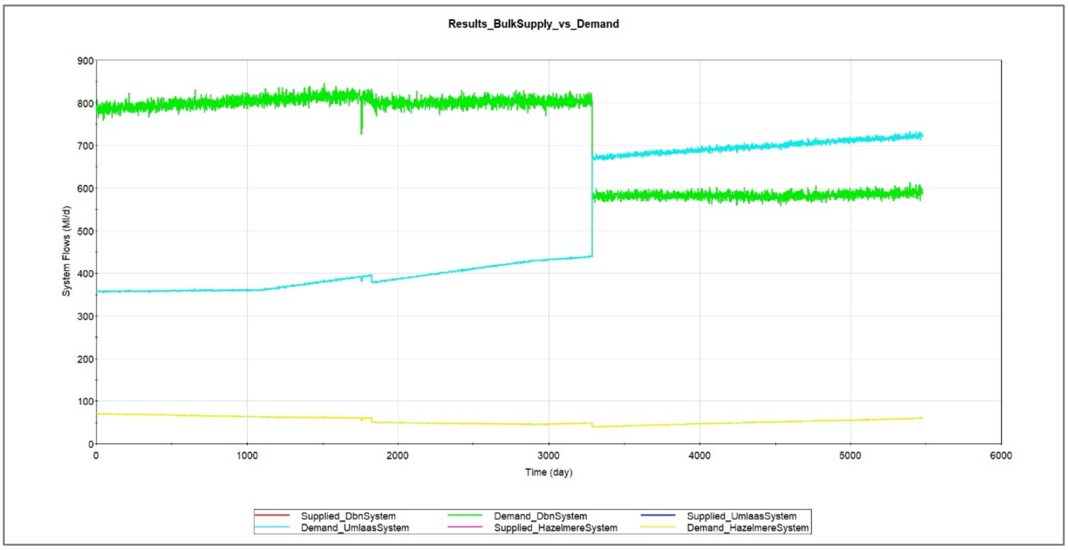


Figure C-139: Demand vs Availability for Water Supply Systems (Groundwater Scenario)

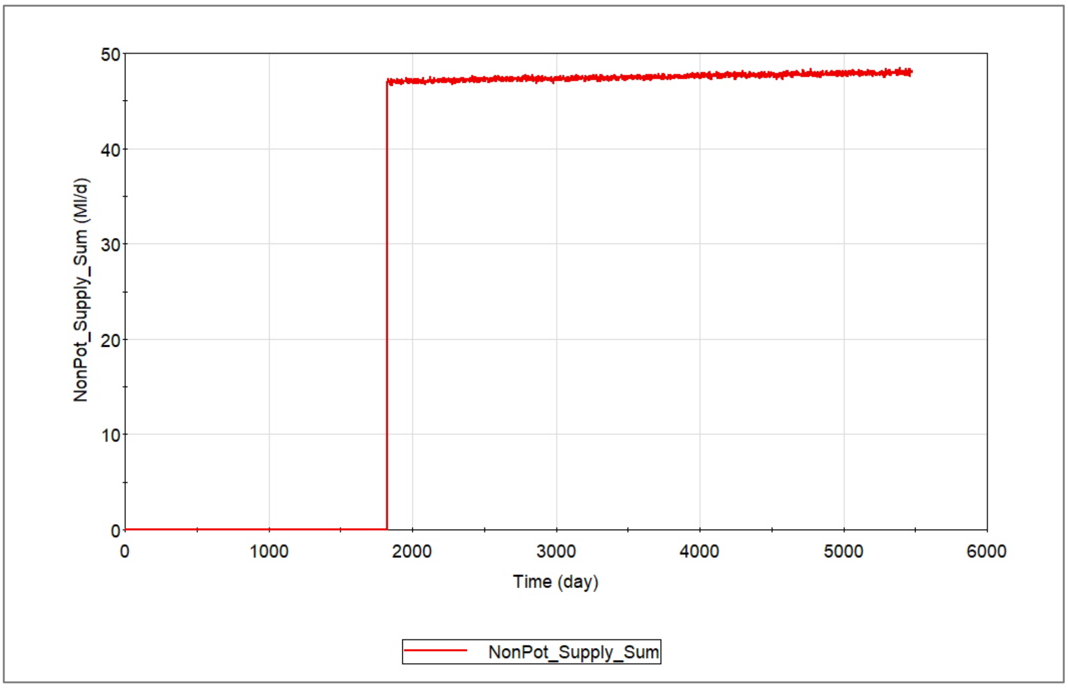


Figure C-140: Total Groundwater Supply

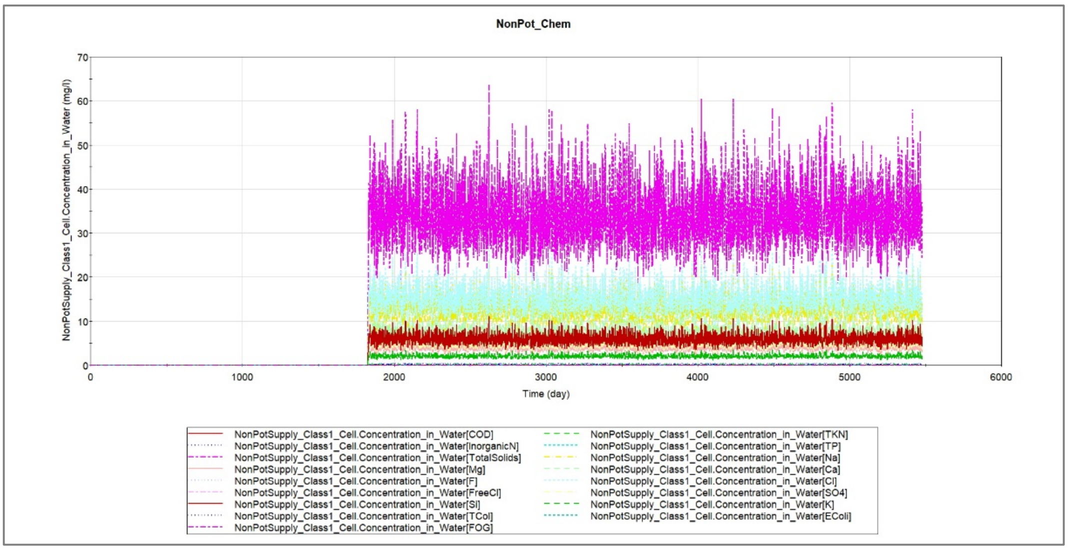


Figure C-141: Groundwater Supply Pollutant Concentrations

Figure C-142 to Figure C-145 show the impact on water resources and volume of potable water supplied.

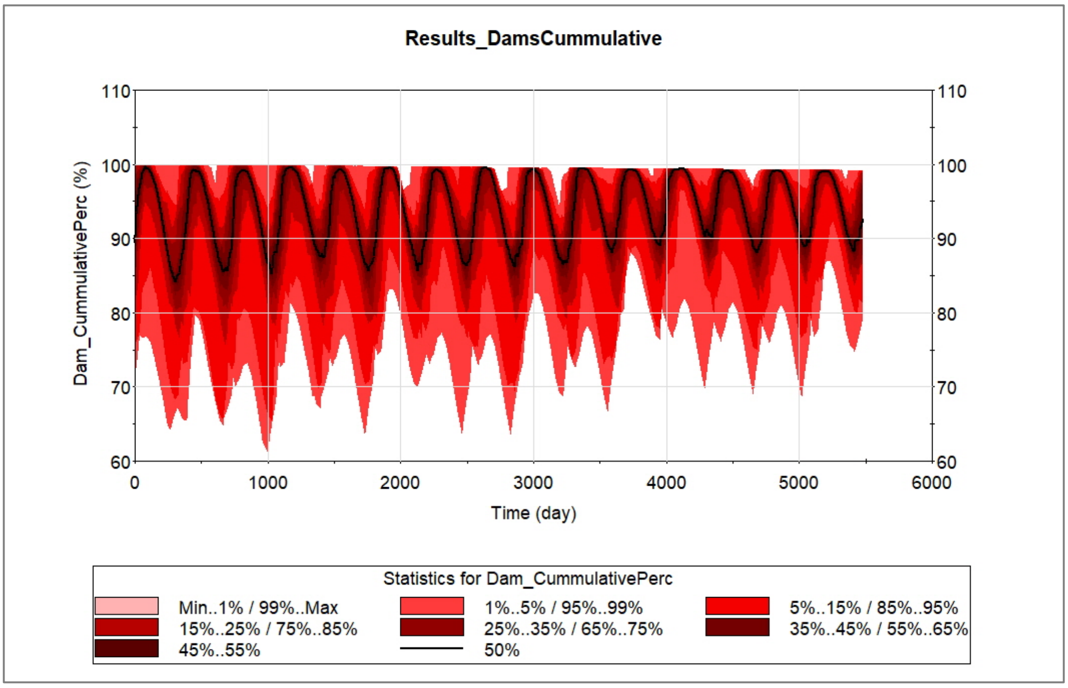


Figure C-142: Cumulative Dam Storage (Groundwater Scenario)

