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Water supply and demand scenarios and their impacts in the Tamale Metropolitan area, Ghana

Guro Emilie Aasen
Water and Environmental Technology

Preface

This thesis symbolizes the end of my 5-year integrated master's degree in water and environmental sciences at the Norwegian University of Life Sciences (NMBU). I be able to do my field work in collaboration with the University for Development Studies (UDS) in Tamale, Ghana, and it is an experience I will forever appreciate.

I am grateful to my supervisor, prof. Harsha Ratnaweera for extending me the opportunity to travel 11 weeks to Tamale in Ghana, and I am happy I got to share the experience with my fellow classmate and friend, Solveig Erga. Thank you to my co-supervisors Tore and Sean for their help with the preparation for the journey.

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Abstract

Water as a resource is extremely important for all life. Still, 26% of the world's population lacks access to a safely managed drinking water service. The part of the population that lacks access is disproportionately spread and Africa is suffering water scarcity the most. With the ever-growing population and effects of climate change, water scarcity and shortages will only be exacerbated. Unfortunately, there are not many studies about the effect climate change has on water resources systems in SSA.

This thesis aims to evaluate and manage potential challenges in urban drinking water supply in the coming decades in the Tamale Metropolitan area. The methods used to acquire results were data acquisition and WEAP Modelling. The modelling resulted in multiple models. One model simulated the future water supply and demand situation with three different annual population growth rates, 2.1%, 3.7% and 5.0%. This model also simulated what would happen to the coverage if the maximum capacity of the transmission link was reduced by 10% and 20%. Four models were developed to provide options for managing the drinking water supply and demand situation, namely the improvement models.

The current challenges to the potable water supply in Tamale Metropolis were found to be unsatisfactory drinking water supply. The reasons for the water supply being unsatisfactory were found to be water loss, operational challenges, and population growth.

If the population increases by 2.1%, 3.7% and 5.0% annually, the coverage will decrease substantially. In 2021 the coverage was around 35%. In 2050 however, the coverage was 19% for the scenario where the annual population growth rate was 2.1%. For the scenario where the annual population growth rate was 3.7%, the coverage in 2050 was 12%. Lastly, when the annual population growth rate was 5.0%, the coverage was 8%. To see the effects the factors influencing the catchment has on the urban water supply, a reduction of 10.0% and 20.0% maximum capacity was simulated. The results of these simulations show that this impacts the supply negatively.

Lastly, the thesis centers on the possibility of managing the weaknesses/challenges of the drinking water supply so that the coverage will increase in the predictable future. Here the challenges are water loss and reuse rate, and transmission link capacity. By developing the improvement models, it was discovered that all actions increase the coverage, but to different extents. The highest increase occurs in the TL, loss rates and reuse rate model, where the

average coverage in 2021 was 82%, and in 2050 varied between 20-45% based on what PGR was used.

Sammendrag

Vann som ressurs er ekstremt viktig for alt liv. Likevel mangler 26% av verdens befolkning tilgang til trygge drikkevannstjenester. Den delen av verden som mangler tilgang er skjevt fordelt, og Afrika lider sterkest. Med den konstant økende befolkningsveksten, samt effekten av klimaendringer, blir vannmangelen bare forverret. Uheldigvis er det få studier som handler om effekten klimaendringer har på vannsystemer i SSA.

Denne masteroppgaven har som mål å evaluere og håndtere mulige utfordringer i urban drikkevannsforsyning i de kommende tiårene i metropolen Tamale. Metodene utnyttet til å oppnå resultatene er: datainnsamling og behandling, samt modellering i WEAP. Modelleringen resulterte i flere modeller. En modell simulerte fremtidens vannforsyning- og behov med tre ulike årlige befolkningsvekster 2.1%, 3.7% og 5.0%. Denne modellen simulerte også hva som ville skje dersom den maksimale kapasiteten i overføringsledningen ville bli redusert med 10.0% og 20.0%. For håndteringen av drikkevannsforsyning- og behov, ble det utviklet fire forbedringsmodeller.

Oppgavens funn indikerer at de nåværende utfordringene i drikkevannsforsyningen i Tamale Metropolis primært skyldes utilstrekkelig tilgang til drikkevann. Resultatene i oppgaven viser at årsakene til utilstrekkelig drikkevannsforsyning handler om vanntap, operasjonelle utfordringer og befolkningsvekst.

Dersom befolkningen øker årlig med 2.1%, 3.7% og 5.0%, vil dekningen reduseres betraktelig. I 2021 var dekningen av drikkevannsbehovet 35% i Tamale. I 2050 var denne dekningen 19% for scenarioet hvor årlig befolkningsvekst var satt til 2.1%. Da den årlige befolkningsveksten ble satt til 3.7% og 5.0%, var dekningen henholdsvis 12% og 8%. Det ble også sett på hvorvidt faktorer som påvirker nedbørfeltet påvirker vannforsyningen til Tamale Metropolis ved å redusere forsyningen med 10.0% og 20.0%, og det fastslås å ha negativ virkning.

Det siste som ble undersøkt var mulighetene til håndtering av utfordringene i drikkevannsforsyningen slik at dekningen av drikkevannsbehovet øker i den forutsigbare fremtiden. Utfordringene det ses på her er vanntap og gjenbruk, samt maksimal kapasitet i overføringsledningen. Det ble funnet at alle grep tatt i modelleringen øker dekningen, men i ulik grad. Den høyeste økningen i dekningen av drikkevannsbehov forekommer i den modellen som utnytter to overføringsledninger på maksimal kapasitet, har redusert tap både i ledningsnettet og på forsyningsstedene, samt gjenbruker en andel av vannet. Her oppnås en

dekning i 2021 på mellom 82%. I 2050 er denne mellom 20-45% basert på den årlige befolkningsveksten valgt.

Table of Contents

List of Figures

List of Tables

List of Equations

List of Acronyms

DGP	Daily greywater production per person
DSL	Demand site loss
DSM	Deman d site improvement
DTP	Dalun treatment plant
DWTP	Drinking water treatment plant
GSS	Ghana Statistical Service
GW	Greywater
GWCL	Ghana Water Company Limited
IPCC	The Intergovernmental Panel on Climate Change
MFV	Maximum flow volume
NMBU	Norwegian University of Life Sciences
NR	Northern Region
NRW	Non-revenue water
PGR	Annual population growth rate
PWC	Potable water consumption per person per day
SSA	Sub-Saharan Africa
UDS	University for Development Studies
UN	United Nations
UNICEF	United Nations Children's Fund
WDN	Water distribution network
WDS	Water distribution system
WEAP	Water Evaluation and Planning
WV	White Volta
WWP	Wastewater production per person

CHAPTER ONE: Introduction

1 Introduction

Water as a resource is extremely important for all life. Still, 26% of the world's population lacks access to a safely managed drinking water service (UN-Water, 2021a). The part of the population that lacks access is disproportionately spread and Africa is suffering water scarcity the most (Mahato et al., 2022). With the ever-growing population, water scarcity and shortages will only be exacerbated (FAO, 2020; Scanlon et al., 2023). This is because population growth and urbanization are increasing water demand, both for domestic and agricultural uses (Leal Filho et al., 2022). Another driver for worsening the water situation is the effects of climate change. Climate change is causing more severe droughts and floodings that in turn makes the water sources more unpredictable both in quality and quantity (FAO, 2020; Leal Filho et al., 2022). Unfortunately, there are not many studies about the effect climate change has on water resources systems in SSA. (Jin et al., 2018; McCartney et al., 2012).

Tamale Metropolis is experiencing very rapid growth in the urban areas (Fuseini & Kemp, 2016; Gyasi et al., 2014; Karg et al., 2019). Simultaneously as the urban population keeps increasing, an increase in water demand follows (GWCL, 2019). Only 41% of the population of Ghana has access to a safely managed drinking water source. The water sources are often unsafe (UN-Water, 2021b; UNDP, 2011). In addition, Northern Ghana is experiencing challenges with flooding in the rainy season caused by poor infrastructure and copious volumes of rain, and too little water in the dry season (UN, 2017). Combining these factors, it is clear that the Tamale Metropolitan area struggles with the potable water supply and demand. Unfortunately, not much has been done regarding the quantity of water supply as the focus has been on water quality. Therefore, it is crucial to investigate what options are available to improve the water supply in Tamale Metropolis.

It is only qualitative one can assume the future scenarios without good modelling tools. Through literature review there were no modelling studies that manage and look adequately at the drinking water demand and supply situation in Tamale. There is a need to systematically evaluate the status using suitable modelling tools. Therefore, this study aims to fill this gap by modelling the current and future water demand and supply situation in Tamale Metropolis using the WEAP system.

1.1 Main objective

The main objective of this thesis is to evaluate and manage potential challenges in urban drinking water supply in the coming decades in the Tamale Metropolitan area. The water supply and demand modelling tool WEAP will be used in this context.

1.1.1 Research questions

- What are the current challenges to the potable water supply in Tamale Metropolis?
- What happens to the drinking water supply and demand in Tamale Metropolis if the population increases with growth rates of 2.1%, 3.7% and 5.0% every year from 2021 to 2050?
- What happens if the water supply to Tamale Metropolis is reduced by 10% or 20% due to factors influencing the catchment area?
- Is it possible to manage the challenges/weaknesses of the potable water supply in the urban area by looking at the water loss and reuse rates, and transmission link capacity, so that the coverage will increase in the predictable future?

CHAPTER TWO: Background

1 Background

This chapter includes important and relevant literature for this thesis. It is divided into six parts that go through the topics needed for better understanding the results and discussions.

1.1 Water Scarcity

Water scarcity is defined in different ways. UN Water defines it as "a relative concept. The amount of water that can be physically accessed varies as supply and demand changes. Water scarcity intensifies as demand increases and/or as water supply is affected by decreasing quantity or quality" (UN, 2023). While UNICEF also adds "water scarcity can either be physical or economic" to the definition (UNICEF, 2021). Mahato et al. (2022) states that water scarcity and water stress is measured by the annual water supply per person. If the annual water supply drops beneath 1700 m^3 per person, it is referred to as water stress. The annual water supply must drop beneath 1000 m^3 per person for it to be seen as water scarcity, and if it drops beneath 500 m^3 per person it is viewed as absolute scarcity.

1.2 Climate change effects

IPCC (2019) defines climate as the average weather, but also more accurately as the "statistical description in terms of the mean and variability of relevant quantities over a period of time". In this definition, quantities are the parameters of which the climate is measured, often precipitation, temperature, and wind. The time period may vary from a short span of months to the longer span of millions of years, but 30 years is the most common time period used (IPCC, 2019). IPCC defines climate change as the identifiable changes in the state of the climate, often over decades. Climate change may be caused by both anthropological attributions and natural causes (IPCC, 2019).

In 2023 IPCC launched an assessment report of the current and future climate change status, (IPCC, 2023). This report is the update on the similar report from 2014, and it establishes the anthropological attributions on climate change. The report also states with high confidence that Africa is amongst the continents hardest affected by climate change, even though Africa's contribution to the emissions is significantly lower than almost all the other continents. It is stated multiple times that areas with poverty and those who contribute less are often hit harder by the adverse effects of climate change, than the ones contributing more (IPCC, 2023). This might be because developing countries often have limited capacity to both prepare in advance and deal with the damages caused by climate change effects, especially regarding infrastructure (IPCC, 2023; UNESCO, 2023; UNICEF, 2021).

The climate in Northern Ghana is dependent on the West African Monsoon and the El Niño Southern Oscillation (Gyasi et al., 2014). The shifts in the Inter-Tropical Convergence Zone are also affecting the pattern of rainfall in Northern Ghana (BIL, 2021; Gyasi et al., 2014; Kayaga et al., 2021). Northern Ghana experiences one rainy season from May to October, the rest of the year is dry season (Kranjac-Berisavljevic et al., 2014).

1.3 Urbanization and population growth

Even though the population growth rate in the world has slowed down from 1950, the world's population keeps increasing. Sub-Saharan Africa is experiencing the world's fastest population growth as the population will increase from 1.066 billion in 2019 to 2.118 billion in 2050 (UN-Desa, 2019). Population growth is a driver for urbanization, and almost the entire increase in population will become urban (UN-Desa, 2019). Currently, over 50% of the world's population is urban and there's already huge challenges related to rapid urbanization (Özkan & Aljaradin, 2022). The continuance of rapid urbanization before the world can adjust leads to exacerbated challenges. Urbanization can be viewed as the shift of a rural setting to an urban setting, and it is said to be a complex socio-economic process (Abubakari et al., 2022; Özkan & Aljaradin, 2022). As the rural communities become urban, the governments are forced to develop infrastructure in the urban centers. It is nearly impossible to accommodate the rural-urban transitions as they happen, and this leads to challenges related to infrastructure and water scarcity (UNICEF, 2021).

For Tamale, urban and rural settings are not so easily defined. As Tamale is rapidly growing, urbanization is happening fast. Tamale now consists of some clearly defined urban areas, some clearly defined rural areas, and a great number of areas that cannot be viewed as solely urban nor rural. These areas are the interfaces between the rural and urban settings and are sometimes referred to as peri-urban. This is well described by Karg et al. (2019), where their results show that it is not simple to define clear boundaries as they are somewhat fleeting and the areas are very interconnected.

1.4 Leakages in the water distribution network

Leakages in the water distribution network (WDN) are a common challenge in all WDN's. Leakages is the biggest part of non-revenue water, and in developing countries it is estimated that this water loss is 45 million m^3 annually (Bhagat et al., 2019). Mubvaruri et al. (2022)

defines non-revenue water as “the unbilled portion of water supply system input volume and consists of unbilled authorized consumption, commercial losses and physical losses”. In SSA alone, the loss of water due to leakages costs 600 million dollars every year (Bhagat et al., 2019). Leakages in general is a huge problem because not only do they cause large losses, but also lead to contamination of the distribution system (Hamilton et al., 2006; Jacobsen et al., 2013; Lee & Schwab, 2005). The water distribution systems in developing countries loses around 50% of their water due to leakages, some countries even up to 75% (Bhagat et al., 2019; Gupta & Kulat, 2018; Samir et al., 2017). GWCL claims that the losses due to leakages in the Northern Region is 30% (GWCL, 2019), but studies shows that the losses might be up to 50% (Bhagat et al., 2019; Jacobsen et al., 2013).

1.5 The White Volta Basin and Nawuni river

The White Volta Basin is part of the artificial Lake Volta (Awotwi et al., 2015; Wagner et al., 2006). The White Volta is situated between latitude 9°30' N and 14°00' N and longitude 2°30 W and 0°30 E (Awotwi et al., 2015), and it is approximately 106 000 km^2 in area (McCartney et al., 2012). It is estimated that 24 million people are dependent on the White Volta as a source of water, and the water is mainly used for agriculture, but there is also water allocated to hydropower. (Awotwi et al., 2015; Jin et al., 2018; McCartney et al., 2012).

The Nawuni river is an important catchment of the White Volta (Tahiru et al., 2020). It is the main source of drinking water for the Northern Region of Ghana, including Tamale Metropolis (Ghana Statistical Service, 2013). Nawuni is found between latitude 9° 87′ N to 11° 15′ N and longitude 0° 5′ W to 1° 26′ W (Tahiru et al., 2020). Examining the land use of the Nawuni catchment, Tahiru et al. (2020) found that 129 453 hectares (ha) is considered grasslands/farmlands. Agodzo et al. (2023) estimated that the water allocated to irrigation of agricultural areas was 4114.42 m^3/year in 2020 and according to McCartney et al. (2012), 2430 ha of the Nawuni catchment land use was irrigation. In Ghana, 3605 million m^3/year of water is used for irrigation, and 63 million m^3/year of water is used for livestock (Mul et al., 2015).

1.6 Water Evaluation and Planning System WEAP

Water Evaluation and Planning (WEAP) was created in 1988 by Stockholm Environmental Institute (SEI, 2023a). WEAP is a software tool that is used for integrated water resource planning. It is meant to be an assisting tool to analyze different water recourse systems (SEI, 2023e). WEAP operates on the general approach of water balance and can be applied to both municipal (domestic and industrial) and agricultural systems (SEI, 2023e). It is possible to look at a single watershed, or transboundary river basin systems (SEI, 2023e). In WEAP, one can model both natural and engineered systems. The natural systems include evapotranspiration, rainfall runoff, baseflow and groundwater recharge. The engineered systems contain reservoirs, groundwater pumping, hydropower generation, pollution tracking and water quality (SEI, 2023d, 2023e).

Another aspect of WEAP is that it is a policy making tool. WEAP includes financial analysis and water allocation improvement. Therefore it can look at the different possible ways to allocate the water in case of competing water systems (SEI, 2023d, 2023e).

One of the great advantages of WEAP is that it is widely used in projects concerning developing countries. For organizations and projects based in developing countries, the license is free (SEI, 2023b). SEI has published countless of studies between 1991 and the current year of 2023 where WEAP has been applied, proving that it is widely used all over the world (SEI, 2023c).

The parameters needed for the simulations are listed in Table 1 below.

Table 1 - List of parameters used in WEAP. Parameters are extracted from the WEAP User Guide (SEI, 2015).

List of parameters used in WEAP	
Parameter	Unit
Headflow	[m^3/s]
Monthly variation	[%]
Annual activity level	[people], [share], [saturation]
Annual water use rate	[m^3]
Loss rate (demand site loss)	[%]
Values for the Water Year Method	-
Population	-
Transmission link: Maximum Flow Volume	[m^3]
Transmission link: Loss rate	[%]

Error! Reference source not found. shows the different parameters used for the WEAP modelling and their respective units. The descriptions of the parameters from **Error! Reference source not found.** are listed below and are all extracted from the WEAP User Guide (SEI, 2015).

- Headflow [m^3/s]: The inflow of the first node on a river. Headflow can be specified in two different ways; originating from catchment or direct input. If it is specified originating from catchment, the values can either be calculated by the Simplified Coefficient or the Soil Moisture Methods. For the specification from direct input, it is possible to either use the Water Year Method, Read from File method, or an expression. For this thesis, the expressions are used.

- Monthly variation [%]: Monthly variation is used when the demand varies from month to month. If there is variation, input each month's demand as a percentage of the annual demand. For this thesis, monthly variation is used.

- Annual activity level: Annual activity levels are used to describe the amount of water required by each demand. To calculate this, multiply the level of activity by the water use rate. Annual activity levels can be used to describe different things. For instance, it can describe the population and how the population is divided. The units are then [people] or [share] of people. It can also describe the share of the population/people that uses different water related appliances, for instance, showers, washing machines, toilets etc. The last part has the unit [saturation] of people.

- Annual water use rate [m^3]: Annual water use rates describe how much water an activity uses per year. The annual water consumption can be specified for each of the activities from the "Annual activity level". For instance, how much water the people use in general, or specifically how much water the showers, toilets, washers etc. use.

- Loss rate (demand site loss) [%]: Loss rate for demand site improvement are the losses within the demand sites or demands that are not accounted for. For this thesis, the loss rate will include the non-revenue water.

- Population: For WEAP, the population is entered as part of the annual activity levels.

- Transmission links, maximum Flow Volume [m^3]: Transmission links are the links in the model that transports water from the river and to the demand sites. For the transmission links it is important to specify the capacity of the links, and this can be done as part of the “Maximum Flow Volume” or “Maximum Flow: % of demand”. Maximum Flow Volume (MFV) is how much water the transmission link is able to transport. MFV can have different units based on the requirements. For instance, it can be volume per time.

- Transmission links, loss rate [%]: This is the percentage of the water that is lost due to evaporation and leakages.

Other important aspects of WEAP for the modelling and simulating of this thesis are expressions, key assumptions, and functions. For this project, the following functions are being applied: GROWTHFROM and GROWTH. These functions are employed to predict the population in all years of the simulation (SEI, 2015).

Key assumptions is another important aspect of the WEAP system. Key assumptions allows construction of variables that are set so when there is a need for a variable to change, one can simply change the key assumption from the expression builder instead of changing the value of the parameter used (SEI, 2015).

Regarding scenarios, the “manage scenarios” in WEAP shows a tree of scenarios, where the scenarios are subordinated to each other depending on their place in the tree (SEI, 2015). As they are subordinate to the above scenario, the subordinated scenario inherits the properties of the scenario above (SEI, 2015).

CHAPTER THREE: Materials and methods

1 Materials and methods

This chapter will go through the materials and methods used to acquire the necessary results to address the research questions stated in the introduction of the thesis. This chapter is divided into six subchapters. The primary part of chapter three includes creating a model in the WEAP system. To do this, different kinds of data have been collected and processed so that the model has the essential inputs to run.

Chapter three begins with the description of the study area. The next segment of this chapter describes data collection and processing. Finally, the chapter proceeds on how the models were created and tweaked to get the results necessary to answer the research questions.

1.1 Description of study area

The study area is Tamale Metropolis. Tamale Metropolis is located between the latitudes 9° 16’ and 9° 34’ North and longitudes 0° 36’ and 0° 57’ West (UNDP, 2011). There are a lot of areas in Tamale that are allocated to agriculture. In Ghana, 60% of the population is involved in agriculture (Naab et al., 2013) and according to UNDP (2011), 15.2% of the area Tamale Metropolis was agriculture.

Since the thesis is examining the drinking water supplied by GWCL for Tamale and the associated supply, Appendix B shows the study area. The distribution network indicates where the pipelines are situated, and the dimensions and materials of the pipes. As previously stated, it is difficult, or hardly achievable, to narrow down the study area to a simple geographic area. GWCL supplies the communities they consider urban. With the urban-rural interfaces kept in mind, the study area claimed to be “urban Tamale” is therefore defined: the areas in and around Tamale which GWCL supply potable water to, specifically the areas supplied from the Nawuni river. The current population growth rate in Ghana is 2,1% (Ghana Statistical Service, 2021a). The population of Tamale is approximately 672 000 per 2021 (Macrotrends LLC, 2023). The drinking water is treated at the Dalun DWTP and is distributed to all urban areas in and close surrounding Tamale Metropolitan area (GWCL, 2019).

Figure 1 - Approximation of the study area (marked with the yellow polygon) based on the borders shown in Appendix B. The map was drawn in Google Earth (Google, 2023).

Figure 1 approximates the study area based on the borders shown in Appendix B.

1.2 Data Collection

The data of this thesis includes:

- Headflow for the Nawuni river
- Potable water supply for Tamale Metropolis
- Potable water demand for Tamale Metropolis
- Loss rates for Tamale Metropolis
- Climatic data for Tamale Metropolis
- Population and annual population growth rates

To obtain the data for potable water supply and demand for Tamale Metropolis, formal discussions were conducted with the department leaders at GWCL – Northern Region, Tamale office. The departments for distribution and water quality provided information on the general water distribution as well as treatment and quality. GWCL provided data on water supply, demand, general information about the distribution system, and drinking water treatment. These datasets should only be used for research purposes.

The climatic- and discharge data were provided by Mr. Precious Blege, a PhD student of Prof. Kranjac-Berisavljevic at UDS, by personal agreement. These datasets should only be used for research purposes.

1.3 Assumptions of data

To utilize the data required for the WEAP model and simulations, it was necessary to make some assumptions. The assumptions made will be analyzed in the discussion chapter. Below is a list of the assumptions made:

- Assuming the production data from GWCL used for the demand and supply from 2022 is the same as the data from 2021.
- Some of the flow data for the Nawuni river is missing, therefore an assumption made is that all missing data has the average value.
- Assuming a population growth rate for Tamale Metropolis to be 3.7% annually as well as constructing a high PGR of 5.0%.
- Assuming that the entire population of Tamale is supplied by GWCL.
- Assuming that the NRW loss is part of the demand site loss.
- Assuming that the monthly variation based on the supply equals the monthly variation based on the demand.
- Assuming that a reduction of 10.0% and 20.0% in the maximum capacity of the transmission link is caused by factors affecting the catchment area.

1.4 Inputs for the WEAP Model

Table 2 - Population of different areas per 2010 and 2021 (Ghana Statistical Service, 2021a), (Macrotrends LLC, 2023).

Year	**Area**	**Population**
2010	Ghana	24658823
2010	Northern Region	1544946
2021	Tamale	672000
2021	Ghana	30792608
2021	Northern Region	2310943

There are no suitable estimations for the population growth rate of Tamale. The following steps are calculations employed to accomplish a more applicable and realistic PGR for Tamale by calculating a probable PGR for the Northern Region applying values from Table 2.

$$1544946 * x^{11} = 2310943 \quad (1)$$

$$x = \sqrt[11]{\frac{2310943}{1544946}} \quad (2)$$

$$x = 1.03728 \approx 3.73\% \quad (3)$$

This growth rate will be used in the simulations by looking at the population of Tamale in 2021 and assuming an average yearly growth rate of 3.7%.

1.5 Data processing

For the data to be implemented, it had to be processed correctly.

Each month of the simulation needs an input headflow value. To get the headflow values, the daily discharge values were averaged for each month.

Monthly variation is a parameter that needs processing as well. To achieve the percentage of supply allocated to each month, the production data for each month were added together to get an annual total value of production. Then, each month's production is divided by the annual total value to get a percentage. This percentage was applied as monthly variation.

1.6 The WEAP Model

To create a WEAP model, the initial step is to set the general parameters. These define the time horizon of the current account's year. For this model, the current account's year is 2021. The last year of scenarios is set to 2050. Twelve time steps per year were assigned and the time step boundary was set to be based on calendar month. The water year start was set to January.

Going forward it is necessary to consider the elements of the schematic view that is needed for the base model. The base model of this thesis consists of one demand site, one river and one transmission link. These elements are drawn into the schematic view of the model. Formal discussions with GWCL state that there is no real return flow, and therefore the model does not have one. The same applies to wastewater treatment plants and reservoirs.

The following step of creating a WEAP model is to input the data.

After entering the data, the next step is to go to the results view to check the results for the current account's year and the reference scenario. The reference scenario is a scenario that shows the development of the water supply and demand situation if nothing changes. For the reference scenario, the PGR is 2.1%. After checking the results, and adjusting the model to correct any mistakes, new scenarios were made.

Since the main objective of the thesis is to figure out how to improve the system, it is important to look at how the system will develop over time if different parameters are changing. This is the reason why different models and scenarios were being made.

The following model created for this study, was the model with the adjusted population growth rates. In this model the main goal was to look at what will happen to Tamale Metropolis if the population increases by 3.7% and 5.0% every year.

To investigate the research questions concerning how to improve the water supply and demand in Tamale, the improvement models were created.

The new loss rate for leakages set at 20% was chosen arbitrarily. The new loss rate for non-revenue water set to 35% was chosen as GWCL had 35% water lost to NRW in 2022. This value was acquired by documents gotten from a personal agreement.

The maximum capacity of the transmission links was chosen by looking at the maximum capacity possible if both of the existing transmission links seen in Appendix B, were run simultaneously at maximum capacity.

The last model created was the "Transmission link maximum capacity reduction". In this model, the maximum capacity of the transmission link was reduced by 10.0% and 20.0%.

CHAPTER FOUR: Results

1 Results

Chapter four presents the results. The results include the data acquisition and the simulations of the models. The results will be presented in six sections. Sections one and two will focus on data acquisition. The third section will present standard/calibrated model. The results from the simulations regarding the PGR model will be presented in the fourth section of this chapter. The fifth section will concentrate on the results from the model where the maximum capacity of the transmission link is reduced by 10.0% and 20.0%. The last section will present the improvement models. Additional results can be found in Appendix A and Appendix C.

1.1 Results from interviews with Ghana Water Company Limited

Most of the results from interviews with GWCL are confidential files. These are regarding how the water supply is operated in the Northern Region, how the water supply situation is in Tamale, and water levels of the river. Still, some important aspects were mentioned in the interviews.

One of the reasons why the water supply only covers about 35% of the demand is water theft. GWCL states that consumers share their water with those not connected and people are stealing water by illegally connecting to the pipe networks. The total water theft is higher than the water lost due to leakages. Water theft is part of the non-revenue water.

1.2 Results from data collection

To get the results necessary to answer the research questions of the thesis, multiple models in WEAP were developed. The development of the models was reliant on the relevant data to be correctly processed and input. This subchapter goes through the results from the data acquisition.

Below follows tables for the inputs of the models:

Table 3 - Discharge of Nawuni in 2021, unit is m^3/s. Source: Personal agreement with GWCL.

Discharge of Nawuni in 2021 [m^3/s]	
January	29.635
February	24.903
March	16.290
April	24.710
May	20.362

June	56.554
July	238.019
August	1252.979
September	1818.264
October	487.615
November	109.372
December	66.119

Table 3 shows the discharges of the Nawuni river in 2021. These values are input as "Headflow" in the WEAP model.

Table 4 - Monthly variation of 2021, unit is %. Source: Personal agreement with GWCL.

Monthly variation of demand in percentage of total demand in 2021	
January	9.748
February	8.167
March	8.147
April	8.107
May	8.605
June	7.960
July	7.791
August	8.628
September	7.657
October	6.577
November	9.480
December	9.133

Table 4 presents the monthly variation of the demand as a percentage of the total demand in 2021.

Table 5 – Inputs for the annual activity level bar in WEAP for 2021. Source: (Ghana Statistical Service, 2021a).

Annual activity level in 2021 [%]	
PGR in Ghana in 2021	2.1
PGR in Northern region in 2021 (calculated)	3.7

PGR high	5.0

Table 5 shows the data used for the annual activity level in 2021 (current account's year). As stated in chapter two, subchapter 1.6, the annual activity level can be represented in multiple ways. Because this thesis is focusing on urban demand and supply, the annual activity level is input as the PGR multiplied with the population.

Table 6 - Population of Tamale in 2021. Source: (Macrotrends LLC, 2023).

Population of Tamale in 2021	
Population in 2021	672000

Table 6 displays the population that is applied into the annual activity levels of the current account's year. The value is found in Macrotrends LLC (2023).

Table 7 - Annual water use rate in 2021 with different population growth rates. Source: (Agodzo et al., 2023) and personal agreement with GWCL.

Annual water use rate in 2021 with different PGR	**[m^3/y/p] Total**	**[l/pd]**
Consumptive water demand: From literature	18.25	50
Consumptive water demand: From GWCL	25.55	70

Table 7 shows the annual water use rate in 2021. 50 l/pd (liters per person per day) is a consumptive water use rate stated by Agodzo et al. (2023). According to Ing. John Paul Dinye, the Regional Distribution Officer for the Northern Region, the potable water supply covers around 35% of the demand. Ing. John Paul Dinye also states that the people GWCL are supplying use 70 l/pd on average. GWCL does prioritize domestic water supply over industry and does not prioritize agriculture at all.

Table 8 – The maximum capacity of the transmission links. Source: Personal agreement with GWCL.

Transmission links		
Pipe nr.	Maximum capacity [m^3/h]	Maximum capacity [m^3/s]
1	1700	0.472
2	700	0.194

Table 8 contains the essential information on the transmission links of the model. Pipe nr. 1 has a diameter of 700 mm and pipe nr. 2 has a diameter of 450 mm. The maximum capacity limits how much water is being transported through the system. According to GWCL, the schedule for the transmission links goes as follows:

- Friday (6am) – Wednesday (6am): 700 mm pipeline is open.
- Wednesday (6am) – Friday (6am): Both the 700 mm and the 450 mm pipes are open.
- 450 mm is used alone when there are operational challenges which limits their production output.

The capacities for when both pipes are active are a total of 1700 m^3/h. Therefore, in the WEAP models of this thesis, the maximum capacity is set to be 0.472 m^3/s in all models except the Only TL, TL and loss rates, and TL, loss rates and reuse rate models.

Table 9 - Loss rates in 2021, both leakages and non-revenue water. Source: Personal agreement with GWCL.

Loss rates (both leakages and NRW) in 2021 [%]	
Valve leakages and pipeline leakages	30
Non-revenue water	44

Table 9 presents the loss rates used in the model. 30% loss from leakages are what GWCL claims they have in their distribution network in the Northern Region (GWCL, 2019). 44% loss from NRW was obtained by personal agreement with GWCL in 2021 and should only be used for research purposes.

Below follows the inputs to the improvement models.

Table 10 - Inputs for improvement models. Source: (Ghana Statistical Service, 2021b; Gyampo, 2012) and a personal agreement with GWCL.

New inputs for the improvement model			
Reuse rates [%]	Loss rate (leakages) [%]	Loss rate (NRW) [%]	Transmission links max capacity [m^3/s]
4.4 22.0	20	35	0.472 0.194

Table 10 shows the changes implemented in the WEAP Model to check if there will be any improvement in coverage. There are three different reuse rates that are being applied to the WEAP model. The values used for the calculations are:

- Wastewater production per person in Ghana
  - According to Gyampo (2012) there are no accurate number for the wastewater production per person in Ghana, but it is projected that in 2020 the total wastewater production in is: 1 452 383 m^3/d.
- Population in Ghana
  - 30 792 608 (Ghana Statistical Service, 2021a).
- Potable water consumption per person in Tamale Metropolis
  - 70 l/pd according to interviews with GWCL.
- Share of wastewater that can be considered greywater.
  - 65 %. Approximately 50-70% of wastewater can be considered greywater according to Rakesh et al. (2020) and Ghaitidak and Yadav (2013) claims it is around 65%.

The calculations below will present how they were acquired.

$$\frac{WWP}{d} = \frac{1452383\frac{m^3}{d} * 1000\frac{l}{m^3}}{30792608p} = 47\frac{l}{pd} \qquad (4)$$

$$\frac{DGP}{d} = 47\frac{l}{pd} * 0.65 = 30.55\frac{l}{pd} \qquad (5)$$

$$\%\frac{GW}{PWC} = \frac{30.55\frac{l}{pd}}{70\frac{l}{pd}} = 0.44\ (44\%) \qquad (6)$$

The last step is to insert the percentage desired to reuse. For this thesis, 10% and 50% were chosen. Multiplying these numbers with the percentage of greywater in the potable water consumption, returns the reuse rates input in the WEAP Model.