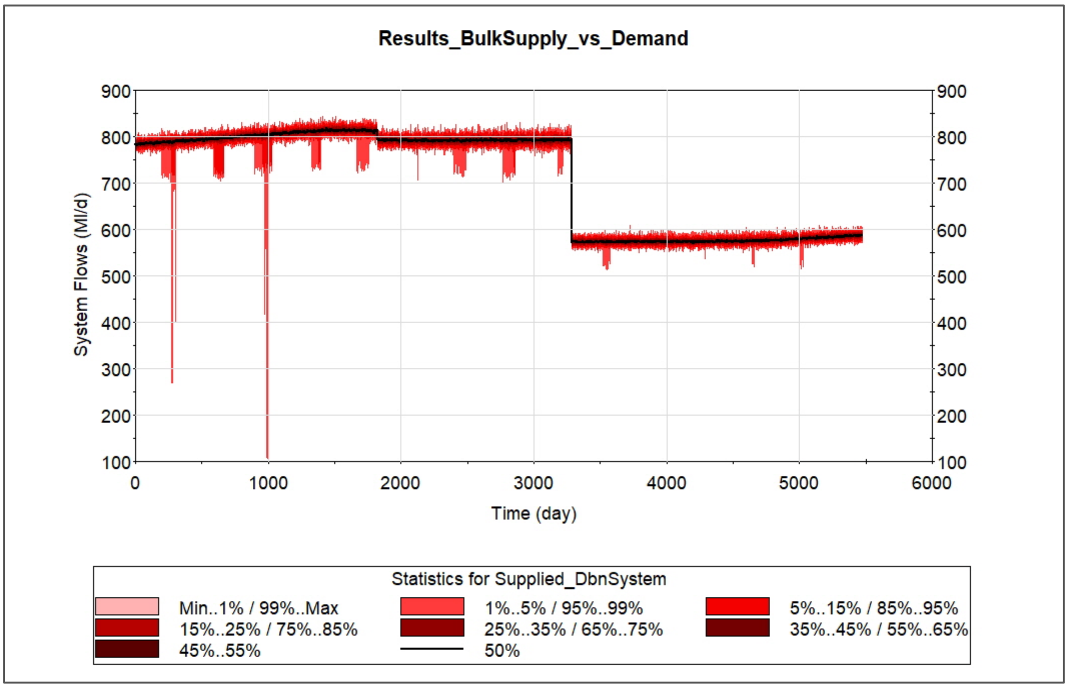


Figure C-143: Monte Carlo Analysis of Demand on Lower Mgeni System (Groundwater Scenario)

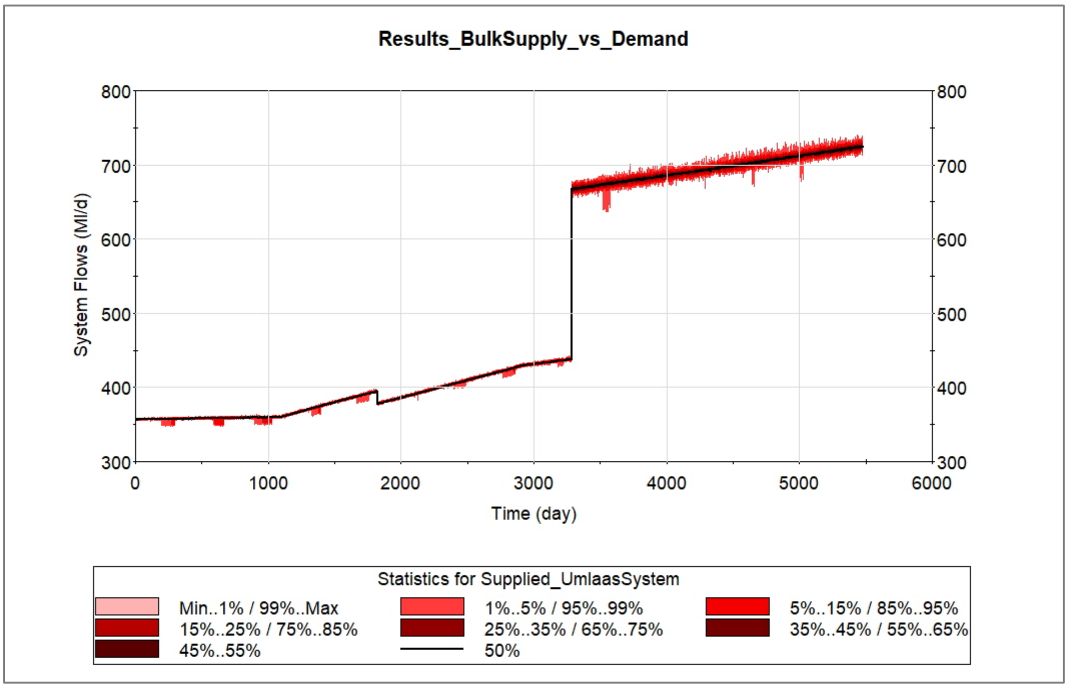


Figure C-144: Monte Carlo Analysis of Demand on Upper Mgeni System (Groundwater Scenario)

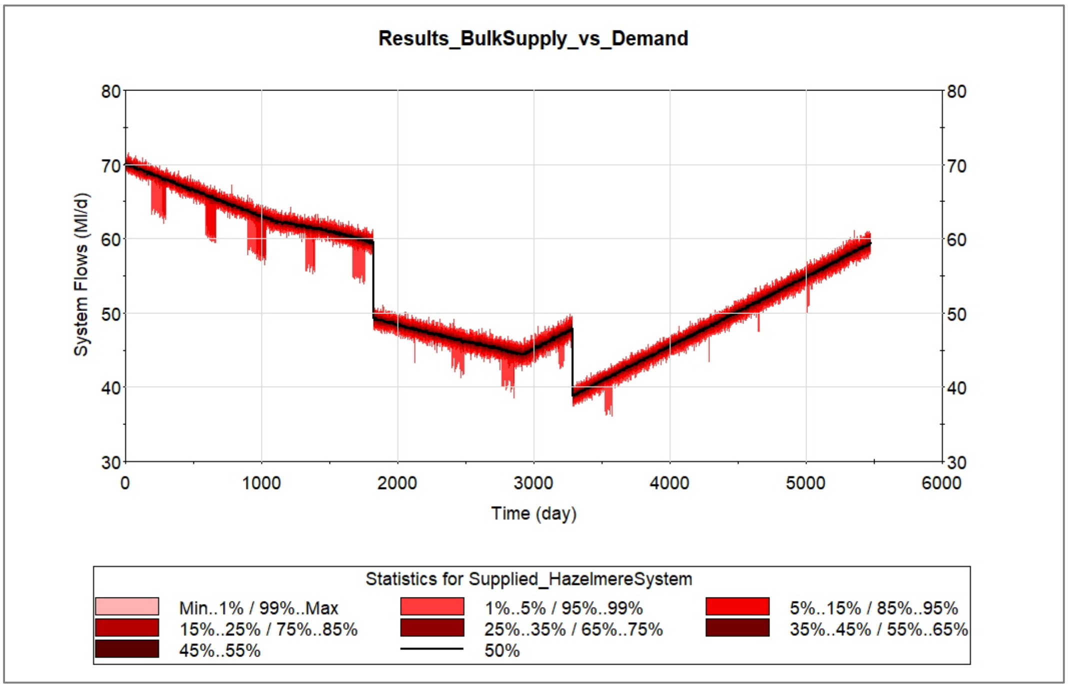


Figure C-145: Monte Carlo Analysis of Demand on Hazelmere System (Groundwater Scenario)

Desalination & Real Loss Reduction

Model outputs for desalination are summarised in the below series of figures. In that the potable water supplied in this scenario is no different to the baseline (inclusive of real loss reduction) as the desalinated water is supplied to the potable water networks, the reduction in the demand on specific treatment works is shown in Figure C-146 to Figure C-148.

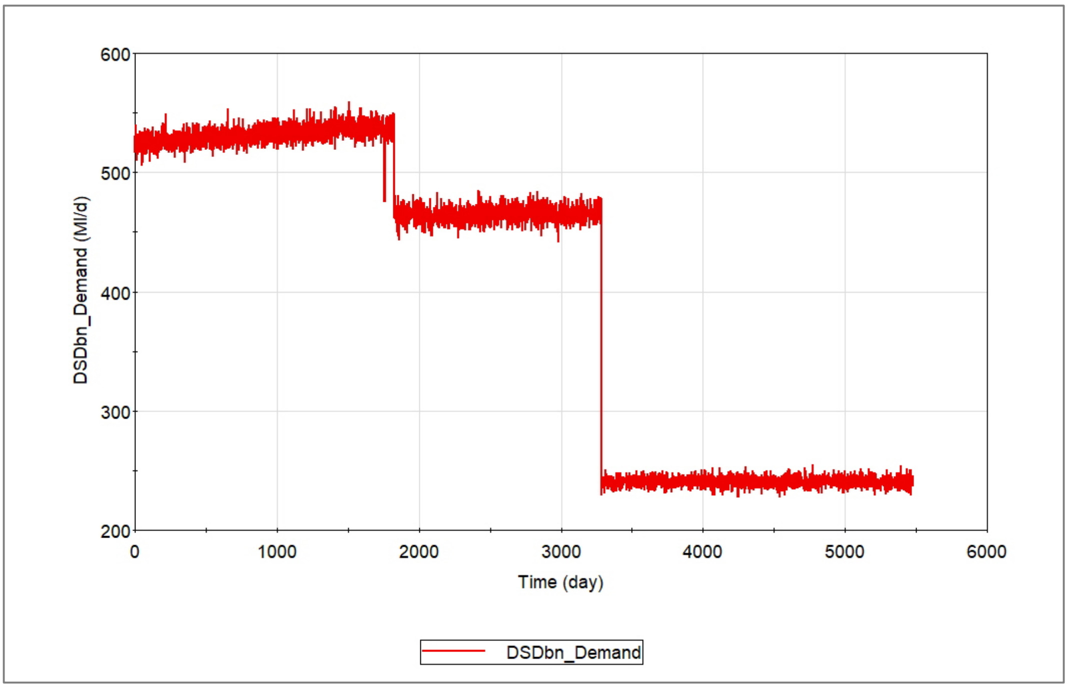


Figure C-146: Demand on Durban Heights Bulk Potable System (Desalination Scenario)

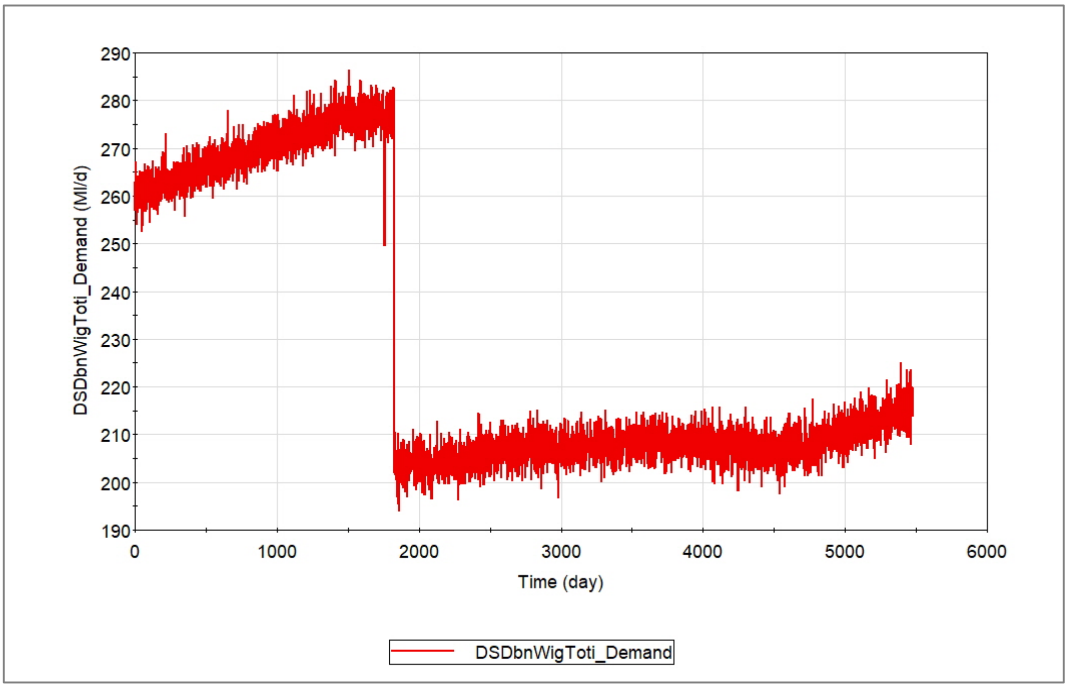


Figure C-147: Demand on Wiggins/Amanzimtoti Bulk Potable System (Desalination Scenario)

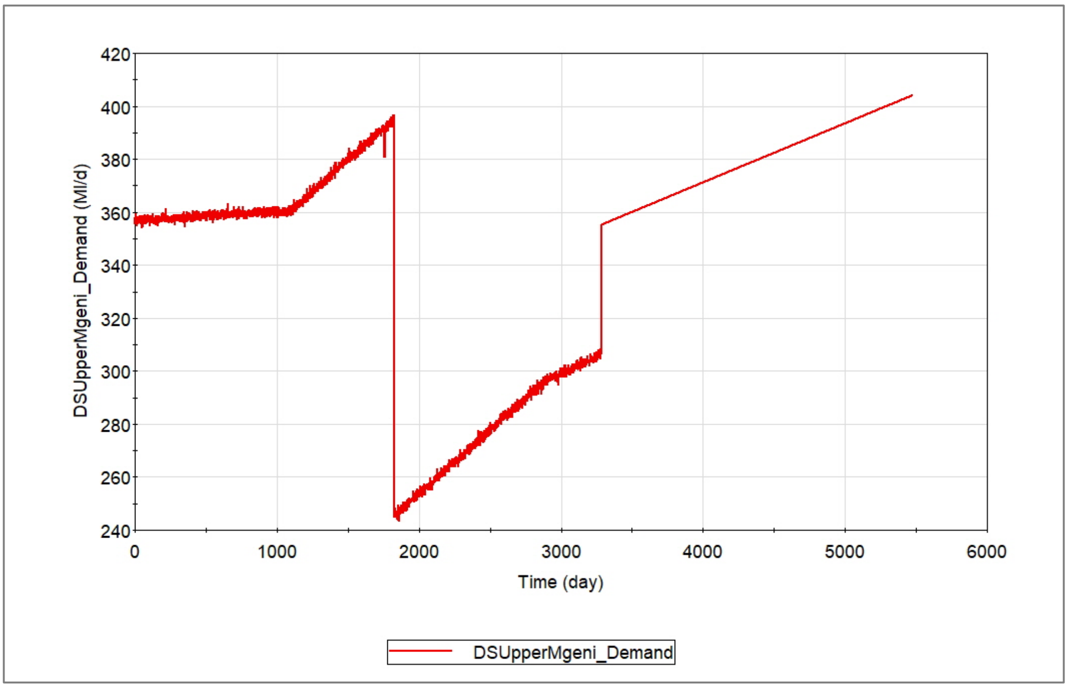


Figure C-148: Demand on Umlaas Road Bulk Potable System (Desalination Scenario)

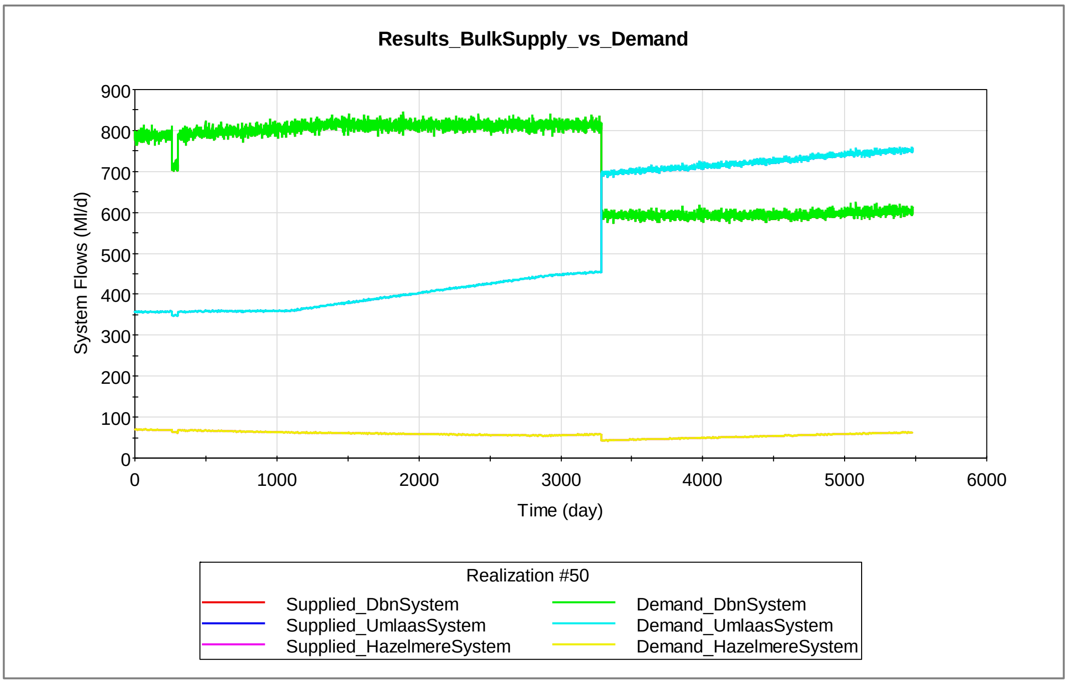


Figure C-149: Demand vs Availability for Water Supply Systems (Desalination Scenario)

Figure C-150 to Figure C-153 show the impact on water resources and volume of potable water supplied.