The new loss rate for leakages set at 20% was chosen arbitrarily. The new loss rate for non-revenue water set to 35% was chosen as GWCL had 35% water lost to NRW in 2022, as was acquired by documents gotten from a personal agreement.

The transmission links maximum capacity was chosen by looking at the maximum capacity possible if both the 450 mm pipe and the 700 mm pipe were run simultaneously. Table 8 contains information about the maximum capacities of both links separately.

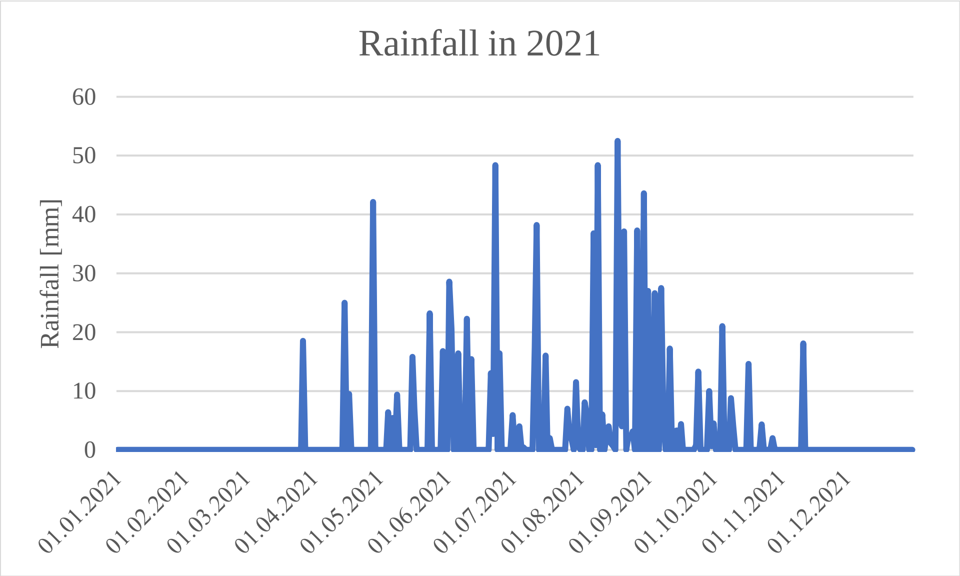

Figure 2 - Amount of rainfall in 2021 in Tamale. Source: Personal agreement with Mr. Precious Blege. Figure created in excel.

Figure 2 illustrates how much rainfall Tamale experienced in 2021. The data used to create the figure was acquired by personal agreement with Mr. Precious Blege.

1.3 Schematic view of all models employing one transmission link

Subchapter 1.3 presents the schematic view of all models that only use one transmission link.

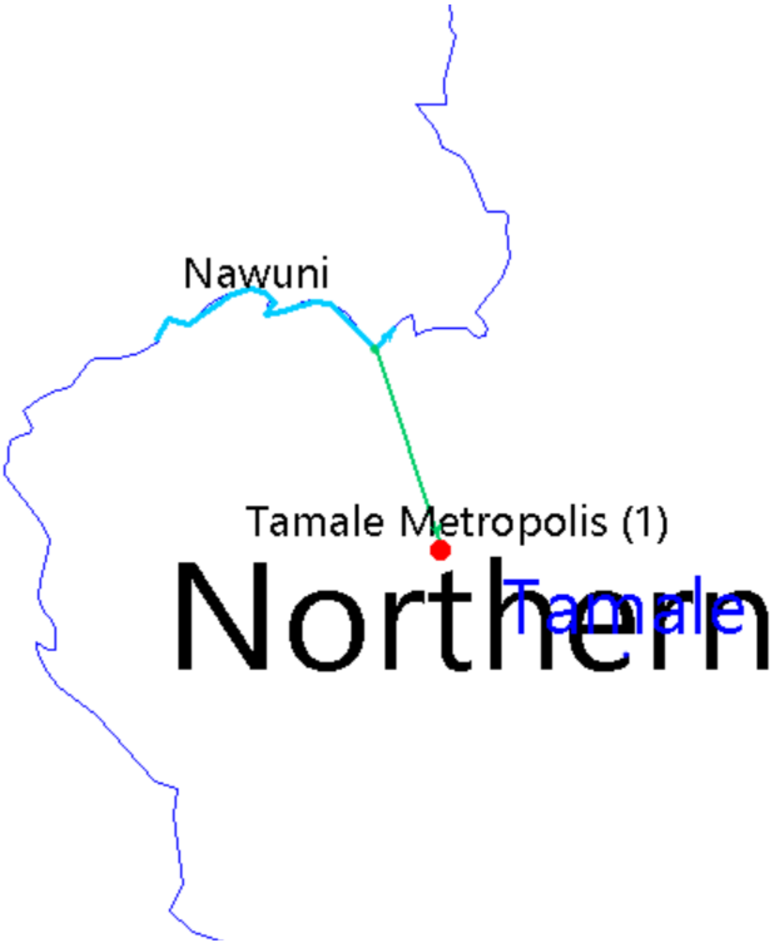

Figure 3 - The Schematic view of the WEAP Model. The model has one river – The Nawuni, one demand site – Tamale Metropolis and one transmission link between the river and the demand site. Screenshot from the schematic view in WEAP.

Figure 3 portrays the schematic view of the WEAP model. The model consists of one river – Nawuni, one demand site – Tamale Metropolis, and one transmission link between the river and the demand site. The river is shown as a thick blue irregular line. The demand site is marked with a red dot. The transmission link is the green line visible in Figure 3. The area is in Tamale in the Northern region of Ghana as illustrated by the writing.

1.4 Increased population growth rate

When simulating the future (2022-2050) in WEAP, the scenarios were created as mentioned in chapter three. This subchapter contains the results of the simulations specifically regarding increased population growth rates. All figures are therefore figures of the PGR model.

The figures below show the results of the forementioned simulations. The scenarios that will be investigated in this subchapter are:

- Calculated Northern Region PGR (3.7%)
- High PGR (5.0%)

- Reference (2.1%)

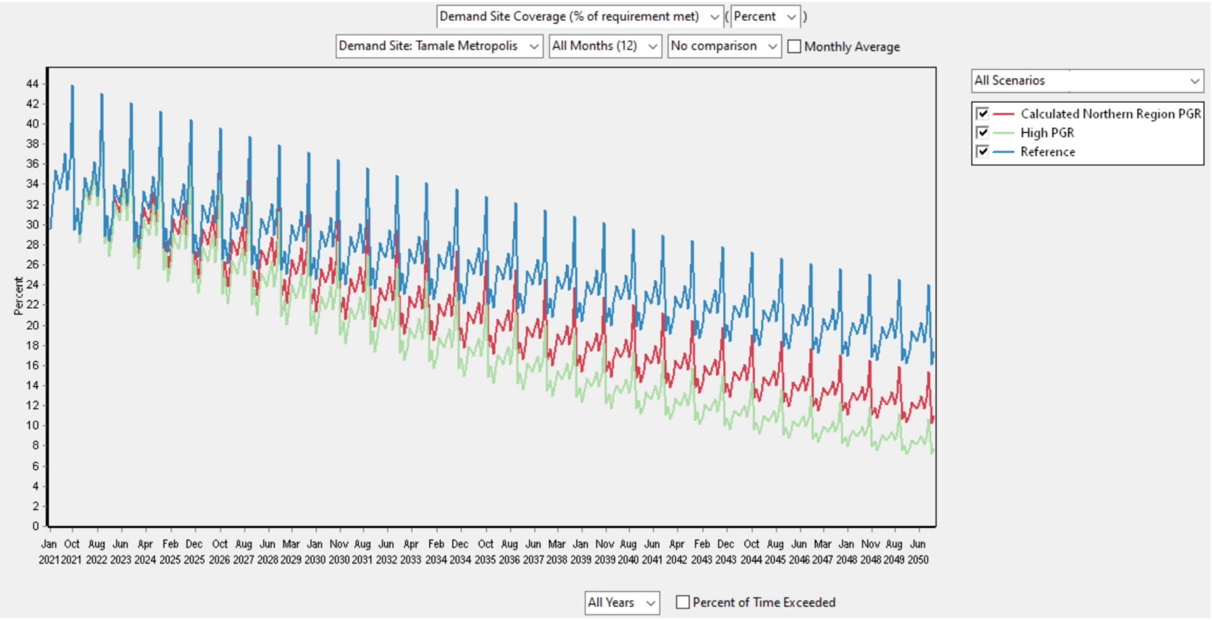

Figure 4 - Demand site coverage for scenarios in the PGR model for all years. Screenshot from the results view in WEAP.

Figure 4 shows how the coverage of Tamale Metropolis develops for the three different scenarios. The unit is percent, and the span goes from January 2021 until January 2050.

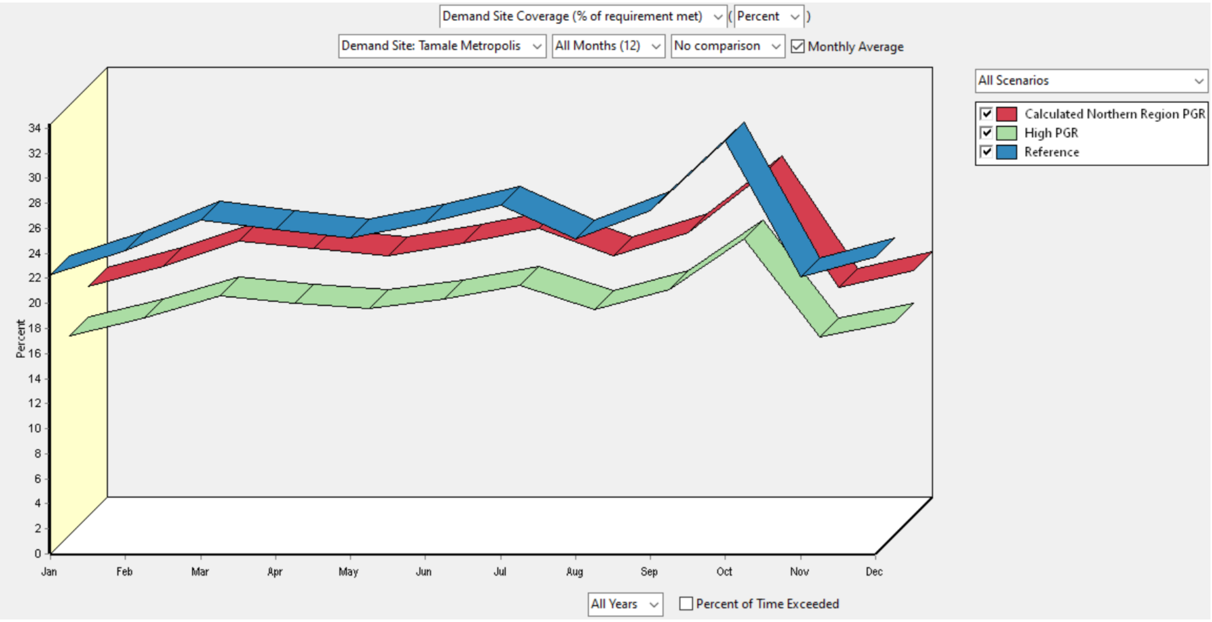

Figure 5 - Demand site coverage for all scenarios in the PGR model, monthly average for all years. Screenshot from the results view in WEAP.

Figure 5 depicts the monthly average of the coverage for all three scenarios during the entire lifespan of the simulations. The unit is percentage, and the span is an average for all months during the lifespan of the simulations.

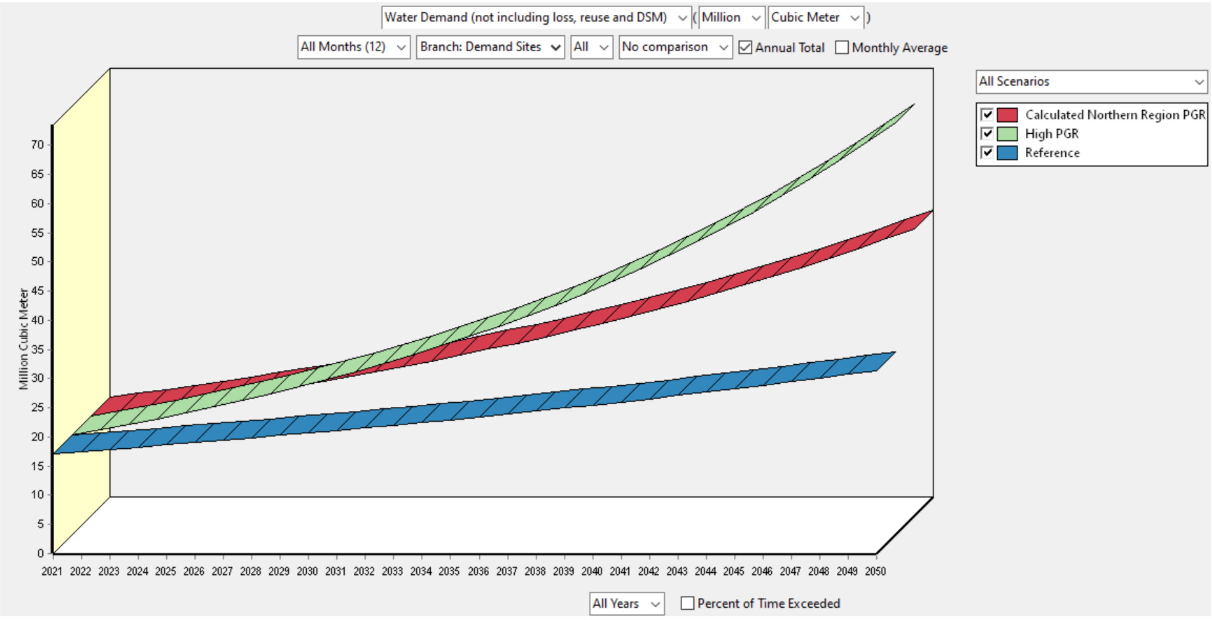

Figure 6 – Annual total of water demand for all scenarios in the PGR model. Screenshot from the results view in WEAP.

Figure 6 shows the water demand for the three scenarios during the entirety of the simulations. Water demand does not include loss, reuse, and DSM (demand site management).

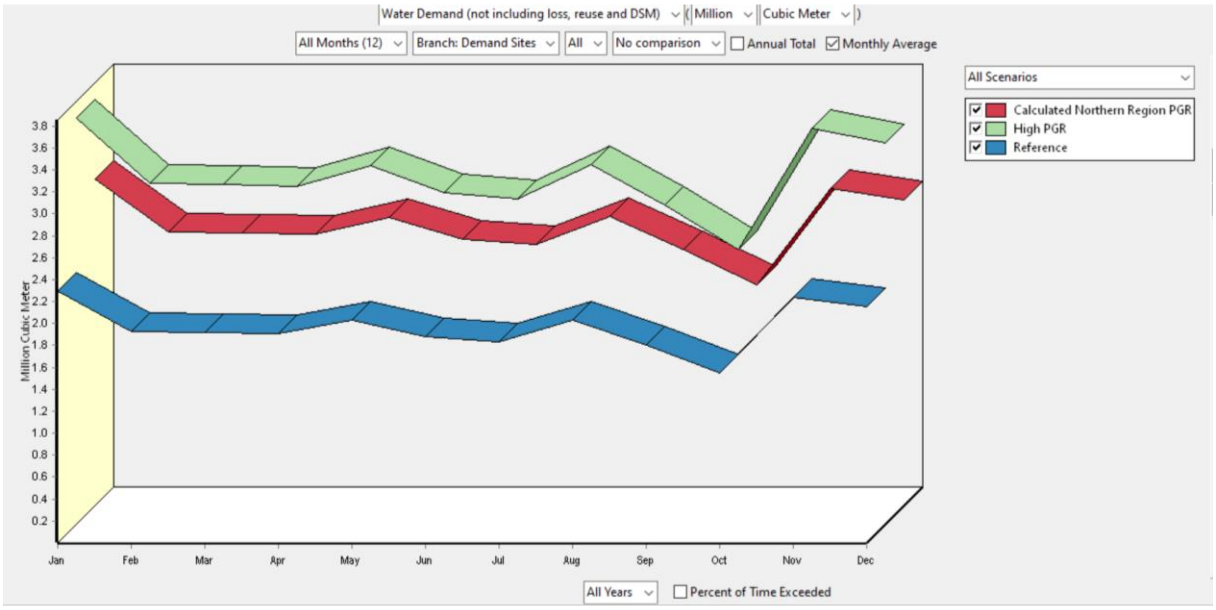

Figure 7 -Monthly average of water demand for all scenarios in the PGR model for all years. Screenshot from the results view in WEAP.

Figure 7 displays the monthly average of the water demand for all the scenarios in the PGR model during all years of the simulation.

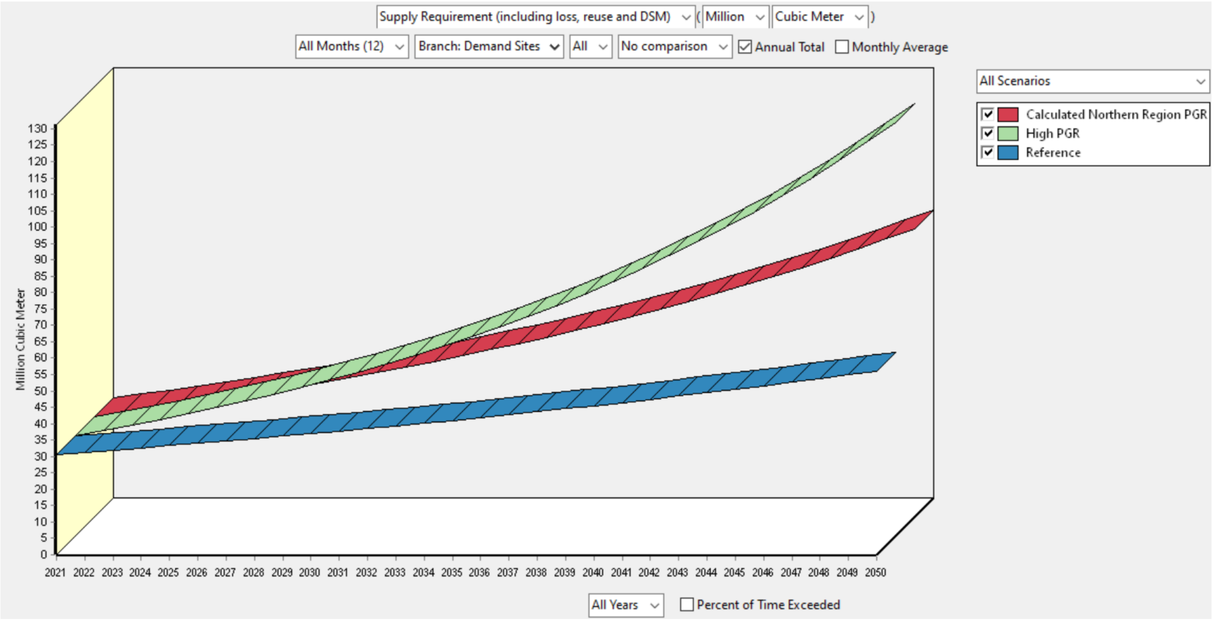

Figure 8 – Annual total of supply requirement for all scenarios in the PGR model. Screenshot from the results view in WEAP.

Figure 8 shows the annual total of supply requirement for the three scenarios. Supply requirements include loss, reuse, and DSM.

Figure 9 – Monthly average of supply requirement for all scenarios in the PGR model for all years. Screenshot from the results view in WEAP.

Figure 9 shows the monthly average of the supply requirement for the three scenarios.

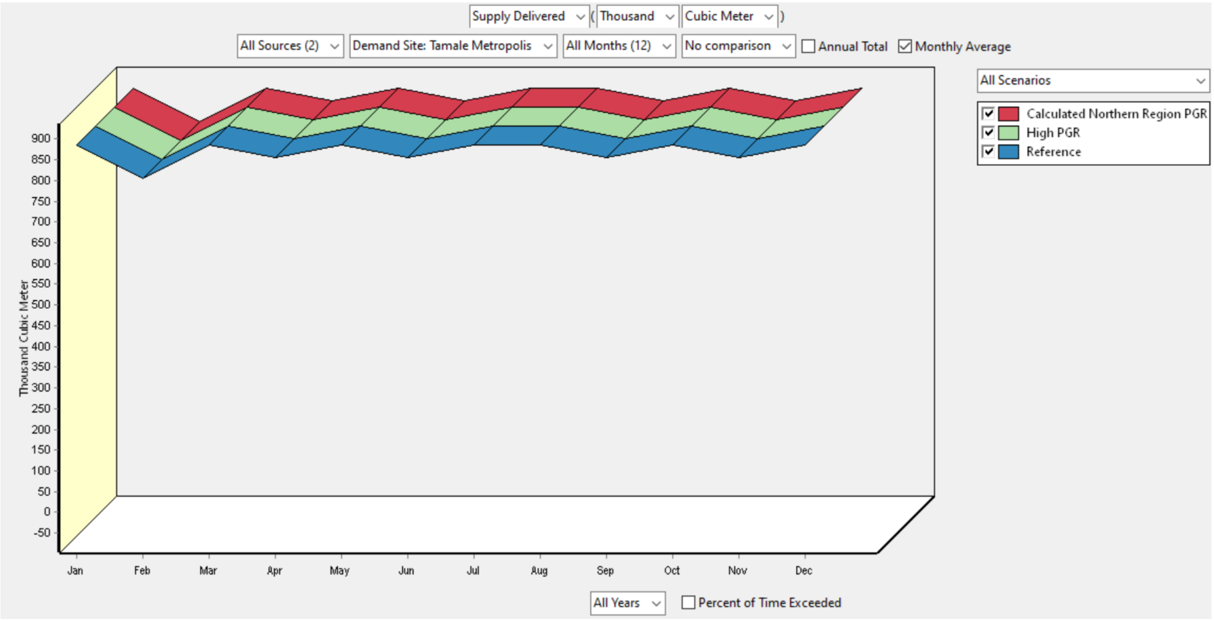

Figure 10 – Monthly average of supply delivered for all scenarios in the PGR model for all years. Screenshot from the results view in WEAP.

Figure 10 shows the supply delivered for all the scenarios in the PGR model, it is a monthly average.

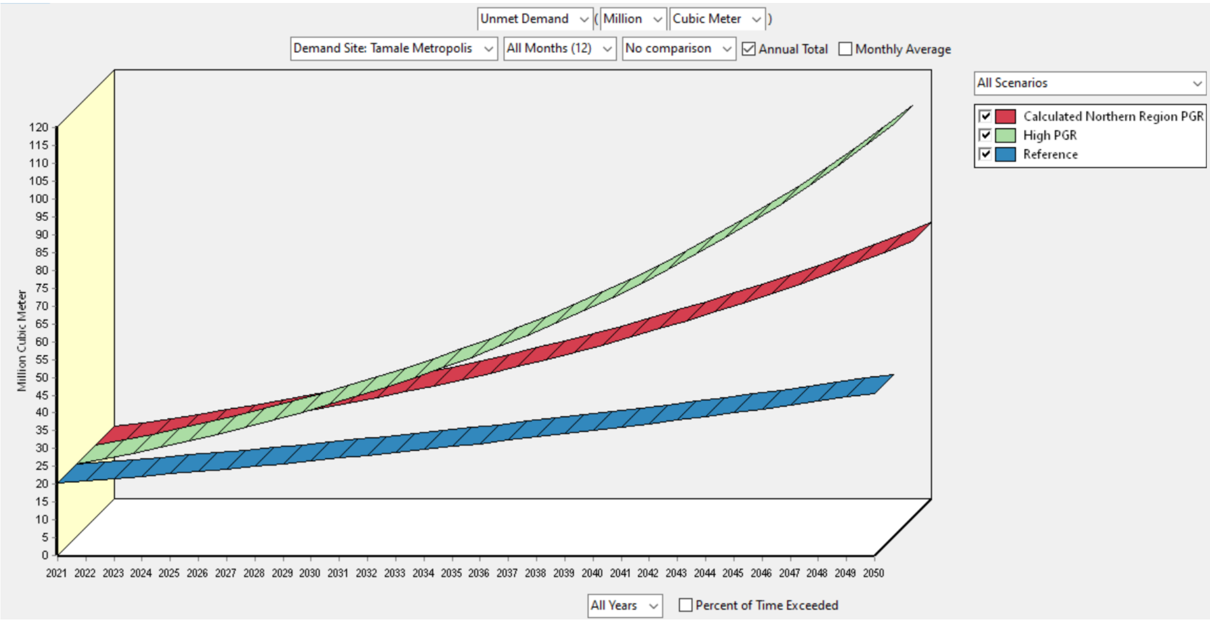

Figure 11 – Annual total of unmet demand for all the scenarios in the PGR model. Screenshot from the results view in WEAP.

Figure 11 shows the annual total unmet demand for the scenarios in the population growth rate model.

Figure 12 - Monthly average of unmet demand for all the scenarios in the PGR model for all years. Screenshot from the results view in WEAP.

Figure 12 shows the monthly average of the unmet demand for all the scenarios in the PGR model.

1.5 Transmission link maximum capacity reduction

Subchapter 1.5 presents the results for the simulations when the maximum capacity of the transmission link is reduced by first 10.0%, then 20.0%.

1.5.1 Ten percent reduction in the transmission link

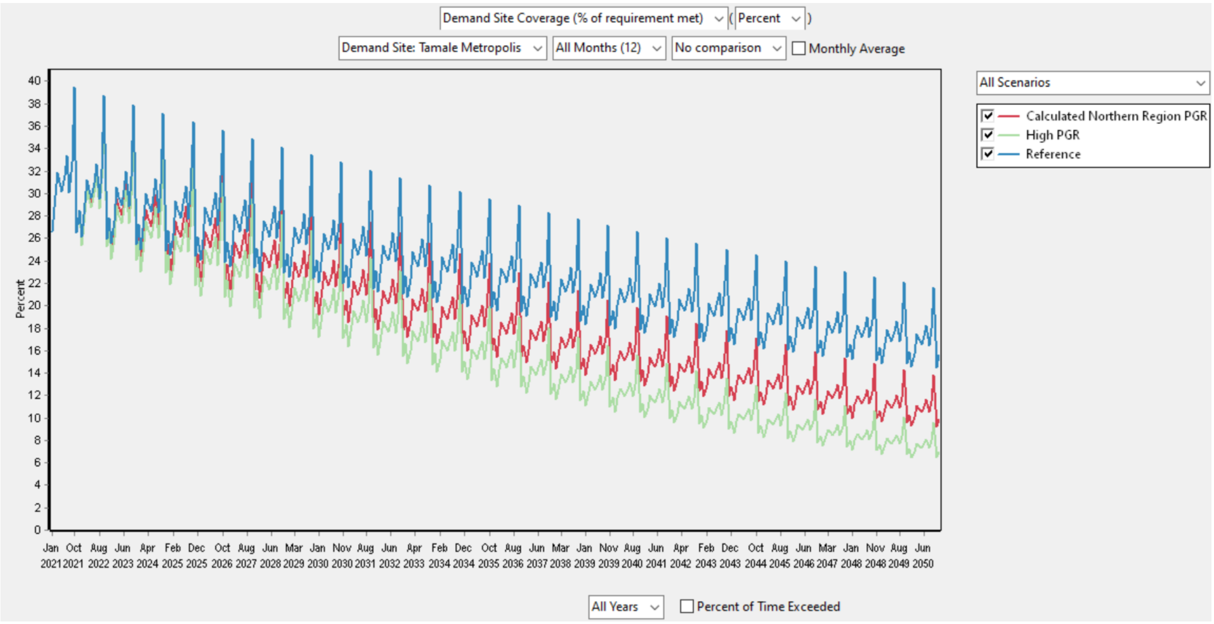

Figure 13 - Coverage for all years when the maximum capacity of the transmission link is reduced with 10.0%. Screenshot from the results view in WEAP.

Figure 13 depicts the coverage for all the scenarios in the PGR model when the maximum capacity of the transmission link is reduced with 10.0%.

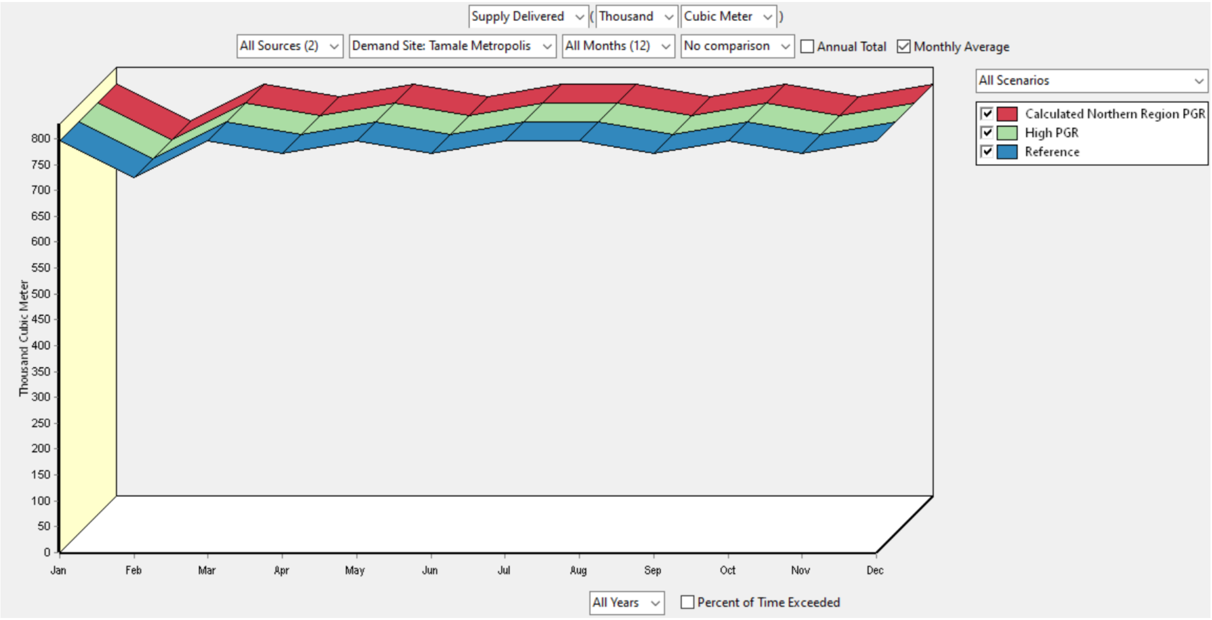

Figure 14 - Monthly average of the supply delivered for all years when the maximum capacity of the transmission link is reduced with 10.0%. Screenshot from the results view in WEAP.

Figure 14 shows the monthly average of the supply delivered for all years for the scenarios when the maximum capacity of the transmission link is reduced with 10.0%.

1.5.2 Twenty percent reduction in the transmission link

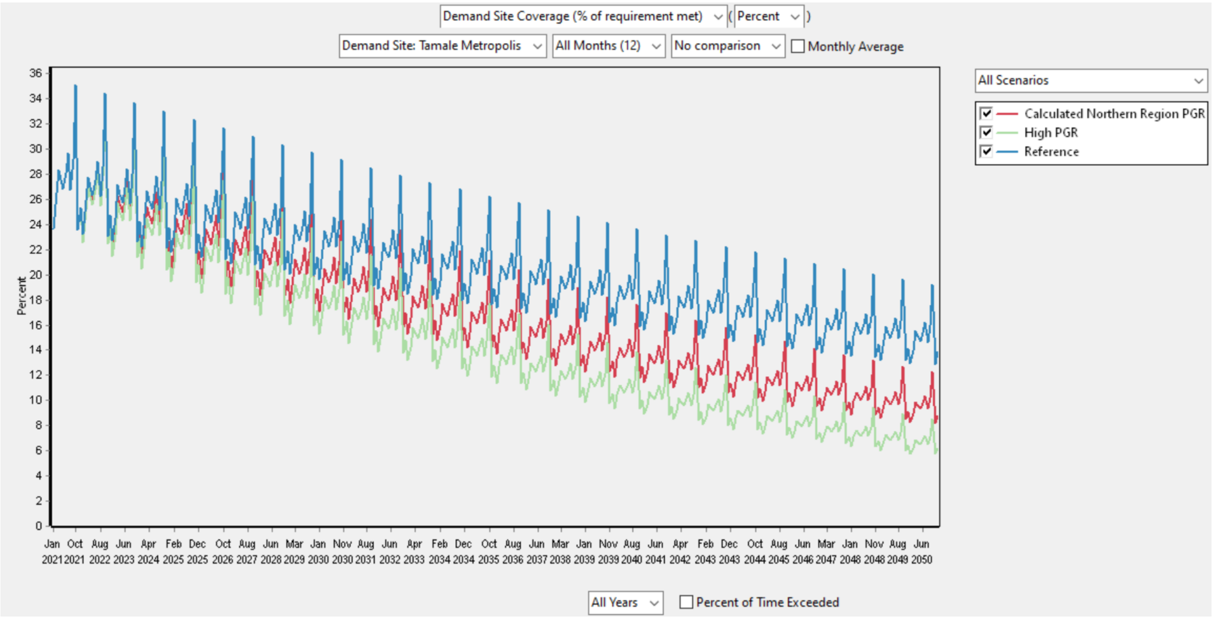

Figure 15 - Coverage for all years when the maximum capacity of the transmission link is reduced with 20.0%. Screenshot from the results view in WEAP.

Figure 15 shows the coverage for all years for the scenarios when the maximum capacity of the transmission link is reduced with 20.0%.

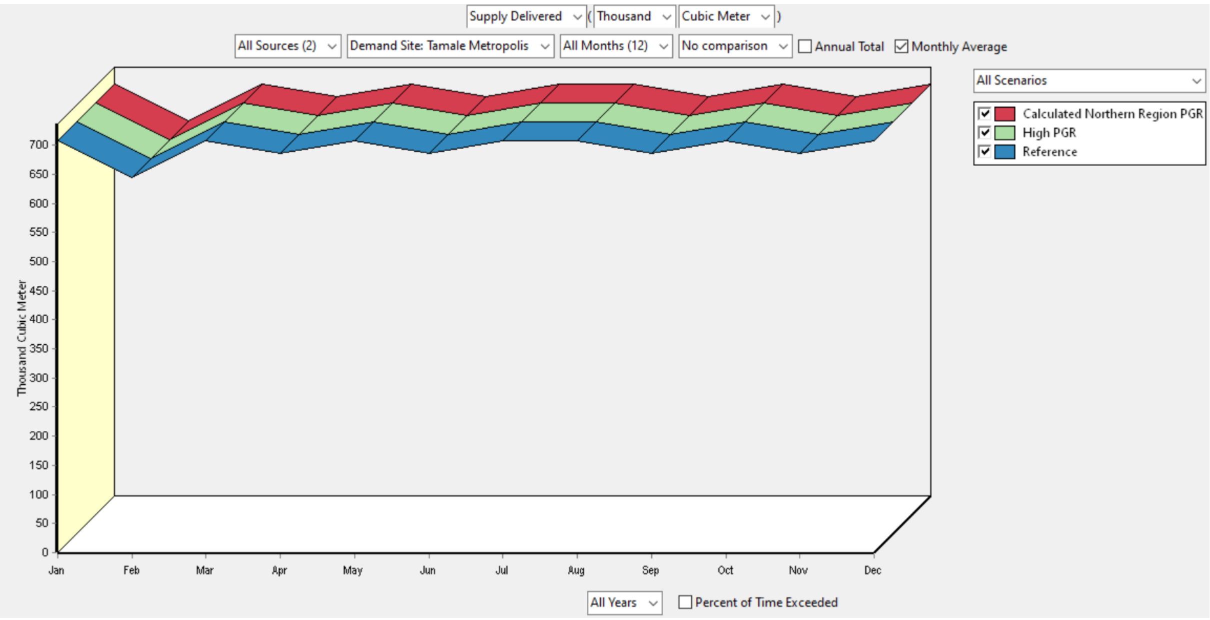

Figure 16 - Monthly average of the supply delivered for all years when the maximum capacity of the transmission link is reduced with 20.0%. Screenshot from the results view in WEAP.

Figure 16 shows the monthly average of the supply delivered for all years for the scenarios when the maximum capacity of the transmission link is reduced with 20.0%.

Table 11 - Monthly average of unmet demand for all scenarios in 2021 with a reduction of 10.0% and 20.0% in the max capacity of the transmission link. Values obtained from results in WEAP.

	Monthly average of Unmet Demand for all scenarios in 2021 with a reduction of 10.0% and 20.0% in the transmission link [10^6 m^3]					
	Reference		**Calculated NR PGR**		**High PGR**	
January	2.19	2.28	2.19	2.28	2.19	2.28
February	1.78	1.86	1.78	1.86	1.78	1.86
March	1.70	1.79	1.70	1.79	1.70	1.79
April	1.71	1.80	1.71	1.80	1.71	1.80
May	1.84	1.93	1.84	1.93	1.84	1.93
June	1.67	1.76	1.67	1.76	1.67	1.76
July	1.59	1.68	1.59	1.68	1.59	1.68
August	1.85	1.94	1.85	1.94	1.85	1.94
September	1.58	1.66	1.58	1.66	1.58	1.66
October	1.22	1.31	1.22	1.31	1.22	1.31

November	2.14	2.22	2.14	2.22	2.14	2.22
December	2.00	2.09	2.00	2.09	2.00	2.09

Table 12 - Monthly average of unmet demand for all scenarios in 2050 with a reduction of 10.0% and 20.0% in the max capacity of the transmission link. Values obtained from results in WEAP.

	Monthly average of Unmet Demand for all scenarios in 2050 with a reduction of 10.0% and 20.0 % in the transmission link [10^6 m^3]					
	Reference		**Calculated NR PGR**		**High PGR**	
January	4.66	4.75	7.78	7.86	11.51	11.59
February	3.86	3.94	6.46	6.54	9.59	9.67
March	3.77	3.86	6.37	6.46	9.49	9.57
April	3.77	3.86	6.36	6.44	9.46	9.55
May	4.02	4.11	6.77	6.86	10.06	10.15
June	3.69	3.77	6.23	6.31	9.27	9.36
July	3.57	3.66	6.05	6.14	9.04	9.12
August	4.04	4.13	6.79	6.88	10.09	10.18
September	3.52	3.60	5.96	6.05	8.89	8.98
October	2.89	2.98	4.99	5.08	7.50	7.59
November	4.54	4.63	7.57	7.65	11.19	11.28
December	4.32	4.41	7.23	7.32	10.73	10.82

Table 11 and Table 12 presents the values of the unmet demand for the scenarios when the maximum capacity of the transmission link is reduced by ten and twenty percent. Table 11 presents these results for 2021 whilst Table 12 presents the results for 2050.

1.6 Improvement models

The improvement models are developed to provide results that after discussion, will help answer the main objective of the thesis "The main objective of this thesis is to evaluate and manage potential challenges in urban drinking water supply in the coming decades in Tamale Metropolitan. The water supply demand modelling tool WEAP will be used in this context."

The improvement models consist of a combination of changes made to the PGR model. The changes implemented to the improvement models are found in Table 10. Not all results and combinations are included here. Those not included can be found in Appendix C.

The results found in this subchapter (including what type of results looked at) is presented in the table below:

Table 13 - The four different improvement models with what they contain, and which results will be included. Values obtained from results in WEAP.

Name of model	**Model content**	**Included in results**
Only TL	A new transmission link included	Coverage, supply delivered and unmet demand
Only loss rates	The loss rates are lowered	Coverage, supply requirement, supply delivered and unmet demand
TL and loss rate	Both new transmission link and lowered loss rates	Coverage, supply delivered and unmet demand
TL, loss rate and reuse rate	New transmission link, lowered loss rates and included a reuse rate of 22.0%	Coverage, supply required and unmet demand

1.6.1 Schematic view of models including the second transmission link (Only TL, TL and loss rate, and TL, loss rate and reuse rate)

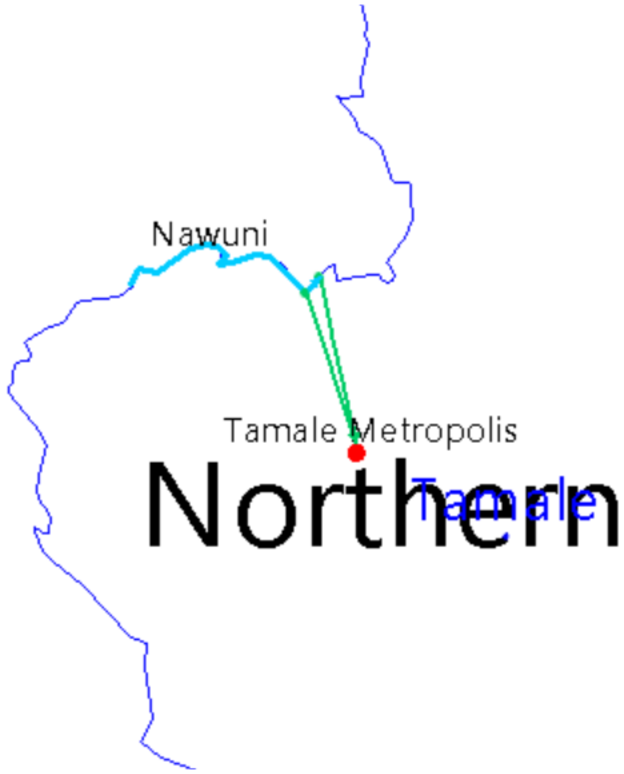

Figure 17 - The Schematic view of the WEAP models that has two transmission links. The models have one river – The Nawuni, one demand site – Tamale Metropolis and two transmission links between the river and the demand site. Screenshot from the schematic view in WEAP.

Figure 17 portrays the schematic view of the WEAP models when a second transmission link is added. The models that include two transmission links are: Only TL, TL and loss rate, and TL, loss rate and reuse rate. The second transmission link is added to the right of the first and is the green line seen in Figure 17.

1.6.2 Combinations of improvement models

This subchapter presents the results of all combinations of the improvement scenarios.

Only TL

This model was created by adding a transmission link to the model. Otherwise, everything is the same.

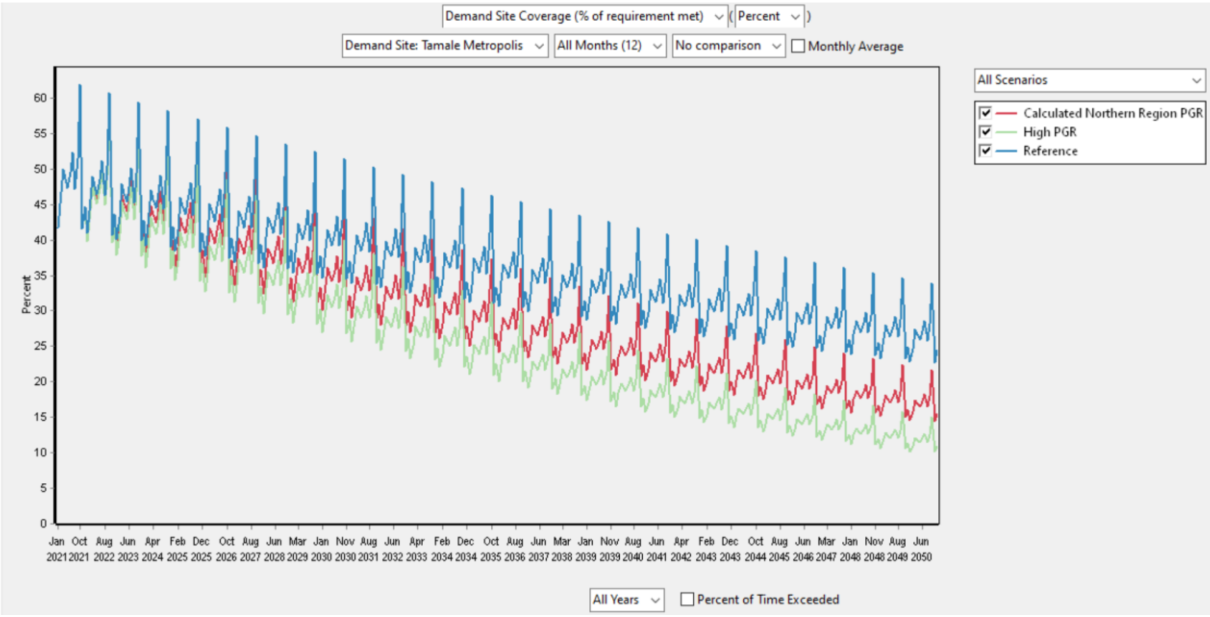

Figure 18 - Coverage for all years when there are two transmission links running at maximum capacity. Screenshot from the results view in WEAP.

Figure 18 shows the coverage of all years in the scenario where the only thing different from the PGR model is that there are two transmission links, both operating at maximum capacity.

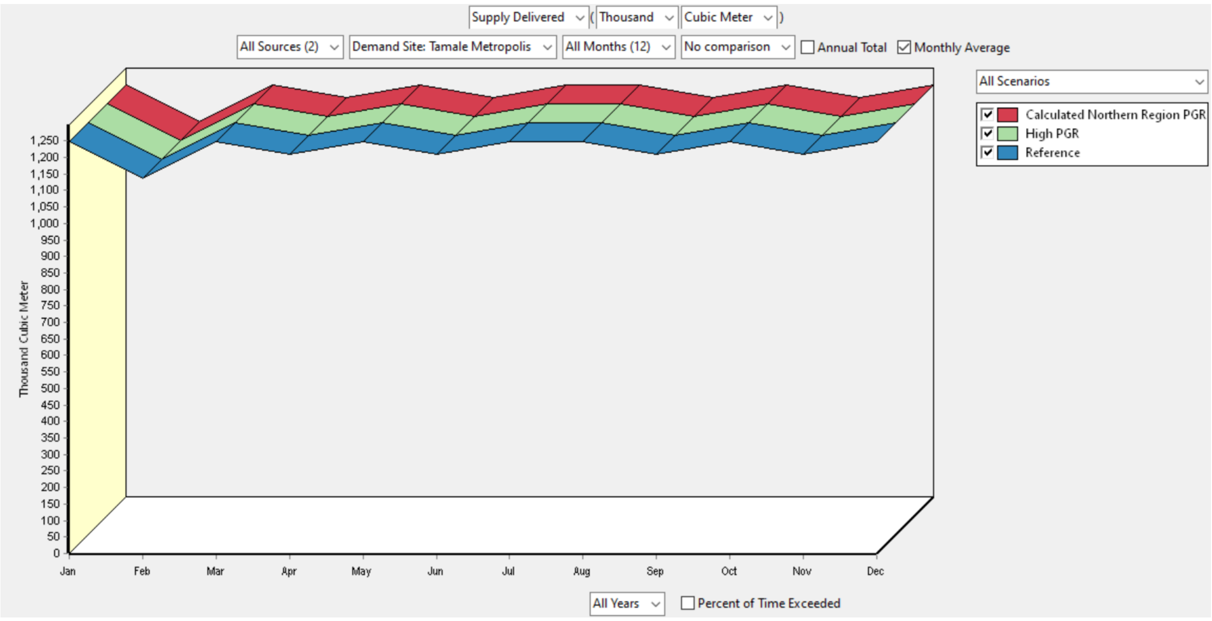

Figure 19 - Monthly average of supply delivered for all years when there are two transmission links operating at maximum capacity. Screenshot from the results view in WEAP.

Figure 19 shows the monthly average of the supply requirement of all years in the model where there are two transmission links, both operating at maximum capacity.

Only loss rates

In this model, there is only one transmission link (like for the PGR model), but the loss rates are reduced. The transmission link loss is reduced from 30% to 20%, and the demand site loss is reduced from 44% to 35%.

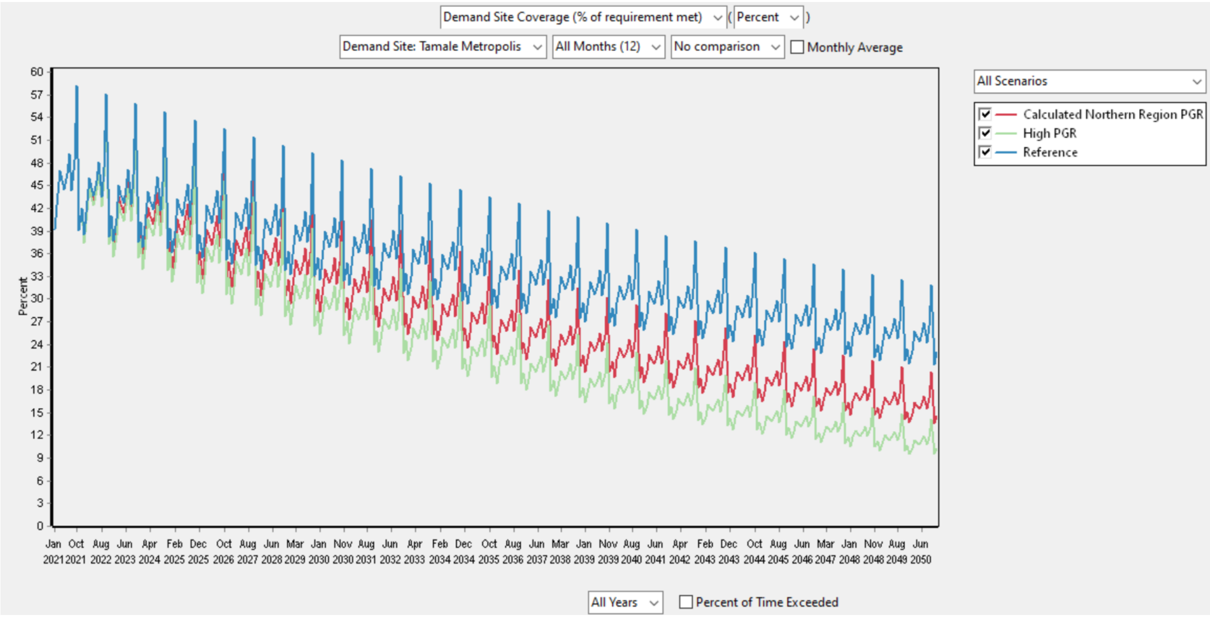

Figure 20 - Coverage for all years when the loss rates are lowered. Screenshot from the results view in WEAP.

Figure 20 shows the coverage of all years in the Only loss rates model.

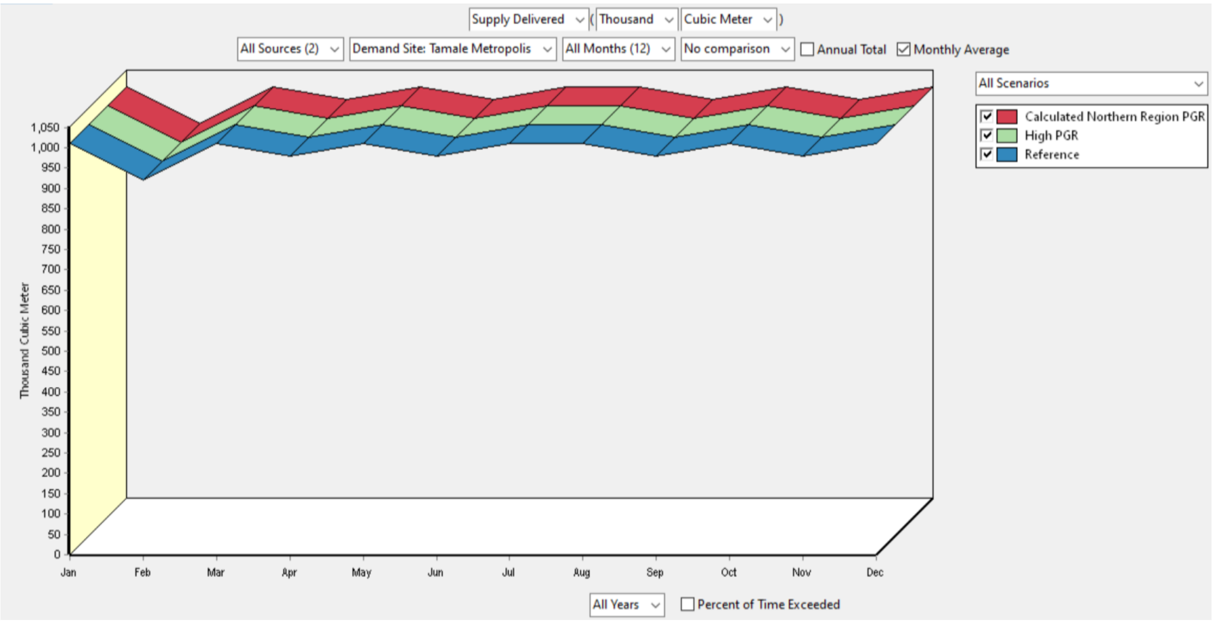

Figure 21 - Monthly average of supply delivered when the loss rates are lowered. Screenshot from the results view in WEAP.

Figure 21 shows monthly average of the supply delivered for all years in the Only loss rates model.

TL and loss rates

The TL and loss rates model is the combination of the Only TL model and the Only loss rates model. Therefore, this model has two transmission links where both are operating at maximum capacity, and reduced loss rates (20% for transmission link loss and 35% for the demand site loss).

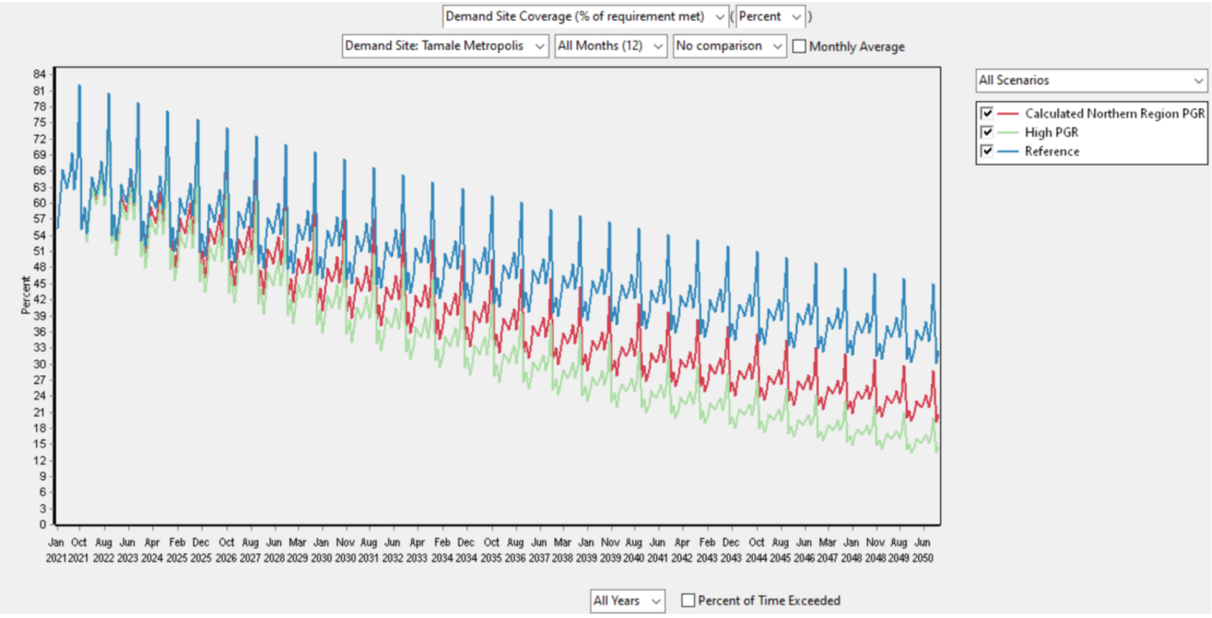

Figure 22 - Coverage for all years when there are two transmission links operating at maximum capacity and reduced loss rates. Screenshot from the results view in WEAP.

Figure 22 shows the coverage of all years in the TL and loss rates model.

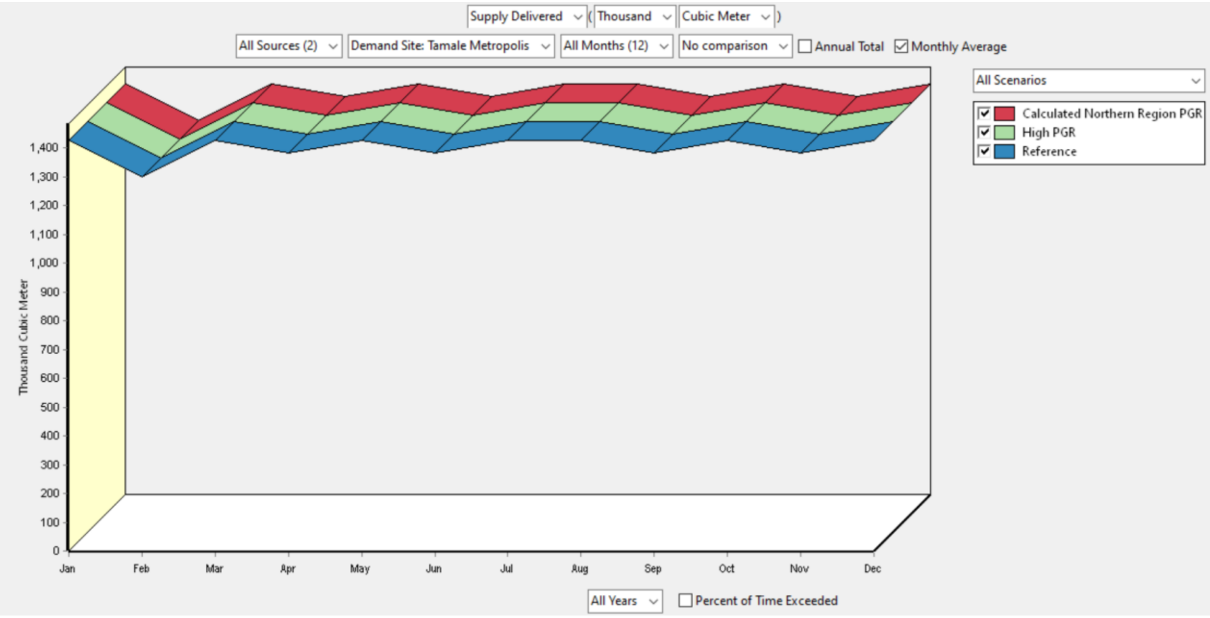

Figure 23 - Monthly average of supply requirement for all years when there are two transmission links operating at maximum capacity and reduced loss rates. Screenshot from the results view in WEAP.

Figure 23 shows monthly average of the supply delivered for all years in the TL and loss rates model.

TL, loss rates and reuse rate

The last model explored in subchapter 1.6 is the TL, loss rate and reuse rate model. This model is a combination of the TL and loss rates model and a reuse rate of 22.0%. The results for the sole reuse rate model can be found in Appendix C.

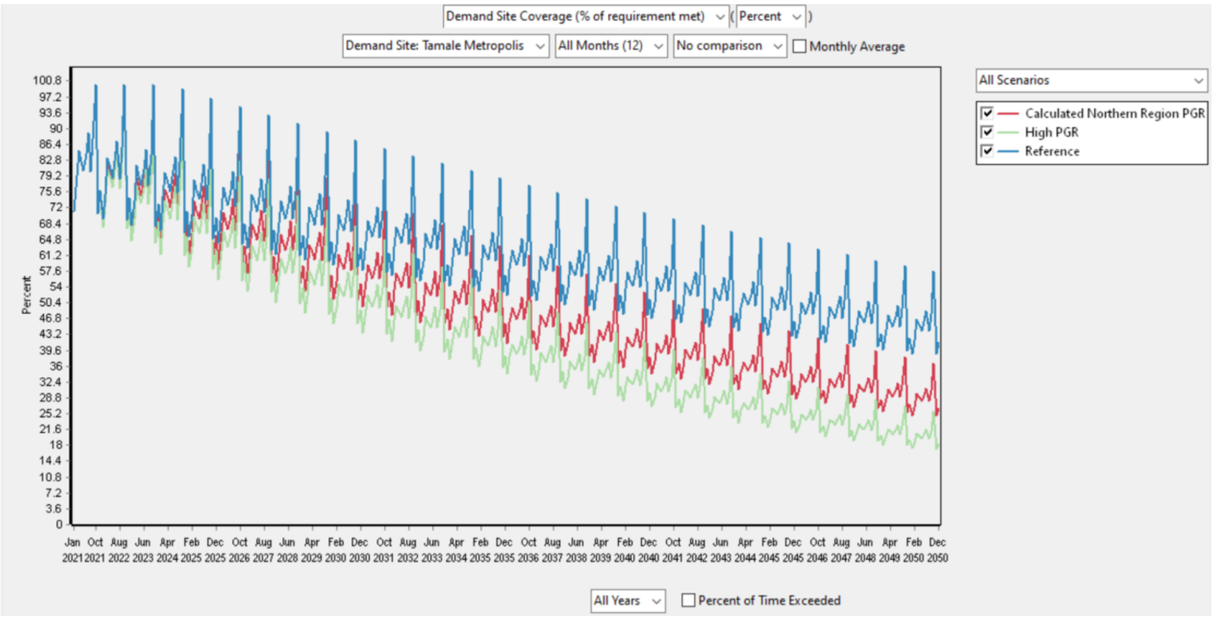

Figure 24 - Coverage for all years when there are two transmission links operating at maximum capacity, reduced loss rates and a reuse rate of 22.0%. Screenshot from the results view in WEAP.

Figure 24 shows the coverage of all years in the TL, loss rates and reuse rate model.

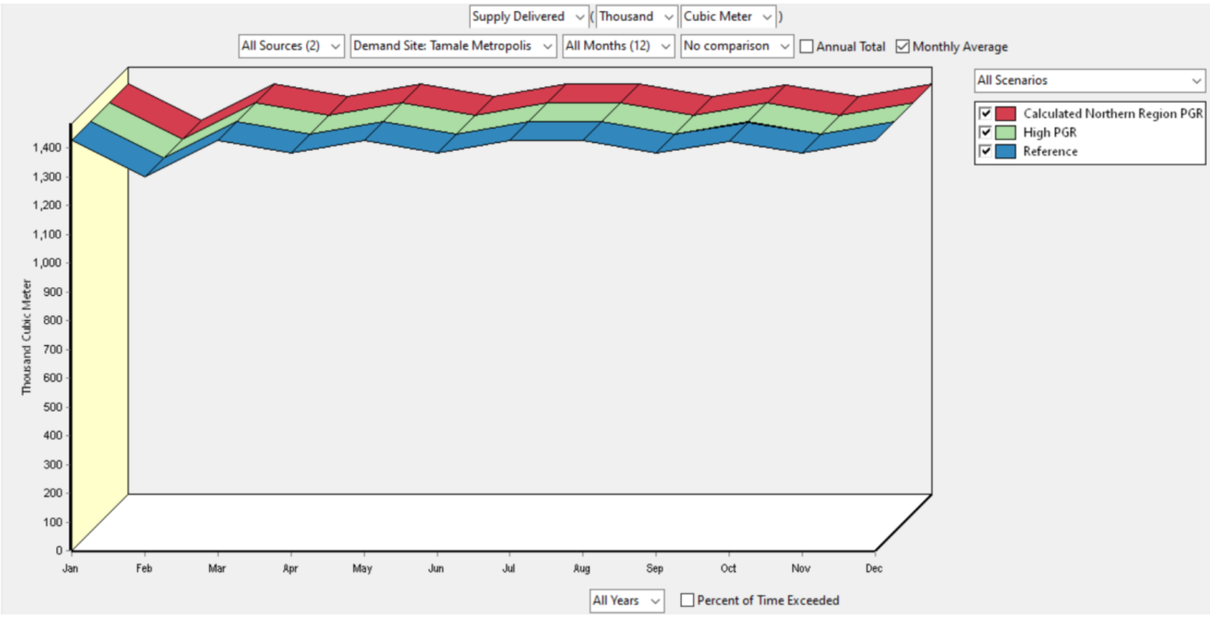

Figure 25 - Monthly average of supply delivered for all years when there are two transmission links operating at maximum capacity, reduced loss rates and a reuse rate of 22.0%. Screenshot from the results view in WEAP.

Figure 25 shows monthly average of the supply delivered for all years in the TL, loss rates and reuse rate model.

CHAPTER FIVE: Discussion

1 Discussion

Chapter five will discuss the results of the simulations in chapter four and answer the research questions. Uncertainties and errors will be discussed in general as they apply for all research questions. The discussion will address the research questions of the thesis, namely:

- What are the current challenges to the potable water supply in Tamale Metropolis?
- What happens to the drinking water supply and demand in Tamale Metropolis if the population increases with growth rates of 2.1%, 3.7% and 5,.0% every year from 2021 to 2050?
- What happens if the water supply to Tamale Metropolis is reduced by 10.0% or 20.0% due to factors influencing the catchment area?
- Is it possible to manage the challenges/weaknesses of the potable water supply in the urban area by looking at the water loss and reuse rates, and transmission link capacity, so that the coverage will increase in the predictable future?

1.1 PGR model

The PGR model is created to look at how the next 29 years might develop with different annual population growth rates implemented to the current population.

Figures 4-12 illustrate the supply and demand situation in Tamale Metropolis during 2021 – 2050 for the three scenarios regarding different annual population growth rates (2.1%, 3.7% and 5.0%).

Figure 4 and Figure 5 illustrates the coverage of the water demand in Tamale Metropolis for the three scenarios. Figure 4 shows the coverage every month from 2021 and to 2050, whilst Figure 5 shows the monthly average coverage for the entire simulation. Looking at Figure 4 it is observed that the monthly variations are fluctuating. In 2021, for all scenarios, the lowest coverage appears in January and is 29.61%. The highest coverage appears in October and is 43.89%. The coverage for all scenarios is equal in 2021 because there has not been any increase in population yet.

When observing the coverage of 2050, the results are quite different from the ones in 2021. For the reference scenario, the lowest coverage is 16.21% in January and the highest is 24.02% in October. The scenario with the calculated NR PGR (3.7%) has the value of 10.32%

in January as the lowest and 15.30% in October as the highest value of coverage. The scenario with the high PGR (5.0%) clearly has the lowest values of coverage. The lowest coverage appears in January and is 7.19%, whilst the highest coverage is 10.66% in October.

It is not surprising that the coverage decreases in all scenarios, or that the decrease is highest in the scenario with the highest population growth rate. This is happening because the population increases exponentially, but the water supply is not changing. This leads to a decrease in coverage.

An interesting observation is that the monthly differences in coverage are also decreasing. For instance, looking at the scenario with the high PGR, the difference between the lowest and highest coverage is 3.47% in 2050, but in 2021 it is 14.28%. The ratio between the lowest and highest coverage is however the same, and it is 67.5%. The difference of coverage from month to month is decreasing because in 2050, all months need considerably more water to satisfy the demand than in 2021, and when there is no increase in the supply, the difference in coverage will decrease as the coverage will be much lower for all months.