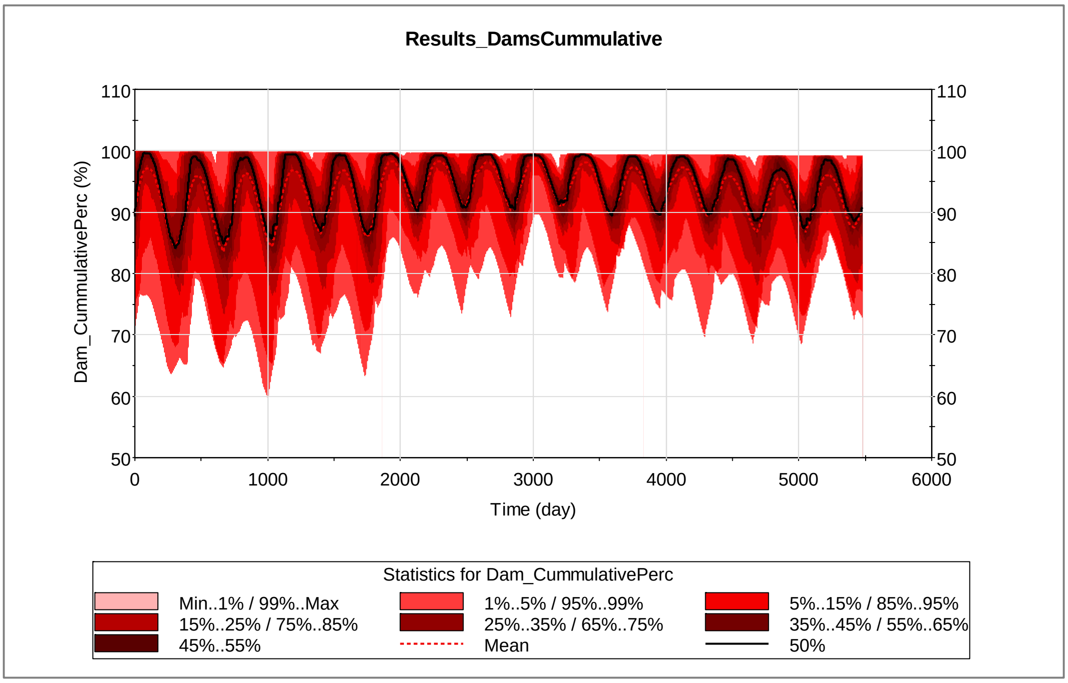


Figure C-150: Cumulative Dam Storage (Desalination Scenario)

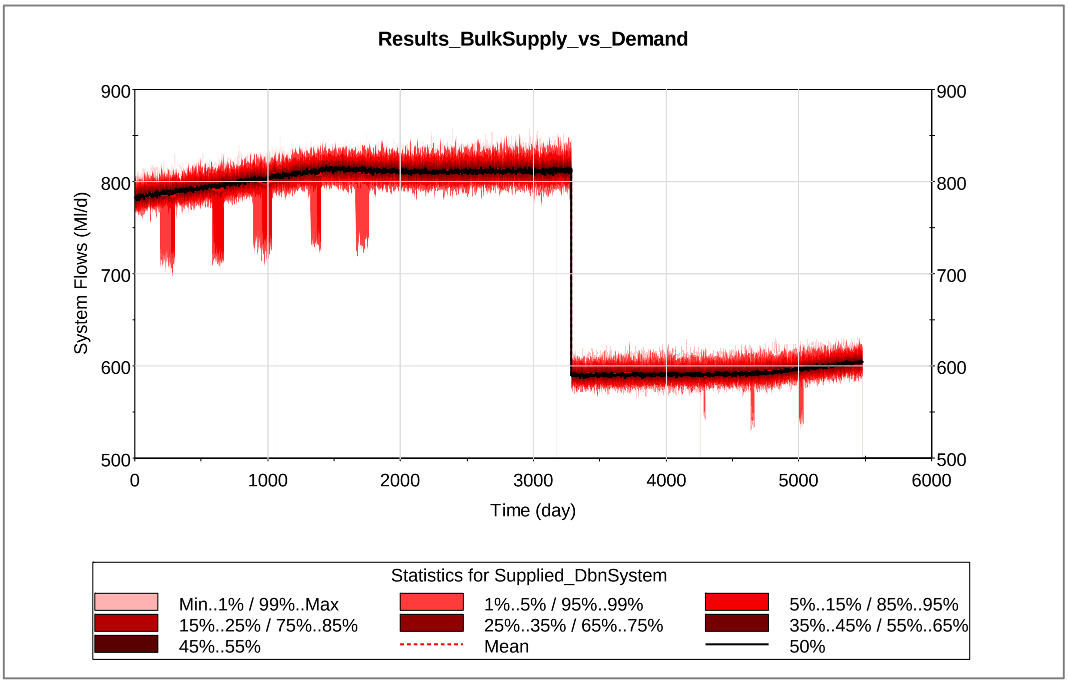


Figure C-151: Monte Carlo Analysis of Demand on Lower Mgeni System (Desalination Scenario)

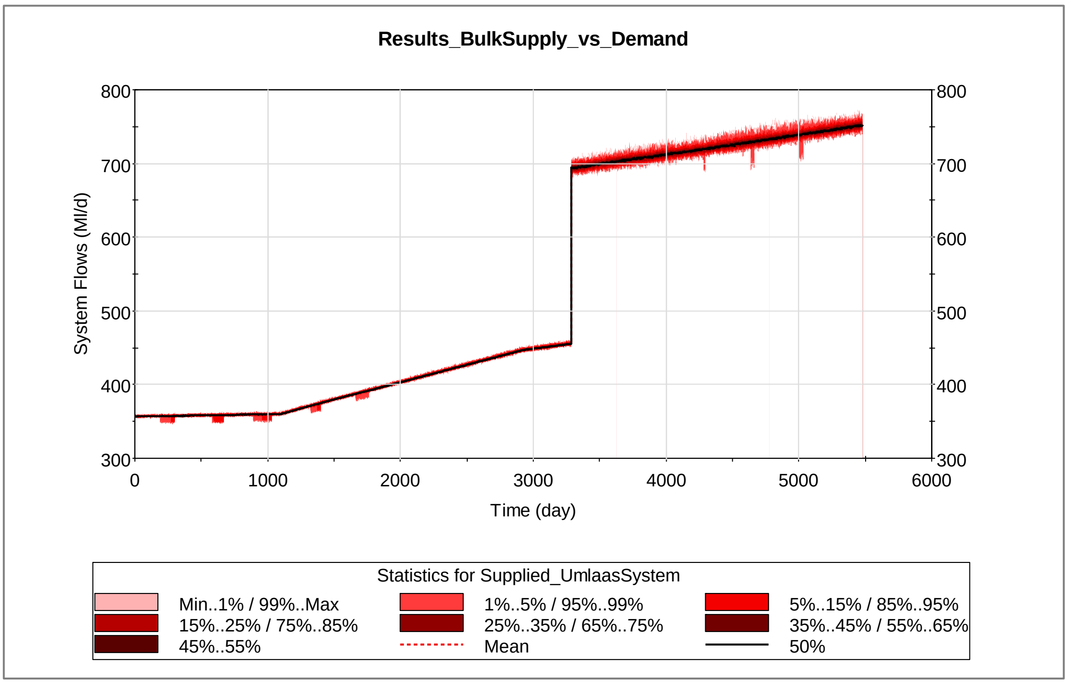


Figure C-152: Monte Carlo Analysis of Demand on Upper Mgeni System (Desalination Scenario)

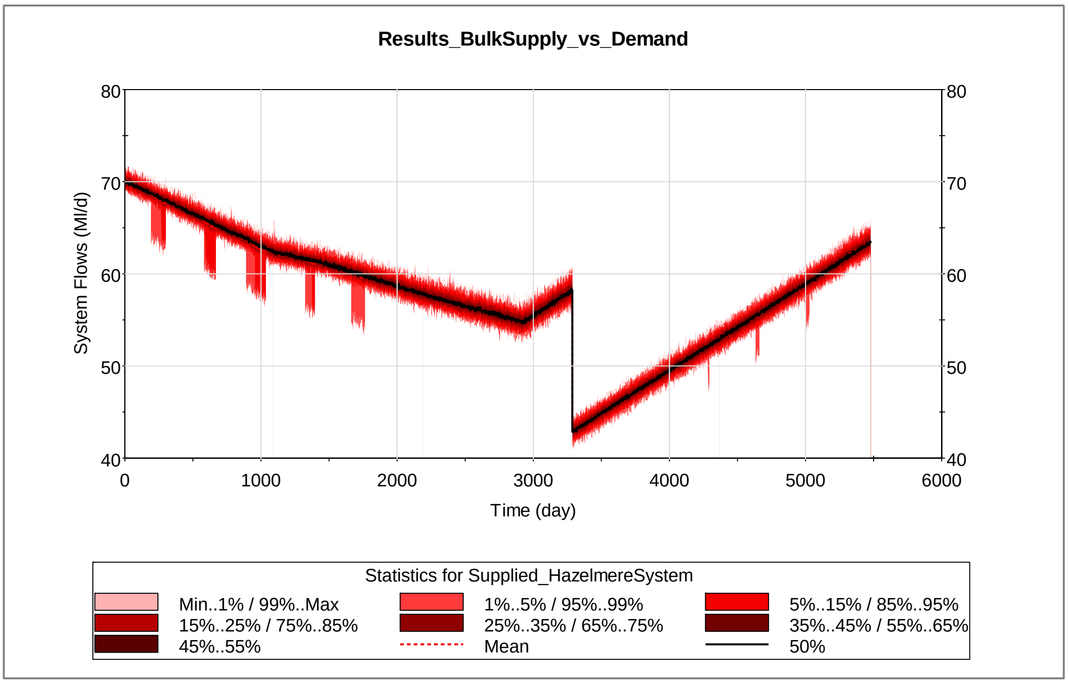
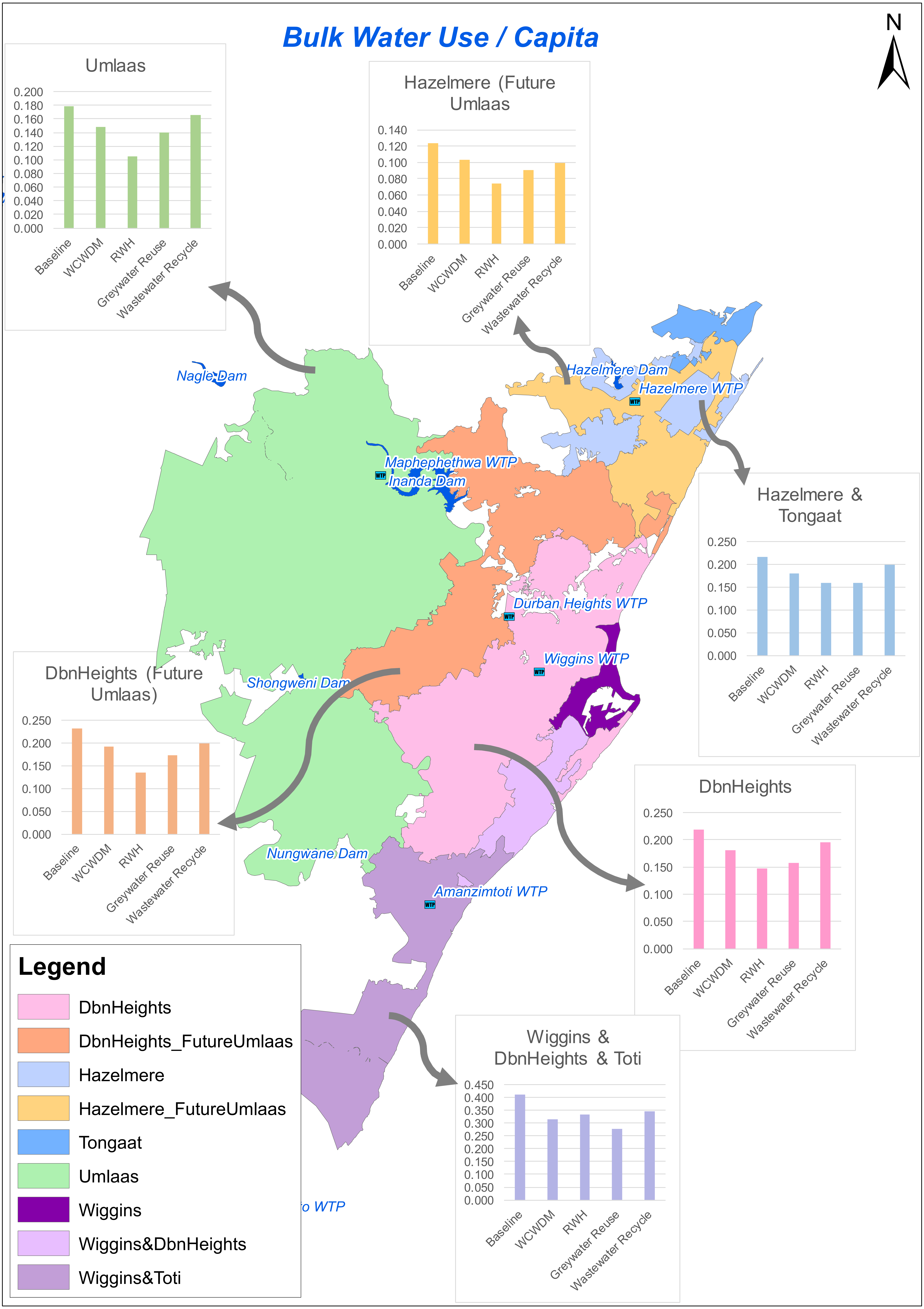