Table 14 - Lowest and highest monthly average of coverage for all scenarios of the PGR model in 2021 and 2050. Values obtained from results in WEAP.

	Reference scenario [%] January, October		**Calculated NR PGR [%] January, October**		**High [%] January, October**	
2021	29.61	43.89	29.61	43.89	29.61	43.89
2050	16.21	24.02	10.32	15.30	7.19	10.66

Table 14 summarizes the lowest and highest coverage in 2021 and 2050 for all scenarios in the PGR model, as monthly average. There are some approximations done in WEAP so the numbers are not exact but looking at Table 14 one can see that the ratio is the same and there is a significant decrease in monthly difference in coverage.

Figure 5 illustrates the monthly average of the coverage, revealing a consistent pattern across all years of the simulations (2021-2050). It is evident that the coverage is on average highest in October and lowest in January. The reason behind this is shown in Table 4, where the monthly variations show the water demand compared to the total annual water demand for each month. October has the lowest percentage and January the highest. Whether or not this is representative is difficult to say. The percentages are based on the amounts of water GWCL can supply each month and how the supply varies. There is an assumption that the demand is based on the supply, which means that the months that are getting the most water need the most water, while the months that are getting the least water are the months that need the least water. By looking at Figure 2 it is observed that the rainy season in Tamale in 2021 peaked in September, and that there were little to no rain in December to March. This can explain why the average coverage is highest in October and lowest in January as rain can be used as a water source.

Figure 6 and Figure 7 present the water demand results. The water demand is the required volume of water needed to satisfy the demand. The water demand does not include loss, reuse, and demand site improvement (DSM). Figure 8 and Figure 9 presents the supply requirements which does include the loss, reuse, and DSM. Figure 6 and Figure 8 shows the annual total of the water demand and supply requirement, whilst Figure 7 and Figure 9 shows the monthly averages. These figures are therefore similar, and the difference observed is attributed to the loss rate. The supply requirement includes the 44 % loss rate and is therefore higher than the water demand. The supply requirements demand 78.57% more than the water demand as is shown in the figures. The calculation is as follows:

$$Supply\ Requirement = \ 1/(1-DSL) \tag{7}$$

$$Supply\ Requirment = \frac{1}{1-0.44} = 1.7857 \tag{8}$$

The table below displays the water demand and supply requirement averages for each month during the simulation, in million m^3, the first value of each row represents the reference scenario, the second value represent the calculated Northern Region PGR, and the third value represents the high PGR scenario.

Table 15 - Monthly average of water demand and supply requirement for all years and all scenarios in the PGR model. Values obtained from results in WEAP.

	Water demand [10^6 m^3] Reference, Calculated NR PGR, High			**Supply requirement [10^6 m^3] Reference, Calculated NR PGR, High**		
January	2.30	2.98	3.71	4.11	5.32	6.62
February	1.93	2.49	3.11	3.44	4.45	5.55
March	1.92	2.49	3.10	3.43	4.44	5.53
April	1.91	2.48	3.08	3.41	4.43	5.50

May	2.03	2.63	3.27	3.62	4.69	5.84
June	1.88	2.43	3.03	3.35	4.34	5.40
July	1.84	2.38	2.96	3.28	4.25	5.29
August	2.03	2.63	3.28	3.63	4.70	5.86
September	1.81	2.34	2.91	3.22	4.18	5.20
October	1.55	2.01	2.50	2.77	3.59	4.47
November	2.24	2.89	3.60	3.99	5.17	6.44
December	2.15	2.79	3.47	3.85	4.98	6.20

Figure 10 illustrates how much water is delivered to Tamale Metropolis as a monthly average for 2021-2050. The supply delivered varies from 799.30 thousand m^3 in February, 856.40 thousand m^3 in April, June, September, and November, and 884.94 thousand m^3 in January, March, May, July, August, October, and December. The variation comes from the number of days of each month. This is because the supply is dependent on the volumes of water the transmission link is able to transport to Tamale. For January, including the 30% loss rate, the calculation for the supply requirements is as follows:

$$0.472\frac{m^3}{s} * 3600\frac{s}{h} * 24\frac{h}{d} * 31\frac{d}{m} * 0.7 = 884.94m^3 \qquad (9)$$

Figure 11 and Figure 12 present the unmet demand, Figure 11 presents the annual total unmet demand and Figure 12 shows the monthly average of the unmet demand. The annual total unmet demand in 2021 is equal for all scenarios and has the value of 20.24 million m^3. In 2050, the unmet demand has increased for all scenarios to 45.60, 77.51 and 115.78 million m^3 for the reference, calculated NR PGR, and high PGR, respectively. The increase noticed stems from the population growth, and it is only logical that the unmet demand increases most for the scenario with the highest PGR.

Table 16 - Monthly average of unmet demand for all scenarios in the PGR model in 2021, 2035 and 2050. Values obtained from results in WEAP.

Monthly average of Unmet Demand for all scenarios in 2021, 2035 and 2050 [10^6 m^3]									
	Reference			**Calculated NR PGR**			**High PGR**		
January	2.10	3.11	4.58	2.10	4.09	7.69	2.10	5.03	11.42

February	1.70	2.55	3.78	1.70	3.36	6.38	1.70	4.16	9.51
March	1.61	2.46	3.68	1.61	3.27	6.28	1.61	4.06	9.40
April	1.63	2.47	3.69	1.63	3.28	6.27	1.63	4.07	9.38
May	1.75	2.64	3.94	1.75	3.50	6.68	1.75	4.34	9.98
June	1.58	2.41	3.60	1.58	3.20	6.14	1.58	3.98	9.19
July	1.50	2.31	3.48	1.50	3.09	5.97	1.50	3.84	8.95
August	1.76	2.65	3.95	1.76	3.51	6.70	1.76	4.35	10.00
September	1.49	2.28	3.43	1.49	3.05	5.88	1.49	3.79	8.81
October	1.13	1.81	2.80	1.13	2.47	4.90	1.13	3.11	7.41
November	2.05	3.03	4.45	2.05	3.98	7.48	2.05	4.90	11.11
December	1.92	2.86	4.23	1.92	3.77	7.15	1.92	4.66	10.64

Table 16 contains the monthly averages for the unmet demand in 2021, 2035 and 2050 for all scenarios in the PGR model. Figure 12 shows the monthly average for all scenarios, during the entire lifespan of the simulations. Table 16 illustrates how the unmet demand develops from 2021 to 2050, with 2035 to provide an insight as to what rate the unmet demand is progressing. Looking at Table 16 it is evident that as the years go by, the increase in the unmet demand is growing, as the population increase is also growing simultaneously.

2.2 Reduction of TL max cap

The purpose of the model which reduces the maximum capacity of the transmission link is to illustrate how the water demand and supply situation changes when the water supply is being reduced. There is more than enough water in the Nawuni river to satisfy the demand, but this is still not achieved according to data and interviews from GWCL. The factors influencing the catchment areas beyond the metropolitan area may impact the amount of water freely available for water supply in Tamale, leading to unsatisfactory water supply. To be able to look at how these factors possibly impact the supply and demand in Tamale, a reduction of 10.0% and 20.0% is applied to the WEAP Model. This reduction is attributed to effects of the climate, agricultural demand, non-urban population increase and aging of the piping networks. Due to limited access of data, a possible reduction of availability of water to urban water supply was proposed to be 10% and 20%.

Figures 13 – 16 illustrate the supply and demand situation in Tamale Metropolis during 2021 – 2050 when the capacity of the transmission link is reduced by 10.0% and 20.0%. More specifically, Figure 13and Figure 14 represent a 10.0% reduction while Figure 15 and Figure 16 represent a 20.0% reduction.

It is evident from Figure 13 and Figure 15 that when the maximum capacity of the transmission link is reduced, both by 10.0% and 20.0%, the coverage decreased. The trends of how the coverage advances are the same as to the scenarios of the PGR model. This is because there is no monthly or annual change to the model, there is only a reduction in the maximum capacity, and this reduction is equal for all months and all years of the simulation.

Figure 14 and Figure 16 presents the monthly average of the supply delivered for all years. It is observed that there is a reduction in the supply delivered. The reduction in the supply delivered is equal to the reduction in the maximum capacity.

The models of this thesis are simplified, and there are factors that will contribute to making the relationship between the reduction in the maximum capacity of the transmission link different from the supply delivered. This is, however, not simulated. Factors that can contribute to the difference are:

- Variations in leakages and non-revenue water can cause variations in the supply that even if the general reduction of maximum capacity is 10.0% or 20.0%, will cause the supply to be reduced at different rates.
- Unforeseen challenges at the DTP that causes the production of drinking water to vary.

Regardless, Figures 13 - 16 show that the various factors that can affect the catchment areas beyond Tamale Metropolis, do undoubtedly negatively impact the urban water supply.

2.3 Improvement models

The improvement models were developed in order to look at possible ways to manage the drinking water supply and demand situation in Tamale Metropolis.

Figures 18 – 25 illustrate the supply and demand situation in Tamale Metropolis during 2021 – 2050 for the scenarios in the models where different adjustments have been made to improve on the coverage.

Only TL

Figure 18 and Figure 19 represent the results for the Only TL model. To see the impact of running both transmission links with maximum capacity, a comparison on coverage and supply delivered will be made between the Only TL model and the PGR model.

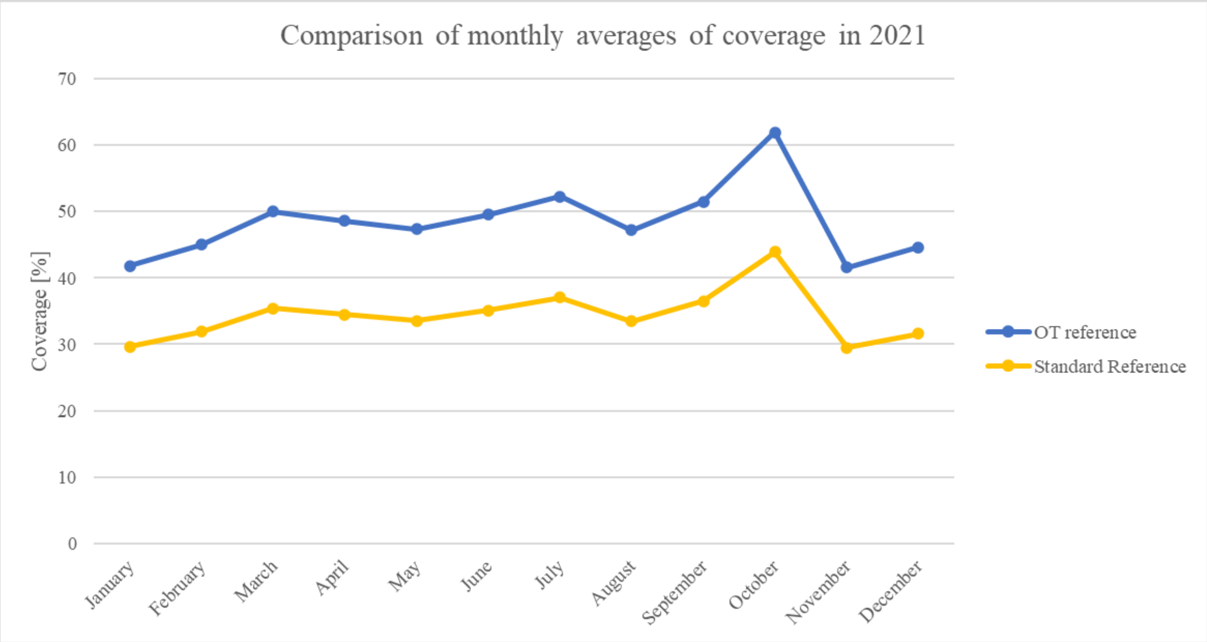

Figure 26 - Comparison of monthly averages in 2021 between the Only TL model and the PGR model. Source: Created in excel with results from WEAP.

Figure 26 provides a comparison between the Only TL model and the PGR model regarding the monthly average of the coverage in 2021. In the year 2021, the coverage is the same for all months and therefore is only represented by the OT reference (blue line) and the Standard Reference (yellow line). The OT reference is the reference scenario from the Only TL model, whilst the Standard Reference is the reference scenario from the PGR model.

There is a clear increase in coverage for the scenarios in the Only TL model as compared to the scenarios in the PGR model. By operating both transmission links at maximum capacity, it is possible to increase the coverage substantially. Even the months that are experiencing the lowest coverage in the scenarios in the Only TL model, have more coverage than 10 out of 12 months for the scenarios in the PGR model. January and November in the OT reference scenario are both slightly lower in coverage than October of the Standard Reference. The coverage for Only TL, however, is still not adequate, as it averages around 50%.

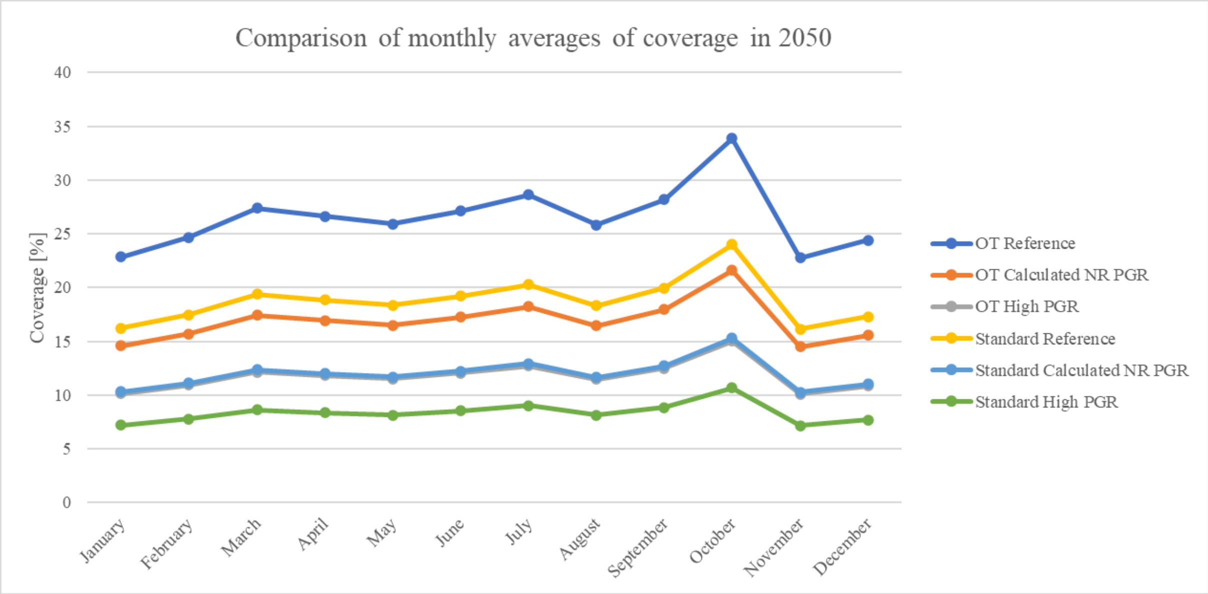

Figure 27 - Comparison of monthly averages in 2050 between the Only TL model and the PGR model

Figure 27 provides a comparison between the Only TL model and the PGR model regarding the monthly average of the coverage in 2050. There are six graphs in Figure 27 which are representing different scenarios:

- OT Reference (dark blue line): Reference scenario for the Only TL model
- OT Calculated NR PGR (orange line): Calculate NR PGR scenario for the Only TL model
- OT High PGR (grey line): High PGR scenario for the Only TL model
- Standard Reference (yellow line): Reference scenario for the PGR model
- Standard Calculated NR PGR (lighter blue line): Calculated NR PGR scenario for the PGR model
- Standard High PGR (green line): High PGR scenario for the PGR model

The OT Reference has the overall highest coverage. The coverage is higher than all scenarios in all months for the OT Reference, except for January and November, as those are both lower in coverage than October in the Standard Reference. The scenarios in the Only TL model have higher average coverage than the scenarios in the PGR model, but the coverage is still very low. The OT reference averages roughly at 26%, the OT calculated NR PGR averages roughly around 16% and the OT High PGR averages roughly around 10%. These averages are far from satisfactory.

Figure 19 shows the monthly average of the supply delivered for all years for the scenarios in the Only TL model and comparing it to Figure 10, it shows a significant increase. Even though the coverage does not necessarily increase substantially, the increase in supply delivered should be considered when looking at ways to improve the supply and demand.

Only loss rates

Figure 20 and Figure 21 represent the results for the Only loss rates model. The effect of reducing the loss rates will be shown by comparing the Only loss rates model with the PGR model.

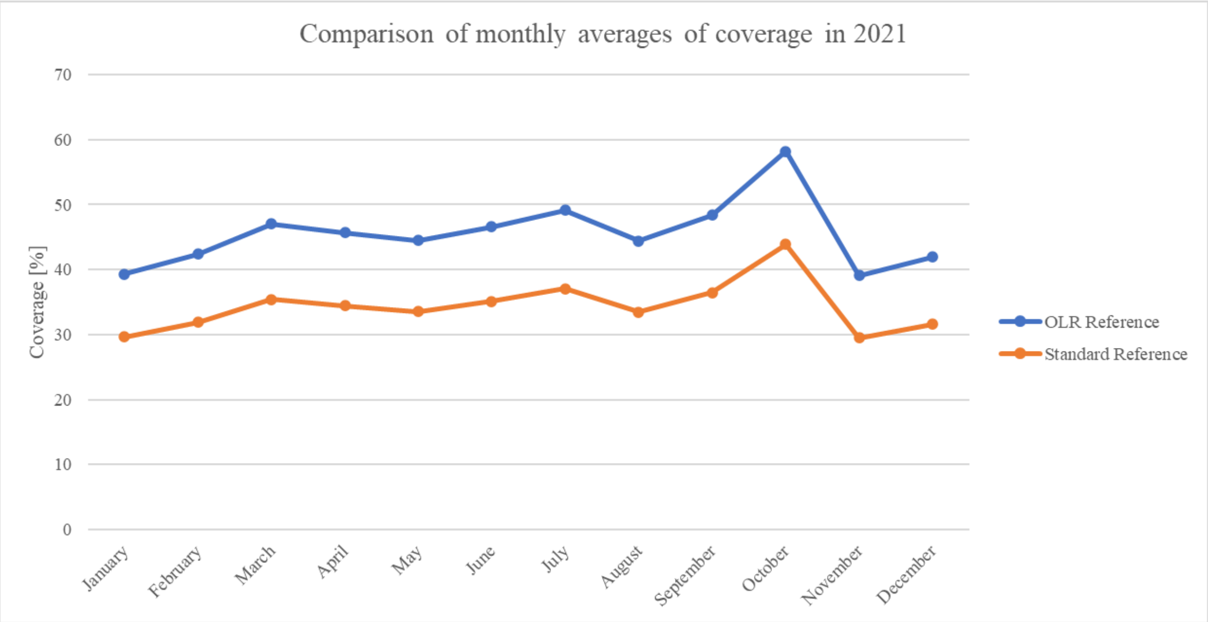

Figure 28 - Comparison of monthly averages in 2021between the Only loss rates model and the PGR model. Source: Created in excel with results from WEAP.

Figure 28 provides a comparison between the Only loss rates model and the PGR model regarding the monthly average of the coverage in 2021. As mentioned, the coverage is equal for all scenarios in the Only loss rates model and the PGR model, and the scenarios are therefore represented by the OLR reference (blue line) and the Standard Reference (yellow line). OLR reference is the Only loss rates reference scenario.

As for the scenarios in the Only TL model, the scenarios in the Only loss rates model are also experiencing more coverage than the scenarios in the PGR model.

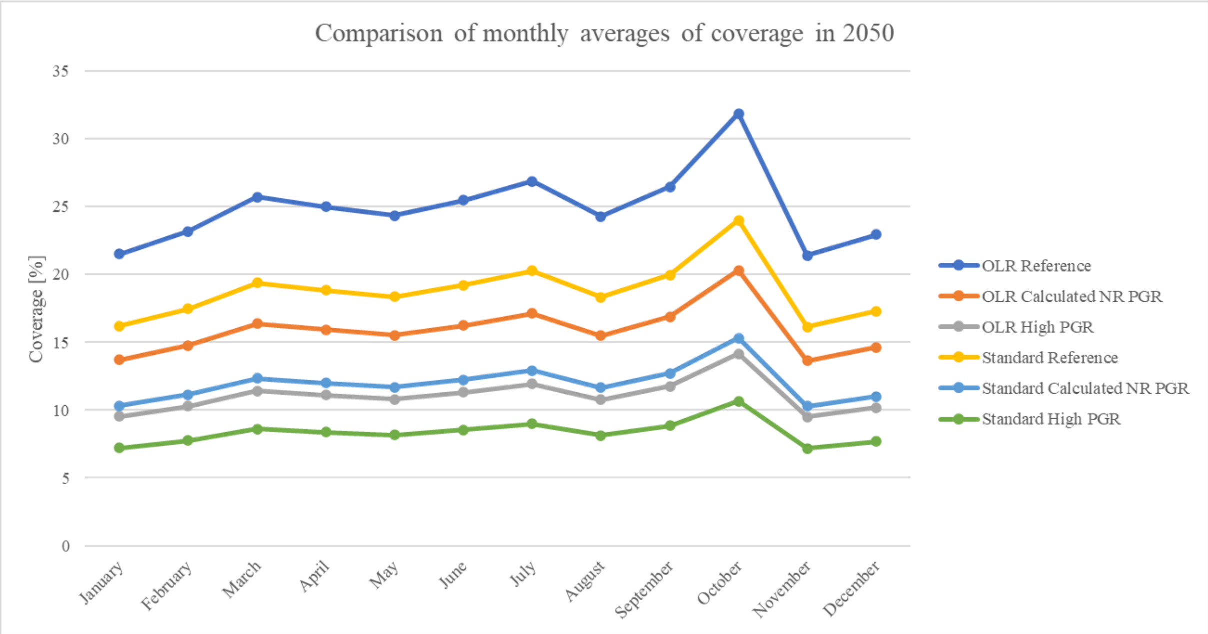

Figure 29 - Comparison of monthly averages in 2050 between the Only loss rates model and the PGR model. Source: Created in excel with results from WEAP.

Figure 29 provides a comparison between the Only loss rates model and the PGR model regarding the monthly average of the coverage in 2050. There are six graphs in Figure 29 which are representing different scenarios:

- OLR Reference (dark blue line): Reference scenario for the Only loss rates model
- OLR Calculated NR PGR (orange line): Calculate NR PGR scenario for the Only loss rates model
- OLR High PGR (grey line): High PGR scenario for the Only loss rates model
- Standard Reference (yellow line): Reference scenario for the PGR model
- Standard Calculated NR PGR (lighter blue line): Calculated NR PGR scenario for the PGR model
- Standard High PGR (green line): High PGR scenario for the PGR model

From Figure 29 it is observed that the OLR Reference has the highest coverage, and that the coverage averages around 25%. The OLR Reference has higher coverage than all scenarios when comparing each month of the scenarios. The Standard Reference, however, has higher coverage in October than January, February, November, and December than the OLR Reference. The coverage for OLR Calculated NR PGR averages around 16% and the OLR High PGR averages around 11%. These are all unsatisfying averages of the coverage for 2050. This is not promising, the measures taken to ensure higher coverage are not adequate.

Figure 21 shows that the supply delivered for the Only loss rate model are higher than for the PGR model which is desirable.

TL and loss rates

The effect of reducing the loss rates simultaneously as there are two transmission links running at maximum capacity will be shown by comparing the TL and loss rates model with the PGR model.

Figure 22 and Figure 23 represent the results for the TL and loss rates model.

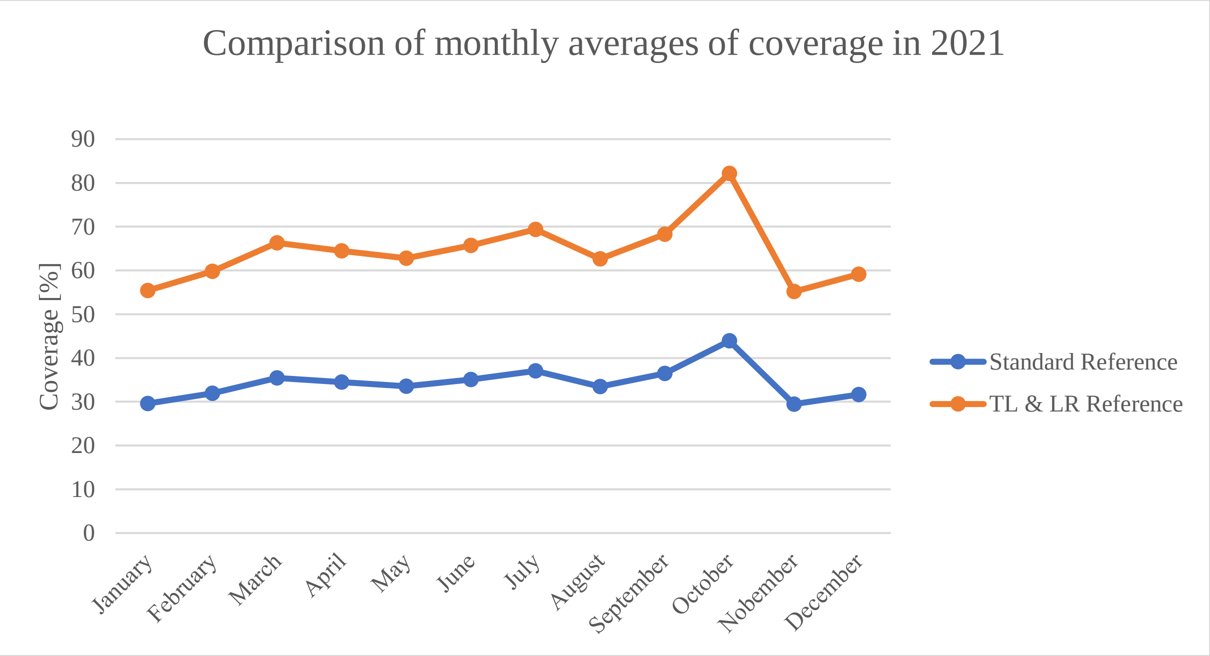

Figure 30 - Comparison of monthly averages in 2021between the TL and loss rates model and the PGR model. Source: Created in excel with results from WEAP.

Figure 30 provides a comparison between the TL and loss rates model and the PGR model regarding the monthly average of the coverage in 2021. As mentioned, the coverage is equal for all scenarios in the TL and loss rates model and the PGR model, and the scenarios are therefore represented by the TL & LR Reference (orange line) and the Standard Reference (blue line). TL & LR reference is the TL and loss rates reference scenario.

The average coverage of the TL & LR Reference is 64%, which is a considerable increase from the Standard reference that averages around 34%. All months in the TL & LR Reference are experiencing significantly more coverage than all months of the Standard Reference.

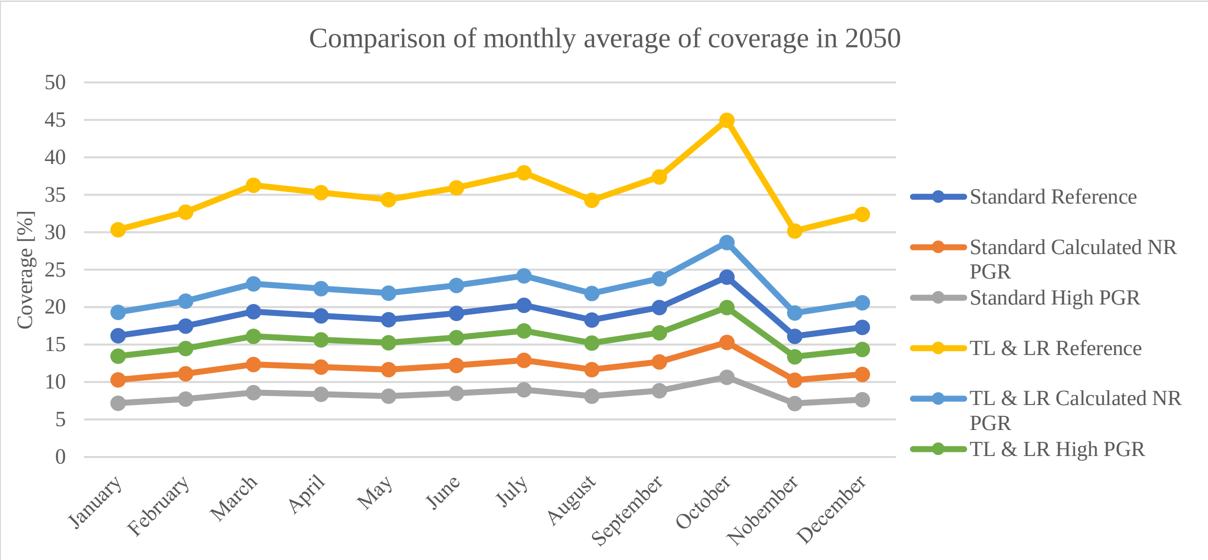

Figure 31 - Comparison of monthly averages in 2050 between the TL and loss rates model and the PGR model. Source: Created in excel with results from WEAP.

Figure 31 provides a comparison between the TL and loss rates model and the PGR model regarding the monthly average of the coverage in 2050. There are six graphs in Figure 31 which are representing different scenarios:

- TL & LR Reference (yellow line): Reference scenario for the TL and loss rates model
- TL & LR Calculated NR PGR (light blue line): Calculate NR PGR scenario for the TL and loss rates model
- TL & LR High PGR (green line): High PGR scenario for the TL and loss rates model
- Standard Reference (dark blue line): Reference scenario for the PGR model
- Standard Calculated NR PGR (orange line): Calculated NR PGR scenario for the PGR model
- Standard High PGR (grey line): High PGR scenario for the PGR model

Figure 31 illustrates that the TL and loss rate model has higher coverage in the reference scenario in 2050, than all months of all scenarios in the PGR model. The TL & LR Reference has a coverage that averages around 35% in 2050, which is almost 1% more than the average of the reference scenario in the PGR model in 2021. The TL & LR High PGR scenario averages around 16% in 2050 and this is approximately 3% lower than the average of the Standard Reference in 2050. This means that with an annual population growth rate of 5.0%, the coverage in the TL & LR High PGR scenario is almost the same as the coverage of the Standard Reference which has an annual population growth rate of 2.1%. This is illustrated in Figure 31 with the dark blue line being slightly above the green line.

The averages for the scenarios in the TL and loss rate model for 2050 are still low, but it is a significant increase from the scenarios in the PGR model.

TL, loss rates and reuse rate

Figure 24 and Figure 25 represent the results for the TL, loss rates and reuse rate model.

To see the impact of operating both transmission links with maximum capacity, reducing the loss rates and reusing 22% of the water, a comparison on coverage and supply delivered will be made between the TL, loss rates and reuse rate model and the PGR model.

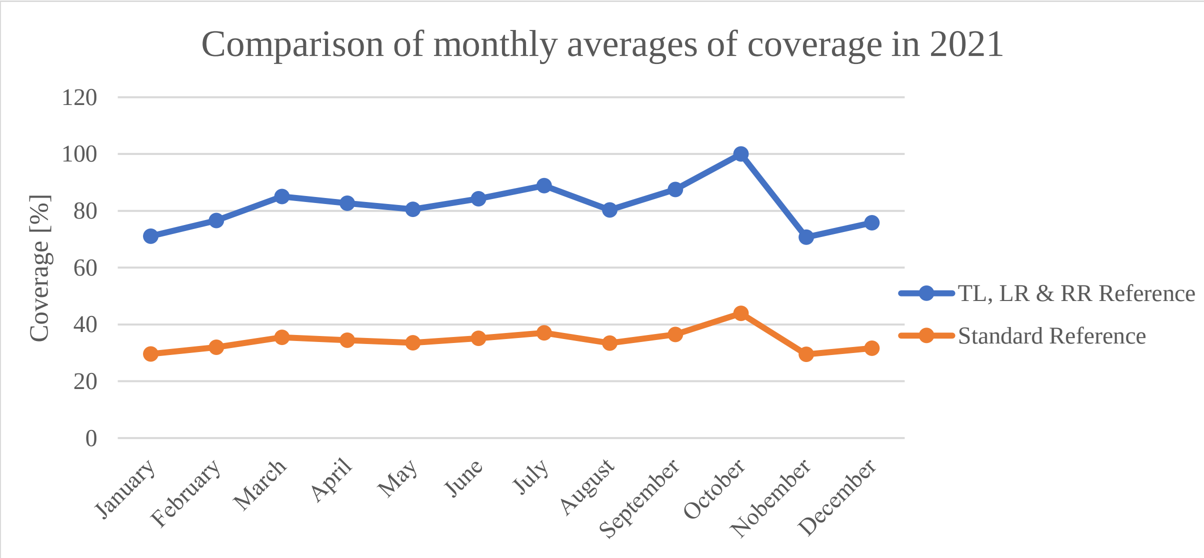

Figure 32 - Comparison of monthly averages in 2021 between the TL, loss rates and reuse rate model and the PGR model. Source: Created in excel with results from WEAP.

Figure 32 provides a comparison between the TL, loss rates and reuse rate model and the PGR model regarding the monthly average of the coverage in 2021. As mentioned, the coverage is equal for all scenarios in the TL, loss rates and reuse rate model and the PGR model, and the scenarios are therefore represented by the TL, LR & RR Reference (blue line) and the Standard Reference (orange line). TL, LR & RR reference is the reference scenario of the TL, loss rates and reuse rate model.

When adding a reuse rate of 22% to the model that already operates two transmission links at maximum capacity and has reduced loss rates (20% loss to leakages and 35% loss to NRW), the coverage for all scenarios in 2021 is very high, the average is 82%. Even though this is not 100% coverage, the average is well beyond the average for all scenarios in the PGR model in

2021. This is visually presented in Figure 32 where it can also be observed that the average coverage has more than doubled.

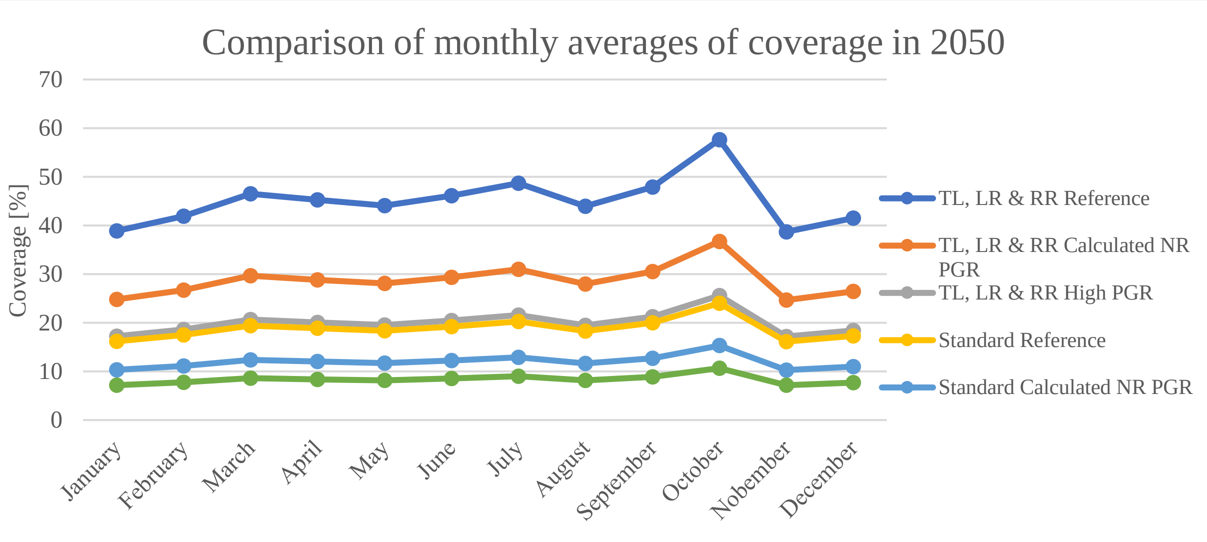

Figure 33 - Comparison of monthly averages in 2050 between the TL, loss rates and reuse rate model and the PGR model. Source: Created in excel with results from WEAP.

Figure 33 provides a comparison between the TL, loss rates and reuse rate model and the PGR model regarding the monthly average of the coverage in 2050. There are six graphs in Figure 31 which are representing different scenarios:

- TL, LR & RR Reference (dark blue line): Reference scenario for the TL, loss rates and reuse rate model
- TL, LR & RR Calculated NR PGR (orange line): Calculate NR PGR scenario for the TL, loss rates and reuse rate model
- TL, LR & RR High PGR (grey line): High PGR scenario for the TL, loss rates and reuse rate model
- Standard Reference (yellow line): Reference scenario for the PGR model
- Standard Calculated NR PGR (light blue line): Calculated NR PGR scenario for the PGR model
- Standard High PGR (green line): High PGR scenario for the PGR model

From Figure 33 it is seen that all scenarios in the TL, loss rates and reuse rate model have higher average coverage than the scenarios in the PGR model in 2050. The average coverage for the TL, LR & RR Reference scenario is 45% in 2050. In 2021 the average coverage for the Standard Reference scenario is 34%. This means that in 2050, the average coverage is 11% higher for the reference scenario in the TL, loss rates and reuse rate model, than the reference scenario in the PGR model is in 2021. Looking at the TL, LR & RR Calculated NR PGR and the TL, LR & RR High, both have averages in coverage in 2050 that are higher than the Standard Reference does in 2050. The calculated NR PGR of the TL, loss rates and reuse rate model has an average coverage of 29% in 2050, and the associated High PGR scenario has an average of 20% in 2050. Annual average coverages of 20% and 29% are not nearly satisfactory, and neither are 45%. Even so, the averages of the scenarios in the TL, loss rate and reuse rate model are notably higher than the averages of the scenarios in the PGR model.

Figure 25, the monthly average of the supply delivered for all scenarios in the TL, loss rates and reuse rate model, is almost 2/3 higher than the monthly average of the supply delivered for all scenarios in the PGR model.

2.4 Discussion assumptions and data limitations

When processing the data, it first had to be thoroughly checked. There are multiple mistakes in the data sets, and some of the data is not recorded and therefore missing. Where the data is lacking, the assumption was made that it was zero in some places. If too much of the data was lacking, the set was disregarded.

Following is a list of assumptions made:

- Assuming the production data from GWCL used for the demand and supply from 2022 is the same as the data from 2021.
- Some of the flow data for the Nawuni river is missing, therefore an assumption made is that all missing data has the average value.
- Assuming a population growth rate for Tamale Metropolis to be 3.7% annually as well as constructing a high PGR of 5.0%.
- Assuming that the entire population of Tamale is supplied by GWCL.
- Assuming that the NRW loss is part of the demand site loss.
- Assuming that the monthly variation based on the supply equals the monthly variation based on the demand.
- Assuming that a reduction of 10.0% and 20.0% in the maximum capacity of the transmission link is caused by factors affecting the catchment area.

The first assumption was made because the production data from GWCL was only provided for the year 2022.

For the second assumption, there were a lot of missing data points during the years of 2018 and 2019. This led to all missing points of data assigned the average value of the year.

The third assumption regarding the PGR of Tamale was made because there was no accurate PGR for Tamale, nor the urban part. Because Tamale is considered rapidly growing, it seemed very inaccurate to assume the general PGR of Ghana, namely 2,1%. Therefore, the calculation of the likely PGR of the Northern Region was made, and the PGR was then applied to Tamale as the growth rate of this thesis. Initially, it is necessary to determine the accuracy of the current PGR for Ghana. This is done by calculating what the population of Ghana would be in 2021 if the growth rate is 2.1% and the start point is the population in 2010. 2.1% is an average growth rate as stated by Ghana Statistical Service (GSS). Therefore, a calculation of the roughly growth rate follows:

$$24658823 * x^{11} = 30792608 \tag{10}$$

$$x = \sqrt[11]{\frac{30792608}{24658823}} \tag{11}$$

$$x = 1.02039 \approx 2.04\% \tag{12}$$

The difference between the calculated growth rate and the average from GSS is 0.06. 2.04 is 97% of 2.1. The growth rates are similar enough for it to be reasonable to approximate further with the population in the Northern Region. This justifies the calculations done in chapter three subchapter 1.4 regarding the PGR of the Northern Region also applied for Tamale. The high PGR of 5.0% is assumed based on what would happen with higher growth rates than the calculated one.

The fourth assumption claims that the entire population of Tamale is supplied by GWCL. This is not true, but because there are not any data giving an accurate number of how many people are supplied by GWCL, and the fact that GWCL themselves claim that the customers they have are outsourcing the water to friends and family that are not connected themselves, the assumption was made.

The fifth assumption states that the NRW is part of the demand site loss. It is important to rightly place the losses in WEAP so that the results are correct. For this thesis, the non-revenue water is part of the demand site loss as big part of it is considered to be water theft.

Regarding the sixth assumption stating that the monthly variation based on the supply is equal to what it would be based on the demand, is made because the actual demand was not possible to obtain.

The last assumption states that the reduction of 10.0% and 20.0% in the maximum capacity of the transmission link is caused by factors affecting the catchment area. This assumption was made so that it would be possible to look at the effects other factors have and is further discussed in subchapter 2.5.

2.5 Impacts of climate, non-urban population increase etc.

When considering how the future drinking water demand and supply situation might develop, it is important to take into account the factors that are not simulated in the WEAP models.

Even though it was not possible to simulate how the climate affects the water supply, the climate most certainly will. As stated in chapter two, subchapter 1.2, the effects of climate change are adversely impacting the infrastructure in Africa. As the drinking water piping network is a great part of infrastructure, it is logical to assume that climate change will have negative consequences on the piping network. There is already a challenge with leakages, flooding, and water quality, but the effects of climate and climate change will most certainly worsen these aspects.

Another factor that may influence the water demand and supply is the rural migration to urban areas. This is happening in Tamale Metropolis and is one of the causes of the rapid growth. In chapter two, subchapter 1.3, it is stated that urbanization is happening at a high rate in the SSA, and Tamale specifically. When the urban population increases faster than the ability the area must adapt, all existing challenges will be exacerbated as well as new ones will appear. The increase of urban areas will increase the water demand. Not only will the water demand that GWCL has responsibility to meet increase, but there most likely will be an increase in the illegal connections that GWCL already claims to struggle with. Illegal connections are part of NRW, and with the increase in population and rural migration to urban areas, it is logical that this will increase. This will cause the demand to expand.

Agriculture is an important economic occupation in Tamale (UNDP, 2011). Because agricultural areas have an extensive need for water, development in agriculture will potentially be impacting the urban water supply. As stated in chapter two subchapter 1.5, there are a lot of agricultural land areas around the White Volta and Nawuni, that need water for irrigation. The agricultural areas around Nawuni will withdraw water from the river, which in turn can affect the discharge of the river. As one of the effects of climate change is more severe and frequent droughts, the agricultural demand might suffer from insufficient water supply, as the domestic water consumption has the priority of drinking water in Tamale.

2.6 Comparison of the improvement models and actions needed to realize them

The parameter chosen for comparing the improvement model is coverage. Seeing as coverage is the relationship between demand and supply, it will give a comprehensive view of the ability the models have to manage the current challenges to the water supply and demand in Tamale.

With respect to the percentage of coverage achieved in the models, the rankings are as follows:

1. TL, loss rates and reuse rate
2. TL and loss rates
3. Only TL
4. Only loss rates

Table 17 - The average coverage of the improvement models in 2021 all scenarios. Values obtained from WEAP.

The average coverage of the improvement models in 2021 all scenarios [%]			
TL, loss rates and reuse rate	TL and loss rates	Only TL	Only loss rates
82	64	48	46

Table 18 - The average coverage of the improvement models in 2050 all scenarios. Values obtained from WEAP.

The average coverage of the improvement models in 2050; Reference, Calculated NR PGR, High PGR [%]											
TL, loss rates and reuse rate			TL and loss rates			Only TL			Only loss rates		
45	29	20	35	22	16	27	17	12	25	16	11

Table 17 and

Table 18 summarize the average coverage for all the improvement models in all scenarios for 2021 and 2050. Looking at the coverage for the reference scenarios in 2050, there is an average of 45% in the TL, loss rates and reuse rate model, and 35% in the TL and loss rates model. According to GWCL, the current coverage is around 35%, which means that if the measures suggested are taken, the current coverage will not worsen by 2050. The average coverage for the TL, loss rates and reuse rate model in 2021 is 82%, and for the TL and loss rates model it is 64%. Both models will therefore increase the coverage substantially. The greatest increase is seen in the TL, loss rates and reuse model. This is reasonable considering that model has taken one additional action to ensure the increase in coverage (adding a reuse rate of 22%).

Assessing the two models with the lowest increase in coverage, namely the Only TL and Only loss rates models, it is observed that the increase is almost equivalent. The increase is between one and two percent higher in the Only TL model than the Only loss rates model. It is interesting that operating the two transmission links at maximum capacity gives almost the same increase as reducing the loss rates to 20% for leakages and 35% for non-revenue water.

As previously stated, the average coverage is still not adequate to satisfy the present and future drinking water demand. Even so, the improvement models all offer somewhat reasonable options to better manage the demand.

All models require that action is taken. For the Only TL model, it is necessary to run both transmission links at maximum capacity, and this might cause challenges for GWCL. The current use for the second transmission link (450 mm), is a backup for when something happens to the main transmission link (700 mm). Whenever they are active simultaneously, they are never operated at maximum capacity. Maximum capacity leads to higher pressure and then in turn higher risk of damage and leakages. Therefore, by running both links at max, it would be important to look at a backup solution to what happens if both break at the same time. Adding another transmission link could solve this, but this of course is costly.

For the Only loss rates model, it is necessary to reduce both the loss in transmission link, and loss in demand site. To achieve this, GWCL would be obliged to assess their pipelines and respond to leakages at a higher rate. This might demand more labor and materials, which are costly. The bigger issue would be to reduce the NRW. It is difficult to prevent water theft and illegal connections, but this is necessary for a reduction.

The combination of these scenarios will require action in all areas mentioned above and is undoubtedly expensive. The model with the highest increase in coverage, TL, loss rates and reuse rate model, also adds a reuse rate of 22%. To successfully reuse water so that the demand decreases, it is necessary to install a new system for handling the wastewater. It would be essential to split the greywater from the blackwater, and then treat the greywater to a satisfying extent. This could be done by educating the population served by GWCL on how to preserve their greywater, and how to treat it domestically. Another option would be that GWCL themselves collect the greywater and treat it before sending it back. GWCL does not currently have a wastewater treatment plant in the Northern Region and building and designing one is expensive. Additionally, the transportation of water from consumers to treatment plant and back would lead to a bigger loss in water caused by potential leakages and operational challenges.

2.7 Validity and limitations of the models

The models developed in WEAP have some weaknesses that are worth mentioning. Firstly, WEAP does not allow the input of daily variation in data, only monthly averages. When looking at discharge of the Nawuni, some days have extremely low rates, whilst other days have extremely high rates. The daily variation impacts the available water that can be used for drinking water supply, but it is not possible to model this into WEAP. It is also impossible to simulate the days that the treatment plant is down, which leads to no supply.

The models of this thesis are all very simple and do not give a precise portrayal of how the real drinking water supply and demand situation is in the Tamale Metropolitan area. The data input also has insecurities which affect the accuracy of the models.

The general validity of the results can be checked by doing some simple calculations in excel. This was done for a few calculations, and can be viewed in Appendix D.

CHAPTER SIX: Conclusions and recommendations

1 Conclusions and recommendations

This thesis evaluated the potential challenges in urban drinking water supply in the coming decades in the Tamale Metropolitan area and suggested options on how to manage these challenges. This was achieved by gathering and processing data as well as modelling the current and future scenarios with the WEAP model.

The modelling resulted in multiple models. One model simulated the future water supply and demand situation with three different annual population growth rates, 2.1%, 3.7% and 5.0%. This model also simulated what would happen to the coverage if the maximum capacity of the transmission link was reduced by 10.0% and 20.0%.

Four models were developed to provide options for managing the drinking water supply and demand situation, namely the improvement models: Only TL, Only loss rates, TL and loss rates, and TL, loss rates and reuse rate.

The current challenges related to the potable water supply in Tamale Metropolis were found to be unsatisfactory drinking water supply. The reasons for the water supply being unsatisfactory were found to be water loss, operational challenges, and rapid population growth.

If the population increases by 2.1%, 3.7% and 5.0% annually, the coverage will decrease substantially. In 2021 the coverage was around 35%. In 2050 however, the coverage was 19% for the scenario where the annual population growth rate was 2.1%. For the scenario where the annual population growth rate was 3.7%, the coverage in 2050 was 12%. Lastly, when the annual population growth rate was 5.0%, the coverage was 8%.

Reducing the water supply to Tamale Metropolis by 10.0% and 20.0% due to factors influencing the catchment area impacts Tamale negatively. This is because the current coverage is not satisfactory as is, and a further reduction of supply naturally further reduces the coverage.

The last research question centers on the possibility of managing the weaknesses/challenges of the drinking water supply so that the coverage will increase in the predictable future. Here the challenges are managed by looking at water loss and reuse rate, and transmission link capacity. By developing the improvement models, it was discovered that all actions increase the coverage, but to different extents. The highest increase occurs in the TL, loss rates and reuse rate model, where the average coverage in 2021 was 82%, and in 2050 varied between 20-45% based on what PGR was used.

Based on the results of this study, the best option to increase coverage of drinking water demand is to run both existing transmission links at maximum capacity simultaneously as working on further reducing the water losses. For this option it is important to consider installing a backup. In the future, with more resources available, it is advised that GWCL works on developing systems for water reuse, but as this might be very costly, it is not advisable right now. Focusing on improving the current state of the supply network by increasing supply through transmission links and reducing loss contributes to higher coverage.

2 Further work

The models of the thesis are all very simple, and it could be interesting to investigate the possible ways to expand and advance.

- Do more extensive field work and data collection so that the accuracy of the model can increase, and the model be more realistic.
- Structural mapping of water use in households in Tamale. This can be used to create a more detailed model that better reflects the real situation and offers possibilities to look at options to increase coverage at household levels. Examples: Map out how much water is allocated to toilets, showers, washers and propose solutions/changes that improve the overall coverage. This kind of mapping will also help discover what households and areas are lacking in development.
- Acquire data and information about the agricultural situation, this can be added to the model to simulate agricultural demand and development.
- Acquire data about groundwater and water quality to further simulate the water demand and supply situation.
- Combine the WEAP model with another software to further validate and improve.

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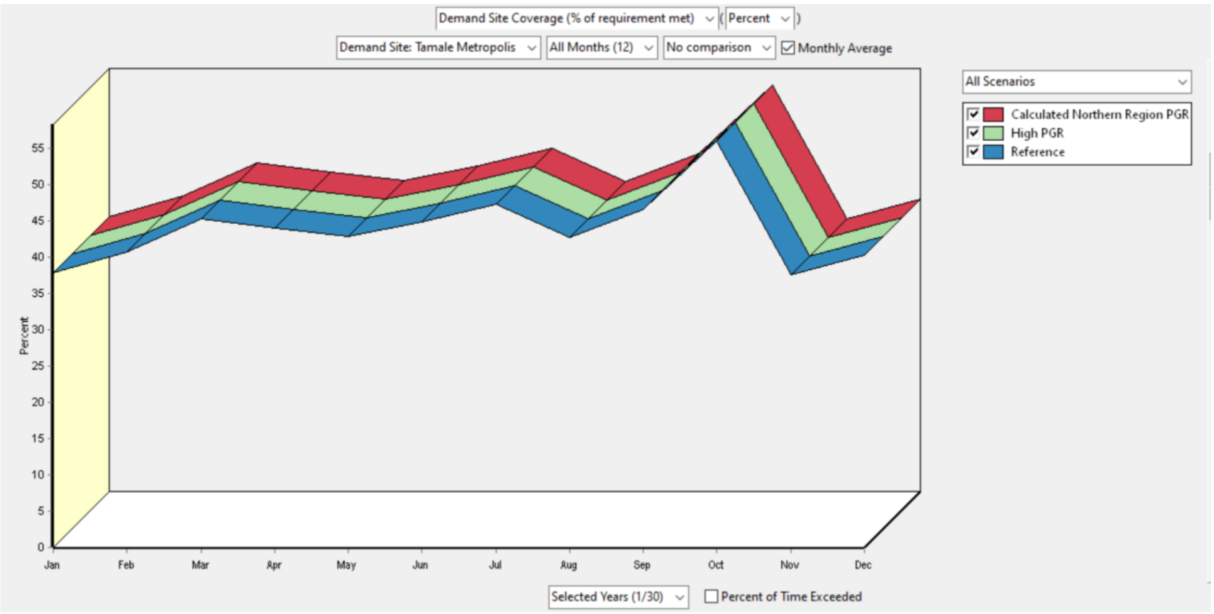
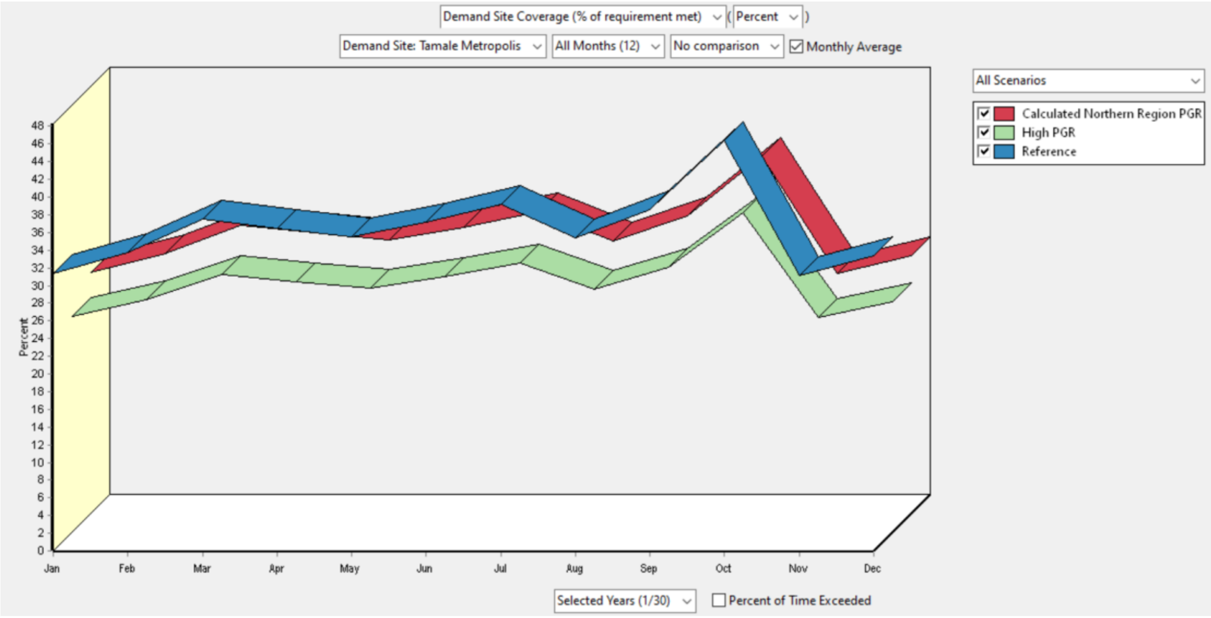
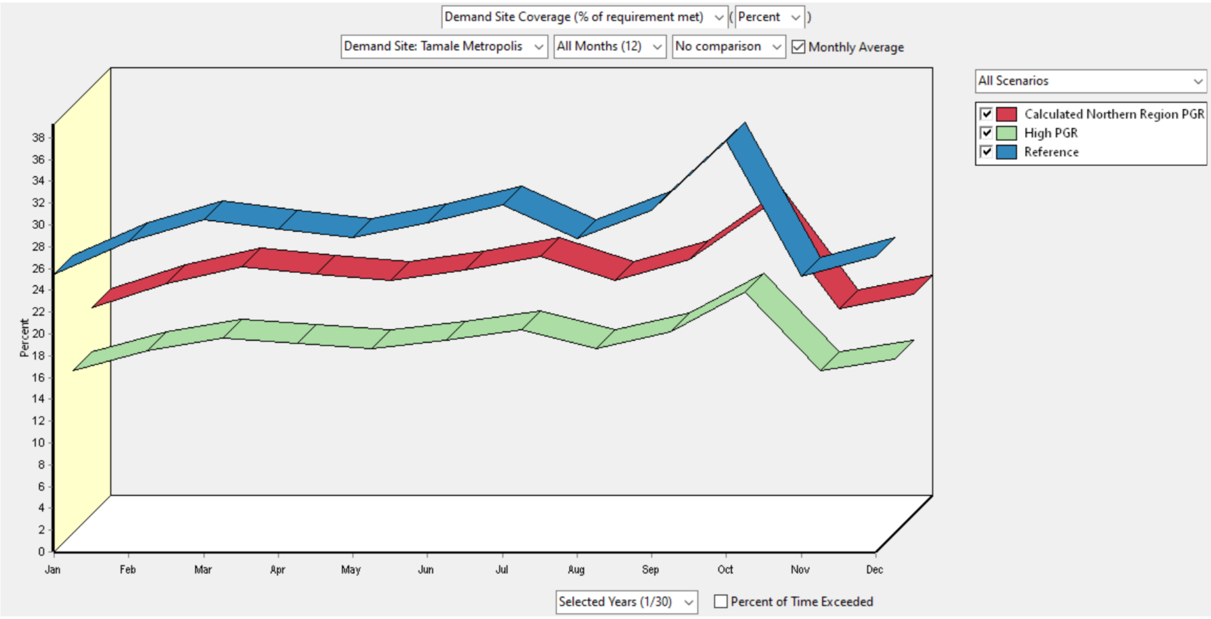
Appendix A. Demand site coverage, monthly averages for: 2021, 2030, 2040 and 2050



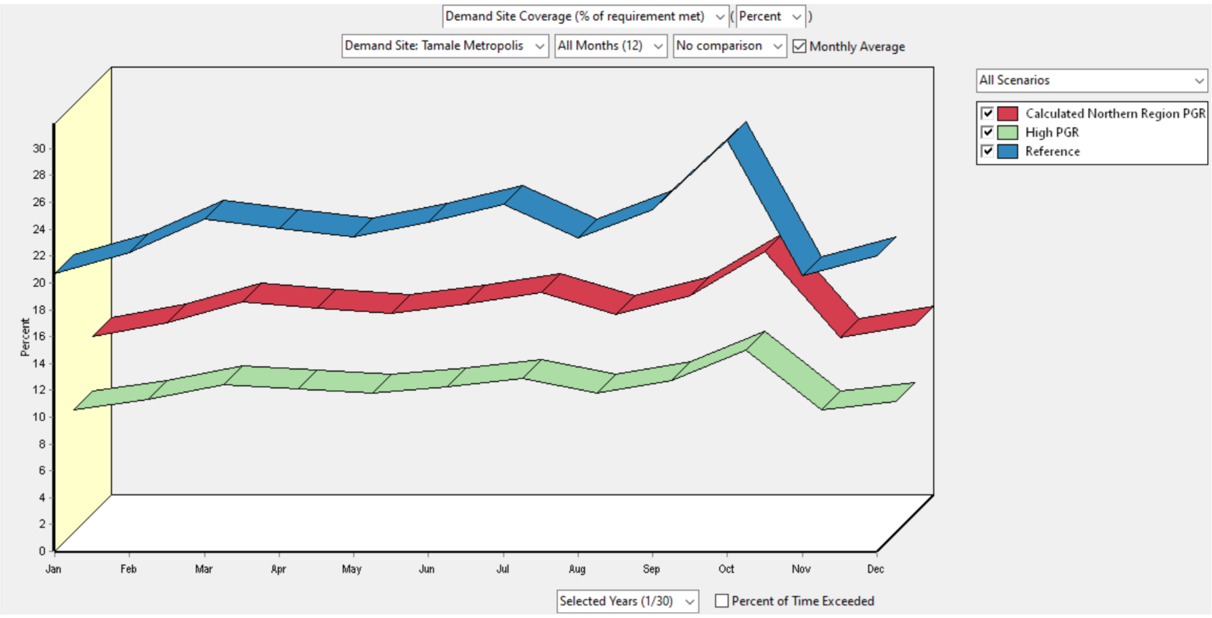
A.A Figure 34 - Monthly average of demand site coverage in 2021 for the scenarios in the PGR model. Screenshot from the results view in WEAP.



A.A Figure 35 - Monthly average of demand site coverage in 2030 for the scenarios in the PGR model. Screenshot from the results view in WEAP.

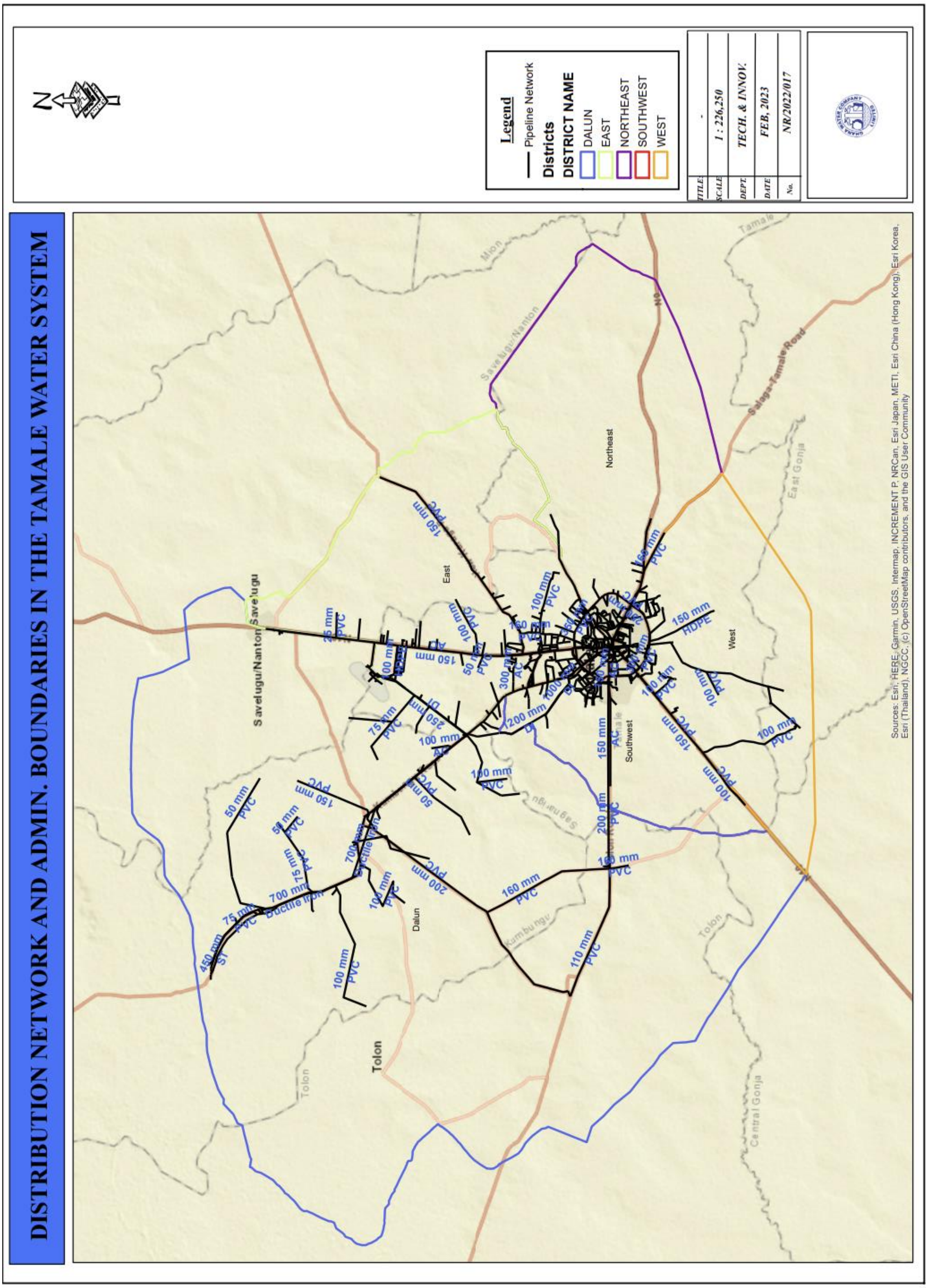


A.A Figure 36 - Monthly average of demand site coverage in 2040 for the scenarios in the PGR model. Screenshot from the results view in WEAP.



A.A Figure 37 - Monthly average of demand site coverage in 2050 for the scenarios in the PGR model. Screenshot from the results view in WEAP.

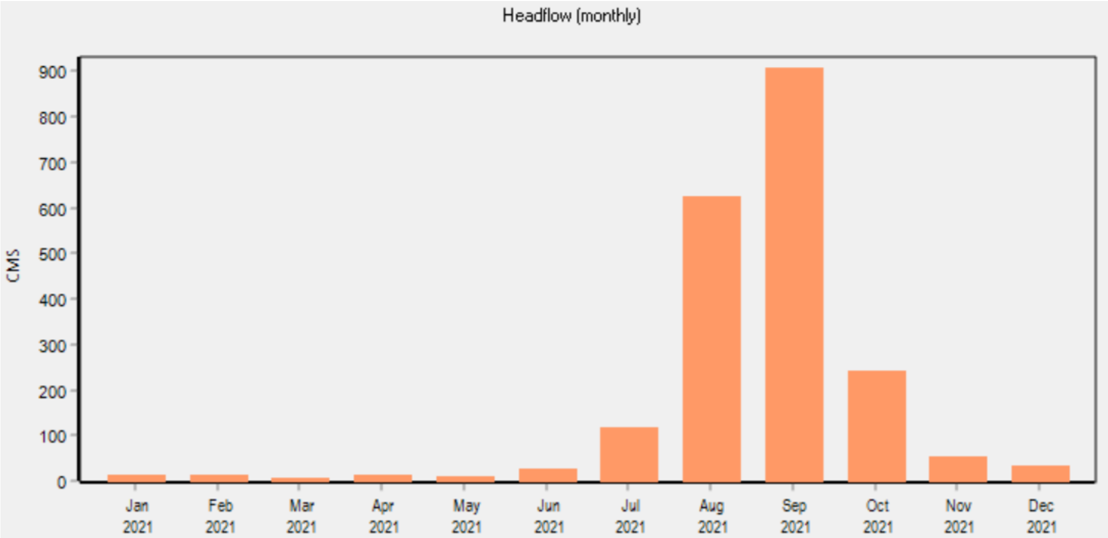
Appendix B. Distribution network and admin. boundaries in the Tamale water system



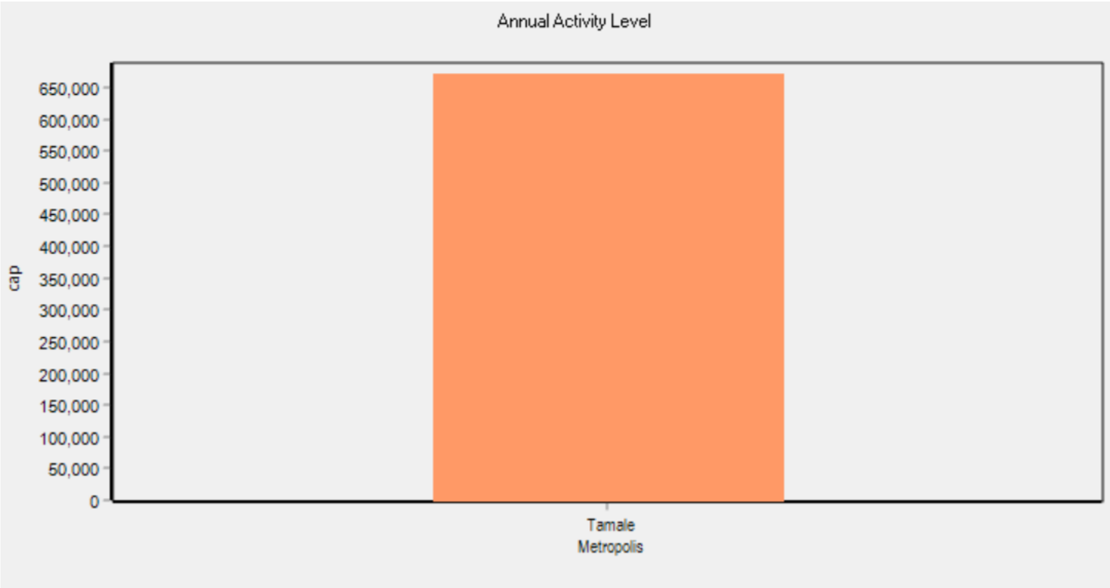
A.B Figure 38 - Distribution network and admin. boundaries in the Tamale water system aquired by personal agreement with GWCL, 2023.