Figure C-153: Monte Carlo Analysis of Demand on Hazelmere System (Desalination Scenario)

Appendix D: Map of Bulk Water per Capita

Bulk Water Use / Capita



Appendix E: Indicator Selection

Table E-1: Indicator Vetting Process – Evaluation Criteria after Rathnayaka, Malano & Arora (2016)

Criteria No.	Criteria Category	Objectives	Evaluation Criteria	Forms part of model?	Is an indicator output of model?	Comment	Measurement / Definition
1	Environmental	River & waterbody health	Quality of wastewater produced and impacts (contribution to acidification and eutrophication, effects on flora and fauna)	Yes	No	Limited to quality	Contaminant loadings
2			Quantity of wastewater produced	Yes	Yes		Volume
3			Stormwater runoff	Yes	No		Volume; and Include stormwater quality as a result of buildup and washoff
4		Maintain river, local creaks, and wetlands	Effect on environmental flow and surface water	Yes	No		Volume
5			Freshwater / potable water saved	Yes	Yes		Volume
6			Effects on groundwater level and pattern (groundwater infiltration, recharge, depletion)	No	No	Surface water / groundwater interaction not modelled, however groundwater extractions limited to what has been defined in GRAII study	
7		Protect land ecosystem	Effects on fauna and flora / biodiversity	No	No	Outside of focus area of study	
8			Effects on habitats and protected natural habitat areas	No	No	Outside of focus area of study	
9			Land cover change effects (e.g. Habitats affected)	No	No	Outside of focus area of study	
10			Solid waste quantity and quality (e.g. sludge)	No	No	Outside of focus area of study	
11		Protect atmospheric ecosystem	Greenhouse gas and other emissions	No	No	Outside of focus area of study	
12			Photochemical oxidant formation	No	No	Outside of focus area of study	
13			Other pollutants (e.g. dust, noise)	No	No	Outside of focus area of study	
14			Energy use and recovery	Yes	Yes		Operational energy use

Criteria No.	Criteria Category	Objectives	Evaluation Criteria	Forms part of model?	Is an indicator output of model?	Comment	Measurement / Definition
15		Efficient resource use	Ability to use renewable energy sources	No	No	Outside of focus area of study; is a separate infrastructure system which could rather be assessed in a detailed project-specific model	
16			Fresh water use	Yes	Yes	Linked to Item #5 to prevent double counting	Volume
17			Land use	No	No	Land use is to be treated as an input to the scenarios for this study, not a result of different water supply options	
18			Materials for construction	No	No	Outside of focus area of study	
19			Chemical use	No	No	Outside of focus area of study	
20			Reuse and recycling of resources	Yes	Yes	Linked to all items which deal with return flows to prevent double counting	Volume
21	Social	Ability to meet user acceptance	User acceptance in terms of water quality	Yes	No	Implement as a variable in models (adoption of greywater use etc)	
22			Willingness to accept demand management options	Yes	No	Implement as a variable in models (compliance with water saving)	
23			Acceptance of increase/decrease in water bill	Yes	No	Implement as a variable in models (impact of tariff structure?)	
24			User awareness and involvement	No	No	Would be limited to a qualitative analysis	
25		Ability to meet community acceptance	Recreational values (visual amenity)	No	No	Would be limited to a qualitative analysis	
26			Impacts on urban heat island effect	No	No	Outside of focus area of study	

Criteria No.	Criteria Category	Objectives	Evaluation Criteria	Forms part of model?	Is an indicator output of model?	Comment	Measurement / Definition
27			Provision of educational opportunities	No	No	Would be limited to a qualitative analysis	
28			Small scale flood mitigation benefits	Yes	No		Volume retained by rainwater harvesting or stormwater harvesting
29			Odour / pests - any other negative impacts on the local community	No	No	Would be limited to a qualitative analysis	
30			Number of jobs created	No	No	Outside of focus area of study	
31		Health and hygeine	Safety (number of incidents / accidents)	No	No	Would be limited to a qualitative analysis; Potential for cross-contamination / incorrect use of different water streams	
32			Risk of infections (number of outbreaks / people affected)	No	No	Would be limited to a qualitative analysis; Potential for cross-contamination / incorrect use of different water streams	
33			Risk of other health hazards (presence of carcinogenic compounds in influent water)	No	No	Outside of focus area of study	
34			Exposure to toxic components (Cd, Hg, Pb) in operation	No	No	Outside of focus area of study	
35		Political approval	Project duration (e.g. design and construction phase)	Yes	No	Accounted for in time to implement alternative interventions	
36			Management / institutional effectiveness and efficiency	No	No	Outside of focus area of study	
37			Uncertainty of volume, timing, cost, approval, and delivery	Yes	No	Accounted for in uncertainty in certain interventions	

Criteria No.	Criteria Category	Objectives	Evaluation Criteria	Forms part of model?	Is an indicator output of model?	Comment	Measurement / Definition
38			State of readiness (availability of institution, documents, policy)	No	No	Outside of focus area of study; nonetheless accounted for in type of interventions considered	
39			Ability to meet environmental or other regulations	Yes	No	Reduction of treated wastewater reaching estuaries	
40	Economic	Total direct cost	Capital cost	No	No	Outside of focus area of study	
41			Maintenance cost	Yes	Yes		Monetary value
42			Operational cost including energy and other costs	Yes	Yes	Linked to Item #14 to prevent double counting	Monetary value
43			Disposal cost	Yes	Yes	Wastewater conveyance and disposal	Monetary value
44			Cost of water distribution-construction, maintenance, and operation	Yes	Yes	Linked to Item #41 & #42 to prevent double counting	Monetary value
45			Cost of water storage-construction, maintenance, and operation	Yes	Yes	Linked to Item #41 & #42 to prevent double counting	Monetary value
46		Total indirect cost	Value of hydropower / energy and other byproducts, such as fertiliser	No	No	Outside of focus area of study	Monetary value
47	Risk-based	Reliability	Probability of supply shortfalls (chance of not meeting the expected production)	Yes	Yes		Percentage occurrence
48		Vulnerability	Magnitude of failure	Yes	Yes		Portion of area / population affected
49		Resilience	Failure duration or how quickly system returns to its satisfactory state after a failure	Yes	Yes		Time
50		Robustness	Ability to perform satisfactorily under a range of system changes (e.g. climate)	Yes	No	Accounted for in Monte Carlo Analyses of scenarios	