Appendix C. Additional results (Improvement models)

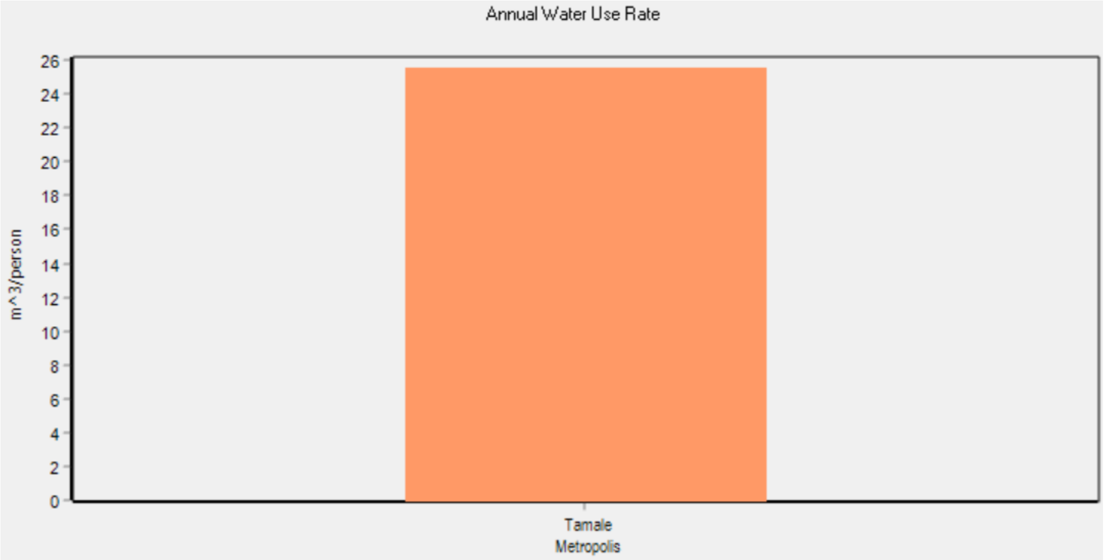
Base model



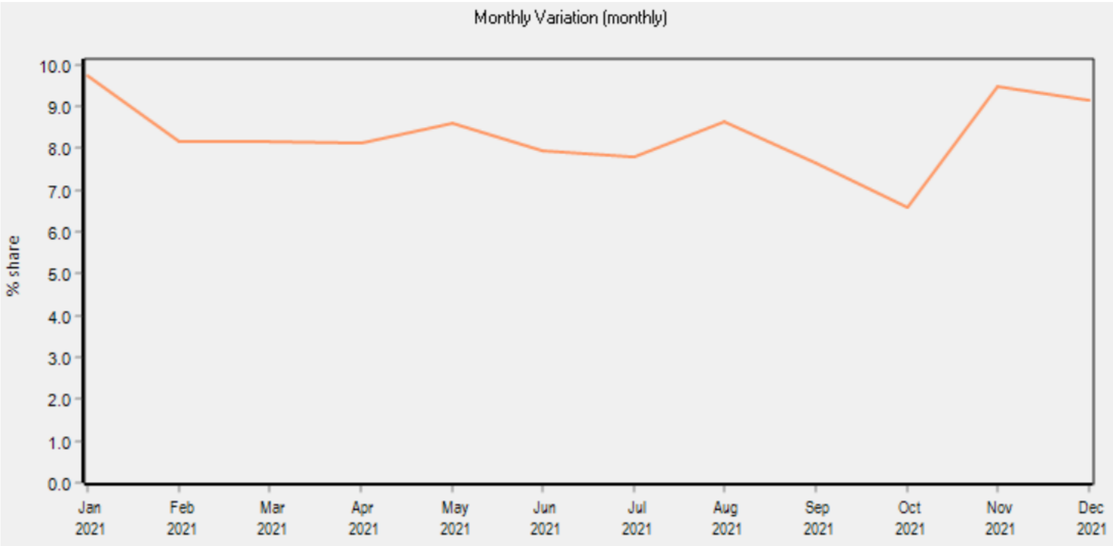
A.C Figure 39 – Headflow is presented for each month with the unit m³/s. The Headflow is for the current account's year but does not change throughout the modelling. Source: Numbers input was acquired by a personal agreement with GWCL, 2023.



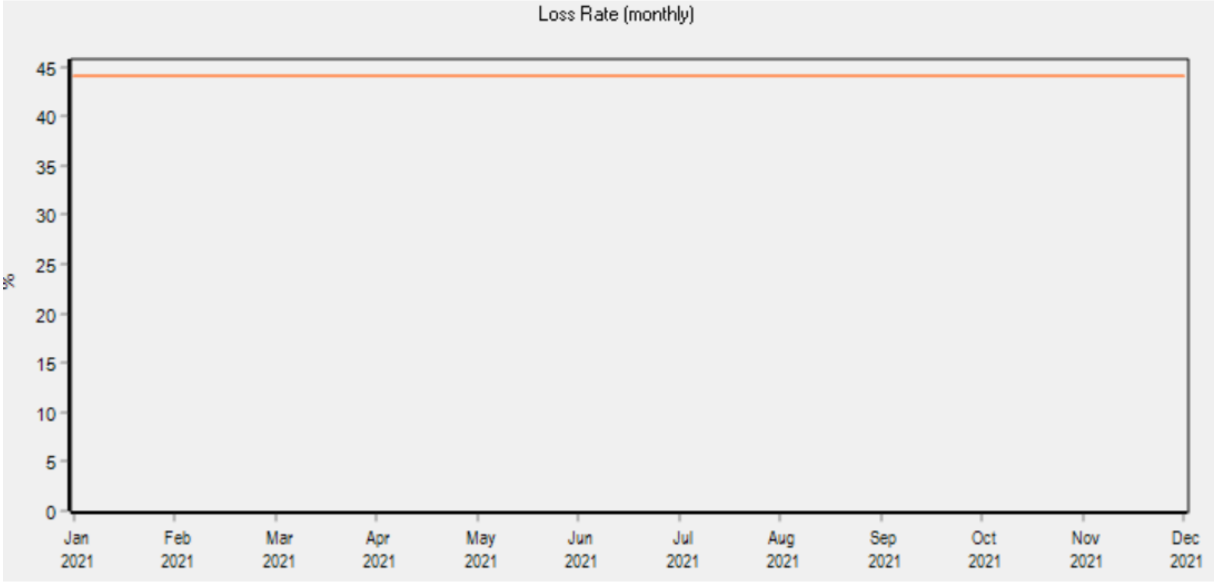
A.C Figure 40 - Annual activity level for the current account's year is presented with people as unit. Source: Macrotrends LLC (2023).



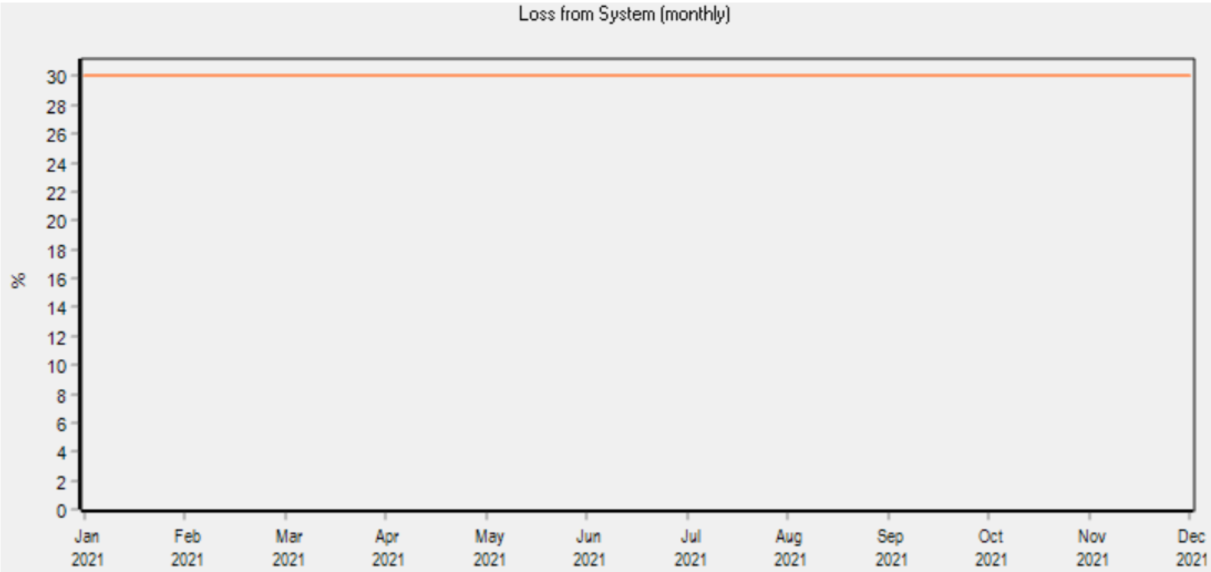
A.C Figure 41 - Annual water use rate for the current account's year with the unit m³/person. Source: Numbers input was acquired by a personal agreement with GWCL, 2023.



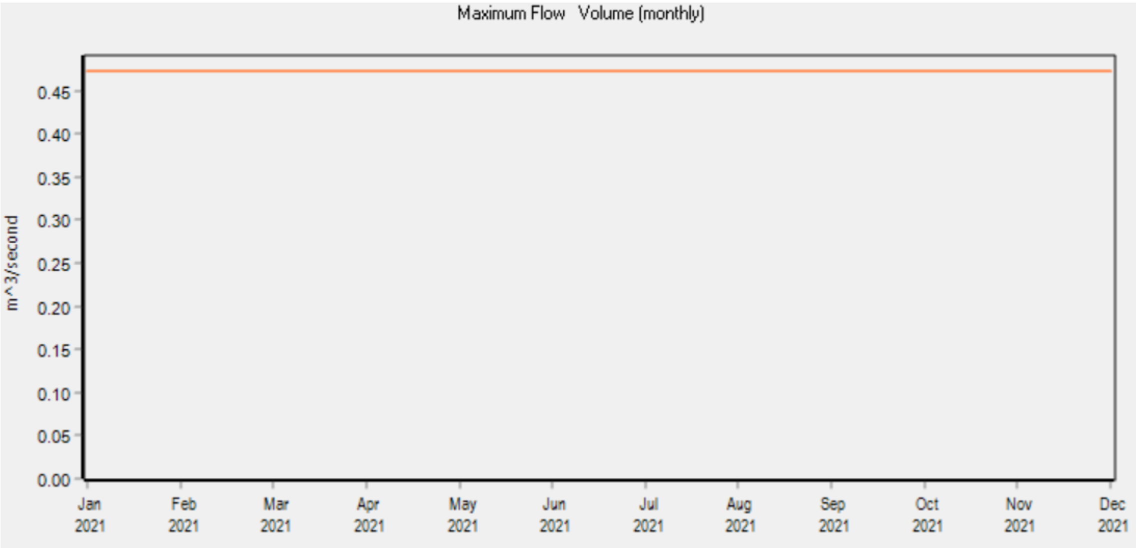
A.C Figure 42 - Monthly variation for current accounts. Source: Numbers input was acquired by a personal agreement with GWCL, 2023.



A.C Figure 43 - Demand site loss rate in 2021.Source: Numbers input was acquired by a personal agreement with GWCL, 2023.

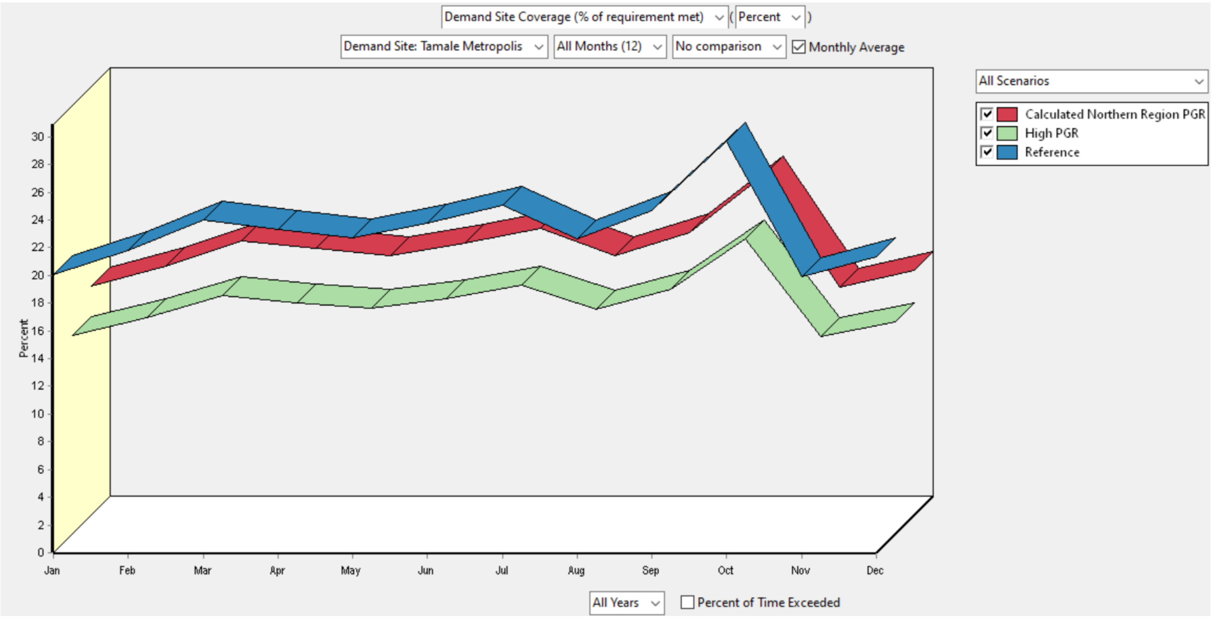


A.C Figure 44 - Loss from leakages in 2021. Source: (GWCL, 2019).

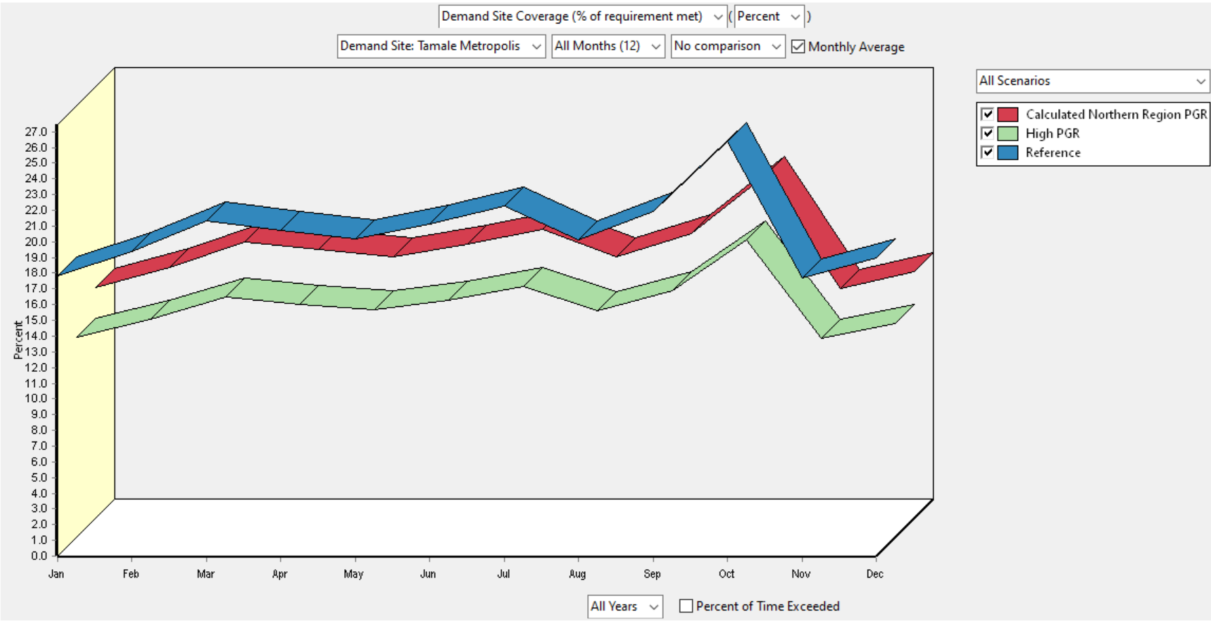


A.C Figure 45 - Maximum flow volume for the transmission link in the current accounts. Source: Numbers input was acquired by a personal agreement with GWCL, 2023.

Reduction of 10 and 20%

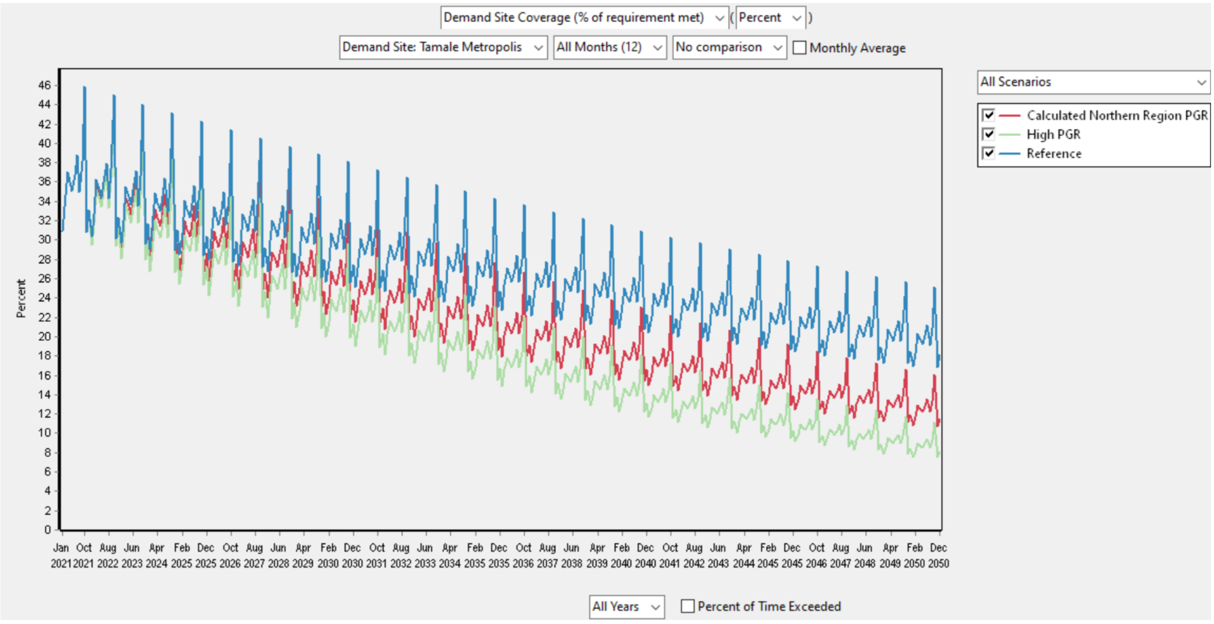


A.C Figure 46 - Monthly average of the coverage for all years when the maximum capacity of the transmission link is reduced with 10.0%. Screenshot from the results view in WEAP.

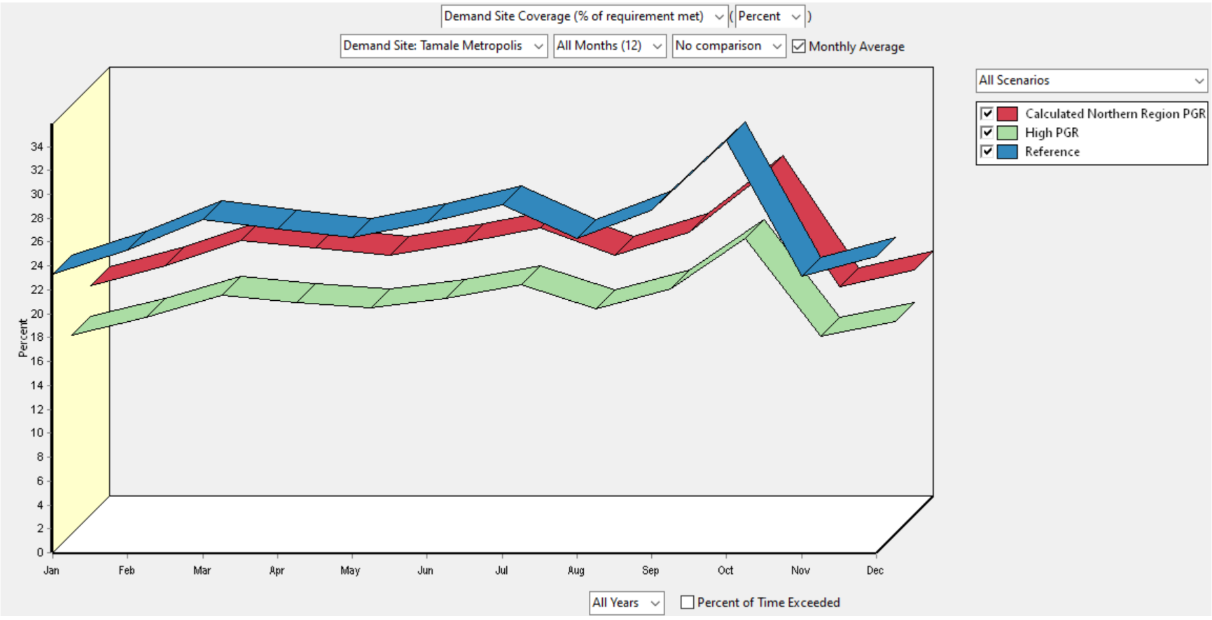


A.C Figure 47 - Monthly average of the coverage for all years when the maximum capacity of the transmission link is reduced with 20.0%. Screenshot from the results view in WEAP.

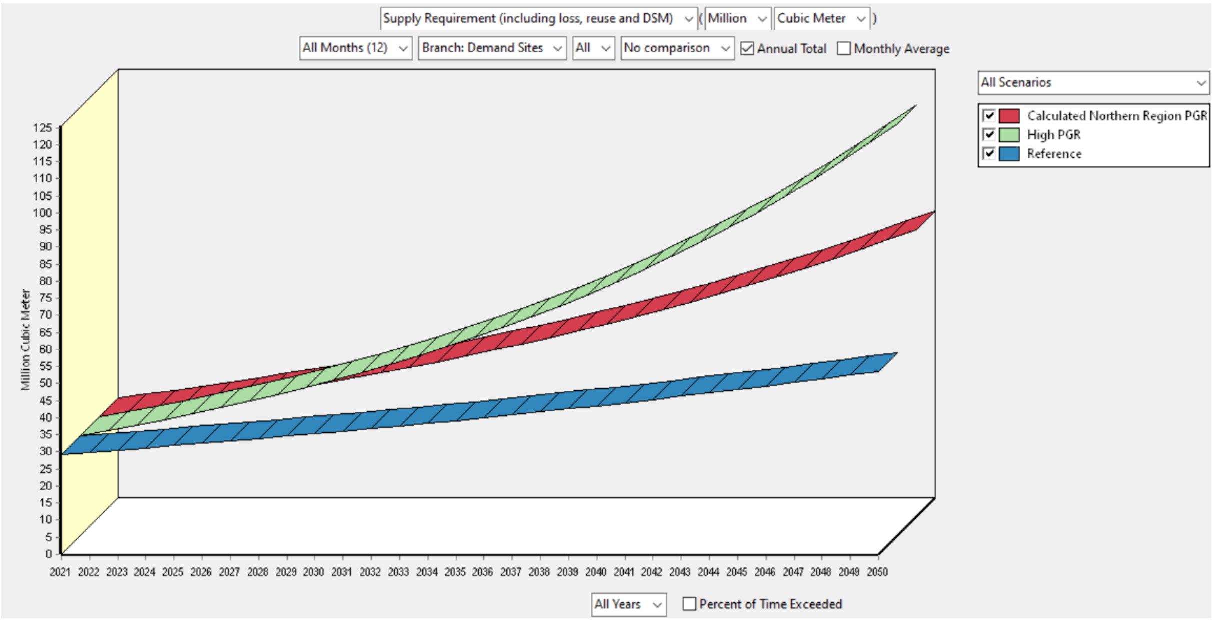
Only reuse rate (4.4%)



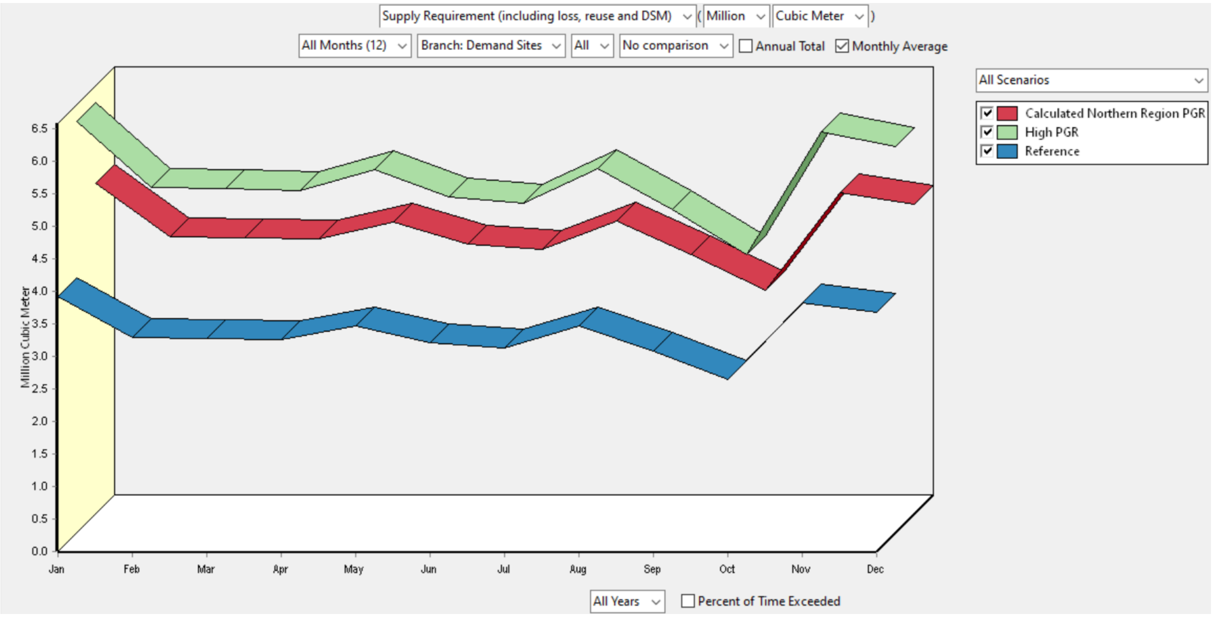
A.C Figure 48 - Coverage for all years when the reuse rate is 4.4%. Screenshot from the results view in WEAP.



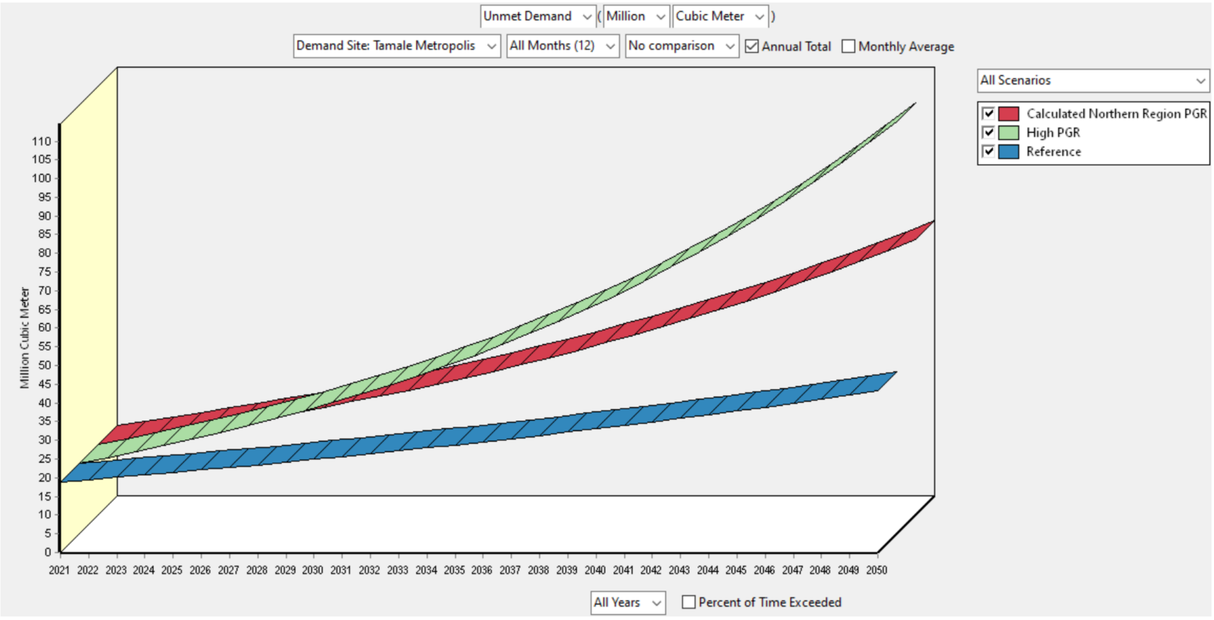
A.C Figure 49 - Monthly average of coverage for all years when the reuse rate is 4.4%. Screenshot from the results view in WEAP.



A.C Figure 50 - Annual total of supply requirement when the reuse rate is 4.4%. Screenshot from the results view in WEAP.



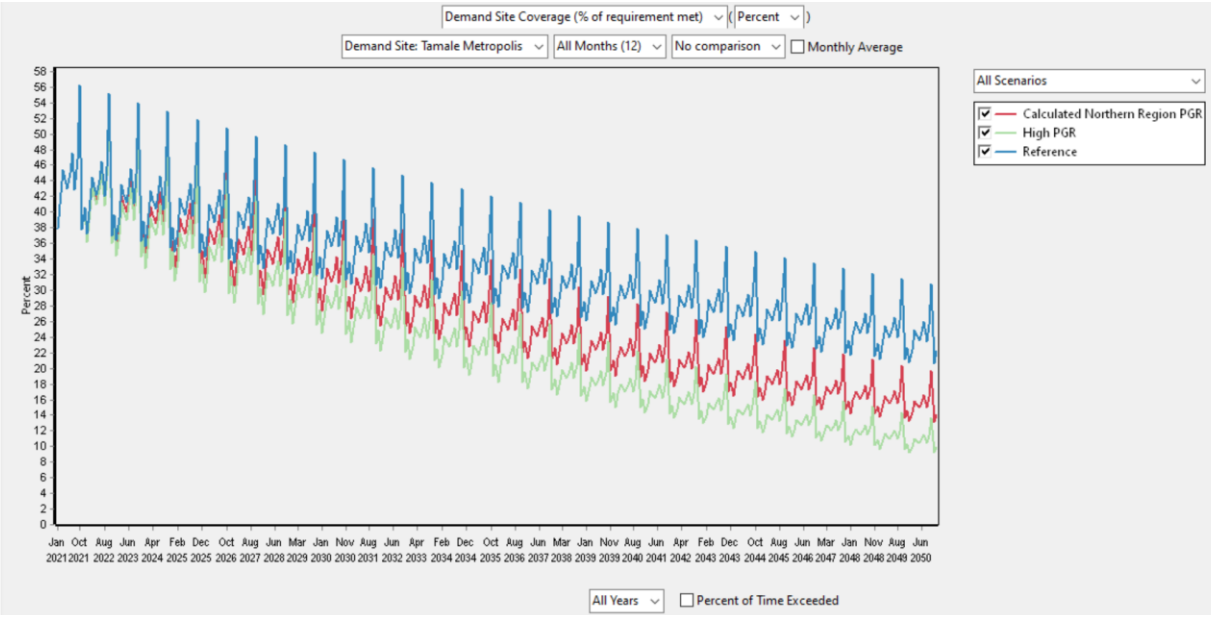
A.C Figure 51 - Monthly average of supply requirement for all years when the reuse rate is 4.4%. Screenshot from the results view in WEAP.



A.C Figure 52 - Annual total of unmet demand when the reuse rate is 4.4%. Screenshot from the results view in WEAP.

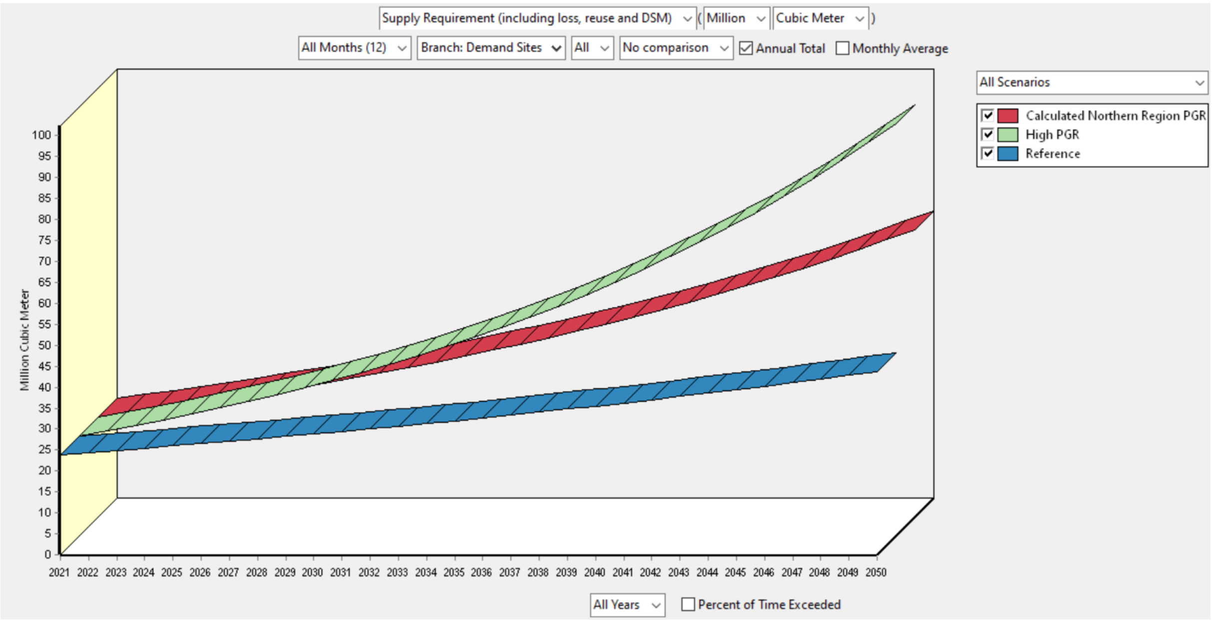
A.C Figure 53 - Monthly average of unmet demand for all years when the reuse rate is 4.4%. Screenshot from the results view in WEAP.

Only reuse rate (22.0%)



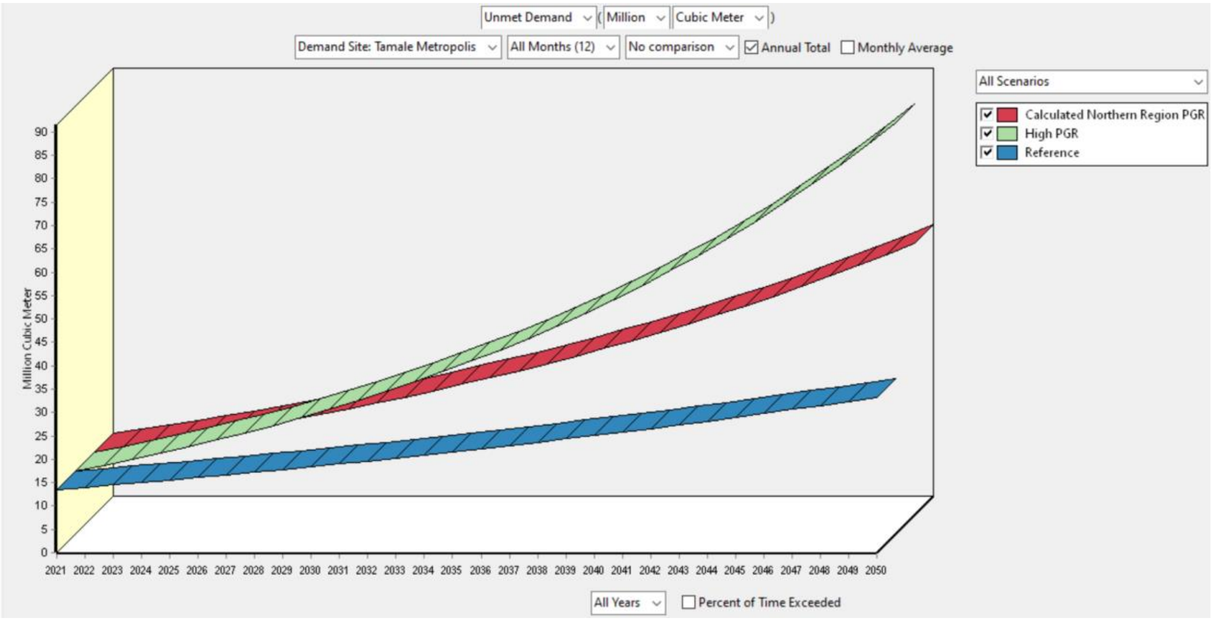
A.C Figure 54 - Coverage for all years when the reuse rate is 22.0%. Screenshot from the results view in WEAP.

A.C Figure 55 - Monthly average of coverage for all years when the reuse rate is 22.0%. Screenshot from the results view in WEAP.



A.C Figure 56 - Annual total of supply requirement when the reuse rate is 22.0%. Screenshot from the results view in WEAP.

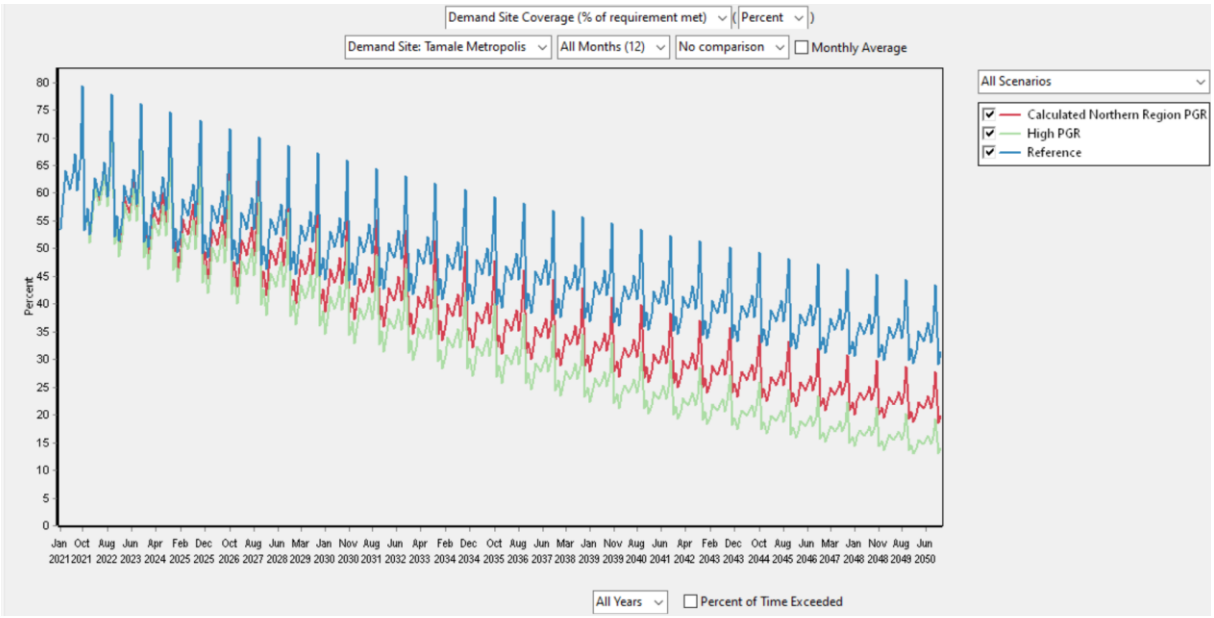
A.C Figure 57 - Monthly average of supply requirement for all years when the reuse rate is 22.0%. Screenshot from the results view in WEAP.



A.C Figure 58 - Annual total of unmet demand when the reuse rate is 22.0%. Screenshot from the results view in WEAP.

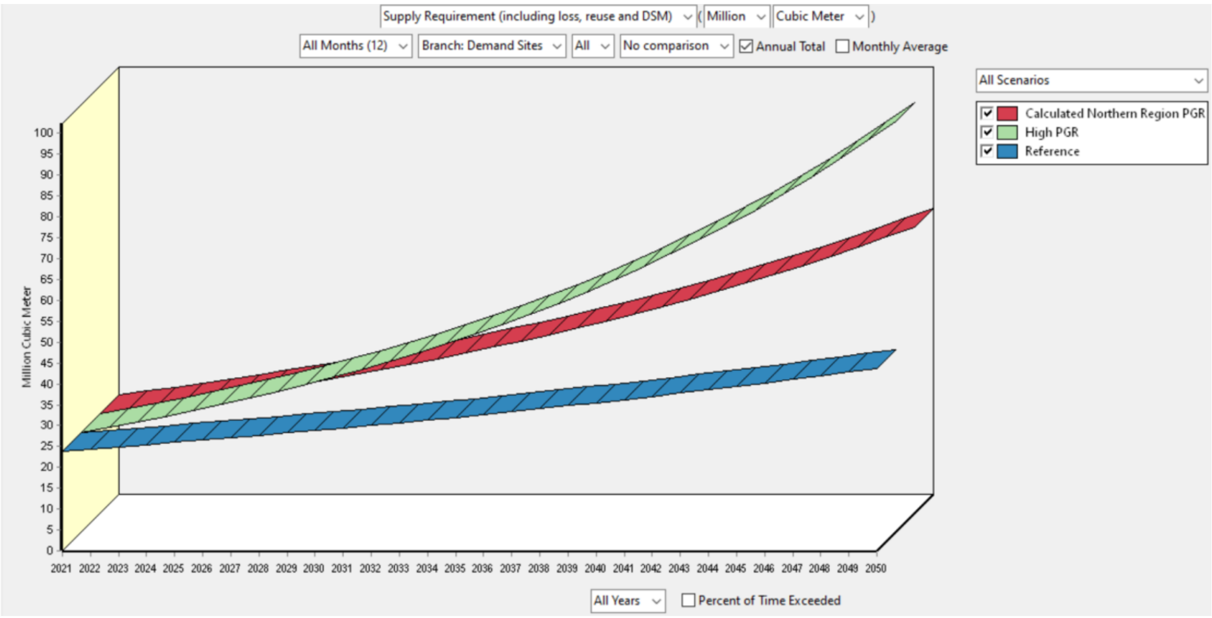
A.C Figure 59 - Monthly average of unmet demand for all years when the reuse rate is 22.0%. Screenshot from the results view in WEAP.

TL and reuse rate (22.0%)

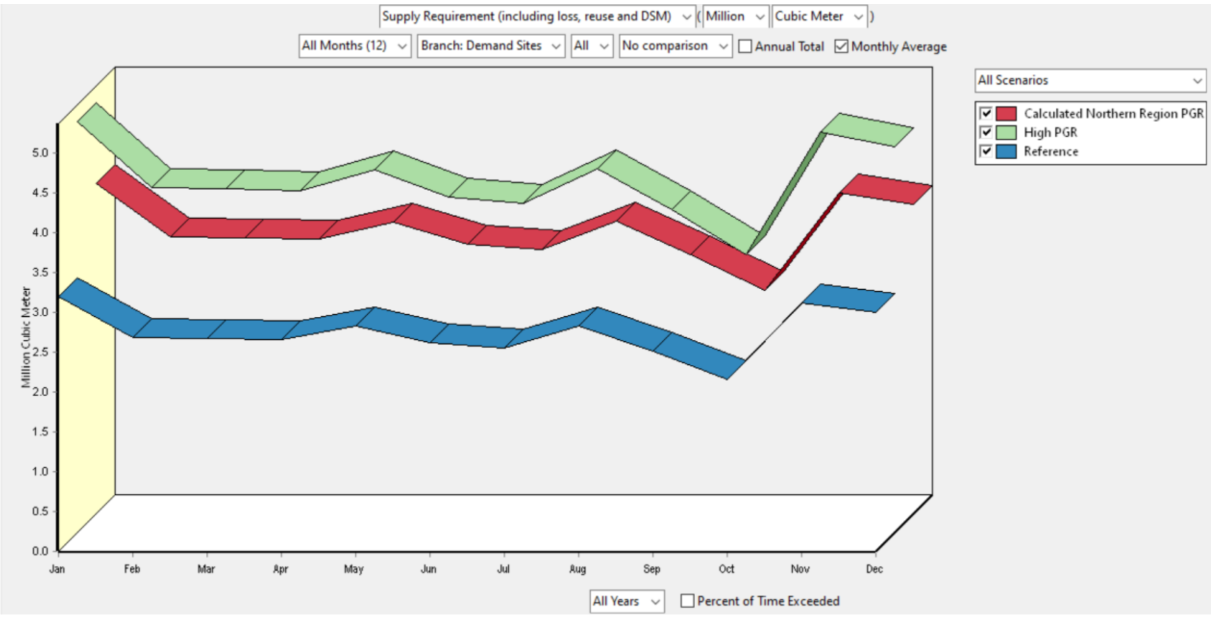


A.C Figure 60 - Coverage for all years when there are two transmission links operating at maximum capacity and a reuse rate of 22.0%. Screenshot from the results view in WEAP.

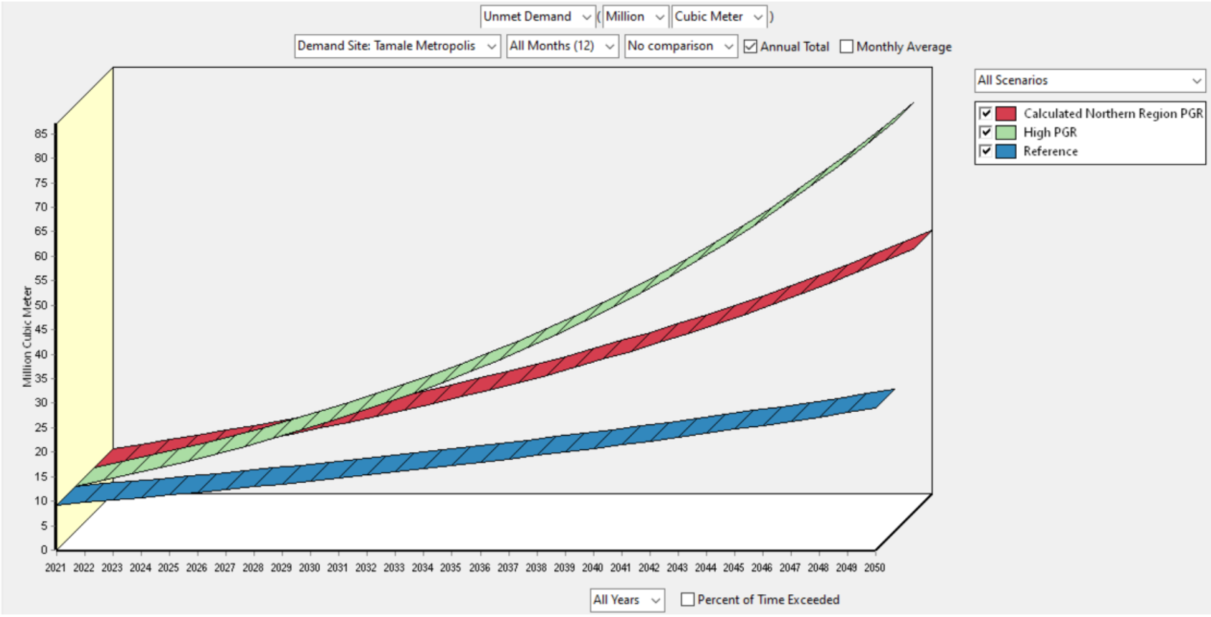
A.C Figure 61 - Monthly average of coverage for all years when there are two transmission links operating at maximum capacity and a reuse rate of 22.0%. Screenshot from the results view in WEAP.



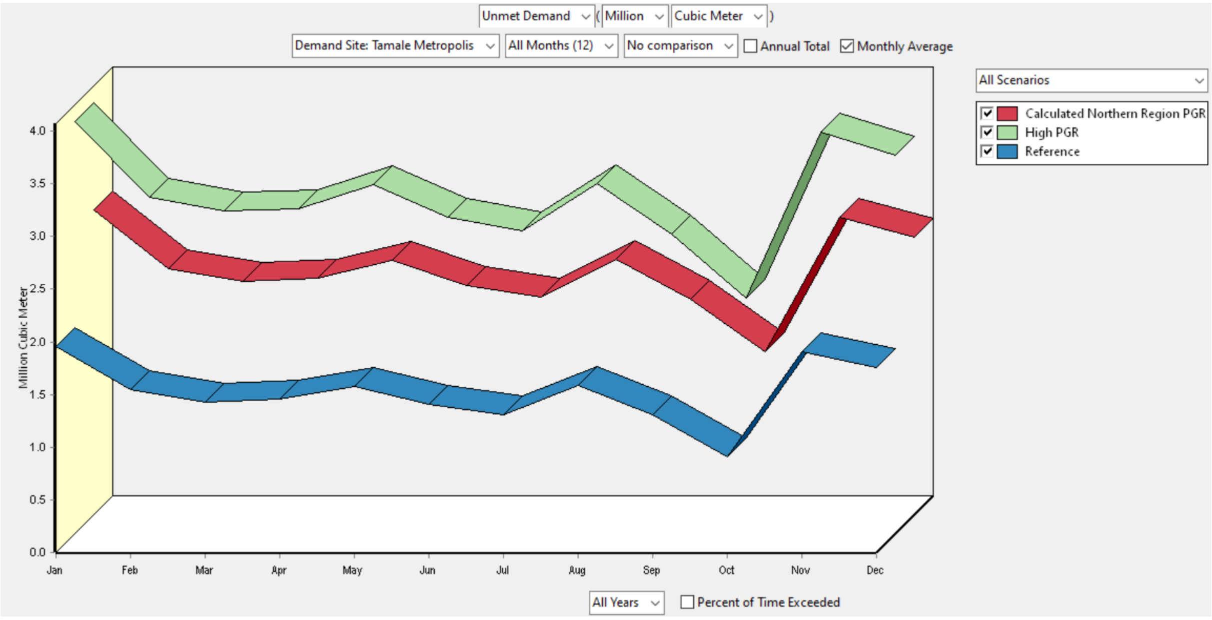
A.C Figure 62 - Annual total of supply requirement when there are two transmission links operating at maximum capacity and a reuse rate of 22.0%. Screenshot from the results view in WEAP.



A.C Figure 63 - Monthly average of supply requirement for all years when there are two transmission links operating at maximum capacity and a reuse rate of 22.0%. Screenshot from the results view in WEAP.

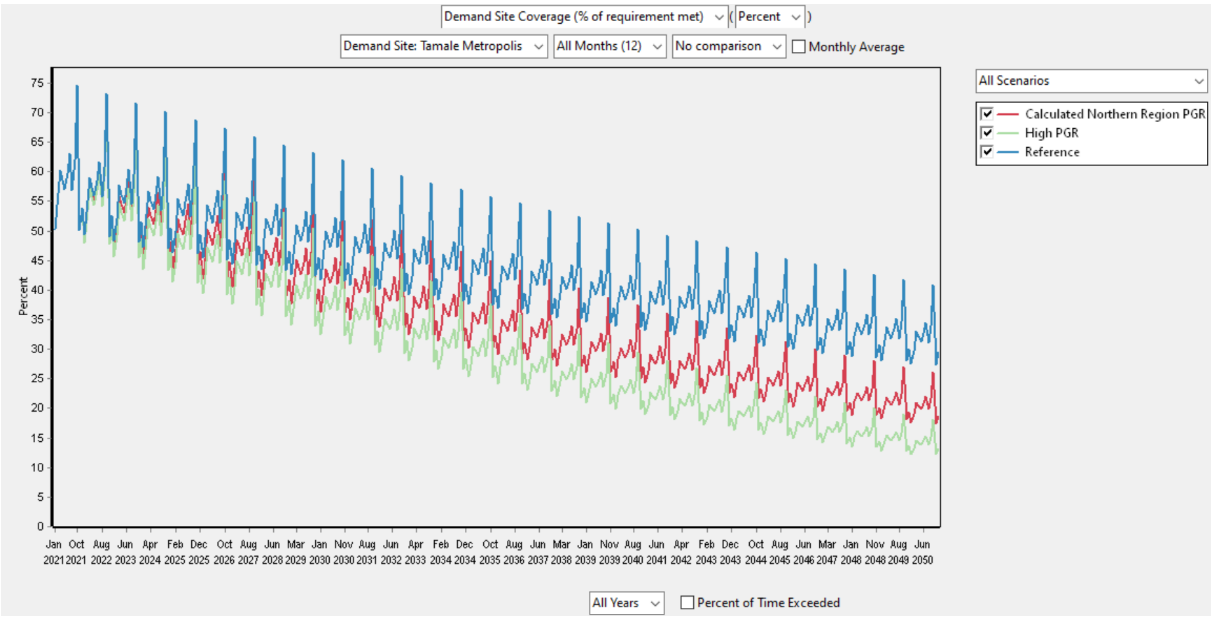


A.C Figure 64 - Annual total of unmet demand when there are two transmission links operating at maximum capacity and a reuse rate of 22.0%. Screenshot from the results view in WEAP.

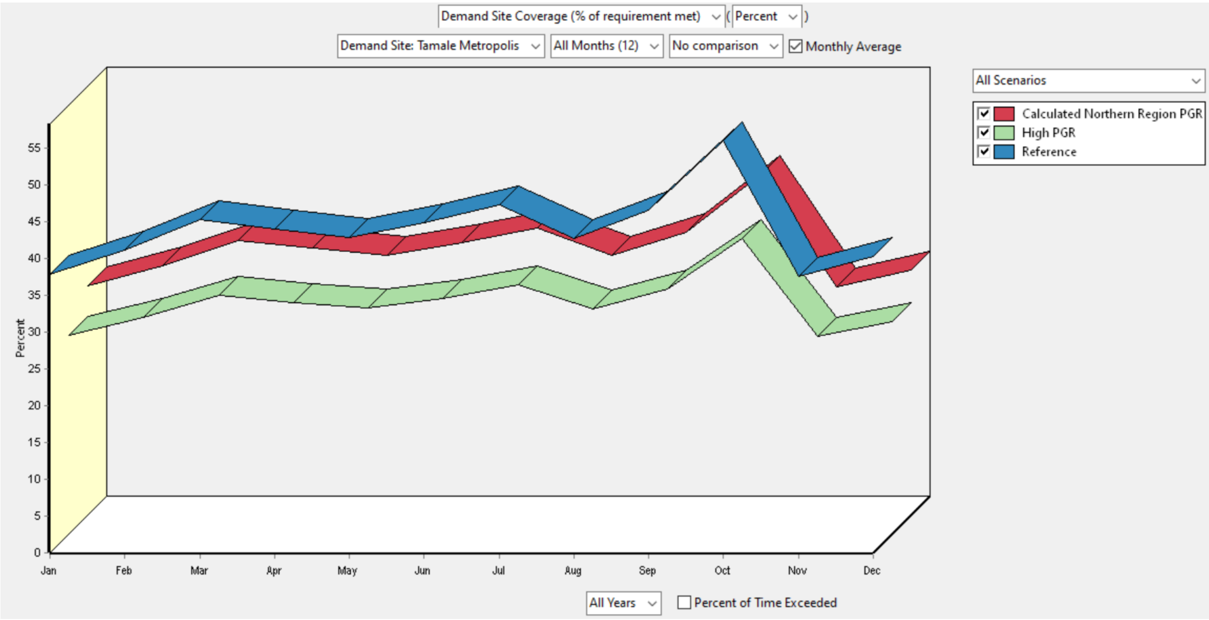


A.C Figure 65 - Monthly average of unmet demand for all years when there are two transmission links operating at maximum capacity and a reuse rate of 22.0%. Screenshot from the results view in WEAP.

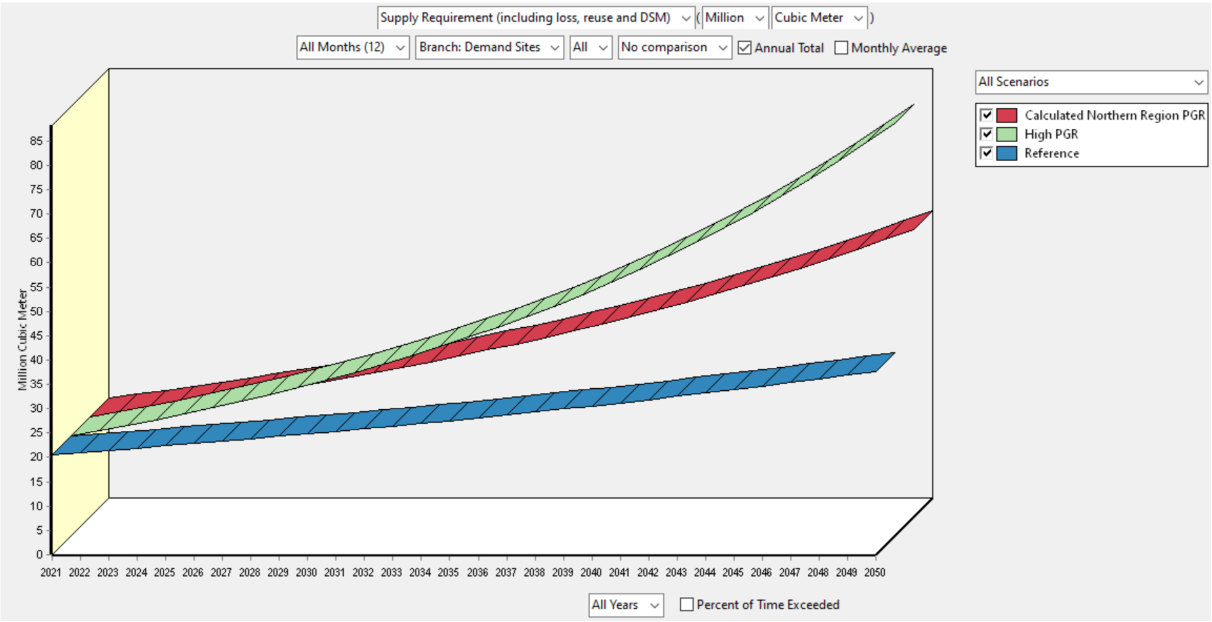
Reuse rate (22.0%) and reduced loss rate



A.C Figure 66 - Coverage for all years when the reuse rate is 22.0% and the loss rates are reduced. Screenshot from the results view in WEAP.

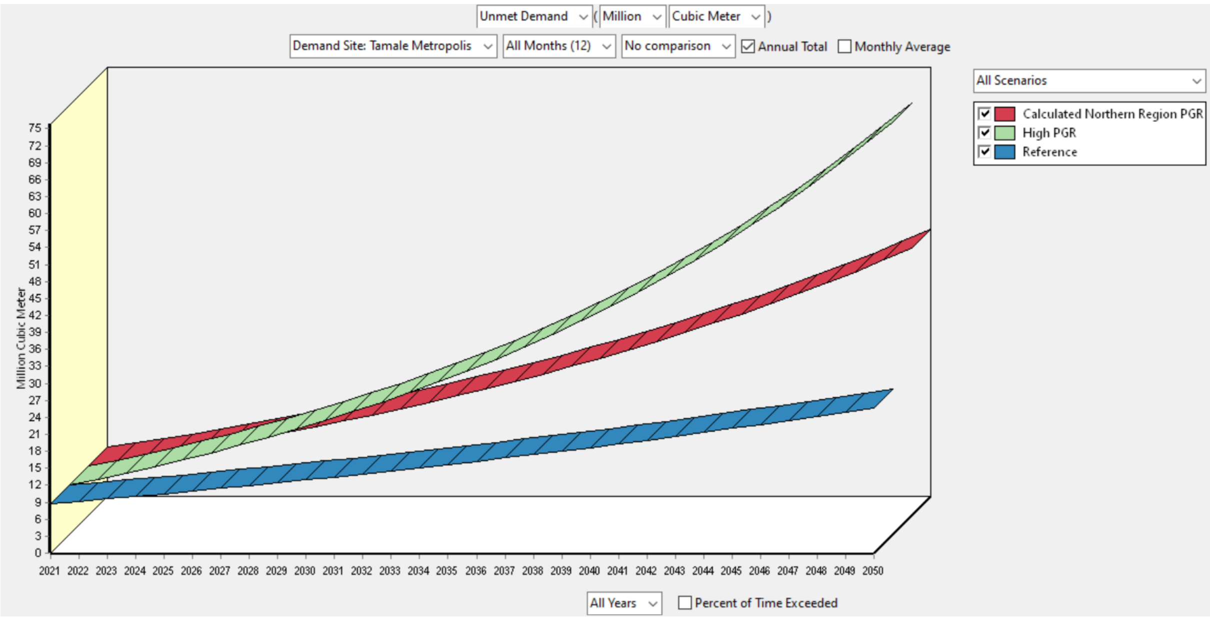


A.C Figure 67 - Monthly average of coverage for all years when the reuse rate is 22.0% and the loss rates are reduced. Screenshot from the results view in WEAP.



A.C Figure 68 - Annual total of supply requirement when the reuse rate is 22.0% and the loss rates are reduced. Screenshot from the results view in WEAP.

A.C Figure 69 - Monthly average of supply requirement for all years when the reuse rate is 22.0% and the loss rates are reduced. Screenshot from the results view in WEAP.

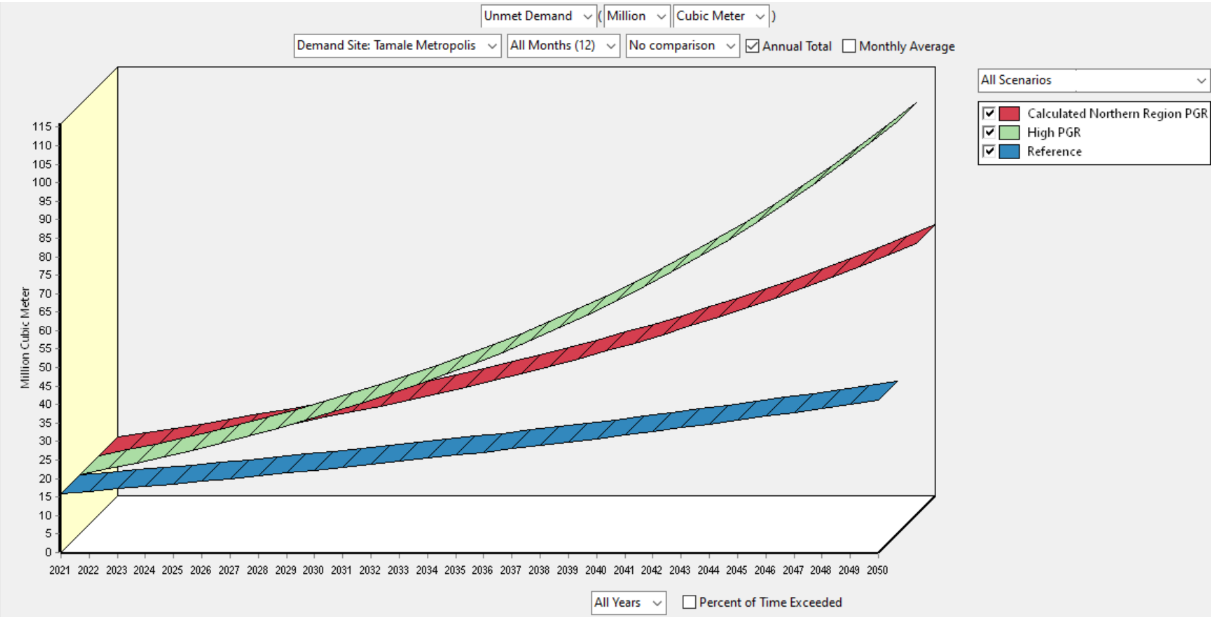


A.C Figure 70 - Annual total of unmet demand when the reuse rate is 22.0% and the loss rates are reduced. Screenshot from the results view in WEAP.