Criteria No.	Criteria Category	Objectives	Evaluation Criteria	Forms part of model?	Is an indicator output of model?	Comment	Measurement / Definition
51	Functional	Flexibility of the option	End-uses it can fit	Yes	Yes	Accounted for in fitness for purpose use of different water supply streams & how it is adopted by communities & therefore impact on potable water demand; nonetheless a measure of resource efficiency introduced	Resource efficiency measures of internal harvesting ratio and internal recycling ratio (as compared against the total water use)
52			Flexibility in scaling	No	No	Would be limited to a qualitative analysis	
53			Capacity / Yield	Yes	No	Accounted for in system set-up & therefore demand vs available supply	
54			Potential for growth	Yes	No	Accounted for in modelling development & growth, & deference of major augmentation to existing centralised systems	
55		Construction flexibility	Challenges with management of site (presence of contaminated soild and underground services)	No	No	Outside of focus area of study	
56			Ability to blend with available supplies / infrastructure	No	No	Outside of focus area of study	
57		Operational and maintenance flexibility	Ease of maintenance including monitoring frequency based on water quality and quantity	No	No	Would be limited to a qualitative analysis	
58			Technical knowledge needed in handling the system	No	No	Would be limited to a qualitative analysis	
59		Durability	Life span of the water supply infrastructure / option	No	No	Would be limited to a qualitative analysis	Years

Criteria No.	Criteria Category	Objectives	Evaluation Criteria	Forms part of model?	Is an indicator output of model?	Comment	Measurement / Definition
60		Interactions between the system components	Effects on sewer distribution network such as sewer blockage, odour, and corrosion	No	No	Analysis is limited without a very detailed hydraulic model	
61			Effects on drainage distribution network	No	No	Peak flows (duration < 1 day not modelled)	
62			Effects on water supply network (e.g. size of pipes)	No	No	Analysis is limited without a very detailed hydraulic model	

Appendix F: Ethics in Research, Letters & Permissions

Application for Approval of Ethics in Research (EiR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

ETHICS APPLICATION FORM

Please Note:
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data. The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook** (available from the UCT EBE, Research Ethics website) prior to completing this application form: http://www.ebe.uct.ac.za/ebe/research/ethics1

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant		Danica Davies
Department		Civil Engineering
Preferred email address of applicant:		dvsdan006@myuct.ac.za
If Student	Your Degree: e.g., MSc, PhD, etc.	MSc Civil Engineering
	Credit Value of Research: e.g., 60/120/180/360 etc.	120
	Name of Supervisor (if supervised):	Dr Kirsty Carden
If this is a researchcontract, indicate the source of funding/sponsorship		/
Project Title		Assessment of Hybrid Water Supply systems in eThekwini Municipality.

I hereby undertake to carry out my research in such a way that:

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

APPLICATION BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	Danica Davies		30/10/19
SUPPORTED BY	Full name	Signature	Date
Supervisor (where applicable)	KIRSTY CARDEN		4/11/2019

APPROVED BY	Full name	Signature	Date
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section 1; and for all Undergraduate research (Including Honours).			
Chair: Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the questions in Section 1.	R Behrens		20 Nov 2019

Signature Removed

University of Cape Town

Department of Civil
Engineering

January 2020

LETTER OF INTRODUCTION & SUMMARY OF RESEARCH PROPOSAL

TITLE OF THE STUDY:
Assessment of Hybrid Water Supply Systems in eThekwini Municipality

RESEARCHER:
Danica Davies

To Whom It May Concern

This letter serves to outline the research proposal for the abovementioned study.

1 BACKGROUND

The situation in South Africa echoes the global challenge. In the Department of Water & Sanitation's (DWS) National Water & Sanitation Masterplan (2018), it is stated South Africa's current water crisis is a result of "insufficient water infrastructure maintenance and investment, recurrent droughts driven by climatic variation, inequities in access to water and sanitation, deteriorating water quality, and a lack of skilled water engineers". The NW&SMP (2018) states the national water deficit could reach between 2.7-3.8 billion cubic metres (or 17% of available water resources) by 2030, should there be no interventions and should the current demand projections hold. Provision of basic services is a significant challenge, particularly in rapidly growing urban areas where it is expected 70% of the national population will reside in urban areas by 2030. In the context of urbanisation and with the potential for climate change to aggravate water shortages, water security is a major concern (Armitage et al., 2014). It is clear that effective water management will be crucial moving forward, with various institutions recognising the need for alternative approaches to water management (Armitage et al., 2014).

The current infrastructure archetype, particularly relating to water services, is based on the most efficient means of conveying a particular water stream (i.e. water, wastewater, or stormwater) from origin to destination (Armitage et al., 2014). Urban water infrastructure is therefore predominantly configured as large-scale and centrally managed systems out of the need to deliver cheap and reliable services and overcome the cost, operational complexity and resource intensiveness associated with service provision (Marlow et al., 2013). The sustainability of such systems has, of recent times, been called into question (Leigh & Lee, 2019). Some of the inefficiencies in design, cost, energy, natural resources, and management are summarised below.

Due to their nature, centralised systems rely on significant networks of pipelines to convey a particular water stream from origin to destination. Marlow et al. (2013) state the pipelines for all water services typically comprise 50-75% of a water service provider's capital and operational costs. Aging centralised systems have severe cost implications for operation and replacement or refurbishment (Leigh & Lee, 2019). Inefficient energy usage is frequently attributed to centralised systems (conveyance of water streams and large-scale treatment works) (Leigh & Lee, 2019). Conveyance of wastewater from origin to destination is associated with the loss of potentially useful resources, such as water, nutrients, and energy (Marlow et al., 2013; Leigh & Lee, 2019). Similarly, stormwater drainage for the sole purpose of flood protection is seen as loss of a potentially useful source of water (Marlow et al., 2013). Large-scale impoundment of water for subsequent treatment as well as discharge of stormwater alters the natural hydrological function of a system and have unforeseen environmental impacts (Marlow et al., 2013; Leigh & Lee, 2019). A small percentage of potable water is utilised for potable purposes; therefore, there exist opportunities to reduce the volume of potable water required (Marlow et al., 2013). Finally, given centralised systems generally rely on a limited number of water sources and are frequently configured as hierarchical systems, they are particularly vulnerable to changes in climate which may result in unexpected floods or droughts (Leigh & Lee, 2019).

All of the aforementioned shortcomings of conventional water systems has driven the development of a more sustainable way forward; hence the emergence of the Sustainable Urban Water Management (SUWM) paradigm (Leigh & Lee, 2019). Given the substantial cost of constructing and operating extensive pipe networks of centralised infrastructure, if dependency on these networks is decreased (i.e. through decentralisation), theoretically there could be cost savings which could be refocussed on treatment of water, wastewater and stormwater (Marlow et al., 2013). Decentralisation is thus a fundamental theme in the SUWM literature (Marlow et al., 2013; Leigh & Lee, 2019). Concomitant with decentralised systems, integration is also a key theme of SUWM through interlinking of water flows which in a conventional system would generally be kept separate, i.e. consideration of the total water cycle is critical. Examples of solutions within the SUWM space include sustainable urban drainage systems, wastewater recycling, improved wastewater effluent quality, managed aquifer recharge, groundwater use, rainwater harvesting, stormwater harvesting, and Water Conservation and Water Demand Management (WC/WDM).

Where water infrastructure is already in place, a complete transition to alternative water provision models is neither economical nor practically feasible, especially where past system decisions are irreversible. Innovations tend to occur at a local level and as additions or retrofits to existing systems, while aging centralised infrastructure is refurbished or replaced incrementally as is needed and/or is most economical (Marlow et al., 2013). Systems in which the process of evolution of the water services configuration occur are termed hybrid systems (Marlow et al., 2013).

2 PROBLEM STATEMENT & RESEARCH AIM

There are three core benefits of SUWM: (1) A more natural water cycle, (2) Improved water security through diversification of sources, and (3) Resource efficiency (Marlow et al., 2013). Despite the potential benefits of integrated management of the water cycle and resulting diversification of water supply sources, the implementation of such has been slow, both internationally and in South Africa. One of the key impediments to implementation are “unknowns” around the performance of alternative solutions and technologies and the effects on existing (centralised) systems (Marlow et al., 2013).

Innovative solutions and the dynamic changes they bring to an existing system may not be intuitive. The uncertainty around these matters may also result in the meeting of one SUWM objective undermining another. Such challenges highlight the need for thorough evaluations of alternative water servicing options against multiple criteria. Even if supported by rigorous decision support methods, less evidence and learned experience on the performance of innovative solutions means uncertainty remains. Experimentation, pilot studies, and trials are therefore recommended to build an empirical foundation and so encourage change (Marlow et al., 2013).

This research therefore aims to contribute to a greater understanding of the net system effects of integrated management of the water cycle where alternative and decentralised solutions are introduced to existing systems in a South African context. This will be achieved by developing and modelling a number of water servicing options under different scenarios for a selected case study area.

3 PROPOSED RESEARCH METHODOLOGY

eThekwini Municipality has been selected as the case study area: this region has a diverse range of consumers to service (fully serviced urban suburbs, informal settlements, peri-urban settlements, and rural areas) and is therefore largely representative of South African cities; the water and sanitation service delivery unit is renowned for continuous investment in research and development and piloting of new technologies; and the region is supplied by a number of surface water resources, but is not without water stresses in some of its catchments.

Studies which evaluate the sustainability of water supply options differ widely in the mechanisms of assessment, but there are generally three key commonalities: water supply and/or demand management options, scenario paths (introduced to assess performance through a range of system variables), and evaluation criteria (used to assess performance and prioritise options) (Rathnayaka, Malano & Arora, 2016).

An assessment framework based on the framework as applied by the United States Environmental Protection Agency (2012) to total water cycle management has been selected for testing of water servicing options in this study. This framework comprises three broad stages: model inputs, system modelling, and decision making.

The below figure summarises the assessment framework for this study, as adapted from EPA (2012).

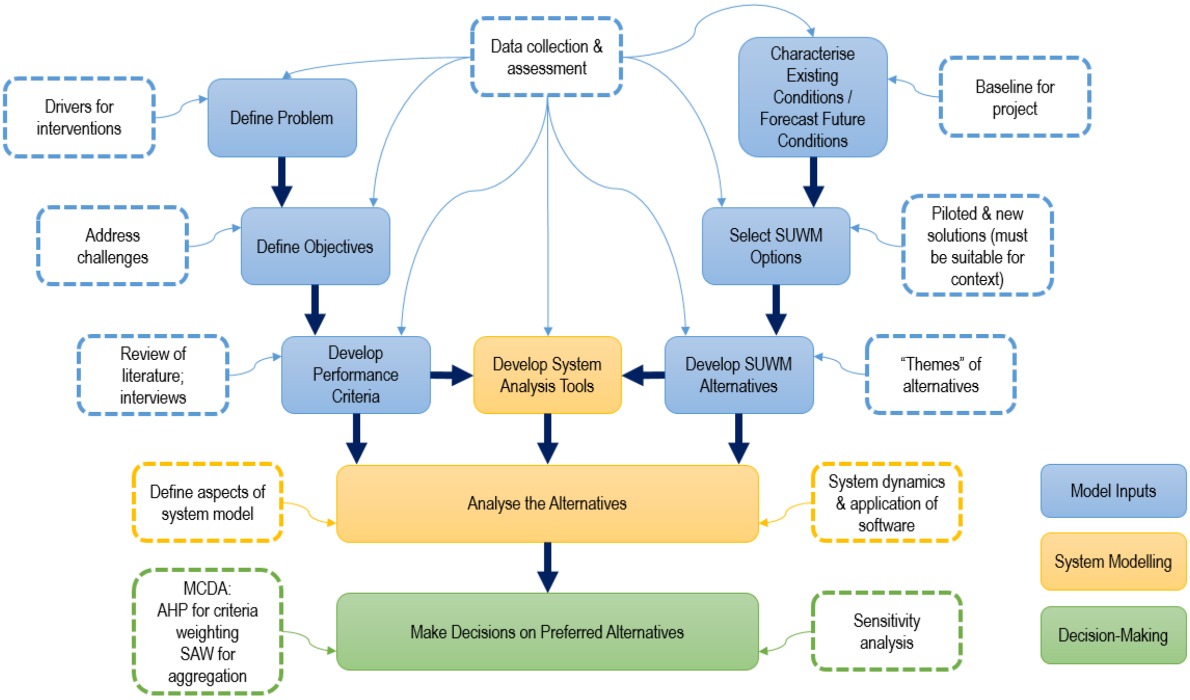


Figure 1: Summary of Actions for Proposed Research Methodology

The assessment framework will be supported by tools such as:

i. Surveys of water industry professionals (especially eThekwini Water and Sanitation staff) to better understand the current status of water services and some of the challenges faced

ii. Surveys of water industry professionals (especially eThekwini Water and Sanitation staff) to determine appropriate criteria against which solutions are to be tested

iii. Surveys of water industry professionals (especially eThekwini Water and Sanitation staff) to determine the relative importance of the selected criteria
iv. System dynamics modelling of the different solutions and scenarios such that each criterion may be measured
v. Multi-criteria decision analysis to rank each alternative.

Other than survey data, information collected will be secondary data and sources are likely to include water infrastructure system information, rainfall data, water consumption data, and municipal documents.

Please do not hesitate to contact me should you have any questions.

Yours faithfully

Signature Removed

Danica Davies

REFERENCES

1. Armitage, N. F.-J. (2014). Water Sensitive Urban Design (WSUD) for South Africa: Framework and guidelines: WRC Project No. K5/2071. Water Research Commission of South Africa. Retrieved April 2019
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University of Cape Town

Department of Civil
Engineering

January 2020

Teddy Gounden
EThekwini Water and Sanitation
3 Prior road
Durban
4001

LETTER OF INTRODUCTION & REQUEST FOR USE OF ETHEKWINI WATER & SANITATION DATA FOR MSC (CIVIL) DISSERTATION

TITLE OF THE STUDY:
Assessment of Hybrid Water Supply Systems in eThekwini Municipality

RESEARCHER:
Danica Davies

Dear Sir

I have been referred to you by my supervisor at the University of Cape Town, Dr Kirsty Carden. This letter serves to request the use of eThekwini Water & Sanitation water services infrastructure data for the abovementioned study.

1 ABOUT THE RESEARCH

The aim of this research is to contribute to a greater understanding of the net system effects of integrated management of the water cycle where alternative and decentralised solutions are introduced to existing systems in a South African context. This will be achieved by developing and modelling a number of water servicing options under different scenarios.

More detailed information on the background to the problem and the proposed research methodology may be found in the letter attached hereto, titled "*LETTER OF INTRODUCTION & SUMMARY OF RESEARCH PROPOSAL*".

eThekwini Municipality has been selected as the case study area for this research due to the diverse range of consumers and areas to service, as well as the proclivity to invest in research and development and piloting of new sustainable technologies and solutions.

2 USE OF DATA

Achieving the aim of this study requires modelling of the water, wastewater, and stormwater systems in eThekwini such that each water servicing option can be measured against a number of criteria (for example, potable water savings, reduction in wastewater flows).

The following data is therefore required:

- Geographical Information System (GIS) shapefiles for water, wastewater, and stormwater systems
- Water and sanitation network schematic diagrams
- Consumer billing data shapefiles (consumer names and addresses are not required)
- Information on piloted technologies, such as DEWATS and Organica wastewater treatment plants. Details of these systems and any documentation on performance would be most useful.

The abovementioned data will be used for the sole purpose of this study and will not be distributed to any other parties.

Any assistance you are able to provide in connection with this request will be highly appreciated.

Please do not hesitate to contact the researcher should you have any questions.

Yours faithfully

Danica Davies

For **eThekwini Water & Sanitation**
Acceptance by:

Teddy Gounden

University of Cape Town

Department of Civil
Engineering

January 2020

LETTER OF INTRODUCTION AND INFORMED CONSENT FOR PARTICIPATION IN ACADEMIC RESEARCH

TITLE OF THE STUDY:
Assessment of Hybrid Water Supply Systems in eThekwini Municipality

RESEARCHER:
Danica Davies

Dear Madam/Sir

You are cordially invited to participate in an academic research study due to your experience and knowledge in the research area, namely water resources and water infrastructure. Each participant must receive, read, understand and sign this document before the start of the study.

Herewith is a brief description of the study. Further information about the study may be provided on request.

Motivation for study:

There are currently numerous and extensive challenges centred around water resources and infrastructure, both globally and in South Africa. Sustainable Urban Water Management (SUWM) is a relatively new approach to water management whereby the whole water cycle is considered and decentralised solutions are a key theme. There are many benefits of such which can be summarised into three broad categories: (1) A more natural water cycle, (2) Improved water security through diversification of sources, and (3) Resource efficiency.

Despite the potential benefits, the implementation of such approaches to SUWM has been slow, both internationally and in South Africa. One of the key impediments to implementation are “unknowns” around the performance of alternative solutions and technologies and the effects on existing (centralised) systems.

This research therefore aims to contribute to a greater understanding of the net system effects of integrated management of the water cycle where alternative and decentralised solutions are introduced to existing systems in a South African context. This will be achieved by developing and modelling a number of water servicing options under different scenarios for a selected case study area.

Purpose of the study:

The purpose of the study is to contribute to a greater understanding of the net system effects of integrated management of the water cycle where alternative and decentralised solutions are introduced in a South African context.

Duration of the study:

The study will be conducted over the course of the next few months and is anticipated to be complete by mid-2020.

Research procedures:
A number of water servicing options will be developed and tested against an assessment framework, using eThekwini Municipality as a case study area. The assessment is primarily quantitative in nature. Data inputs are predominantly secondary data and comprises water infrastructure system information, rainfall data, water consumption data, and municipal documents. As part of the research methodology, the researcher has elected to engage with water industry experts to:

i. Discuss various aspects of water services to gather contextual information for the case study area
ii. Determine which criteria should be used to assess water supply options: this will comprise a series of questions and discussion around how water supply options are assessed and/or should be assessed
iii. Determine the relative importance of criteria for later use in a multi-criteria analysis: This will comprise a series of pairwise comparisons for participants to complete; i.e. the importance of Criterion A compared to Criterion B is assigned a number on a defined scale.

You may choose not to participate in this study and you may also stop participating at any time without stating any reasons and without any negative consequences. You, as participant, may contact the researcher at any time in order to clarify any issues pertaining to this research. The respondent as well as the researcher must each keep a copy of this signed document.

All information will be treated as confidential. Participants may elect to have their names and/or their organisations kept anonymous. Only the author of this study will have access to the raw data. The relevant data will be destroyed, should you choose to withdraw. You will be provided with a summary of the findings on request. No participants' names will be used in the final publication, unless specifically requested by the participant.

WRITTEN INFORMED CONSENT

I hereby confirm that I have been informed about the nature of this research.
I understand that I may, at any stage, without prejudice, withdraw my consent and participation in the research. I have had sufficient opportunity to ask questions.

Respondent: ______________________

Respondent would like name kept anonymous: Yes / No

Respondent would like organisation kept anonymous: Yes / No

Researcher: ______________________

Date: ______________________

Contact number of the Researcher: 083 643 4321
Please do not hesitate to contact the researcher should you have any further questions.

University of Cape Town

Department of Civil
Engineering

January 2020

INTERVIEW QUESTIONS: GENERAL DISCUSSIONS ABOUT WATER SERVICES

TITLE OF THE STUDY:
Assessment of Hybrid Water Supply Systems in eThekwini Municipality

RESEARCHER:
Danica Davies

Dear Madam/Sir

Thank you for agreeing to participate in this academic research study; your contribution is highly appreciated.

The purpose of this particular interview is to discuss various aspects of water services in eThekwini.

Detailed information on the background to the problem and the proposed research methodology may be found in the letter attached hereto, titled "*LETTER OF INTRODUCTION & SUMMARY OF RESEARCH PROPOSAL*".

QUESTIONNAIRE / INTERVIEW

1 BRIEF BACKGROUND TO QUESTIONS

One of the fundamental steps in this particular research plan is understanding the current conditions of the water cycle and the related infrastructure in eThekwini; this will inform the different theoretical scenarios which will be developed and tested.

2 QUESTIONS

1. What are some of the key strengths with water supply? What are some of the challenges in this space?

2. What are some of the key strengths with sanitation provision? What are some of the challenges in this space?

3. What are some of the key strengths with stormwater services? What are some of the challenges in this space?

4. In terms of water, sanitation, and stormwater infrastructure, in your view what aspects are currently sustainable? And what aspects are unsustainable?

5. What are eThekwini's current plans / initiatives / programmes to address the impacts of climate change?

6. Would you say eThekwini practices an Integrated Water Resources Management approach?

7. Has the Water Services Development Plan (as published in 2012) been updated? If no, in terms of planning, are there any major departures from what has been documented there?

8. Umgeni Water sells bulk water to eThekwini at a number of locations. What arrangements are in place in the event of bulk water shortages as a result of low rainfall seasons? If eThekwini requires additional supply to new and/or expanded areas, how is this planned and negotiated with Umgeni Water?

9. What is the current total water consumption, and what is the split between agriculture, industry, and residential? Is there pressure to change the current allocations?

10. Would you say water users are aware of water conservation practices in their homes? What has been the water users' response to encouraging reduction in potable water – for example through rainwater tanks or through awareness campaigns?

11. Is household level reuse of greywater encouraged?

12. What is the current Non-Revenue Water level? What Water Conservation & Demand Management programmes have had the largest impact? What are some of the challenges currently faced with reducing NRW?

13. Is groundwater a water source which features in eThekwini?

14. A number of years ago there were plans to recycle wastewater to potable standards, but the projects were never carried forward. Are there any plans to attempt implementation in future?

15. Are there plans to extend the current DEWATS technology outside of the current pilot project?

16. What is the current status of river health in eThekwini? Are there on-going initiatives to improve river health?

17. Rainwater tanks have been installed in certain areas. When was this done and are these units still in service?

18. What type of SuDS solutions have been implemented in eThekwini?

19. Is stormwater harvested in eThekwini? If not, are there any plans to do so?

20. In addition to some of the initiatives mentioned above, what other alternative / sustainable pilot projects has eThekwini implemented?

21. General questions about pilot projects / sustainable solutions implemented:

    a. How have these pilot projects performed in practice?
    b. What have been the driving forces or motivations for implementing these projects?
    c. What other pilot projects would you like to see implemented?

22. What sustainable solutions are currently encouraged or adopted in new housing developments?

Thank you for your time and contribution to this study.

Yours faithfully

Signature Removed

Danica Davies

Appendix Removed

Due to having unremovable

Signatures

UMGENI WATER	
Engineering and Scientific Services Division Planning Services	ESS/PLS/Temp/07
Data Request Form	Rev.: Draft 1

Umgeni Water Planning Services Data Request Form

Please submit this *completed form electronically* to the Data Analyst at nombuso.dladla@umgeni.co.za.

1. Data Request Details

1.1 Data set/s requested:

Dams, pipelines, water treatment works, pumpstations, reservoirs, and service area polygons

1.2 Project for which the data set/s are requested:

MSc (Civil Engineering) Thesis

1.3 Select the Water Services Authority in which the project is located (select with "X") :

eThekwini	☒	Msunduzi	☐	uMgungundlovu	☐
Harry Gwala	☐	iLembe	☐	Ugu	☐

1.4 Project purpose:

Development of a theoretical model to assess the impact on existing water supply systems/sanitation systems/stormwater systems when introducing alternative and/or decentralised water supply options. Case study area is eThekwini

1.5 Date of final completion of project:

End 2020

2. Data Requester Details

2.1 Project client name:

University of Cape Town

2.2 Client's organisation type (select with "X"):

Public sector: ☐ Academic: ☒

Private sector: ☐ NGO: ☐

2.3 Project manager's name within client's organisation:

Study supervisor: Dr Kirsty Carden

2.4 Project manager's contact details:

C: 083 292 2647; Email: Kirsty.Carden@uct.ac.za

2.5 Data requester's name:

Danica Davies

2.6 Data requester's role in project:

Researcher

2.7 Data requester's contact details:

C: 083 643 4321; Email: ddavies@gibb.co.za

Please ensure that you read and fully understand the conditions stated overleaf. By signing this form the signatory, and by extension his/her organisation and the client's organisation, accepts the conditions as stated. Please note incomplete forms and forms with no signature will not be processed.

3. General Conditions

Recipient(s) undertake:

1. To acknowledge the source of the data as Umgeni Water using the citation “Umgeni Water Infrastructure Master Plan 2019” in any documentation derived from or associated with the use of these data set/s;
2. To not distribute the data obtained to third parties, either at a cost or at no cost;
3. To adhere to any further conditions that may be stipulated (you will be contacted if this is applicable);
4. To use the data set only in accordance with the conditions specified below and only for the project applied for;
5. To notify Umgeni Water if the data provided is used in projects other than that applied for;
6. To re-apply if updates to the data are required;
7. To provide Umgeni Water with a free electronic copy of each product(s) generated in whole, or in part, from the data provided within 30 days of completion of the project.
8. To provide Umgeni Water with a free geodatabase of derivative datasets obtained from the Umgeni Water datasets provided within 30 days of completion of the project.

4. Additional Conditions (if applicable):

1. (Enter if applicable).
2. (Enter if applicable).

5. Signatures

	Danica Davies	8 May 2020
Signature of Data Requester	**Name of Data Requester**	**Date**
	Kirsty Carden	8 May 2020
Signature of Project Manager in Client’s Organisation	**Name of Project Manager**	**Date**
	Interim Director - Future Water Research Institute (UCT)	
	Position of Project Manager	

Signatures Removed

6. Disclaimer

Although utmost care has been taken in the preparation of this data, neither Umgeni Water nor its employees shall be held liable for loss, damage, inconvenience or any other liability suffered as a consequence of the use of this data.

Should any deficiency be identified in the data provided, the Recipient is requested to report this to Umgeni Water within 30 days of receipt of the data (as per Section 17(1) of the Spatial Data Infrastructure Act (No. 54 of 2003)) using the attached Form.

UMGENI WATER	
Engineering and Scientific Services Division Planning Services	ESS/PLS/Temp/07
Form Reporting Error in Data	Rev.: Draft 1

Report Regarding Error or Perceived Deficiency in the Quality of Umgeni Water Spatial Information

This form is based on Form D of the Spatial Data Infrastructure Act Regulations, 2017. It is to be completed by the data requester on discovering any error or deficiency in the quality of spatial information provided by Umgeni Water.

The Data Requester is requested to report any identified errors or perceived deficiencies in the quality of the spatial information to Umgeni Water (Section 17(1) of the Spatial Data Infrastructure Act (No. 54 of 2003) and Section 8 of the Spatial Data Infrastructure Act Regulations, 2017).

1. Complainant Details

Complainant Name: ____________________

Date data received: ____________________

Date of deficiency discovery: ____________________

2. Data Set Details

Data set title: ____________________

Data set reference number: ____________________

Data set publication date: ____________________

3. Type of perceived deficiency (mark with X)

Misclassification *(e.g. river classified as a road)* ☐

Positional accuracy *(e.g. latitude/longitude coordinates wrong)* ☐

Completeness *(e.g. land parcels omitted from the cadastre layer)* ☐

Precision *(e.g. data captured in single precision that should be double precision)* ☐

Reclassification *(e.g. 4 classes that should actually be 5 classes for the same data)* ☐

Consistency *(e.g. features with wrong attribute types within a selected feature class)* ☐

Duplication *(e.g. more than one feature lying on top of each other at a specific location)* ☐

Generalisation *(e.g. rivers that should have more line segments than indicated)* ☐

Inconsistency *(e.g. gaps in the data where there should be none)* ☐

Other *(not covered by any of the above)* ☐

4. Problem Description

Problem description: ____________________

Suggested solution: ____________________

Appendix G: GoldSim Model

A copy of the GoldSim model developed as part of this study is included in the digital submission.

GoldSim Player (freeware) may be used to view and run the model, and may be downloaded from the below link:

https://www.goldsim.com/Web/Customers/Downloads/Player/