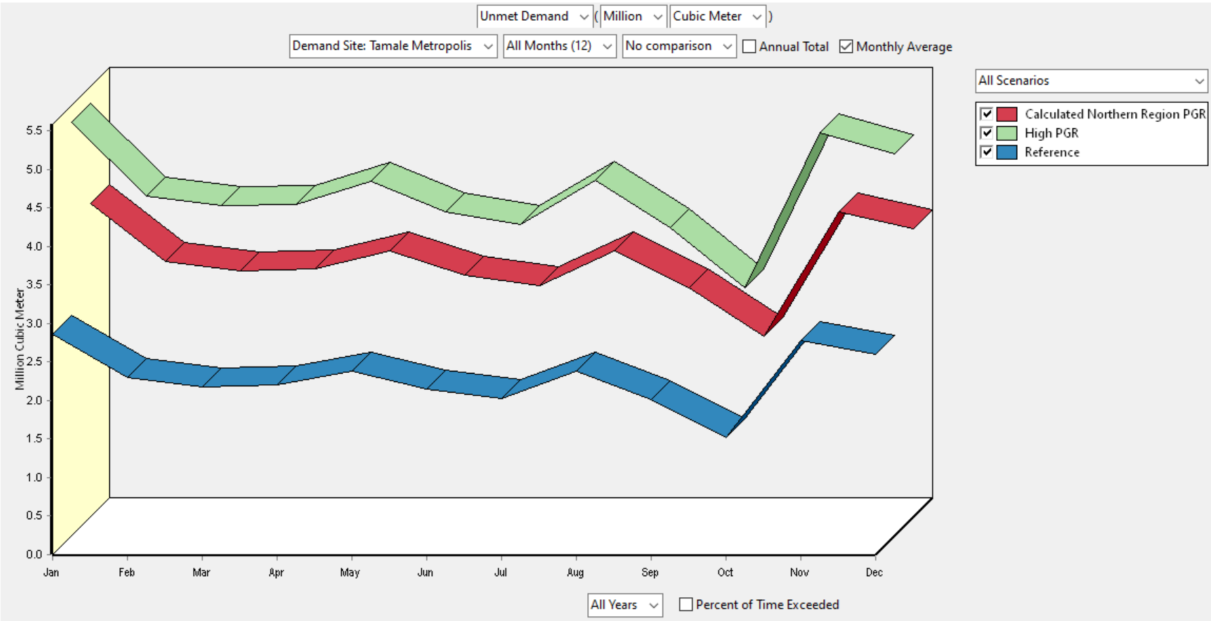
A.C Figure 71 - Monthly average of unmet demand for all years when the reuse rate is 22.0% and the loss rates are reduced. Screenshot from the results view in WEAP.

Additional results for Only TL

A.C Figure 72 - Monthly average for coverage for all years when there are two transmission links operating at maximum capacity. Screenshot from the results view in WEAP.

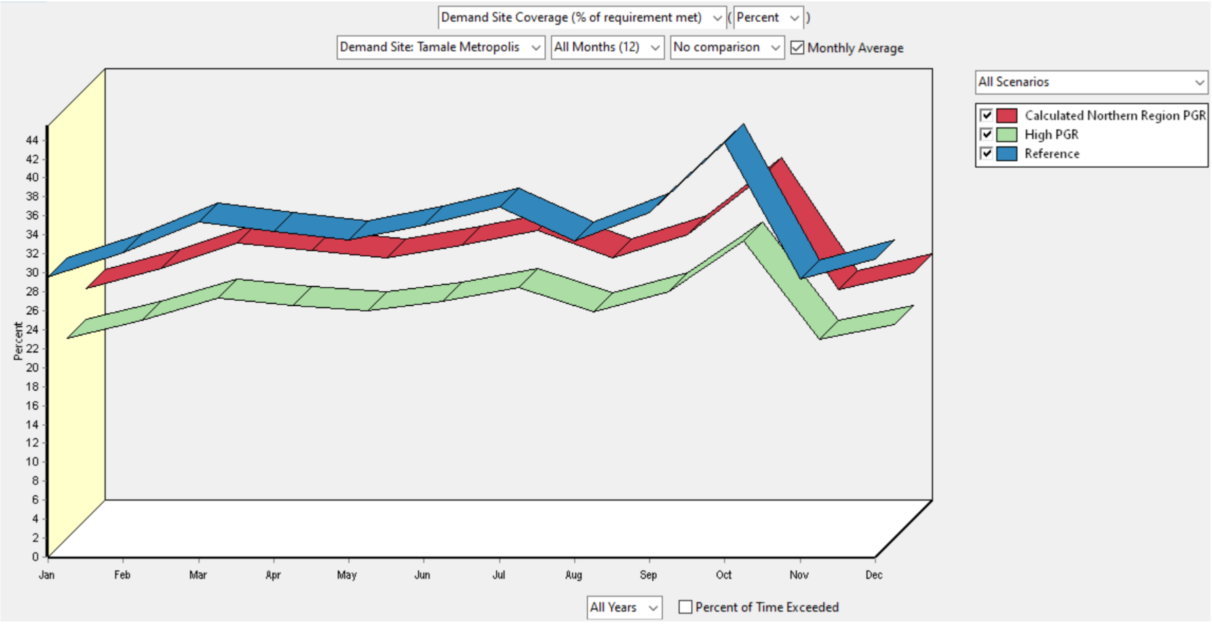


A.C Figure 73 - Annual total of unmet demand when there are two transmission links operating at maximum capacity. Screenshot from the results view in WEAP.

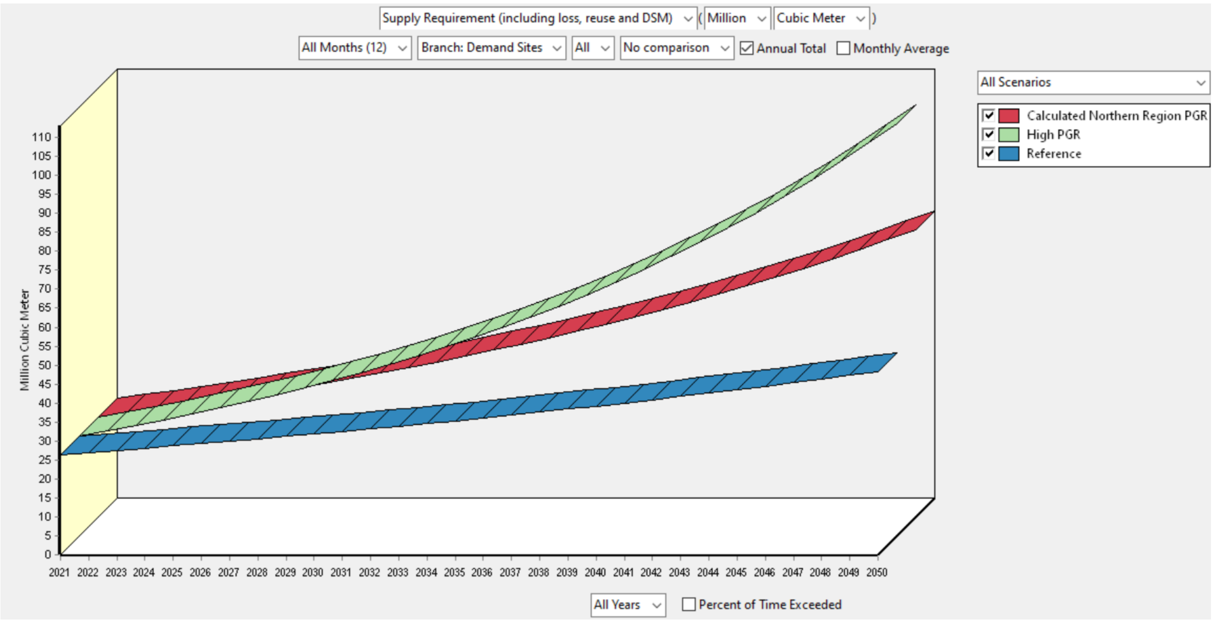


A.C Figure 74 - Monthly average of unmet demand for all years when there are two transmission links operating at maximum capacity. Screenshot from the results view in WEAP.

Additional results for Only loss rates

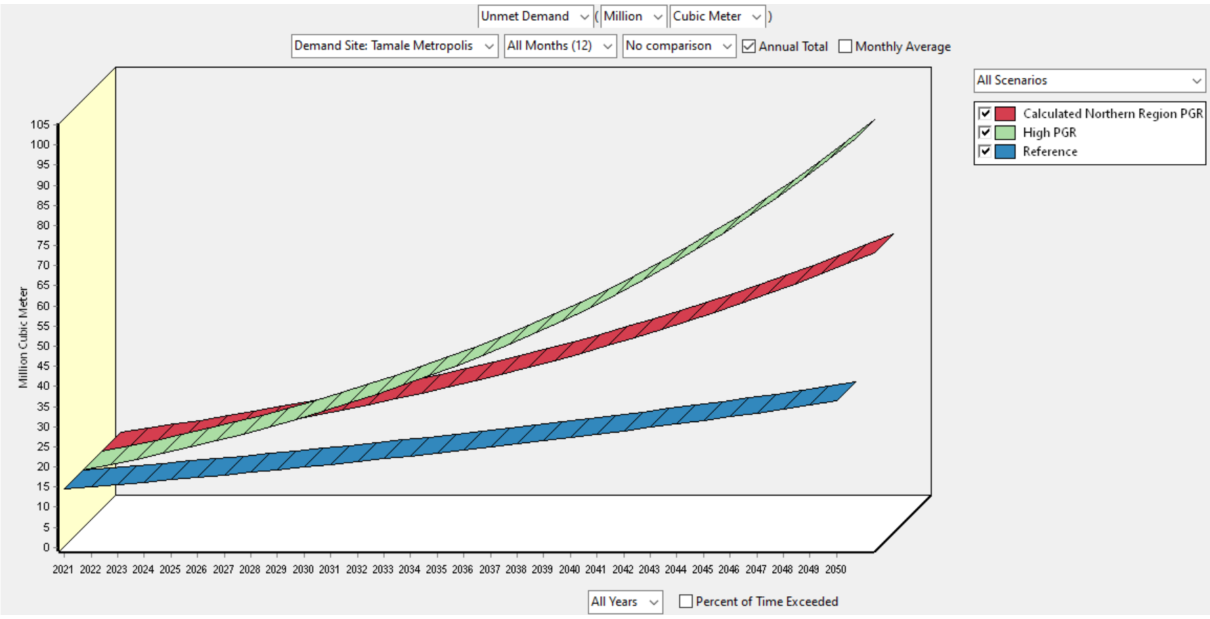


A.C Figure 75 - Monthly average of coverage for all years when the loss rates are reduced. Screenshot from the results view in WEAP.

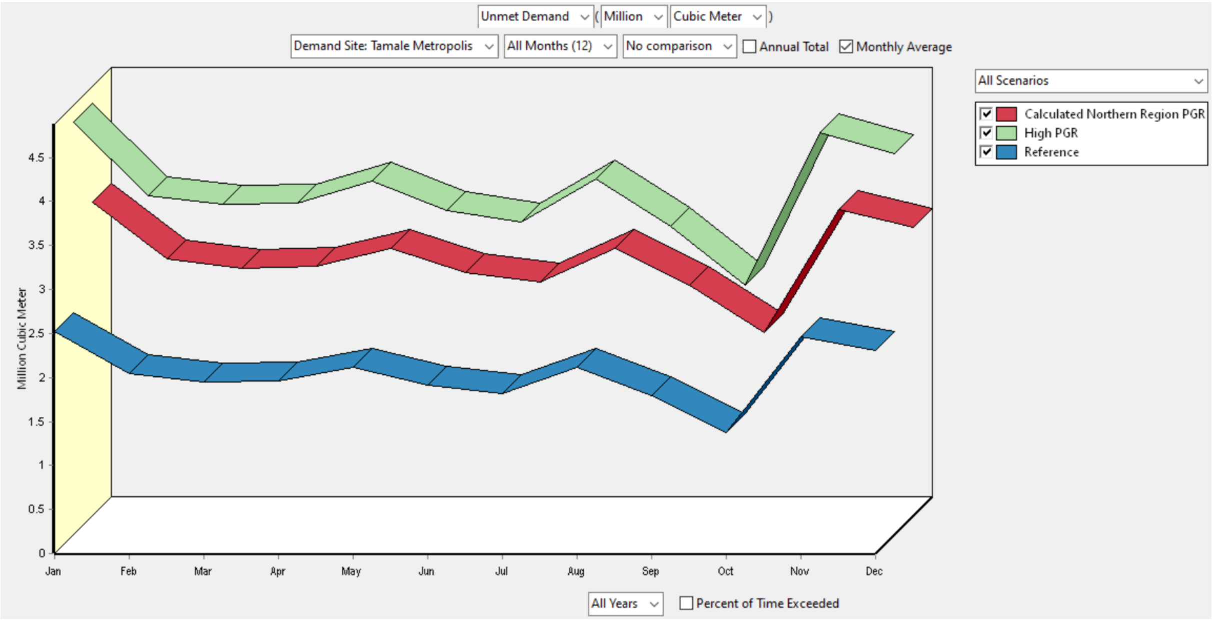


A.C Figure 76 - Annual total of supply requirement when the loss rates are reduced. Screenshot from the results view in WEAP.

A.C Figure 77 - Monthly average of supply requirement for all years when the loss rates are reduced. Screenshot from the results view in WEAP.



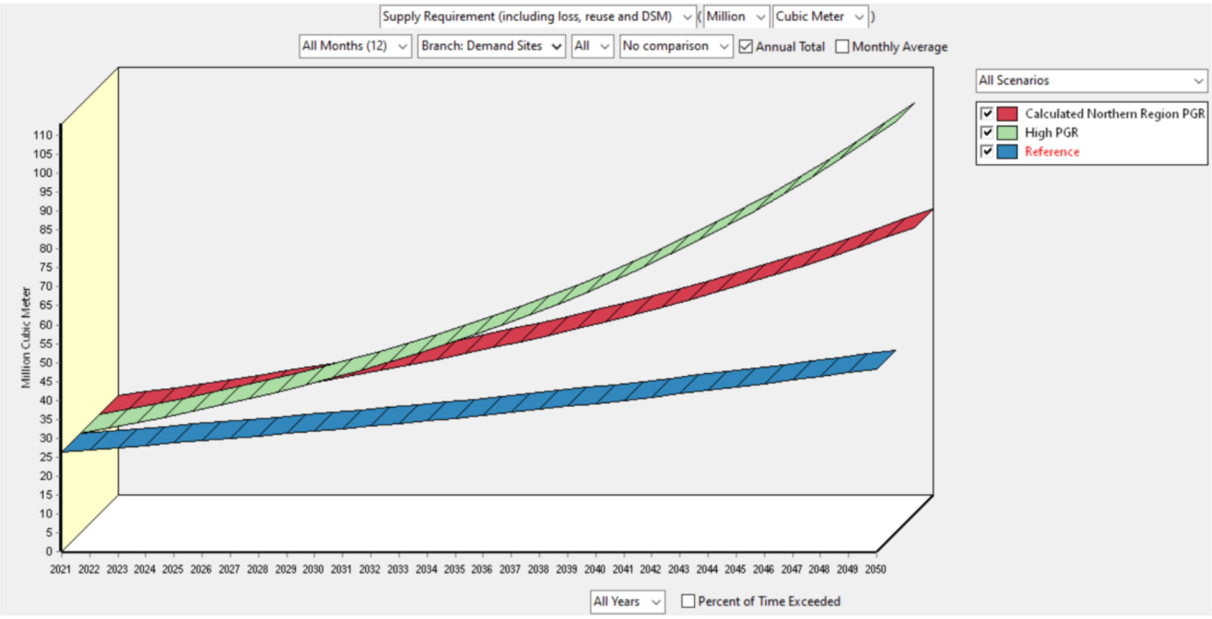
A.C Figure 78 - Annual total of unmet demand when the loss rates are reduced. Screenshot from the results view in WEAP.



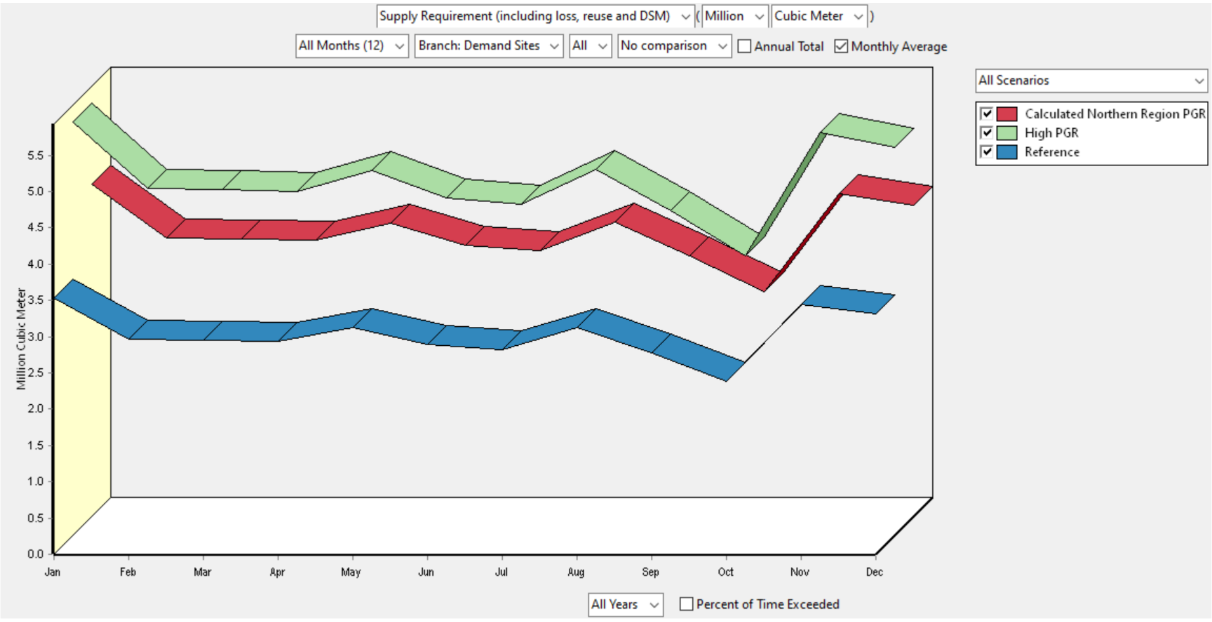
A.C Figure 79 - Monthly average of unmet demand for all years when the loss rates are reduced. Screenshot from the results view in WEAP.

Additional results for TL and loss rates

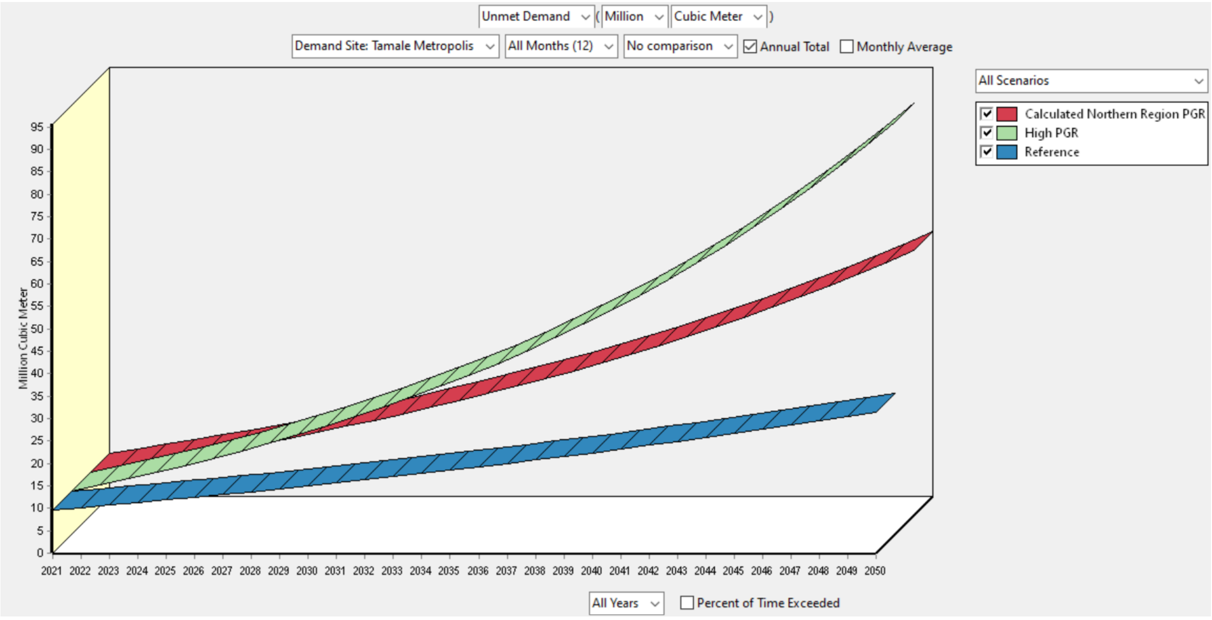
A.C Figure 80 - Monthly average of coverage for all years when there are two transmission links operating at maximum capacity and reduced loss rates. Screenshot from the results view in WEAP.



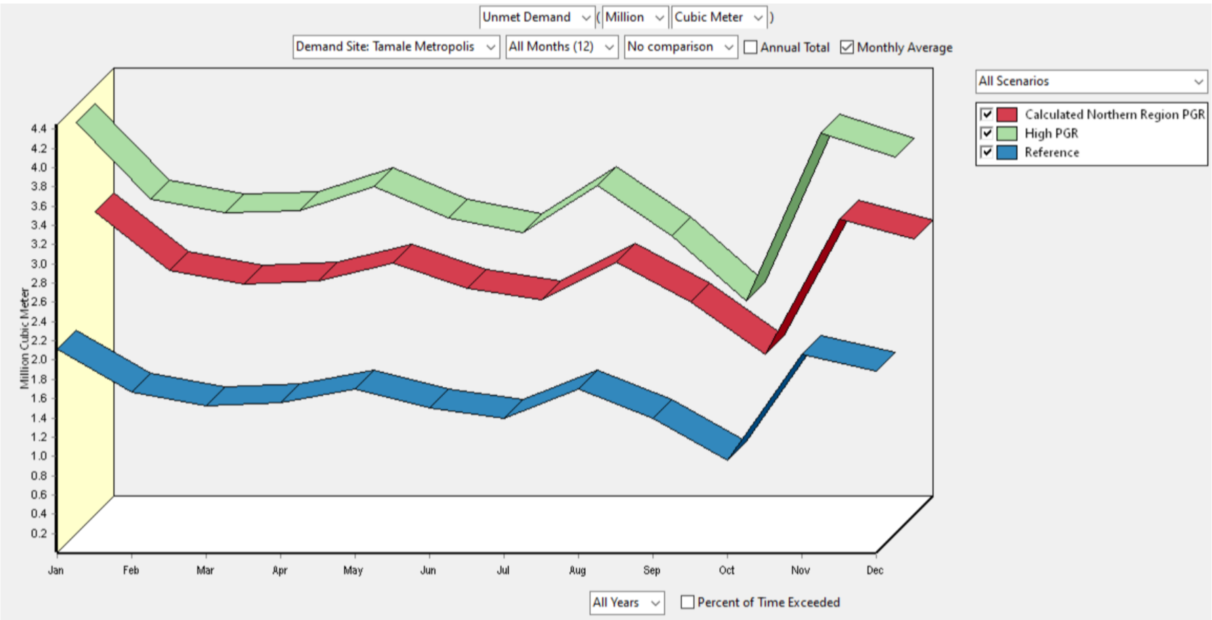
A.C Figure 81 - Annual total of supply requirement when there are two transmission links operating at maximum capacity and reduced loss rates. Screenshot from the results view in WEAP.



A.C Figure 82 - Monthly average of supply requirement for all years when there are two transmission links operating at maximum capacity and reduced loss rates. Screenshot from the results view in WEAP.



A.C Figure 83 - Annual total of unmet demand when there are two transmission links operating at maximum capacity and reduced loss rates. Screenshot from the results view in WEAP.



A.C Figure 84 - Monthly average for unmet demand for all years when there are two transmission links operating at maximum capacity and reduced loss rates. Screenshot from the results view in WEAP.

Additional results for TL, loss rates and reuse rate

A.C Figure 85 - Monthly average of coverage for all years when there are two transmission links operating at maximum capacity, reduced loss rates and a reuse rate of 22.0%. Screenshot from the results view in WEAP.

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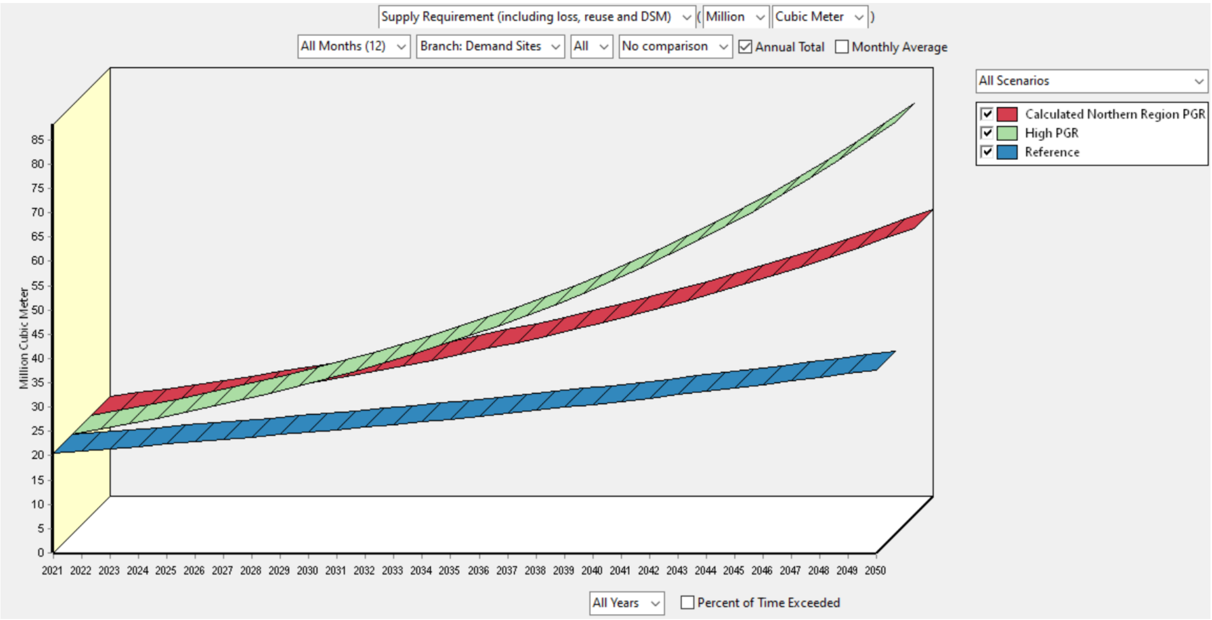
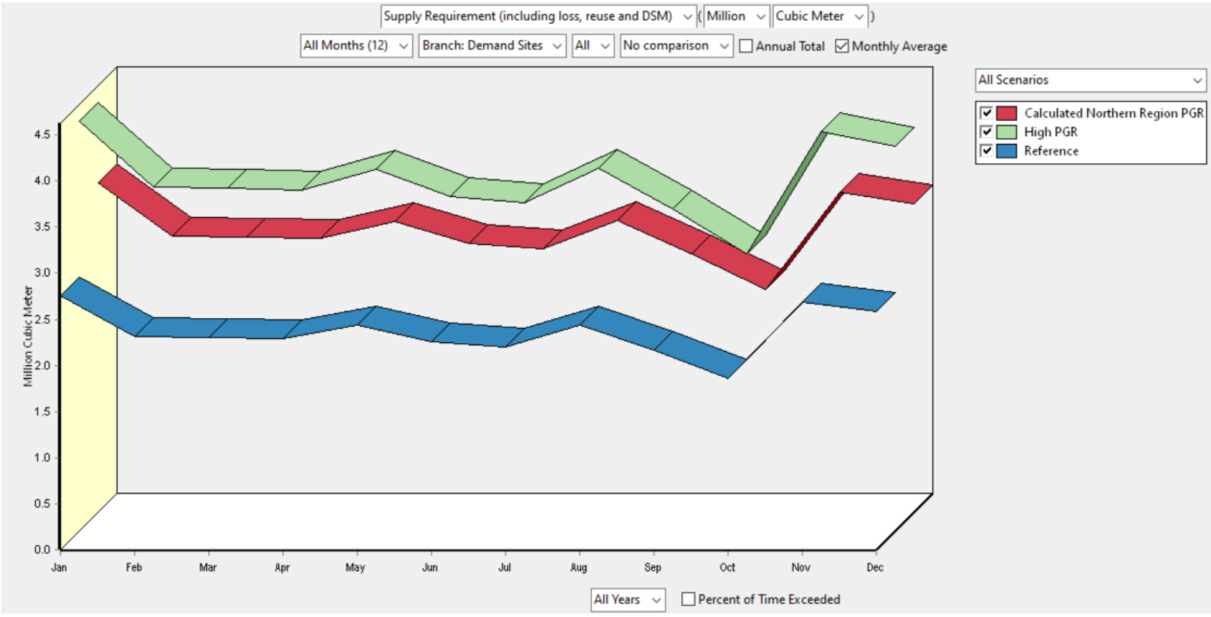
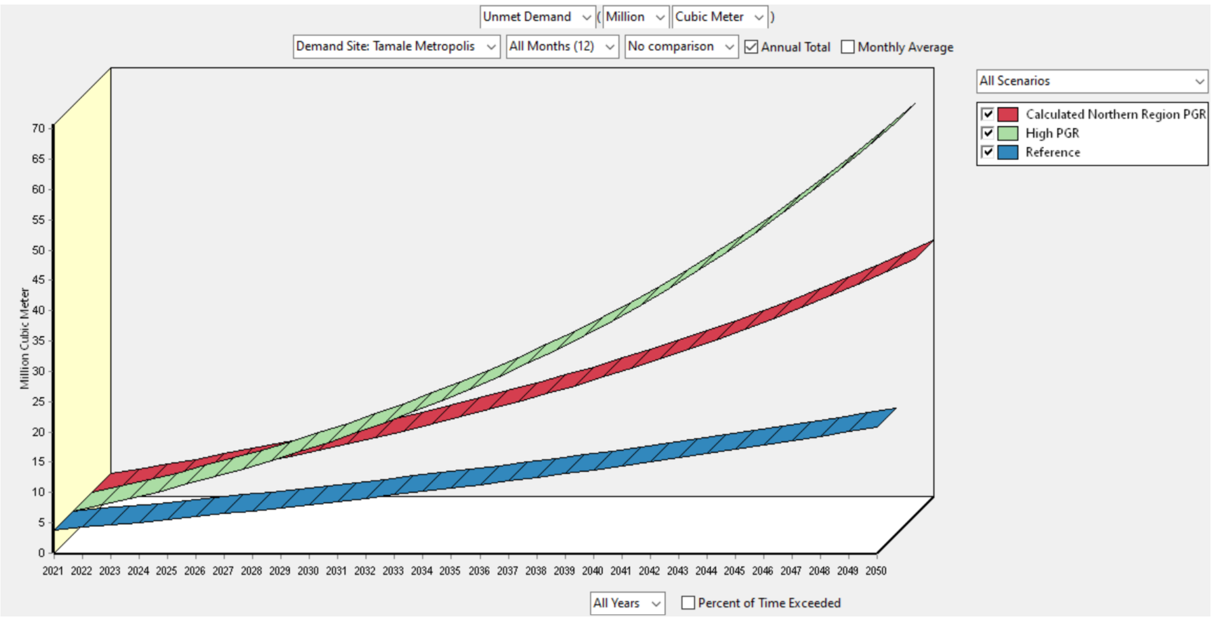


A.C Figure 86 - Annual total supply requirement when there are two transmission links operating at maximum capacity, reduced loss rates and a reuse rate of 22.0%. Screenshot from the results view in WEAP.



A.C Figure 87 - Monthly average of supply requirement for all years when there are two transmission links operating at maximum capacity, reduced loss rates and a reuse rate of 22.0%. Screenshot from the results view in WEAP.



A.C Figure 88 - Annual total of unmet demand when there are two transmission links operating at maximum capacity, reduced loss rates and a reuse rate of 22.0%. Screenshot from the results view in WEAP.

A.C Figure 89 - Monthly average for unmet demand for all years when there are two transmission links operating at maximum capacity, reduced loss rates and a reuse rate of 22.0%. Screenshot from the results view in WEAP.

Appendix D. Validity check done in excel

General:

Supply delivered: Calculated in Equation (9)

Coverage: Supply delivered / supply requirement

A.D Table 19 - Parameters for validation calculations done in excel.

Demand site loss (NRW)	Population in Tamale in 2021	Annual water use rate/person	Annual growth rate	Years of simulation
0.44	672 000	25.55	0.21	29

For 2021

Supply requirement: 672 000 * 25.55 * Monthly variation / (1 – 0.44)

For 2050

Supply requirement: 672000 * 25.55 * 1.021^{29} * Monthly variation / (1 – 0.44)

A.D Table 20 - Calculations of the monthly average of coverage for 2021 done in excel.

Calculations of the monthly average of coverage for 2021			
	Supply required [m^3]	Supply delivered [m^3]	Coverage
January	2988737	884943.36	0.29609277
February	2504002	799303.68	0.3192105
March	2497870	884943.36	0.3542792
April	2485606	856396.8	0.3445424
May	2638293	884943.36	0.3354227
June	2440536	856396.8	0.3509052
July	2388721	884943.3	0.370467
August	2645345	884943.36	0.3345285
September	2347636	856396.8	0.3647911
October	2016508	884943.36	0.4388494
November	2906568	856396.8	0.2946419
December	2800178	884943.36	0.3160311

A.D Table 21 - Calculations of the monthly average of coverage for 2050 done in excel.

Calculations of the monthly average of coverage for 2050			
	Supply required [m^3]	Supply delivered [m^3]	Coverage [%]
January	5460522.38	884943.36	0.16206203
February	4574896	799303.68	0.1747152
March	4563692.6	884943.36	0.1939095
April	4541285.9	856396.8	0.1885802
May	4820249.8	884943.36	0.1835887
June	4458941.1	856396.8	0.1920628
July	4364272.7	884943.3	0.20277
August	4833133.7	884943.36	0.1830993
September	4289210.1	856396.8	0.1996631
October	3684228.1	884943.36	0.2401978
November	5310397.2	856396.8	0.1612679
December	5116018.8	884943.36	0.172975

Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway