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FINAL REPORT

Increase of Water Supply Safety by Managed Aquifer Recharge along the North-South Carrier – A pre-feasibility study

ANDREAS LINDHE, LARS ROSÉN, PER-OLOF JOHANSSON, TOMMY NORBERG

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PREFACE

The present pre-feasibility study on artificial groundwater recharge in Botswana was carried out within the Swedish International Development Cooperation Agency's (Sida) policy framework *Partner Driven Cooperation (PDC) with* Botswana Department of Water Affairs (DWA) and Chalmers University of Technology, Department of Civil and Environmental Engineering as the two main partners.

A planning grant was received from Sida and an application for a PDC Cooperation Grant was developed jointly by Chalmers and DWA. In October 2012 Sida made the decision to finance the pre-feasibility study and the project was started in November 2012 and ended in March 2014.

The project involves the development of a water supply safety model that is capable of modelling future water supply scenarios, taking into account the dynamic variations over time of water availability and demand in the supply system along the so called North-South Carrier (NSC) distribution system in eastern Botswana. Possible future scenarios of Managed Aquifer Recharge (MAR) are defined, where identified groundwater aquifers and already existing wellfields are used for injection of treated surface water to improve the supply safety of the system. The project assesses the need for increased water supply safety, if large-scale MAR can provide the desired increase in water supply safety, and if MAR is economically viable.

It is our sincere belief that the development of the water supply safety model, the results achieved in this project, and future developments and applications of the model by the DWA will provide important support to decisions at DWA on more efficient and sustainable use of water resources in Botswana.

Lars Rosén, Andreas Lindhe, Per-Olof Johansson, Tommy Norberg

Executive summary

Background

Water scarcity is a major challenge for sustainable development in Botswana and calls for integrated water resources management, including measures to avoid water losses, efficient use of water, introduction of water saving technologies, as well as of water re-use and recycling. Furthermore, expected climate change implies risks for rainfall seasons being shorter and less reliable in the future.

The arid and semi-arid climate of Botswana provides a situation with low rainfall and high rates of potential evapotranspiration. Combined with the country's generally very flat topography, this results in low rates of surface runoff and low rates of recharge to groundwater. There are no perennial streams originating in Botswana.

Most of Botswana's population lives in the eastern grassland region of the country, along the border with South Africa and Zimbabwe. The hydrological conditions and a continuously increasing water demand in this area results in a water stressed situation.

Managed Aquifer Recharge (MAR), sometimes denoted Artificial groundwater Recharge (AR), is a well-established technique to increase available water quantities for water supply and to improve water quality. Water scarcity accentuated by urban growth, especially in semi-arid and arid regions, has resulted in a growing interest in MAR as a basis for water supply by collection of surface water runoff for infiltration to avoid evaporation losses.

Scope and objectives

> *The overall aim of this project is to investigate the potential for using large scale MAR to improve future water supply safety in Botswana.*

This pre-feasibility study focuses on the area along the North-South Carrier (NSC), which is a bulk water supply system running from north to south in eastern Botswana, connecting a number of surface water dams, groundwater aquifers and water treatment facilities. The NSC supplies drinking water to a large portion of the Botswana population. According to previous studies, there exist a number of opportunities for conjunctive surface water and groundwater use along the NSC.

In order to meet the overall aim of the project, the specific objectives of the study are to:

- Define the need for increased water supply safety.
- Assess if large-scale MAR can provide the desired increase in water supply safety.
- Assess the economic viability of MAR for provision of the desired water supply safety.

The study of the potential for MAR along NSC is divided into the following major parts:

- Evaluation of the NSC water supply system and identification of components to be included in the water supply safety study.

- Development of a risk-based water supply safety model, taking into account the water demands and availability over a specified future time horizon.
- Definition of modelling scenarios, including MAR scenarios and Non-MAR scenarios.
- Modelling of the potential effects on water supply safety in the NSC from implementing MAR.
- Evaluation of the cost-effectiveness of MAR.

The current study supplements previous studies performed in the area by studying in detail the effects on water supply safety from MAR with respect to the temporal variability of water availability and predicted future demand.

Project realization

The project was carried out in collaboration between Chalmers University of Technology, Department of Civil and Environmental Engineering, in Sweden and the Department of Water Affairs of Botswana. The Swedish part of the project was financed within the Swedish International Development Cooperation Agency (Sida) policy framework programme *Partner Driven Cooperation (PDC)*. The Botswana part of the project was financed by The Ministry of Minerals, Energy and Water Resources.

Capacity building was an important component of the project including seminars, workshops and on-the-job training on concepts, methods and conceptual design of MAR facilities as well as on water supply safety modelling.

The project was implemented during the period of November 2012 – March 2014. The Swedish partners visited Botswana 5 times during this period.

The study area

In eastern and southern Botswana, with its relatively high density of population and substantial water demand, a number of surface water dams have been constructed to collect and store rain water. The largest dams are the Shashe, Dikgatlhong, Letsibogo, and Gaborone Dams. The storages of the dams are very variable due to the highly seasonal, occasional and variable riverflows. In addition, the need to store water for drought periods and the flat topography in most areas result in large losses of water to evaporation from these dams.

Surface water dams in eastern Botswana have been connected through a pipeline transfer system denoted the North-South Carrier (NSC), providing possibilities to transfer water to urban centres and thus improving the reliability of the water supply in this part of the country. In addition to the surface water dams a number of groundwater wellfields are connected or are planned to be connected to demand centres supplied with water from the NSC, e.g. Palla Road, Chepete, Masama, Makhujwane, Malotwane, and Palapye Wellfields.

The demand centres, surface water dams and aquifers included in this study are shown in Figure A.

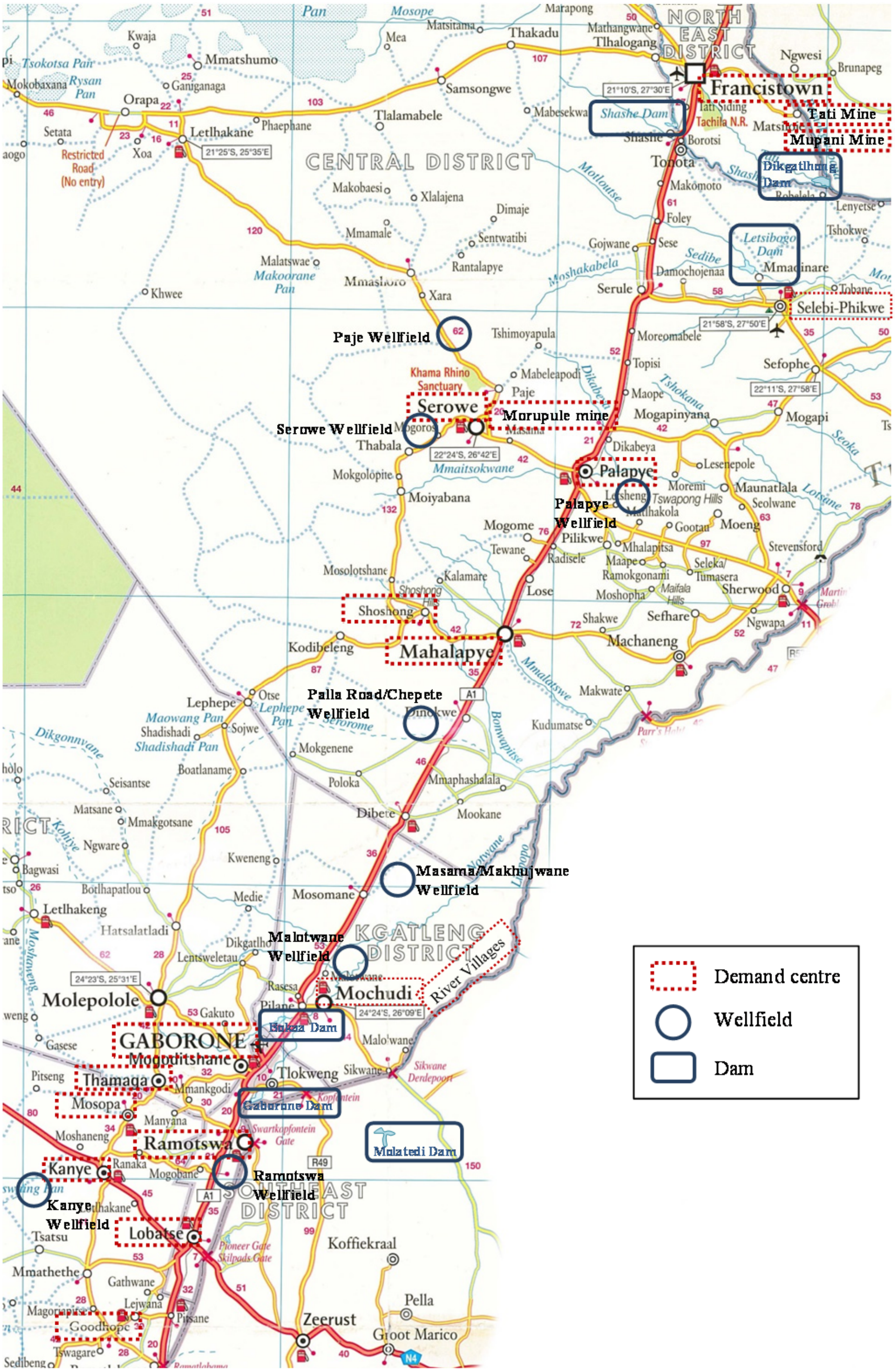


Figure A. *Map showing the demand centres, wellfields and surface water dams included in this study.*

Due to the highly variable storage in surface water dams, the groundwater aquifers have a potential to support the NSC demand centres during drought periods. Because of the very limited natural recharge to these aquifers their long-term sustainable capacity could be improved if artificially recharged with surface water. Artificial recharge with collected surface water from dams may also reduce the total loss of water to evaporation.

The NSC water supply system

This pre-feasibility study focuses on the area along the North-South Carrier (NSC) in eastern Botswana. The main focus of the analysis is to evaluate the possibility and effects on the water supply safety of MAR-scenarios including the Palla Road/Chepete and/or the Masama/Makhujwane Wellfields.

Figure B provides a schematic illustration of the NSC water supply system. In total the system included in the analysis and implemented in the water supply safety model includes:

- 6 surface water dams
- 8 wellfields
- 7 water works
- 18 demand centres

In the northern part of the system the Shashe Dam and the demand centres Francistown, Tati mine and Mupani mine are situated. These parts of the system are not connected to the NSC but are included in the analysis since water from the Shashe Dam can be supplied to Selebi-Phikwe via the local water works. Hence, to make sure an accurate estimation of, for example, the possible supply from the Shahse Dam also the supply to Francistown and the mines must be considered. The northern part of the system is, however, not the main focus of this study.

The NSC makes it possible to supply bulk water from the northern parts of the system down to Gaborone as well as to other demand centres along the pipeline. Currently the only dam supplying water to the NSC is the Letsibogo Dam which also is the dedicated water source for Selebi-Phikwe. As mentioned above it is possible to supply water to Selebi-Phikwe also from the Shashe Dam.

The recently constructed Dikgatlhong Dam will be connected to the NSC and additional planned upgrading of the system also includes a new pipe from the Break Pressure Tank 1 (BPT1) down to Pump Station 3 (PS3), construction of PS4, and increased treatment capacity in the Mmamashia water works (WW). These improvements of the system will provide an increased access to surface water and an increased transfer capacity as well as treatment capacity for parts of the system.

The Palapye WW is supplied with water from the NSC and the treated water is transferred to Palapye, Serowe and the Morupule mine. These three demand centres are also supplied with water from the Palapye, Serowe and Paje Wellfields, respectively. Similarly, Mahalapye and Shoshong can be supplied with water from the Palla Road/Chepete Wellfield and from the NSC via the Mahalapye WW.

Gaborone is the largest demand centre in the system and currently the demand centres Mochudi, Ramotswa, Lobatse and Good Hope Cluster are also connected to Gaborone and supplied from the two water works Gaborone and Mmamashia. The two water works jointly supply the needed water to Gaborone and the connected demand centres. The Mmamashia WW can be supplied with water from the NSC and from the Bokaa Dam.

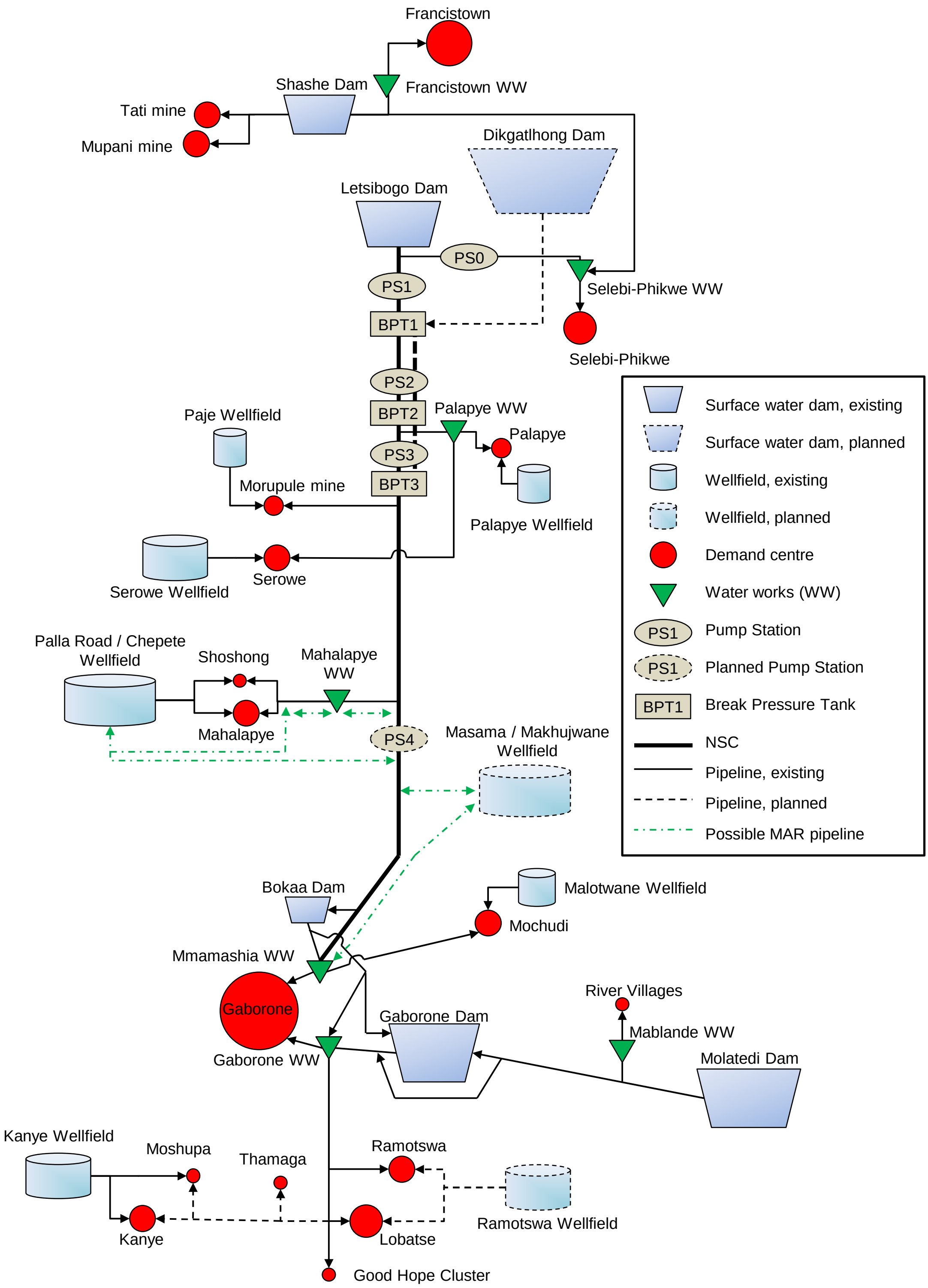


Figure B. *Schematic illustration of the water supply system linked to the NSC.*

The Gaborone WW is primarily supplied with water from the Gaborone Dam and from the Molatedi Dam in South Africa. The Molatedi Dam is also the dedicated water source to the River Villages and the surplus is transferred either directly to the Gaborone WW or to the Gaborone Dam (the abstraction rate from the dam is limited and the water from Molatedi is therefore under normal operation transferred directly to the WW). It is also possible to supply water from the Bokaa Dam to the Gaborone

WW and water from the NSC can be transferred to the Gaborone WW via the Bokaa Dam.

The southern part of the system will be upgraded and the demand centres Thamaga, Moshupa and Kanye will be connected to the Gaborone system. Currently Kanye and Moshupa are supplied with water from the Kanye Wellfield, which still will be included in the system after the new connections. Furthermore, the Ramotswa Wellfield will be connected to supply water to Ramotswa and Lobatse. Currently also the Malotwane Wellfield is included in the system and can be used in Mochudi but no other demand centres.

This pre-feasibility study is focused on the possibility of using the Palla Road/Chepete and Masama/Makhujwane Wellfields for MAR in order to increase the water supply safety. Currently the Palla Road Wellfield is used for water supply to Mahalapye and Shoshong. The Masama Wellfield is currently not in use but the plan is to use the wellfield for emergency water supply (i.e. abstraction exceeding the sustainable yield for periods and rely on natural recharge for recover).

Scenarios to improve water supply safety along NSC

DWA, the Water Utilities Council (WUC) and Chalmers agreed to include six water supply scenarios in the pre-feasibility study:

Scenario 1: Current system

In this scenario the current system is simulated according to the structure shown in Figure B.

Scenario 2: Current system + Dikgatlhong Dam

In addition to the features of Scenario 1, the Dikgatlhong Dam is connected to the NSC. Pumping Station PS4 is in operation, doubling the NSC-capacity south of the station. Kanye, Thamaga and Moshupa are connected to the NSC. The water works capacities are increased.

Scenario 3: Current system + Dikgatlhong Dam + Masama/Makhujwane Wellfields

In addition to the features of Scenario 2, the Masama/Makhujwane Wellfields are connected to the NSC as an emergency supply, with no limitation of the abstraction rate to sustainable yield. The maximum abstraction rate is set to c. 21 600 m^3/d and the maximum active storage to 40 Mm^3. The abstraction rate is the same as for the Masama/Makhujwane Wellfields MAR baseline scenario (Scenario 5), but for comparison also an increased abstraction rate of c. 38 000 m^3/d, as for the extended MAR-scenario, was simulated.

Scenario 4: Current system + Dikgatlhong Dam+Palla Road/Chepete Wellfields, MAR

In this scenario, in addition to Scenario 2, facilities for MAR are provided for the Palla Road/Chepete Wellfields. The existing transfer capacity from the wellfields to Mahalapye is upgraded to allow for reversed flow for supply of treated water from the Mahalapye Water Works to the wellfields for injection. For full scale abstraction and injection an additional pipeline is most likely needed as well as an upgrading of the capacity of the Mahalapye Water Works. There are two alternatives for transfer of water to the NSC from the wellfields:

- The abstracted water is pumped back to Mahalapye in the pipeline used for injection and from there to the NSC in the existing pipeline between Mahalapye and the NSC used for the water supply today. Upgrading is necessary to allow for reversed flow.
- A new pipeline is constructed for transfer of abstracted water from the Palla Road/Chepete Wellfields directly to the NSC.

Scenario 4 has one baseline and one extended sub-scenario. The difference between the scenarios is the c. 50 % higher maximum abstraction rate and maximum active storage of the extended sub-scenario; abstraction rates of 21 300 m^3/d compared with 14 200 m^3/d for the baseline sub-scenario, and active storages of 43 Mm^3 compared with 26 Mm^3 for the baseline sub-scenario.

Scenario 5: Current system + Dikgatlhong + Masama/Makhujwane Wellfields, MAR

In this scenario, in addition to Scenario 2, facilities for MAR are provided for the Masama/Makhujwane Wellfields. Two alternatives are simulated:

- The connection to the NSC from the wellfields is upgraded to allow reversed flow to allow transfer of water from the NSC to the wellfields for injection, and for the extended scenario also for a higher transfer rate. A new water treatment plant is constructed for treatment of the water to be injected. When water is abstracted from the wellfields, it is transferred back to the NSC as in Scenario 3.
- A new pipeline is constructed from the Mmamashia Water Works to Masama for supply of treated water for injection. The same pipeline is used when water is abstracted from the wellfields and delivered directly to the water distribution system (if necessary after some minor treatment).

Like Scenario 4, Scenario 5 has one baseline and one extended sub-scenario. The difference between the sub-scenarios is the c. 75 % higher maximum abstraction rate of the extended sub-scenario, 37 800 m^3/d, compared with 21 600 m^3/d for the baseline sub-scenario.

Scenario 6: Current system + Dikgatlhong Dam + Palla Road/Chepete Wellfields, MAR + Masama/Makhujwane Wellfields, MAR

In this scenario, Scenario 2 is combined with the MAR-facilities of both Scenario 4 and 5. The same alternatives for treatment of the injection water and the connections to the NSC as for Scenarios 4 and 5 are included as well as the baseline and extended sub-scenarios.

The water supply safety model

A water supply safety model was developed to enable a thorough assessment of the effects of implementing MAR and other measures in the water supply system, see scenarios described above. The aim of the model is thus to provide results that can be used to evaluate and compare the water supply safety of the current system and possible future scenarios. The developed model includes the area along the NSC and included components are available source water, groundwater aquifers, water supply infrastructure, water demand centres etc. The existing water supply system is the baseline and MAR options and coming upgrading of the system are included as scenarios (see above) to enable a comparison to the present day situation in terms of incremental increase in water supply safety.

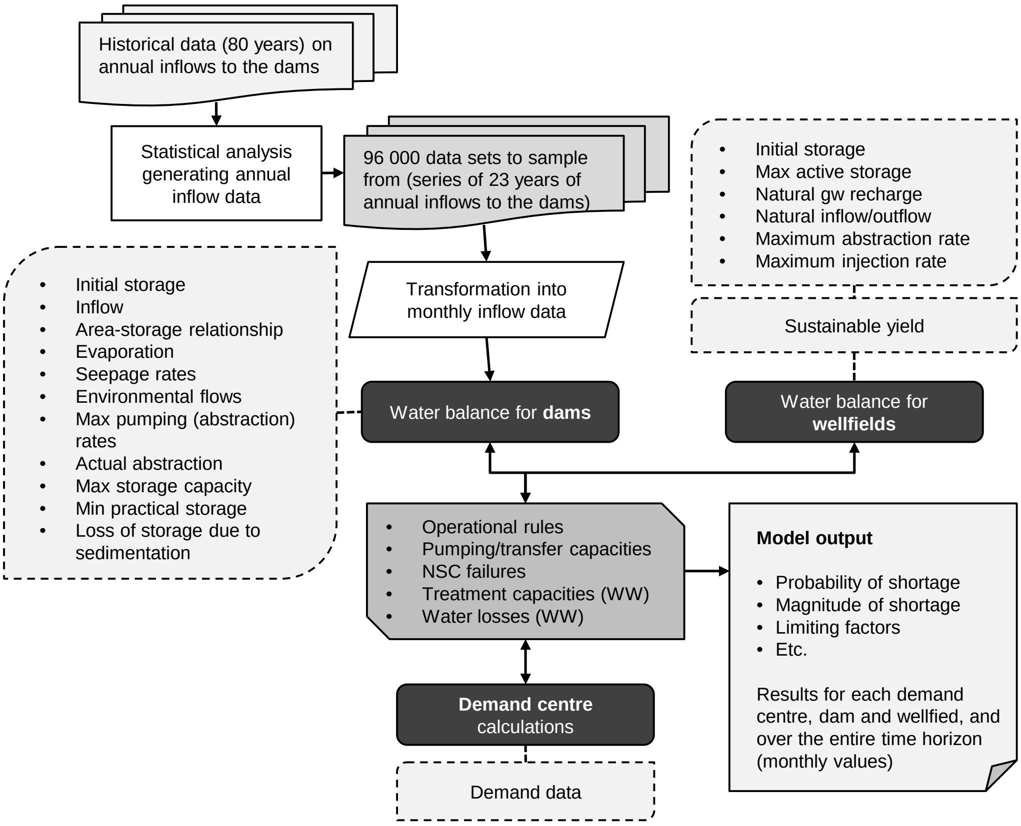
The model is a dynamic water balance model where statistically generated time series of the availability of source water are used, together with dynamic storages in dams and aquifers, and water demands to simulate the magnitude and probability of water supply shortages. Previous models, such as the WATHNET-model used in the National Water Master Plan Review (NWMPR) from 2006, provide similar opportunities to analyse the supply system. The previous models were, however, not specifically developed to consider MAR-scenarios. Furthermore, the primary aim of the model developed in the present study was to provide an easily accessible model that can be run without expert knowledge. The water supply safety model is therefore developed as a spreadsheet model in Excel. To enable statistical analysis considering uncertainties in results etc., an add-in software (Oracle Crystal Ball) is used to run Monte Carlo simulations.

The dynamic water balance model is used to simulate (mainly) the NSC system and connected components from year 2013 to 2035 (23 years). The simulations are performed with a time step of one month and for each month the demand, available storage in dams and aquifers as well as treatment capacities, water losses etc. are considered.

In Figur C, a schematic illustration is presented of the parameters considered in the model and the link between them and the model components.

Based on historical data on inflow to the dams, a large set (96 000) of possible time series are generated and used to sample from when running the model. The generated time series consider the correlation between the dams and each generated data set includes all five dams. The annual inflow data is transformed into monthly data based on the closest historical annual inflow and the monthly distribution that year. Since the dams are spatially correlated, the historical data for the Gaborone Dam is used when transforming the simulated annual data for the Bokaa and Gaborone Dams. In the same way the historical data for the Dikgatlhong Dam is used for the Letsibogo, Shashe and Dikgatlhong Dams.

For each dam and wellfield, water balance calculations are done for each month. However, for the wellfields not considered relevant for MAR only the sustainable yield is considered (i.e. abstraction is allowed up to sustainable yield). A set of operational rules (see the grey shaded box in the middle of Figure C) determine to what extend different sources are used and how much water can be transferred etc.



Figur C. Overview of the parameters considered in the model and the link between them.

Modelling results

The following main results are provided for the different scenarios:

- Percentage of months with water shortage for each demand centre (P10; Mean; P90).
- Total water shortage (i.e. summed over the simulated 23 years) for each demand centre (P10; Mean; P90).
- Percentage of demand (per month) not met given water shortage for each demand centre (P10; Mean; P90).
- Number of months until first water shortage event for each demand centre (P10; Mean; P90).
- Maximum annual water shortage (Mm^3) within the simulated period (23 years) versus reverse cumulative probability.
- Total water shortage (i.e. summed over the simulated 23 years) versus reverse cumulative probability.
- Expected probability of annual water shortage of different magnitude (e.g. >2 Mm^3, >5 Mm^3, etc.) versus time.
- Total net evaporation loss savings versus reverse cumulative probability.
- Expected groundwater storage versus time.

- Groundwater storage at end of simulated period versus reverse cumulative probability.
- Proportion of limiting factors for different steps in the supply chain.

Economic Viability of MAR

In order to assess the economic viability of including MAR in the NSC system a comparison of the increased safety to the costs for implementing, operating and maintaining MAR is needed. An economic assessment should be performed for selected MAR and Non-MAR scenarios to provide a relevant decision support and basis for prioritization regarding future investments for improving water supply safety.

It was not possible within the scope of this study to perform a quantitative economic valuation of MAR. However, forms to be applied for quantification of MAR cost items were developed and are presented in Appendix 4. Some of the costs have been obtained from DWA and other organizations during the study and to proceed with quantification of remaining cost items is necessary for a relevant economic valuation.

It is suggested that the economic valuation is performed as a cost-effectiveness analysis (CEA), including the following steps:

- Scenarios that are considered to provide acceptable water supply safety are identified.
- A time horizon is selected. In this study a 23-year time horizon was applied, but other time horizons may be found justified. It is important that the selected time horizon is agreed upon among all parties involved in the decision-making process.
- Investments and the streams of operation and maintenance costs over the selected time horizon are quantified for each scenario, using the developed forms in Appendix 4.
- A present value (PV) is calculated for the total cost for each scenario, using the selected time horizon and discount rate.
- Prioritization of scenarios is performed, based on the relationship between the increase in water safety and the total cost (PV) for each alternative, i.e. the cost-effectiveness.

If MAR is considered as a feasible option to increase water supply safety, field investigations and field tests are necessary to show that the MAR-scenarios outlined in this study are realistic in terms of abstraction and injection rates and sizes of active storage. Furthermore, the tests are needed to ensure that injection water quality is appropriate as well as the quality of the abstracted water. The field tests will also give experience of practical issues, for example if well clogging may cause a problem.

Results and conclusions

The development of the water supply safety model and performed simulations provide an increased knowledge of the possibilities for improving the water supply safety in the NSC system. It facilitates modelling of effects from implementing MAR in groundwater aquifers, as well as effects from other upgrades of the system. A number of scenarios have been studied within the scope of this study, but the model can also be used for analysing other scenarios that may be identified and considered to be of interest. It should be noted that the model includes information on the NSC system, water demand, water availability, etc. as known today, but as new information becomes available the model should be updated accordingly to provide relevant results.

The pre-feasibility study provides the following major results and conclusions.

The current supply system is, as expected, clearly insufficient to meet the water demand within the simulated period of 23 years. Water shortage is likely to be a problem already early in the simulated period (2013-2035).

The connection of the Dikgatlhong Dam to the NSC and additional upgrades (including water works upgrading, an additional pipeline down to Palapye, and installation of Pump Station 4) will have a large positive effect on the supply safety and reduce the expected total water shortage (summed over the 23 years) by approximately 90 %. However, the model results show that there still will be a significant risk for water shortage for Gaborone and connected demand centres during the late part of the simulation period. The effects of connecting the Dikgatlhong dam on different levels of water shortage for Gaborone and connected demand centres are shown in Figure D and Figure E.

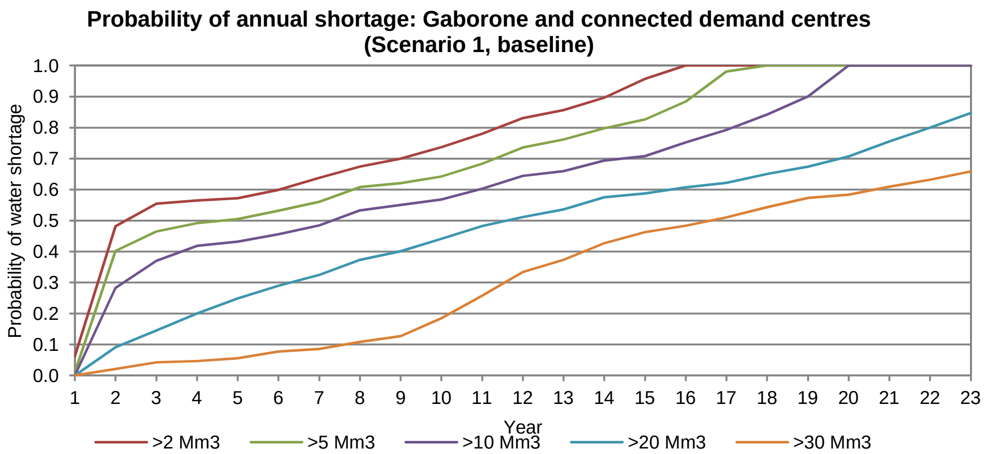


Figure D. Expected probability of annual water shortage of different magnitudes for each year in Scenario 1, i.e. current system.

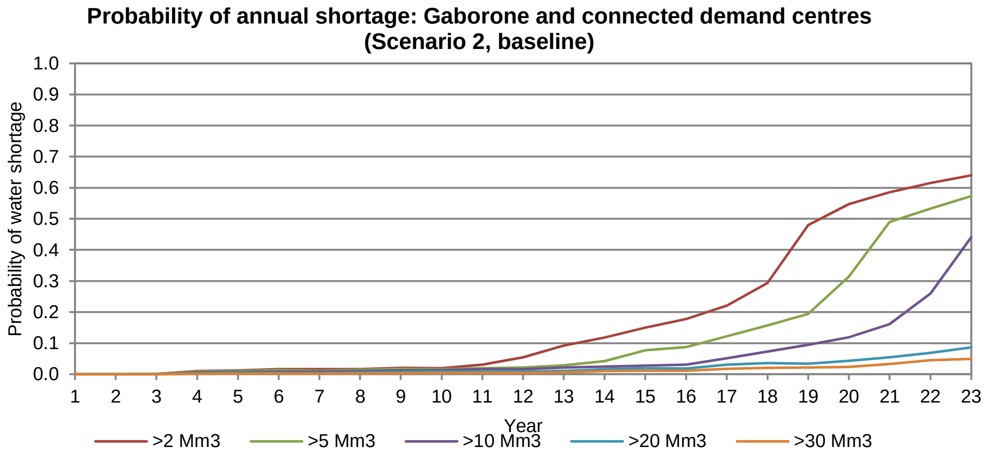


Figure E. *Expected probability of annual water shortage of different magnitudes for each year in Scenario 2 including the Dikgatlhong Dam.*

The connection of Masama/Makhujwane Wellfields as a Non-MAR scheme will further increase the supply safety. However, the effect is limited by the abstraction rate and the possibility to treat the water from the wellfields. Based on the expected development of the demand, it is clear that abstraction from Masama will be needed often and groundwater mining is likely since there will not be enough time for recovery.

The modelled Palla Road/Chepete and Masama/Makhujwane MAR-scenarios provide additional water supply safety. In the extended MAR sub-scenario, a total storage capacity of 80 Mm^3 is added to the system, i.e. an increased storage corresponding to an additional dam of the same size as the Shashe Dam. However, as for the Masama/Makhujwane Non-MAR scenario, the effects of MAR are to some extent limited by different system properties, see Figure F.

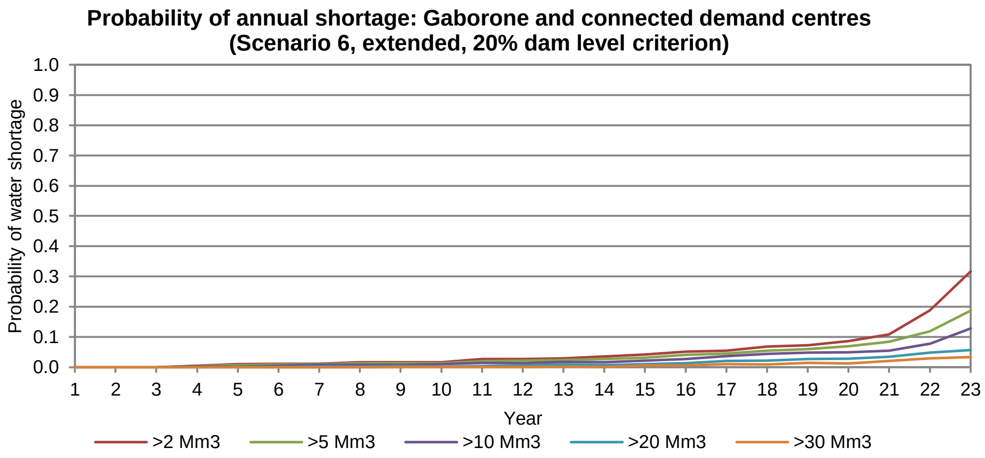


Figure F. *Expected probability of annual water shortage of different magnitudes for each year in Scenario 6, i.e. including Masama/Makhujwane and Palla Road/Chepete, MAR.*

The active storages of the MAR wellfield aquifers, as defined in the present study, have average recovery times from empty to full by natural recharge of 25 and 42 years for the baseline and extended MAR sub-scenarios, respectively, at Palla Road/Chepete Wellfields. The recovery time for Masama/Makhujwane is 35 years for both baseline and extended MAR-scenarios. With continuous injection at maximum rates, the corresponding recovery times are 5 and 6 years for the baseline and extended MAR sub-scenarios, respectively, for Palla Road/Chepete Wellfields, and 5-6 years for Masama/Makhujwane.

The Masama/Makhujwane Non-MAR scenario and Palla Road/Chepete and Masama/Makhujwane MAR-scenario delays the risk for substantial water storage by c. 5 and 10 years, respectively.

The Palla Road/Chepete and Masama/Makhujwane MAR-scenario reduces the probability of having a 10 % (8 Mm^3) water shortage in Gaborone and connected demand centres in 2035 to 10 %, compared to c. 25 % for the Masama Non-MAR scenario and c. 40 % for scenario with only connecting the Dikagathlong Dam, see Figure E and Figure F above.

The impacts of the MAR-scenarios are limited by:

- availability of water for injection in the dams
- abstraction rates from the dams
- water works capacities
- transfer capacities
- maximum abstraction and injection rates and active storages for the wellfields

The MAR-scenarios with the baseline water demand forecast show a considerable risk for groundwater storage deficits at the end of the simulated period (2035), i.e. groundwater is mined in this time perspective, see Figure G and Figure H. The major reason for this is that there is not sufficient time for injection, given the maximum abstraction rates from the dams and the limitations in injection rates, especially during the last years of the simulated period when the demand is high.

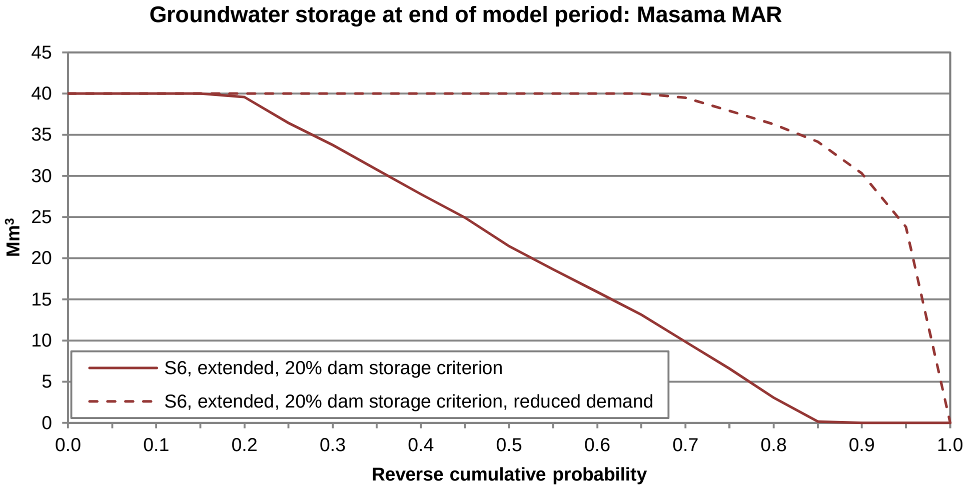


Figure G. Groundwater storage at the end of the model period (year 2035) for Masama/Makhujwane Wellfields in Scenario 6 (extended sub-scenario).

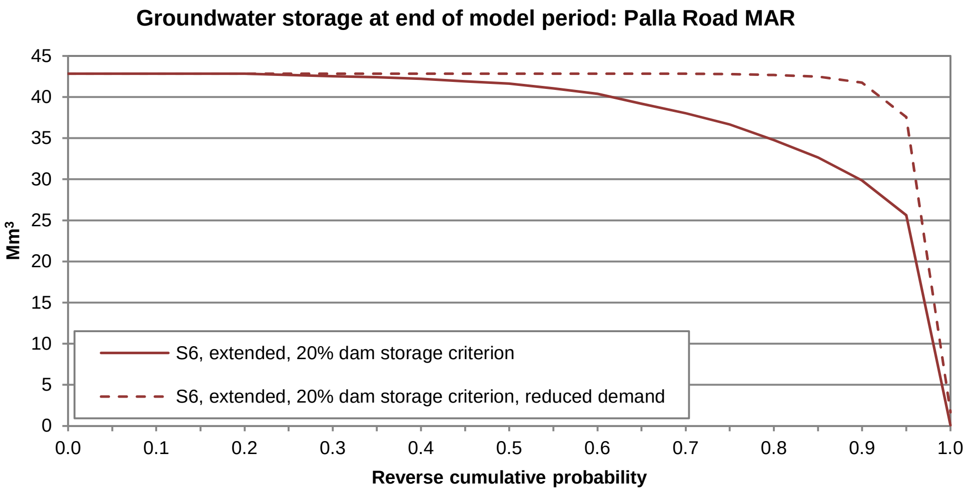


Figure H. Groundwater storage at the end of the model period (year 2035) for Palla Road/Chepete Wellfields in Scenario 6 (extended sub-scenario).

To investigate the sensitivity of the results to the future demand, comparative simulations were performed with a reduced increase in water demand, linearly lower from 0 % at the start to 20 % at the end of the period. As a result, the mining is much lower in the simulations with a reduced increase in demand.

The MAR-scenarios only have a marginal influence on the evaporation losses from the dams, i.e. only relatively insignificant volumes of water are saved. The reason is that only relatively small volumes are abstracted extra from the dams for injection due to infrastructural limitations in abstraction rates from the dams, treatment capacities of the water works and injection rates at the wellfields.

The total abstraction in the Non-MAR scenario of Masama/Makhujwane can be doubled from 13 to 27 Mm^3 over the 23-year period if the abstraction in this scenario is increased to the same rate as for the extended MAR-sub-scenario (from c 21 500 to 37 500 m^3/d) and if the limitations in treatment and transfer capacities are eliminated. However, this will give 50 % probability of a storage deficit of 25 Mm^3 or more at the end of the period compared to the same probability for a 10 Mm^3 or more deficit in the baseline Non MAR-scenario.

The water safety provided by the MAR-scenarios may be further increased if combined with other NSC-system improvements. A 50 % increase of the abstraction rates from the Letsibogo and Dikgatlhong Dams, a doubling of the transfer capacity from NSC to Gaborone WW via Bokaa, and allowing wellfield injection down to the minimum operational levels of the dams, will reduce the probability for a 2.5 % (2 Mm^3) water deficit for Gaborone and connected demand centres to c. 10 % in 2035, see Figure I. This increase will be reached without any substantial risk for mining the wellfields, see Figure J and Figure K.

Due to the increasing water demand and the fact that the abstraction from the MAR wellfields cannot meet the full demand of Gaborone and connected demand centres, the abstraction from the wellfields should start before the dam storages are too low to achieve an extended period of simultaneous abstraction from surface water dams and wells. It is not considered realistic to increase wellfield abstraction rates substantially relatively to the extended MAR-scenarios.

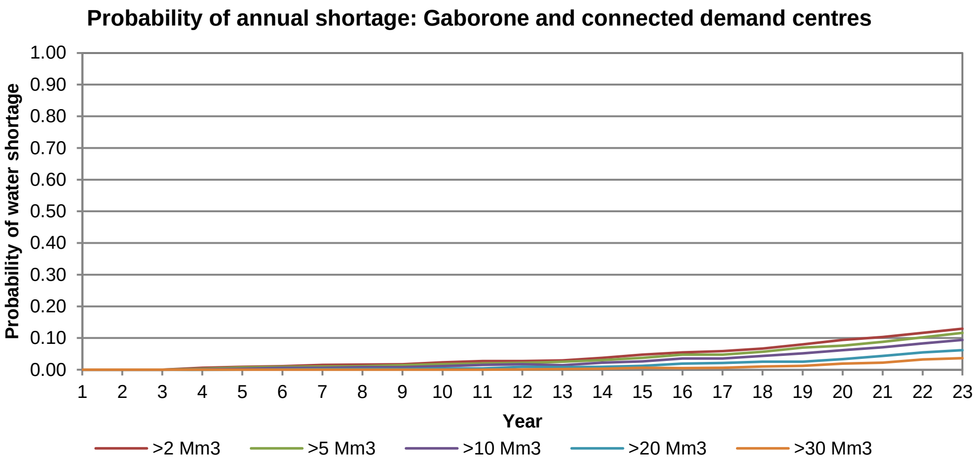


Figure I. *Expected probability of annual water shortage of different magnitudes for each year in Scenario 6 with increased abstraction rates for the dams etc.*

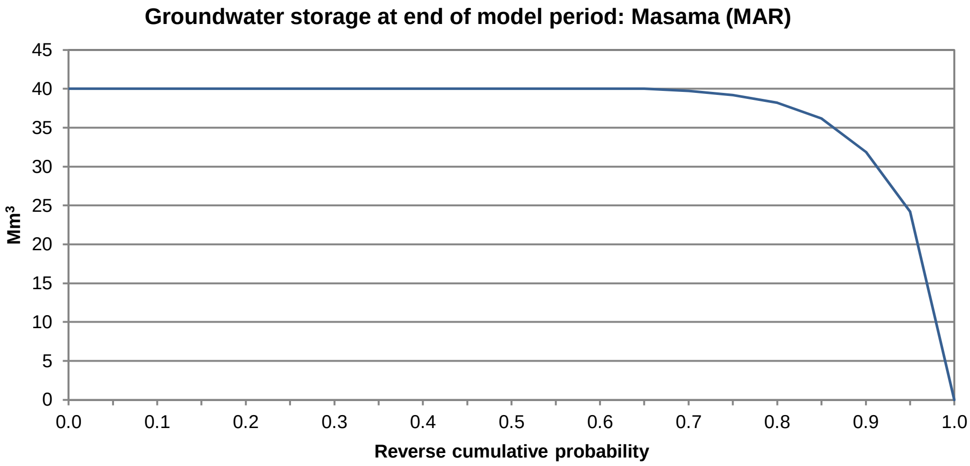


Figure J. *Groundwater storage at the end of the simulated period (year 2035) for Masama/Makhujwane Wellfields in the presented adjusted version of Scenario 6.*

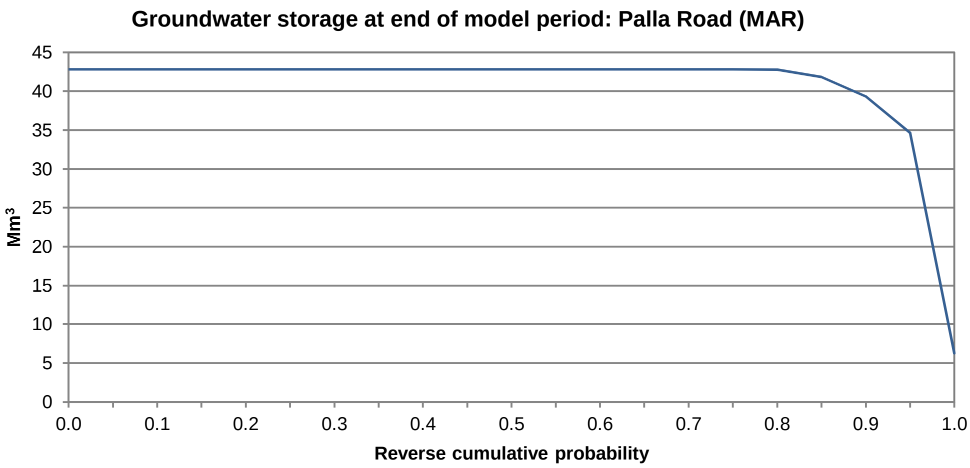


Figure K. *Groundwater storage at the end of the simulated period (year 2035) for Palla Road/Chepete Wellfields in the presented adjusted version of Scenario 6.*

The modelling highlights the impact of the assumed drastic increase in water demand. The NWMPR water demand “base case” forecast is used in the model, but adjusted for actual consumption 2012. According to this forecast the water demand is assumed to increase from c. 72 Mm^3/year in 2012 to c. 144 Mm^3/year in 2035 for the water demand centres included in the water supply system, i.e. an increase by 100 %. The present study focuses on the resource component of the water supply, but the results show that the certainty/reliability of the demand forecast is crucial for assessment of the probabilities of water shortage, especially for the years 10 and onwards during the 23-year simulation period. Comparative simulations were performed with a reduced increase in water demand, linearly lower from 0 % at the start to 20 % at the end of the period. With this reduction in the water demand increase, the risk of substantial water shortage is delayed by c. five years.

Recommendations

The performed study addresses the possible effects of implementing MAR in the NSC system. It is concluded that the current NSC system with the Dikgatlhong dam connected but without MAR is not likely be able to provide a safe water supply over the studied time period. The study further shows that connection of the Masama/Makhujwane Wellfields to NSC and implementation of MAR at Palla Road/Chepete and Masama/Makhujwane Wellfields will not completely eliminate the risk of future water shortage. However, implementation of these scenarios may still be of significant importance in managing the water supply situation in Eastern Botswana over the next 23 years.

Based on the results of this study, we recommend the following future work:

Definition of acceptable risk for water supply shortage

To enable an analysis of the cost-effectiveness of options to increase water supply safety the goal for the improvements of the system needs to be clearly defined, i.e. an acceptable risk level has to be defined. The acceptable risk needs to be defined with respect to the acceptable number of occasions of shortage, the acceptable magnitude of shortages, and the acceptable durations of shortages.

Review of water demand forecast reliability

The performed water supply safety modelling highlights the impact of the assumed drastic increase in water demand. The NWMPR water demand “base case” forecast is used in the model, but adjusted for actual consumption 2012. According to this forecast the water demand is assumed to increase by 100 % from 2013 to 2035. The pre-feasibility study focused on the resource component of the water supply, but the results show that the certainty/reliability of the demand forecast is crucial for assessment of the probabilities of water shortage, especially for the years 10 and onwards during the 23-year simulation period.

Simulation of preliminary full-scale MAR schemes by existing groundwater models

The necessary parameters for the water supply modelling of the MAR-scenarios are derived from the results of recent studies. The preliminary outline of field tests and full-scale MAR-schemes, proposed in the pre-feasibility study, should be modelled by the existing groundwater models to confirm that the assumed maximum storages and injection and abstraction rates are possible and imply acceptable groundwater level drawdowns.

Revisions of the model to allow abstraction from the MAR-wellfields based on prognoses of water shortages

The impact of the MAR-scenarios is to some extent limited by the maximum abstraction rates from the wellfields. It is not considered realistic to increase these rates substantially above the rates used in the pre-feasibility study. However, the pre-feasibility modelling results indicate that the number of water shortages may be decreased if abstraction from the MAR-wellfields is started well before the water shortage appear. The water supply safety model should thus be revised to allow simultaneous abstraction from the dams and the MAR wellfields based on a water shortage prognosis. Rules have to be set for when to start abstracting water from the MAR-wellfields, to what extent etc. After revision the model can be used to evaluate the impact on water supply safety and the risk for groundwater mining.

Inclusion of an additional scenario in the model

In the pre-feasibility study six different scenarios were identified and analysed. According to the results it is indicated that another scenario should be of interest from both a technical and economic point of view: Current system + Dikgatlhong Dam + Masama/Makhujwane Wellfields Non-MAR + Palla Road/Chepete Wellfields MAR. It is possible that this scenario could be more cost-effective than the scenario with MAR also at Masama/Makhujwane Wellfield, i.e. provide substantial reduction in the risk for water shortage but at a considerably lower cost, maybe in combination with elimination of some other infrastructural limitations.

Identification of scenarios providing acceptable risk levels

Based on the definition of acceptable risk performed according to the first item above, the scenarios providing the desirable water supply safety among the modelled scenarios in the pre-feasibility study and the supplementary scenario proposed above, are identified.

Completion of cost estimations for all scenarios providing acceptable risk levels

Estimations of cost items related to modelled scenarios need to be completed, using the forms developed in the pre-feasibility study. Cost estimations are also necessary for upgrades of the system identified as necessary to facilitate the implementation of modelled MAR and Non-MAR scenarios. In order to provide a well-founded decision support on implementation of MAR in the NSC, comparisons of modelled scenarios with other options to improve water supply safety, e.g. connection to the Chobe River, need to be performed. It is therefore necessary to compile previously performed cost estimations of such options.

Evaluation of cost-effectiveness of scenarios providing acceptable risk levels

The aim of performing a cost-effectiveness analysis (CEA) is to provide a combined assessment of both the cost of implementing a specific measure and the effect in terms of reduced water shortage risk. The analysis is performed for the scenarios identified to provide an acceptable water shortage safety. Important steps of the CEA are to: (i) select time horizon (23 years) and discount rate; (ii) quantify investments and the streams of operation and maintenance costs over the selected time horizon for each scenario; (iii) calculate for each scenario a present value (PV) for the total cost for each scenario; and (iv) prioritize scenarios based on the relationship between increase in water safety and the total cost (PV) for each alternative, i.e. the cost-effectiveness.

Comparison of MAR-scenarios with respect to water management options

A number of management options are possible to improve the water supply safety in the NSC system, e.g. measures to reduce the water demand, including reduction of technical losses of water and implementation of water saving technologies.

Advanced course on Water Supply Safety Model

To secure knowledge transfer of the water supply safety model and to make it possible for the DWA staff to operate and develop the model in accordance with future developments of the NSC system, advanced training for future modelling experts at DWA is necessary (2-3 dedicated future operators of the water supply safety model).

Possible pilot-scale field test of MAR

The already performed pre-feasibility study and the execution of the supplementary items above will give the necessary information for evaluation of the economic viability of MAR for increased water supply safety along the NSC. Given economic viability a pilot-scale field test should be carried out. The Palla Road Wellfield seems to be the most feasible site for a first MAR field test, because of existing infrastructure. The Mahalapye Water Works has at present spare treatment capacity to allow for treatment of injection water. By upgrading of the existing pipeline from the wellfield to Mahalapye to allow for reversed flow, injection water will be available at the wellfield with only minor investments, and during the abstraction phase the water could be pumped to Mahalapye to be used for water supply. A preliminary outline for field investigations and a MAR field test with abstraction and injection of approximately 2 500 m^3/d, at least three abstraction and injection cycles, and a total duration approximately 1.5 years, was given in the pre-feasibility study as well as a form for cost estimation.

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

Water scarcity is a major challenge for sustainable development in Botswana and calls for integrated water resources management, including measures to avoid water losses, efficient use of water, introduction of water saving technologies, as well as of water re-use and recycling. Furthermore, expected climate change implies risks for rainfall seasons being shorter and less reliable in the future.

Artificial groundwater recharge (AR) is a well-established technique to increase available water quantities for water supply and to improve water quality. Water scarcity accentuated by urban growth, especially in semi-arid and arid regions, has resulted in a growing interest in AR as a basis for water supply by collection of surface water runoff for infiltration to avoid evaporation losses. Another potential purpose of AR is for re-use of water by infiltration of pre-treated storm water and sewage water. Use of underground storage of water in so called Artifical Storage and Recovery facilities (ASR) is also a measure to bridge periods of drought in perspective of climate change.

During the last years, the term "Managed Aquifer Recharge" (MAR) has often been used instead of AR, for example is the international symposium on the topic called International Symposium of Managed Aquifer Recharge (ISMAR). MAR may be defined as intentional storage and/or treatment in aquifers. The term MAR will be used in this report.

1.2 Scope and objectives of the study

The overall aim of this project is to investigate the potential for using large scale MAR to improve future water supply safety in Botswana.

This pre-feasibility study focuses on the area along the North-South Carrier (NSC), which is a bulk water supply system running from north to south in eastern Botswana, connecting a number of surface water dams, groundwater aquifers and water treatment facilities. The NSC supplies drinking water to a large portion of the Botswana population. Along the system a number of opportunities for conjunctive surface water and groundwater use exist according to a study financed by the Department of Water Affairs (DWA) within the Ministry of Minerals, Energy and Water Resources of Botswana and UNESCO (Groundwater Africa, 2012).

In order to meet the overall aim of the project, the specific objectives of the study along the NSC are to:

- Define the need for increased water supply safety.
- Assess if large-scale MAR can provide the desired increase in water supply safety.
- Assess the economic viability of MAR for provision of the desired water supply safety.

The study of the potential for MAR along NSC is divided into the following major parts:

- Evaluation of the NSC water supply system and identification components to be included in the water supply safety study.
- Development of a risk-based water supply safety model, taking into account the water demands and availability over a specified future time horizon.
- Definition of modelling scenarios, including MAR scenarios and Non-MAR scenarios.
- Modelling of the potential effects on water supply safety in the NSC from implementing MAR.
- Evaluation of the cost-effectiveness of MAR.

1.3 Project organization and implementation

The project was carried out as a collaboration between Chalmers University of Technology, Department of Civil and Environmental Engineering, in Sweden and the Department of Water Affairs of Botswana. The Swedish part of the project was financed within the Swedish International Development Cooperation Agency (Sida) policy framework programme *Partner Driven Cooperation (PDC).* The Botswana part of the project was financed by The Ministry of Minerals, Energy and Water Resources.

The project management team and its main responsibilities are shown in Figure 1.1. and Figure 1.2.

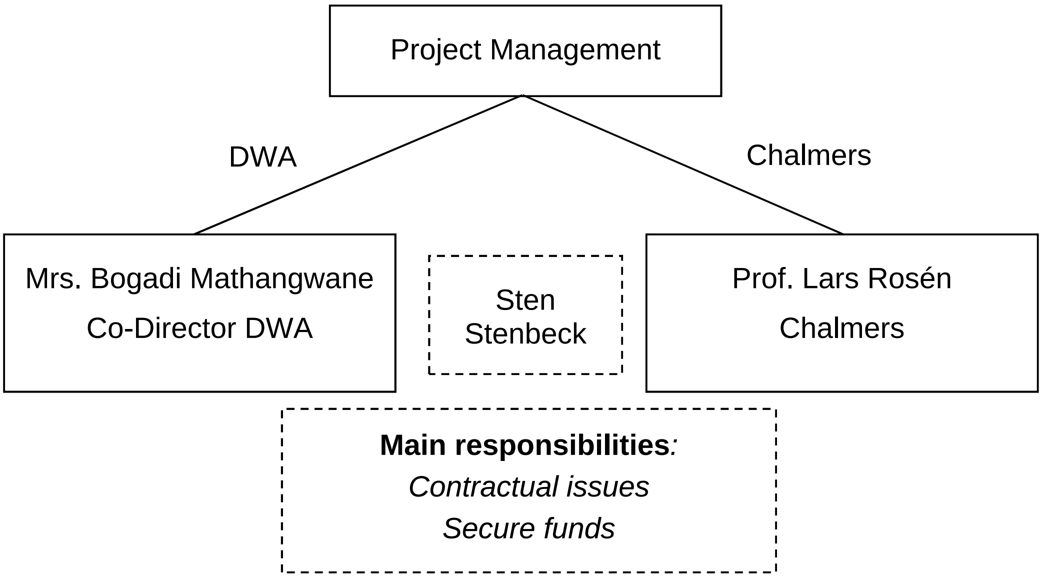


Figure 1.1. Project management.

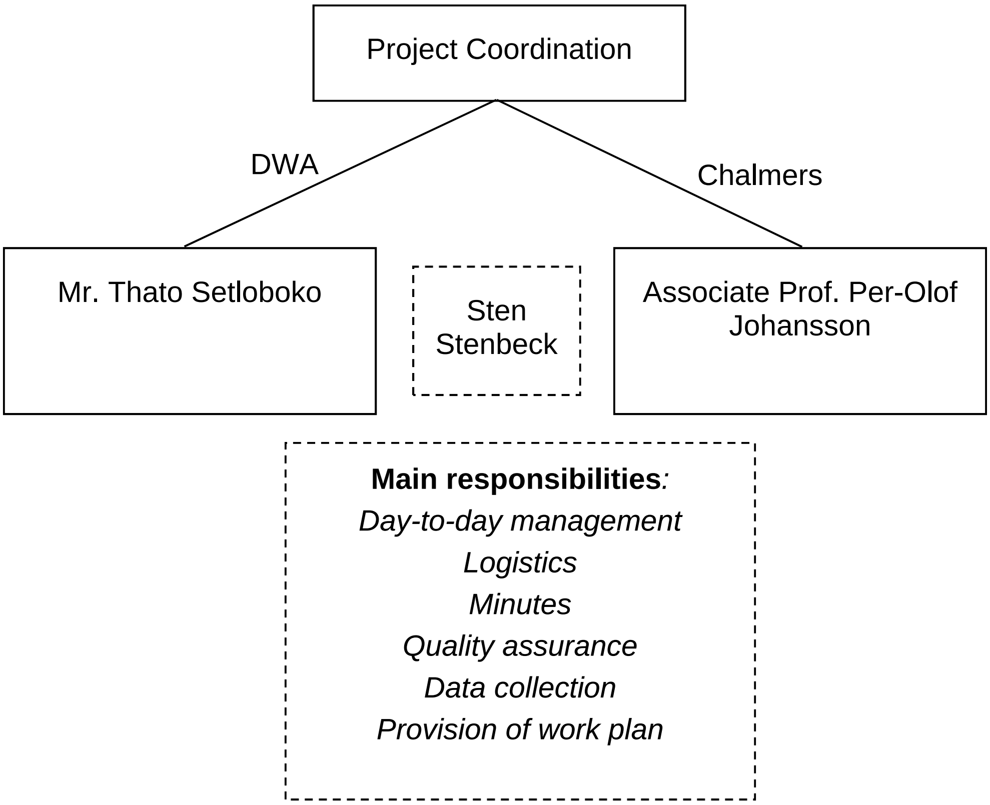


Figure 1.2. Project coordination.

Sten Stenbeck had, as a Swedish consultant based in Gaborone, the role as a facilitator.

Capacity building was an important component of the project including seminars workshops and on-the-job training on concepts, methods and conceptual design of MAR facilities as well as on water supply safety modelling.

The activity leaders appointed for the activities listed in the project work plan (see Appendix 1) are presented in Table 1.1. The role of the activity leaders were to act as contact persons, coordinate the work of the activities, and besides their own contributions to arrange for all additional contributions necessary to solve the tasks according to the time schedule of the work plan.

The project was implemented during the period of November 2012 – March 2014. The Swedish partners visited Botswana 5 times during this period.

Table 1.1. List of activities and activity leaders.

Activity	Activity Leader, Chalmers	Activity Leader, DWA
Inception phase	Prof. Lars Rosén	Mrs. Bogadi Mathangwane
Compilation and evaluation of existing data	Assoc. Prof. Per-Olof Johansson	Mr Thato Setloboko Mr Ben Morake Mr. Oakantse M. Moehadu
Development of a water supply safety model	Dr. Andreas Lindhe	Mr. Keodumetse Keetile
Identification, modelling, and comparison of alternative groundwater recharge scenarios	Assoc. Prof. Per-Olof Johansson	Mr. Thato Setloboko Mr. Oakantse M. Moehadu Mr. Ben Morake Mr. Keodumetse Keetile
Seminar and final reporting	Assoc. Prof. Per-Olof Johansson	Mr Ben Morake Mr. Thato Setloboko Mr. Oakante M. Moehadu
Capacity building	Prof. Lars Rosén	Mrs. Bogadi Mathangwane Mr Thato Setloboko Mr. Ben Morake
Evaluation of feasibility of continued cooperation and application for funding	Prof. Lars Rosén	Mrs. Bogadi Mathangwane

2 Study area – overview

2.1 Location and landscape

Botswana is located in south-central Africa and occupies an area of approximately 582 000 km^2. It borders to Namibia (to the west and north), South Africa (east and south), Zimbabwe (north-east) and a small portion of Zambia (north), see Figure 2.1.

Figure 2.1. Location of Botswana and major urban areas (DWA, 2006a).

The country is predominantly flat with some parts having a slightly rolling landscape. Botswana is dominated by the Kalahari Desert, covering about 70 % of the total area. The Okavango Delta, located in the northwest, is one of the world's largest inland deltas and with a unique wildlife habitat. The Makgadikgadi Pan is a large salt pan, in the northern part of the country.

2.2 Climate

The climate of Botswana is arid to semi-arid. There are four, although not very distinct, weather seasons in Botswana (DWA, 2006a):

- Dry/Winter season – May to August
- Rainy/Summer season – November to March
- Spring Transition or Pre-rainy period – September to October
- Autumn Transition or Post-rainy period – April

The north-east part of Botswana has an annual precipitation of about 600 mm with a variability of about 30 %, whereas the drier south-west receives, on average, only 200 mm per year, with a variability of about 80 %. Rain tends to fall in short, sometimes very intense thundershowers. Although occasional rains occur in September and October, more than 90 % of the precipitation falls in December, January and February (DWA, 2006a). Rainfalls are typically short but may last up to a few days. The rainfalls are generally interspersed with longer dry periods. Rainfalls have a high temporal and spatial variability across entire Botswana.

Due to the arid to semi-arid climate, potential evapotranspiration rates exceed the total rainfall at all times of the year (DWA, 2006a).

2.3 Surface water resources

The arid and semi-arid climate of Botswana provides a situation with low rainfall and high rates of potential evapotranspiration. Combined with the country’s generally very flat topography, this results in low rates of surface runoff and low rates of recharge to groundwater. There are no perennial streams originating in Botswana. It is estimated that mean annual rates of surface runoff do not exceed 50 mm anywhere except in small steep rocky catchments (DWA, 2006a). In the western and central parts of Botswana there is no surface runoff.

The major surface water streams in Botswana are:

- The Limpopo River with tributaries located in eastern Botswana: the Notwane, Bonwapitse, Mahalapswe, Lotsane, Motloutse and the Shashe Rivers.
- The Chobe River in the north, forming the boundary between Botswana and Namibia. The Chobe River meets with the Zambezi River at Kazungula.
- The Molopo River in the southwest, forming a border with South Africa. It is a minor tributary of the Orange River and receives most of its sporadic flows from its tributaries in the Northern Cape Province.

None of these main river systems originates wholly within Botswana. The headwaters of the Limpopo are in the vicinity of Johannesburg in South Africa. In the north-east, the Limpopo tributary Shashe River forms part of the border between Botswana and

Zimbabwe and receives tributary inflows from Zimbabwe. The Okavango River and delta receives all its waters from Angola through its two main tributaries, the Cubango and the Cuito Rivers. Similarly, the Kwando-Linyanti-Chobe system, which is tributary to the Zambezi River, receives almost all its flows from Angola.

The Makgadikgadi Pans are primarily supplied by the Nata River, which has most of its catchments in Zimbabwe. Since all of Botswana's main river systems are international, any development of the water resources of these rivers must be subject to international agreement. Also, developments in the upper basins of these rivers could have very significant impacts in Botswana (DWA, 2006a).

2.4 Groundwater resources

The National Water Master Plan Review, Volume 4 (DWA, 2006b), provides an excellent and comprehensive overview of the groundwater resources.

The annual recharge to aquifers from rainfall reaches a maximum of about 40 mm in small areas in the Chobe District in the north. For most of the Kalahari region the natural groundwater recharge is less than 1 mm/year.

Even though the natural groundwater recharge is very limited, a majority of the population relies on groundwater for their water supply. There is also competition of groundwater resources from the mining industry and from cattle farming. Due to the very limited or non-existent natural recharge, the abstracted groundwater is in many areas several thousand years old. This also means that most groundwater abstraction in Botswana has an element of "mining" and is not sustainable (DWA, 2006b).

Groundwater aquifers occur in a wide variety of geologic formations across Botswana. The majority of groundwater aquifers are located in rock formations, see Figure 2.2 and Table 2.1. Some rock formations are igneous and metamorphic with primarily secondary porosity due to fractures and joints. Other rock formations are sedimentary or slightly metamorphic, providing a higher degree of primary porosity. The largest groundwater resources are in the Kalahari sediments (including the Okavango Delta), the Ntane Sandstone, the Ecca Sandstones, and the Damaran and Ghanzi Rock Formations.

In addition to the aquifers formed in rocks, there are fluvial sand deposits along rivers, forming important aquifers. "Sand rivers" have historically been used as a water resource in Botswana. In some areas this is the only resource available. Today there are few places that rely solely on sands river deposits, although these aquifers can provide a sustainable yield in some areas. Due to the high permeability and flow porosity and being situated near the ground surface, the sand river aquifers are vulnerable to pollution incidents occurring either within the confines of the river itself or within the larger river catchment area.

DWA (2006b) presents the estimated sustainable yield of unconfined sand river aquifers. The largest aquifers are located along the Shashe, Motloutse and Ramokwebana Rivers.

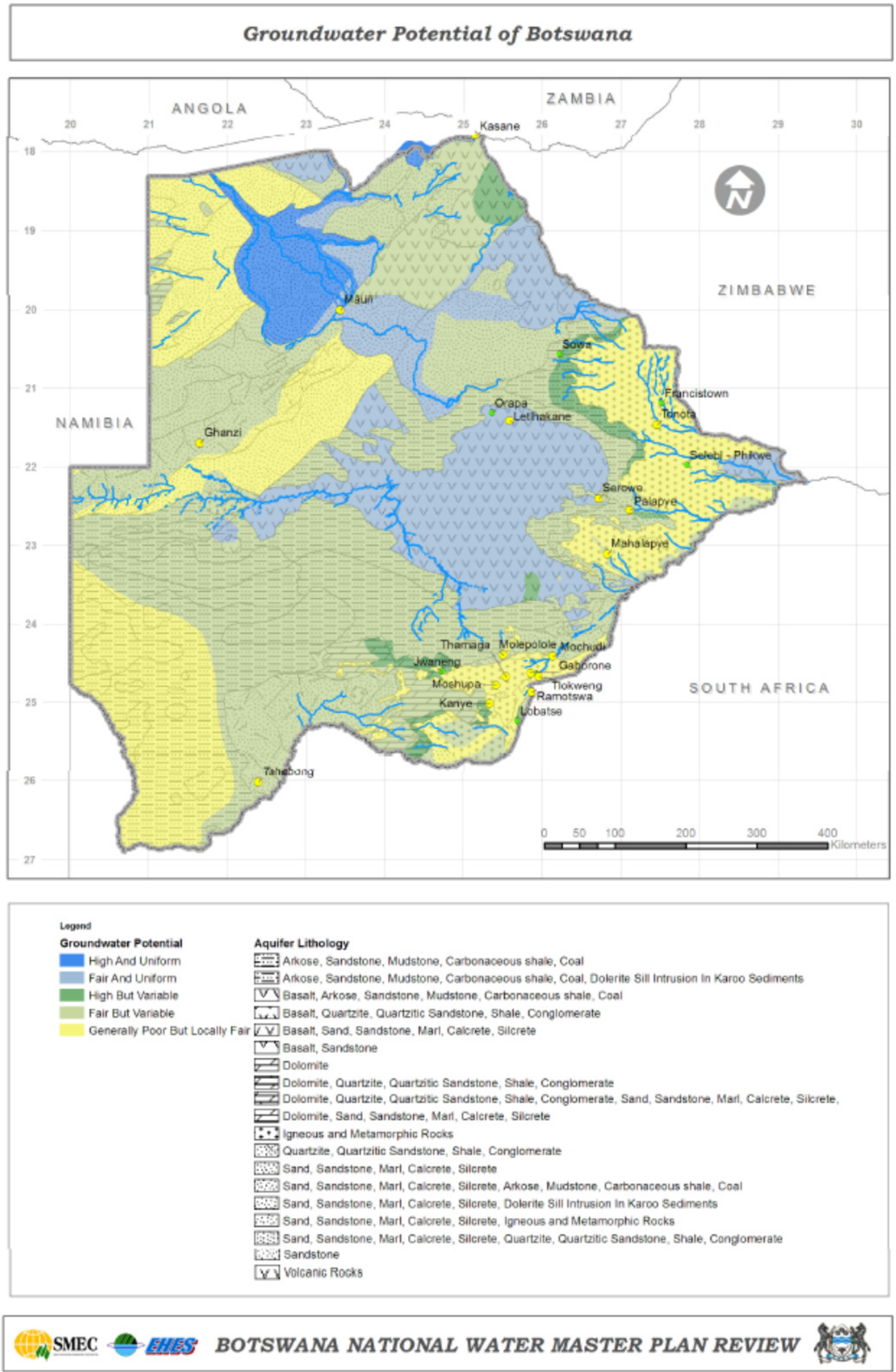


Figure 2.2. Major groundwater resources in Botswana and their potential (DWA, 2006b).

Table 2.1. Estimation of groundwater resources in Botswana (DWA, 2006b).

Aquifer	Sustainable Resource	Short Term Pumping (where appropriate) or largest estimate	Method of Quantification /Comment
Kalahari Sediments - including the Okavango Delta	47,300	N/a	This does not include Pan Handle village abstractions
Ntane Sandstone/Lebung Formation Modelled Aquifers and Wellfields Country wide assessment New areas listed in report	68,690 m^3/d 30,000 m^3/d 3,000 m^3/d	78590 m^3/d using highest GRES recharge estimate - 333,000 m^3/d 10,000 m^3/d	Computer modelled Outcrop and GRES recharge findings Potential New Areas
Ecca Sandstones Potential new areas listed in report	54,000 m^3/d 1,500 m^3/d	60,000 m^3/d 2,500 m^3/d	Computer modelled New Areas
Waterberg Palapye (Tswapong Formation) Transvaal Dolomites	3,750 m^3/d 2,400 m^3/d 13,700 m^3/d	4,750 m^3/d 7,400 m^3/d 30,900 m^3/d	Historical Data - Not computer modelled Modelled Part modelled and partly based on historical evidence
Damaran and Ghanzi Rocks	39,900 m^3/d	Not quantified	Modelled/outcrop and GRES recharge figures
Archaean Basement	Not quantified		

2.5 Population

The total population of Botswana is slightly over 2 million and one of the most sparsely populated countries in the world. The Tswana is the majority ethnic group in Botswana, making up nearly 80 % of the population. The largest minority ethnic group is the San (or Basarwa) people with approximately 55,000 inhabitants in Botswana. Other tribes are Bayei, Bambukushu, Basubia, Baherero and Bakgalagadi. In addition, there are small numbers of whites and Indians.

As described by DWA (2006a), most of Botswana's population lives in the eastern grassland region of the country, along the border with South Africa and Zimbabwe. In 2001, 87 % of the population was located in the Eastern and South-Eastern Planning Regions. The Northern Region, which includes the fertile Okavango Delta, has less than 10 % of the country's population. The Western Region, which is dominated by the Kalahari Desert, is sparsely populated.

Botswana is one of the most urbanized countries in Sub-Saharan Africa with more than half its population living in urban areas. The capital Gaborone is the largest city with a population of approximately 230,000, according to the 2011 population and housing census (Central Statistics Office of Botswana, 2011). Other major urban areas are Francistown, Selebi-Phikwe, Maun, Serowe, Mahalapye, Molopolole, Kanye, and Lobatse.

Since its independence from the UK in 1964, Botswana has had one of the fastest growth rates in per capita income in the world. Botswana has transformed itself from one of the poorest countries in the world to a middle-income country. Important sectors of the economy are mining - predominantly diamonds but also e.g. gold, uranium and copper - cattle farming and a well-functioning banking system. The headquarters of the Southern African Development Community (SADC) is located in Gaborone.

Botswana is one of the most severely hit countries in the world by the AIDS pandemic. The prevalence of HIV/AIDS in Botswana was estimated at 24 % for adults in 2006 and it was estimated that life expectancy at birth had dropped from 65 to 35 years (Kallings, 2008). However, after Botswana's 2011 census (Central Statistics Office of Botswana, 2011) the current life expectancy is estimated at 54.5 years. This revision shows the difficulty of accurately estimating the prevalence and impact of HIV/AIDS. In 2003, the government began a comprehensive programme involving free or cheap generic anti-retroviral drugs as well as an information campaign designed to stop the spread of the virus.

2.6 Water supply

Water scarcity makes water supply to inhabitants and operations in Botswana a major challenge. As the population increases and the economy grows the demand for water increases. There has been a remarkable increase in the population’s access to piped/tapped (i.e. piped indoors, piped outdoors and communal tap) since 1981 when only 56 % of the country’s population had access to piped/tapped water (DWA, 2006a). By 1991, this had increased to 77 % (52.5 % of households with access to piped/tapped water lived in Cities/Towns and Urban Villages and 24.5 % lived in Rural Areas), and in 2001 the figure was 87.7 % (56.9 % located in Cities/Towns and Urban Villages and 30.8 % in Rural Areas).

Many areas of Botswana depend on groundwater resources to which natural recharge is very low or non-existent, resulting in groundwater mining and a continuous reduction in groundwater storage. In eastern and southern Botswana, with its relatively high density of population and substantial water demand, a number of surface water dams have been constructed to collect and store rain water. The largest dams are the Shashe, Dikgatlhong, Letsibogo, and Gaborone Dams. The storages of the dams are very variable due to the highly seasonal, occasional and variable riverflows. In addition, the need to store water for drought periods and the flat topography in most areas result in large losses of water to evaporation from these dams.

Surface water dams in eastern Botswana have been connected through a pipeline transfer system denoted the North-South Carrier (NSC), providing possibilities to transfer water to urban centres and thus improving the reliability of the water supply in this part of the country. In addition to the surface water dams a number of groundwater wellfields are connected or are planned to be connected to the NSC, e.g. Palla Road, Chepete, Masama, Makhujwane, Malotwane, and Palapye Wellfields.

The demand centres, surface water dams and aquifers included in this study are shown in Figure 2.3.

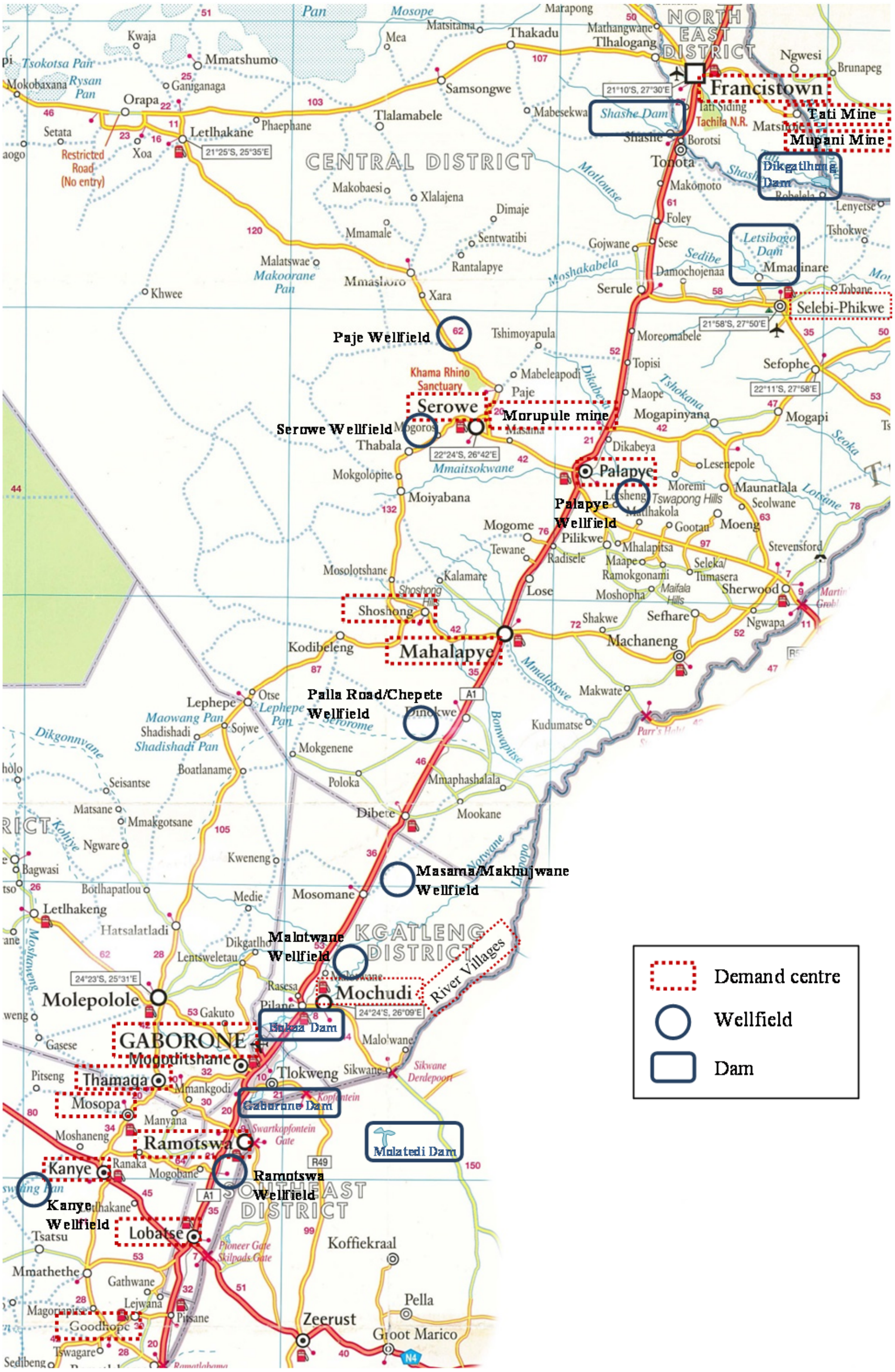


Figure 2.3. *Map showing the demand centres, wellfields and surface water dams included in this study.*

Due to the highly variable storage in surface water dams, the groundwater aquifers have a potential to support the NSC demand centres during drought periods. Because of the very limited natural recharge to these aquifers their long-term sustainable capacity could be improved if artificially recharged with surface water. Artificial recharge with collected surface water from dams may also reduce the total loss of water to evaporation.

The present study aims at investigating the potential for Managed Aquifer Recharge (MAR) as a measure to improve the water supply safety in the NSC system. The potential for artificial recharge has previously been discussed and investigated by e.g. DWA (2006b) and Groundwater Africa (2012). The current study supplements the previous studies by studying in detail the effects on water supply safety from MAR with respect to the temporal variability of water availability and predicted future demand.

3 Water supply system

In this chapter the analysed water supply system is presented to provide an overview of the system structure, included demand centres, dams, wellfields and water works. Details on input data to the water supply safety model and the model itself, are provided in Chapter 4 and 0, respectively.

This pre-feasibility study focuses on the area along the North-South Carrier (NSC) in eastern Botswana. An overview of the study area is presented in Chapter 2 and Figure 2.3 illustrates the location of the dams, wellfields and demand centres included in the system. The aim of this study is to analyse the water supply safety (i.e. the risk of water shortage events) of the North-South Carrier (NSC) in Botswana and specifically to assess the potential for Managed Aquifer Recharge (MAR) as a measure to improve the supply safety. Hence, the main focus of the analysis is to evaluate the possibility and effects of MAR-scenarios including the Palla Road/Chepete and/or the Masama/Makhujwane Wellfields.

In Figure 3.1, a schematic illustration of the water supply system is presented. In total the system included in the analysis and implemented in the water supply safety model includes:

- 6 surface water dams
    - Shashe
    - Letsibogo
    - Dikgatlhong
    - Bokaa
    - Gaborone
    - Molatedi
- 8 wellfields
    - Paje
    - Serowe
    - Palapye
    - Palla Road/Chepete
    - Masama/Makhujwane
    - Malotwane
    - Kanye
    - Ramotswa
- 18 demand centres
    - Francistown, incl. Tati Siding and Tonota
    - Tati mine
    - Mupani mine
    - Selebi-Phikwe, incl. Mmadinare, excl. Bobonong and BCL-mine
    - Palapye
    - Moropule mine
    - Serowe
    - Mahalapye, incl. Palla Road

        - Shoshong, incl. Mmutlande, Kalamare and Bonwapitse
        - Mochudi, incl. Bokaa, Oodi, Metsimotlhaba, Rasesa, Morwa, Modipane, Mmopane
        - Gaborone, incl. Tlokweng and Mogoditshane
        - Ramotswa, incl. Ramotswa stn., Mmankgodi and Manyana
        - Lobatse, incl. Mogobane and Otse
        - Kanye, incl. Lotlakane
        - Thamaga, excl. Mmankgodi and Manyana
        - Moshupa, excl. Mmankgodi and Manyana
        - River Villages, incl. Sikwane, Dikwididi, Malolwane, Mabalane, Mmathubudukwane and Ramonaka
        - Goodhope Cluster, incl. Goodhope, Kgoro, Lejwana, Gamajaalela and Gathwane
- 7 water works (WW)
    - Francistown WW
    - Selebi-Phikwe WW
    - Palapye WW
    - Mahalapye WW
    - Mmamashia WW
    - Gaborone WW
    - Mablane WW

In the northern part of the system the Shashe Dam and the demand centres Francistown, Tati and Mupani mines are situated. These parts of the system are not connected to the NSC but are included in the analysis since water from the Shashe Dam can be supplied to Selebi-Phikwe via the local water works. Hence, to make sure an accurate estimation of, for example, the possible supply from the Shahse Dam also the supply to Francistown and the mines must be considered. The northern part of the system is, however, not the main focus of this study.

The water transfer scheme denoted the North-South Carrier (NSC), makes it possible to supply bulk water from the northern parts of the system down to Gaborone as well as to other demand centres along the pipeline. Currently the only dam supplying water to the NSC is the Letsibogo Dam which also is the dedicated water source for Selebi-Phikwe. As mentioned above it is possible to supply water to Selebi-Phikwe also from the Shashe Dam.

The recently constructed Dikgatlhong Dam will be connected to the NSC and additional planned upgrading of the system also includes a new pipe from the Break Pressure Tank 1 (BPT1) down to Pump Station 3 (PS3), construction of PS4, and increased treatment capacity in the Mmamashia water works (WW). These improvements of the system will provide an increased access to surface water and an increased transfer capacity as well as treatment capacity for parts of the system.

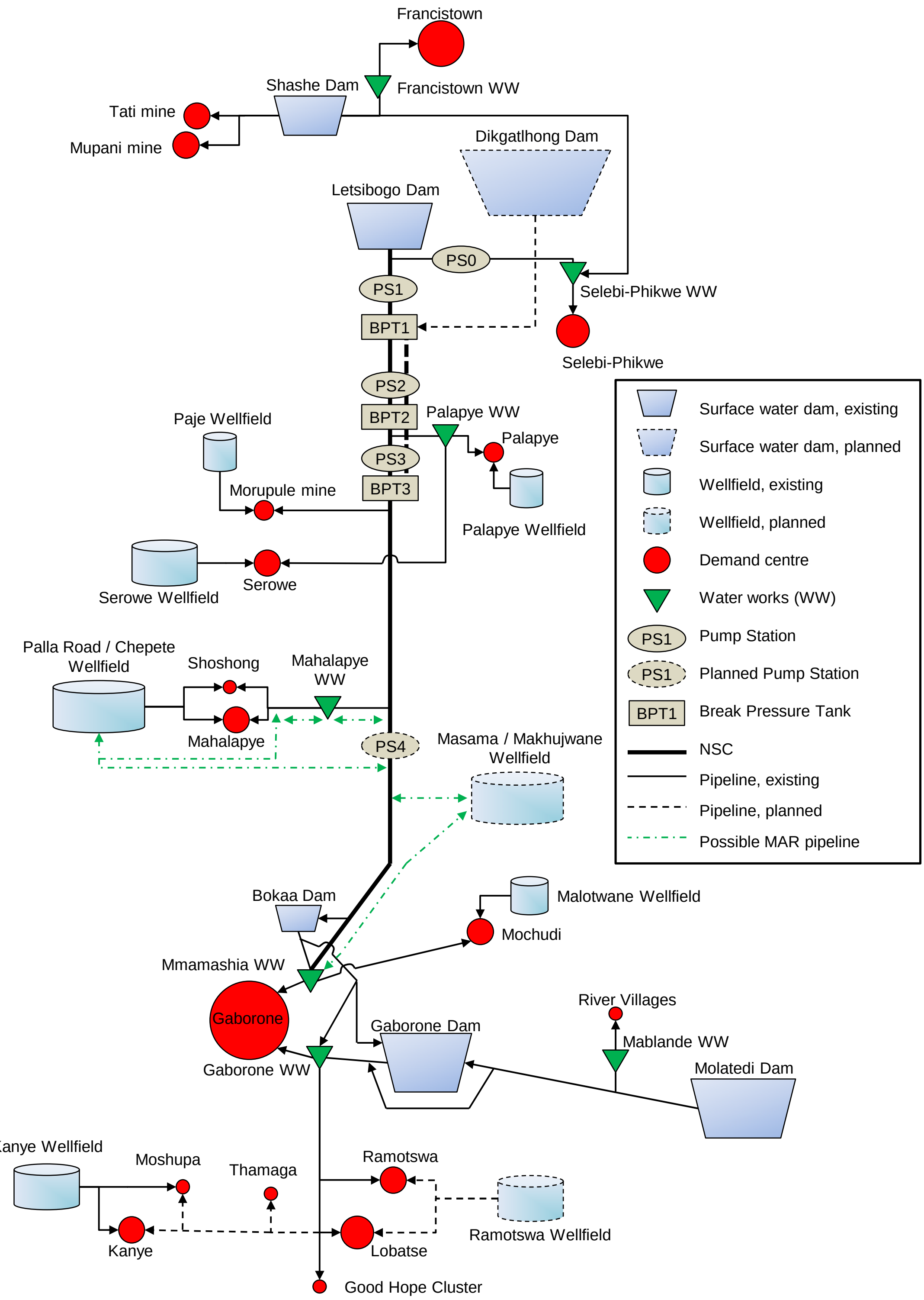


Figure 3.1. *Schematic illustration of the water supply system linked to the NSC.*

The Palapye WW is supplied with water from the NSC and the treated water is transferred to Palapye, Serowe and the Morupule mine. These three demand centres are also supplied with water from the Palapye, Serowe and Paje Wellfield, respectively. Similarly, Mahalapye and Shoshong can be supplied with water from the Palla Road/Chepete Wellfield and from the NSC via the Mahalapye WW.

Gaborone is the largest demand centre in the system and currently the demand centres Mochudi, Ramotswa, Lobatse and Good Hope Cluster are also connected to Gaborone and supplied from the two water works Gaborone and Mmamashia. The two water works jointly supply the needed water to Gaborone and the connected demand centres. The Mmamashia WW can be supplied with water from the NSC and from the Bokaa Dam. The Gaborone WW is primarily supplied with water from the Gaborone Dam and from the Molatedi Dam in South Africa. The Molatedi Dam is also the dedicated water source to the River Villages and the surplus is transferred either directly to the Gaborone WW or to the Gaborone Dam (the abstraction rate from the dam is limited and the water from Molatedi is therefore under normal operation transferred directly to the WW). It is also possible to supply water from the Bokaa Dam to the Gaborone WW and water from the NSC can be transferred to the Gaborone WW via the Bokaa Dam.

The southern part of the system will be upgraded and the demand centres Thamaga, Moshupa and Kanye will be connected to the Gaborone system. Currently Kanye and Moshupa are supplied with water from the Kanye Wellfield, which still will be included in the system after the new connections. Furthermore, the Ramotswa Wellfield will be connected to supply water to Ramotswa and Lobatse. Currently also the Malotwane Wellfield is included in the system and can be used water to Mochudi but no other demand centres.

This pre-feasibility study is focused on the possibility of using the Palla Road/Chepete and Masama/Makhujwane Wellfields for MAR in order to increase the water supply safety. Currently the Palla Road Wellfield is used for water supply to Mahalapye and Shoshong. The Masama Wellfield is currently not in use but the plan is to use the wellfield for emergency water supply (i.e. abstraction exceeding the sustainable yield for periods and rely on natural recharge for recover).

4 Data compilation and evaluation

4.1 Present and future water demand

The public water demand centres to be included in the study and in the water supply safety modelling were identified, discussed and agreed upon in workshops with representatives of DWA, WUC and Chalmers. The demand centres are listed in Table 4.1 and their location and position in the water supply system are shown in Figure 2.3 and Figure 3.1, respectively.

Table 4.1. Public water supply demand centres included in the study and in the water supply safety modelling, and the actual water consumption of 2012 (data supplied by WUC).

Demand centre	**Water consumption 2012 (Mm3/year)**
Francistown	12.87
Selebi-Phikwe, incl Mmadinare	6.40
Palapye	1.49
Serowe	2.84
Mahalapye	3.00
Shoshong	0.54
Mochudi	3.13
Gaborone	28.88
Ramotswa, incl. Ramotswa stn., Mmamankodi, Manyana	2.85
Lobatse	4.70
Kanye	3.44
Thamaga	0.80
Moshupa	0.59
River Villages	0.23
Good Hope Cluster	0.31
TOTAL	**72.08**
TOTAL (Ml/d)	**197.47**
TOTAL (m3/d)	**197 473**
TOTAL (l/s)	**2 286**

The National Water Master Plan Review (NWMPR) "base case" is used for the water demand forecast for 2013-2035 (DWA, 2006c). In the NWMPR the CSO population forecast of 2001, revised May 2005, is used as a basis for the demand forecast. The "base case" includes assumptions on rate in changes from stand pipe to yard and yard to house connections. The assumed industrial, commercial and institutional annual growth rate is 3 %. Unaccounted for water (UFW), including technical losses and non-technical losses (unmetered consumption and illegal connections), is included in the forecast. For more details on the water demand forecast see DWA (2006c). The demand centres were defined slightly different in the NWMPR compared with how they are defined in the present study. The NWMPR-data have been re-grouped to represent the present demand-centre definitions, see Chapter 3 for demand centre specifications.

The original data used in the water supply modelling were taken from an Excel-file supplied by WUC, hec5dataphase1B.xls. This file was used in the WATHNET-modelling performed in the NWMPR (DWA, 2006d, e).

From Table 4.1 it can be seen that the actual water consumption 2012 deviates from the NWMPR demand forecast for the same year. Two revised demand forecasts were calculated for the water supply safety modelling based on the original NWMPR forecast: (i) the deviation between the actual consumption and the forecast of 2012 in m^3 was used for adjustment of the demand values 2013-2035, and (ii) the deviation between the actual consumption and the forecast of 2012 in % was used for the demand adjustment of the demand values of 2013-2035. In the model it is optional to use the original, m^3-adjusted or %-adjusted water demand forecasts. In Table 4.2 the three different water demand forecasts are presented.

Table 4.2. The original NWMPR water demand forecast and the m^3- and %-adjusted forecasts based on actual water consumption in 2012.

Demand centre	2012 actual	2012 orig. forecast	2035 orig. forecast	2035 m3-adjusted	2035 %-adjusted
Francistown	12.87	12.71	30.83	31.59	31.21
Selebi-Phikwe, incl. Mmadinare	6.40	9.05	19.90	17.25	14.08
Palapye	1.49	1.32	2.06	2.23	2.32
Serowe	2.84	1.93	2.85	3.77	4.20
Mahalapye	3.00	2.52	4.79	5.27	5.71
Shoshong	0.54	0.32	0.66	0.88	1.11
Mochudi*	3.13	2.46	3.91	4.57	4.96
Gaborone*	28.88	34.96	60.88	54.79	50.42
Ramotswa, incl. Ramotswa stn., Mmamankodi, Manyana*	2.85	1.57	2.59	3.87	4.69
Lobatse*	4.70	4.95	12.24	11.99	11.62
Kanye*	3.44	2.23	3.40	4.61	5.25
Thamaga*	0.80	0.88	1.27	1.20	1.16
Moshupa*	0.59	0.86	1.23	0.97	0.86
River Villages	0.23	0.15	0.15	0.23	0.24
Good Hope Cluster*	0.31	0.13	0.20	0.37	0.47
TOTAL (Mm3/year)	**72.08**	**76.03**	**146.95**	**143.60**	**138.30**
TOTAL (Ml/d)	**197.47**	**208.31**	**402.60**	**393.41**	**378.91**
TOTAL (m3/d)	**197 473**	**208 310**	**402 596**	**393 414**	**378 911**
TOTAL (l/s)	**2 286**	**2 411**	**4 660**	**4 553**	**4 386**

*Included in "Gaborone and connected demand centres", referred to in Ch. 7

It was decided to use the m^3-adjusted demand as the "base case" in the modelling, but to make sensitivity tests with the other demand forecasts. The full monthly water demand time series are included in the Water Supply Safety Model delivered on CD together with the present report.

Besides the public water supply, the water demand of the Morupole, Tati and Mopani Mines are included in the water supply modelling. In the modelling, the supply to Morupole was kept constant at 4 000 m^3/d and to the Tati and Mopani Mines together a constant supply of 20 000 m^3/d was assumed.

4.2 Identification of aquifers/wellfields suitable for MAR

In the inception phase it was agreed to focus the study on the area along the NSC, to explore the opportunities for conjunctive surface water and groundwater use by MAR.

In a recent study financed by DWA and Unesco (Groundwater Africa, 2012*)* aquifers (existing wellfields) potentially of interest for artificial recharge along the NSC were identified and rough estimates were made of possible recharge and abstraction rates. The estimates were based on the assumption that the aquifers can be pumped 2-4 years at a rate of 2-4 times the maximum historic or estimated yield of the existing wellfields. The results of the study are summarized in Table 4.3. It is stressed in the report of the study that figures are given as very first estimates.

Table 4.3. Maximum wellfield yields with MAR according to (Groundwater Africa, 2012).

Wellfield	Wellfield yield (Mm3/year)	Comment	2-year supply		4-year supply	
			2 x wellfield yield (Mm3)	4 x wellfield yield (Mm3)	2 x wellfield yield (Mm3)	4 x wellfield yield (Mm3)
Palapye	1	max. historic yield	4	8	8	16
Palla Road	2	max. historic yield	8	16	16	32
Masama	9	max. rec. yield	36	72	72	144
Malotwane	0.45	max. prodn. yield	1.8	3.6	3.6	7.2
Gaotlhobogwe	2	modeled prodn. yield	8	16	16	32
Ramotswa	1.8	est. sustainable yield	7.2	14.4	14.4	28.8
Serowe	0.57	est. sustainable yield	2.3	4.6	4.6	9.1
Kanye	3	est. sustainable yield	12	24	24	48

For short descriptions of the hydrogeology of the aquifers/wellfields, the reader is referred to Groundwater Africa (2012).

The study referred to above, where DWA staff was actively involved in supplying hydrogeological information, was used as the starting point for identification of the aquifers to be included in the water supply modelling.

Additional information and reports on the wellfields were supplied from DWA, DGS and WUC to the Chalmers team for review (GCS, 2000; GCS, 2006; WCS, 2007; ERM, 2007; Geo World, 2009; WSB, 2008; WSB, 2010a b; WRC, 2012; WRC, 2013a, b).

From the review of the reports and the knowledge and experience from the wellfields of the DWA, DGS and WUC staff, shared at workshops, additional information on sustainable yield of the aquifers considered of interest for MAR was compiled, see Table 4.4.

Table 4.4. Compilation of sustainable yield estimates of aquifers/wellfields identified as of interest for MAR by water from NSC and to be included in the water supply safety modelling.

Wellfield	DWA/Unesco report, Mm3/year (Groundwater Africa, 2012)	WATHNETmodelling, Mm3/year (NWMPR, vol. 11, 2006)	Demand cluster report Mm3/year (WSB, 2008)	Other_sources, Mm3/year	Source spcifikation	Selected value for the water supply safety modeling, Mm3/year	Comment
Paje		0.73	0.70				Demand Cluster: Expanded 2.0 Mm3/year
Palapye	1.00	1.83	0.70			0.70	Demand Cluster: High 1.1 Mm3/year
Serowe	0.57	2.12	1.83			1.83	Demand Cluster: Developed 2.12Mm3/year
Palla Road	2.00	1.50	1.50	3.77	WRC Modelling Rep., 2013	3.20	Other sources: WRC estimate incl. Chepete and Kudumatse. WCS, 2007, estimates recharge to 1.71 Mm3/year for the same area. Rough estimate is that 85% of recharge can be used in Palla Road/Chepete
Chepete		2.19	1.46				Demand Cluster: High 2.19 Mm3/year
Masama	9.00	1.95		1.26	Geo World Modelling Rep., 2009	1.26	DWA/Unesco: Incl. Makhujwane. DWA, 1999: 2.81 Mm3/year. HCL, 2007: 1.02 Mm3/year. All for Masama incl. Makhujwane.
Makhujwane		0.37					
Malotwane	0.45		0.18			0.20	Demand Cluster: Up to 0.35 Mm3/year may be sustainable
Gaotlhobogwe	0.50	2.67	2.67	<2	WSB Modelling Rep., 2010	1.00	Unesco: High 1.0 Mm3/year. WSB, 2010: 2.1 Mm3 gives a drawdown of up to 29 m in 15 years. Over total model area 10.31 Mm3 (incl. Jwaneng Northern Wellfield)
Kanye	3.00	2.52	3.00			2.00	Demand Cluster comm: Known to be unsustainable
Ramotswa	1.80	1.83	1.83			1.80	
Jwaneng Northern		10.95					WATHNET: sustainable for 40 years. but means mining

	Max historic yield		Incl. Chepete
	Max. production yield		Incl. Makhujwane
	Max. rec. yield		
	Wellfield 2		

Based on preliminary assessments of the potential for MAR from a hydrogeological point of view, existing infrastructure and location in the NSC system, it was decided to include MAR-scenarios for Palla Road/Chepete and Masama/Makhujwane Wellfields in the water supply safety modelling. As can be seen from Table 4.4 also the Ramotswa and Kanye wellfields were considered to have a good potential for MAR. However, at this stage is was decided not to include these aquifers in the modelling due to potential risks for problems to control groundwater flow formed by injection and abstraction in the dolomite aquifers, but also due to the transboundary character of the aquifers.

Below a short description of the hydrogeology of Palla Road/Chepete and Masama/Makhujwane Wellfields are given. For more information on the hydrogeology see e.g WCS (2007), Geo World (2009), WRC (2012), and WRC (2013a, b).

4.2.1 Palla Road/Chepete Wellfields

Palla Road and Chepete Wellfields are located c. 160 km north of Gaborone, see Figure 2.3. The hydrogeological description below is based on the recent Post-Auditing of the Palla Road Ground Water Model (WRC, 2013a and b). The new model area also includes the proposed CIC Energy Wellfield in the Kudumatse area, east of Palla Road Wellfield, and covers an area of c. 3 700 km^2.

Geology, hydrostratigraphic units and Ntane Sandstone Aquifer characteristics

The geology of the area is shown in Figure 4.1 and a NW-SE hydrogeological cross-section in Figure 4.2. The main aquifer in the area is the Ntane Sandstone. The aquifer is compartmentalised due to block faulting, where the lateral continuity has been interrupted due to vertical movements. There is a hydraulic connection between the blocks along the faults where they occur in juxtaposition. Over large areas the Ntane Sandstone is overlain by the Stormberg Basalt. In these parts the Ntane Aquifer is confined, while it is generally unconfined in areas where the basalt is missing. The average thickness of the Ntane Aquifer is c. 120 m and it is underlain by the Mosolotsane Formation (siltstone and fine sandstone), which separates the Ntane Aquifer from the Ecca Group deposits. The developed numerical model comprises four layers roughly representing (1) the Stormberg Basalt and the overlaying Kalahari Group Sediments, (2) the Ntane Sandstone, (3) the Mosolotsane Formation, and (4) the Ecca Group deposits.

The Ntane Sandstone is a double porosity aquifer, i.e. water is stored both in the matrix and in the factures. Transmissivity is in relative terms higher in areas where the aquifer is heavily fractured and the sandstone less cemented. Storativity values are in the range of $5 \cdot 10^{-5}$ to 0.03, whereas transmissivity values generally vary between 10 and 3 300 m^2/d (geometric mean 43 m^2/d). The depth to water strike is in the range of 24 to 264 m (average 130 m). Borehole yields vary between 8 and 100 m^3/hr with an average yield of 34 m^3/h.

Regional groundwater flow and model boundaries

The regional groundwater flow in the area is from NW to SE, following the general topography and also some of the major faults of the area. A groundwater level contour map of the Ntane Aquifer is shown in Figure 4.3, together with the model area of the new numerical groundwater model developed in WRC, 2013a.

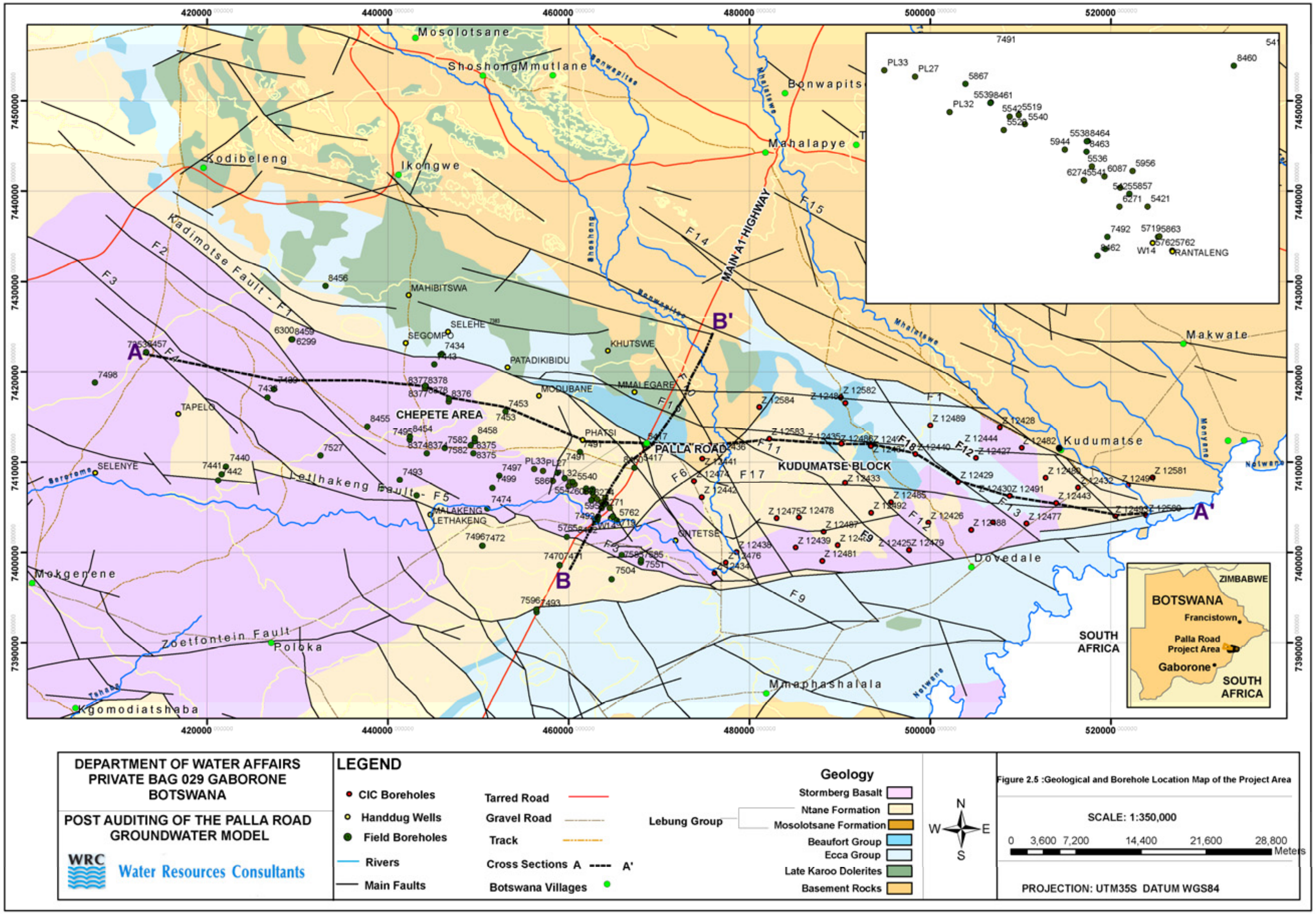


Figure 4.1. The geology of the Palla Road, Chepete and Kudumatse areas (WRC, 2013a).

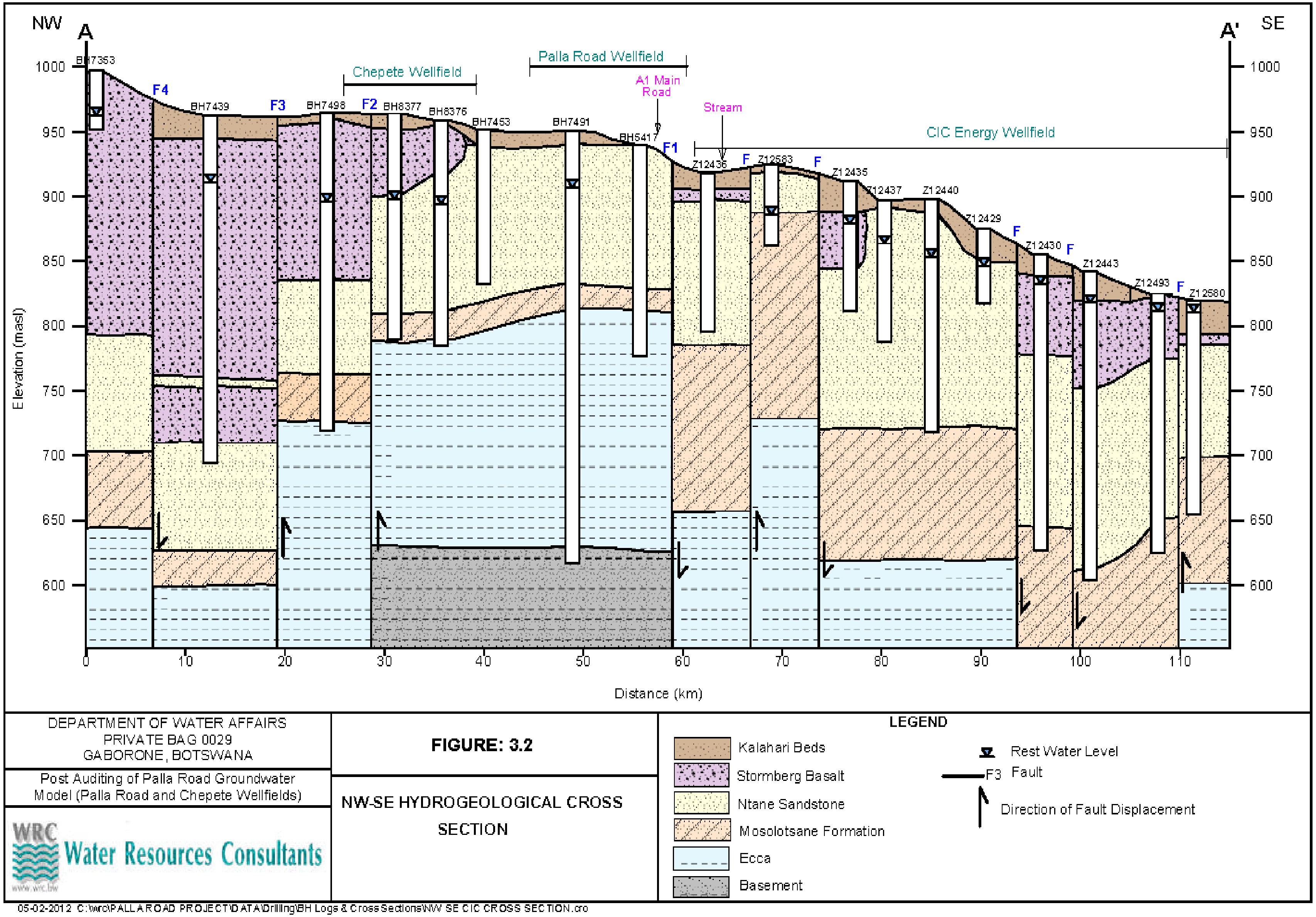


Figure 4.2. NW-SE hydrogeological cross-section (A-A´) of the Palla Road, Chepete and Kudumatse areas (WRC, 2013a). See Figure 4-1 for the location of the profile.

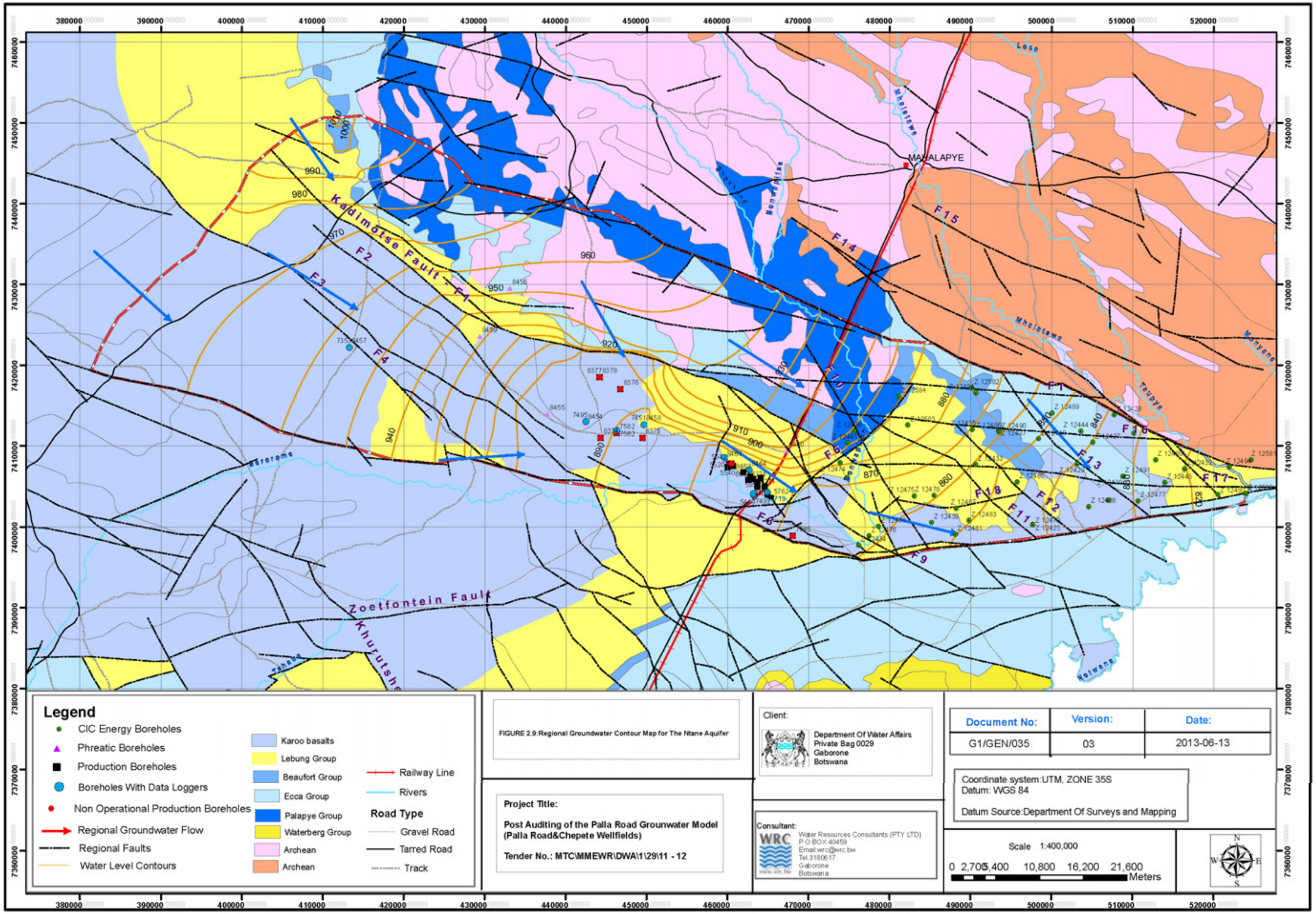


Figure 4.3. Groundwater level contour map of the Ntane Aquifer and the model area of the WRC numerical model (WRC, 2013a).

The western boundary of the model area is located along the topographical water divide of Serorome River and considered as a no-flow boundary. The northern boundary of the model domain is also set as a no-flow boundary, but associated with the Mahalapye Fault and the contact zone with the Karoo sediments and the Archean basement. The south-western boundary runs along the Letlhakeng Fault and the F3 fault until it merges with the Zoetfontein Fault and is considered as a no-flow boundary as well. The southern boundary is set as an inflow boundary to reflect observed water levels, while the south-eastern and eastern boundaries along the Zoetfontein Fault and Taupye River in the modelling was set as general head boundaries to allow groundwater flow across the fault and to the river.

Groundwater recharge and discharge

The groundwater recharge in the model area has been estimated in several previous studies and the recharge values used in the new modelling were based on these studies, with recharge values varying between 0.2 and 5 mm/year. The higher values are set in areas where the Ntane Sandstone outcrops or is not covered by basalt. Groundwater discharge takes place to non-perennial rivers, baseflow towards the Limpopo/Taupye river system and regional groundwater flow across the Zoefontein Fault.

Water budget

The water budget for the steady-state calibration of the new numerical model (WRC, 2013a) is presented in Table 4.5.

Table 4.5. Water budget for the steady-state calibration of the new numerical model of the Palla Road, Chepete and Kudumatse areas (WRC, 2013a).

Direct recharge into the model domain	+12 383 m3/d
South-easterly outflow towards the Serorome Valley and the Zoetfontein Fault	- 8 870 m^3/d
Easterly outflow towards the Limpopo/Taupye river system	- 3 433 m^3/d
Discharge to non-perennial rivers within the central model region	insignificant

Water quality

In the post-auditing of the Palla Road groundwater model, water samples were taken for chemical analysis in 10 production wells in Palla Road and compared to previous analyses from 1980´ies and 1990´ies. The analyses show that the Ntane Aquifer has fresh water with TDS (total dissolved solids) ranging from 107 to 663 mg/L and the majority of the parameters fall within Class I of the Botswana drinking water standard (BOS 32:2009). The exceptions are a chloride value above 200 mg/L (213 mg/L) in one of the well and manganese values above 0.1 mg /L in four of the wells (max. 0.48 mg/L). Sodium concentrations varies between 7 and 60 mg/L and calcium varies between 4 and 58 mg/L, while alkalinity and sulphate are in the range of 34-195 and 0.13 and 22 mg/L, respectively.

The water quality has been approximately the same over the last 20 years, with exception of three boreholes, where TDS increases by a factor 3-4. The interpretation of the increase is that water has been drawn from the Ecca Aquifer due to heavily increased pumping and it is recommended to reduce the abstraction rates and to monitor the water quality regularly.

Modelling scenarios used as basis for the water supply safety modelling

After calibration, the Post-audit Palla Road Wellfield Groundwater Model (WRC, 2013a) was used for predictive modelling of selected abstraction scenarios. One of these scenarios (1c) and the results from the simulations were used to derive necessary input data to the MAR-scenario of the Palla Road/Chepete Wellfields in the water supply safety modelling.

In Scenario 1c of the WRC-report abstraction of c. 14 200 m^3/d was simulated from 18 wells in the Palla Road Wellfield (15 existing and 3 new boreholes, total abstraction 11 740 m^3/d) and 6 existing wells in the Chepete Wellfield (total abstraction 2 488 m^3/d) for six years with 16 hours daily duty cycles and with intermittent recovery of six years. During a 6-year cycle of pumping, the total abstraction was 31.2 Mm^3 compared with the natural groundwater recharge of 27.1 Mm^3 (based on the average annual recharge of 12 383 m3/d, see water budget above).

The outflow to Serorome Valley/Zoetfontein Fault decreased from 7 246 m^3/d during the first year of the first simulated cycle to 4 544 m^3/d during the sixth year of the first cycle. The outflow to the Taupye/Limpopo River system was practically constant at 3 433 m^3/d during the cycle and not influenced by the pumping according to the simulation. In total, the groundwater outflow during the first six-year cycle was 20.0 Mm^3. This means that the groundwater storage was depleted by 31.2+20.0-27.1=24.1 Mm^3 during the first six-year cycle. This depletion resulted in a simulated cone of depression (2 m cut-off value) extending c. 9 km to the east of the Chepete Wellfield and c. 18 km to the south-east of the Palla Road Wellfield. Boreholes in the Palla Road Wellfield showed drawdowns of 9-11 m, in the Chepete Wellfield c. 7 m, and in a borehole midway between the wellfields c. 9 m.

In the water supply safety modelling it was assumed that the aquifer should be recharged to its groundwater levels of Jan. 1, 2012, which was the start date for the post-audit groundwater modelling. The storage depletion during the simulation period 2012-2018, was 26.2 Mm^3 (adding deficit due to actual abstraction 2012 to the 24.1 Mm^3 of the 2013-2018 cycle). Since the simulated drawdowns in the aquifer after the first cycle were considered acceptable, 26.2 Mm^3 was chosen as the active storage in a baseline MAR sub-scenario for Palla Road/Chepete Wellfields in the water supply safety modelling. The initial storage was set to 24.0 Mm^3.

In the Draft Final Modelling Report of the Post-audit of the Palla Road Groundwater Model (WRC, 2012), a scenario, 1d, was presented that was left out in the final report. This scenario was the same as 1c, presented above, with the exception that the boreholes were pumped 24 h daily. Based on the 1d scenario, but with minor adjustments of natural recharge, groundwater outflow and abstraction rates according to the final modelling, the storage depletion after the first 6-year cycle of pumping was 40.6 Mm^3 after a daily total abstraction rate of c. 21 300 m^3/d. This depletion, according to the modelling, gave maximum drawdowns of more than 20 m in the central part of the Palla Road Wellfield. The implications of such high abstraction rates and large storage depletion have to be evaluated in detail. However, it was decided to include such a scenario in the water supply safety modelling as an extended MAR sub-scenario for the Palla Road/Chepete Wellfields.

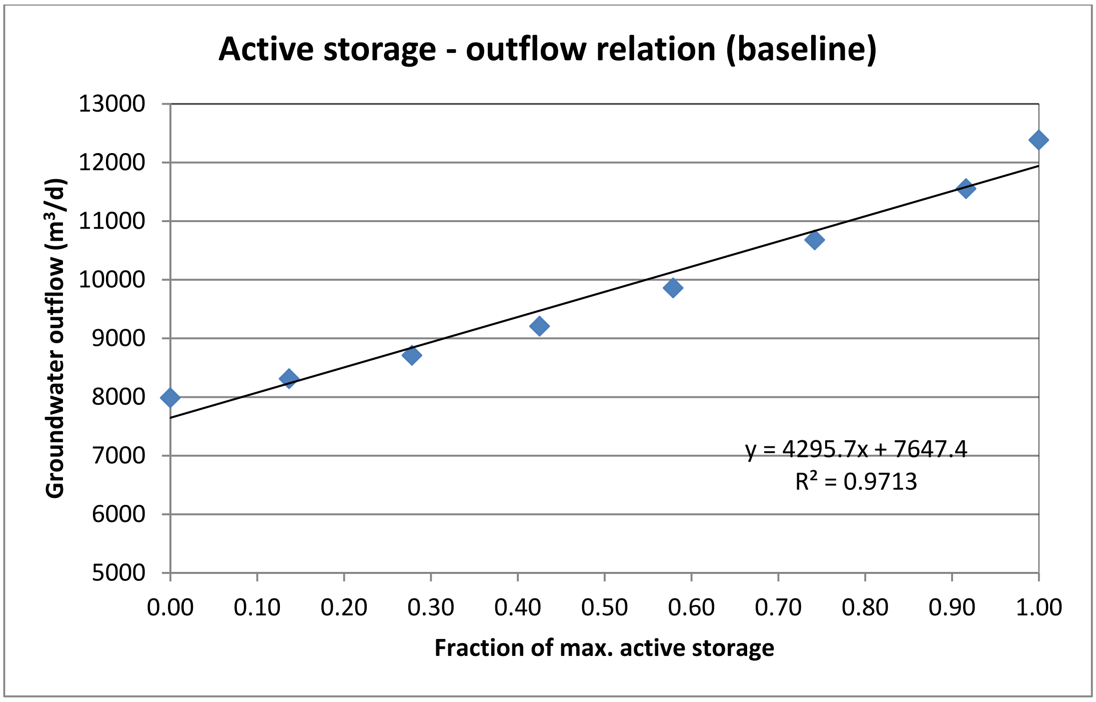
For more information on the post-audit groundwater modelling of the Palla Road Wellfield, including Chepete Wellfield and the Kudumatse area, the reader is referred to WRC (2012, 2013a, and 2013b).

The input data needed for the water supply safety modelling derived from the post-audit of the Palla Road Groundwater Model are summarized in Table 4.6 and Figure 4.4.

Table 4.6. Input data for the water supply modelling derived from the post-audit of the Palla Road Groundwater Model (WRC, 2012 and WRC, 2013a).

	Palla Road/Chepete, baseline	**Palla Road/Chepete, extended**
Maximum active storage (Mm^{3})	26.2	42.8
Initial storage (Mm^3)	24	40.5
Natural groundwater recharge (m^3/d)	12 383	12 383
Groundwater inflow (m^3/d)	0	0
Groundwater outflow (m^3/d)	see Figure 4.4	see Figure 4.4
Maximum abstraction and injection rates (m^3/d)	14 228	21 342

From Figure 4.4, it can be seen that, according to the groundwater modelling, the active storage - groundwater outflow relationship for the groundwater outflow in the south-east is very similar during the six-year cycle for the two sub-scenarios although the abstraction, and also the active storage is 50 % higher in the extended sub-scenario compared to the baseline sub-scenario.



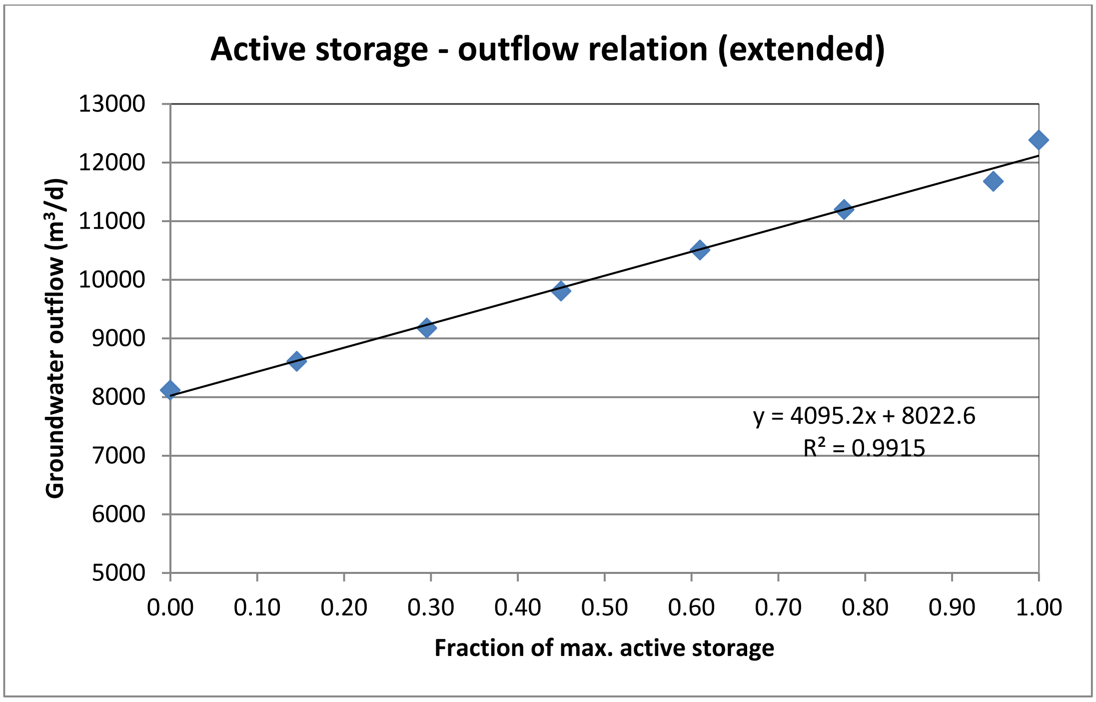


Figure 4.4. *Active storage-groundwater outflow relationships for Palla Road/Chepete Wellfields baseline and extended MAR sub-scenarios derived from the post-audit of the Palla Road Groundwater Model (WRC, 2012 and WRC, 2013a).*

4.2.2 Masama/Makhujwane Wellfields

The Masama and Makhujwane Wellfields are located c. 100 km north of Gaborone, see Figure 2.3. The hydrogeological description below is based on groundwater modelling report of the Masama Groundwater Resources Evaluation Project (Geo World, 2009). The modelling was performed in connection to the drilling of new boreholes in the Masama and Makhujwane Wellfields.

Geology, hydrostratigraphic units and Ntane Sandstone Aquifer characteristics

The geology of the area is shown in Figure 4.5 and a S-N geological cross-section in Figure 4-6. A number of structural features in the form of faults are present in the area, e.g. the Khurutshe fault and the Makhujwane Fault, see Figure 4.5 and Figure 4.6. Along the faults the vertical displacement has been up to more than 200 m. The hydrostratigraphic units in the area are: Kalahari Group Sediments, Stormberg Basalt, Ntane Sandstone, Mosolotsane/Tlhabala Mudstone Units, Ecca Group Deposits (alternating argillaceous and arenaceous units). The Waterberg Group occurs south of the area and forms a geologic contact with the Ntane Sandstone along the Seswane Fault (see Figure 4.5).

Like in the Palla Road/Chepete area, the Ntane Sandstone is the main aquifer. The Ntane Sandstone is compartmentalised due to block faulting and lateral continuity has been interrupted due to vertical movements. Where the vertical displacement has been large, like at the Makhujwane Fault, the direct hydraulic connection between the Ntane Sandstone blocks has been interrupted. Also like in the Palla Road/Chepete area, Stormberg Basalt is overlaying the Ntane Sandstone in large areas. The thickness of the Stormberg Basalt is more than 300 m in parts of the Makhujwane Wellfield, south of the Makhujwane Fault, while the Ntane Sandstone is outcropping in parts of the Masama Wellfield, north of the fault. In areas where the Ntane Sandstone is overlain by the Stormberg Basalt, the aquifer is confined, while it is generally unconfined in areas where the basalt is missing. The average thickness of the Ntane Aquifer in the Masama and Makhujwane Wellfields is in the range of 100 to 160 m. The Ntane Sandstone it is underlain by the Mosolotsane/Tlhabala Mudstone Units which separates the Ntane Aquifer from the Ecca Group Deposits.

The Ntane Sandstone is a double porosity aquifer, i.e. water is stored both in the matrix and in the factures. The transmissivity is relatively higher in areas where the aquifer is heavily fractured and the sandstone less cemented. According to the results of pumping tests, most of the storativity values are in the range of $1 \cdot 10^{-4}$ to 0.02, while transmissivity values are in the range of 1.5 to 735 m^2/d. The water strikes in the Ntane Sandstone is mostly encountered in the top part of the aquifer, in the “baked” heavily factured sandstone in contact with the basalt. Borehole yields as high as 160-200 m^3/hr have been obtained in the Masama Wellfield. In the calibrated numerical model, the transmissivity values are in the range of 2-165 m^2/d, with some small narrow W-E-stretching zones with values as high as 250 m^2/d.

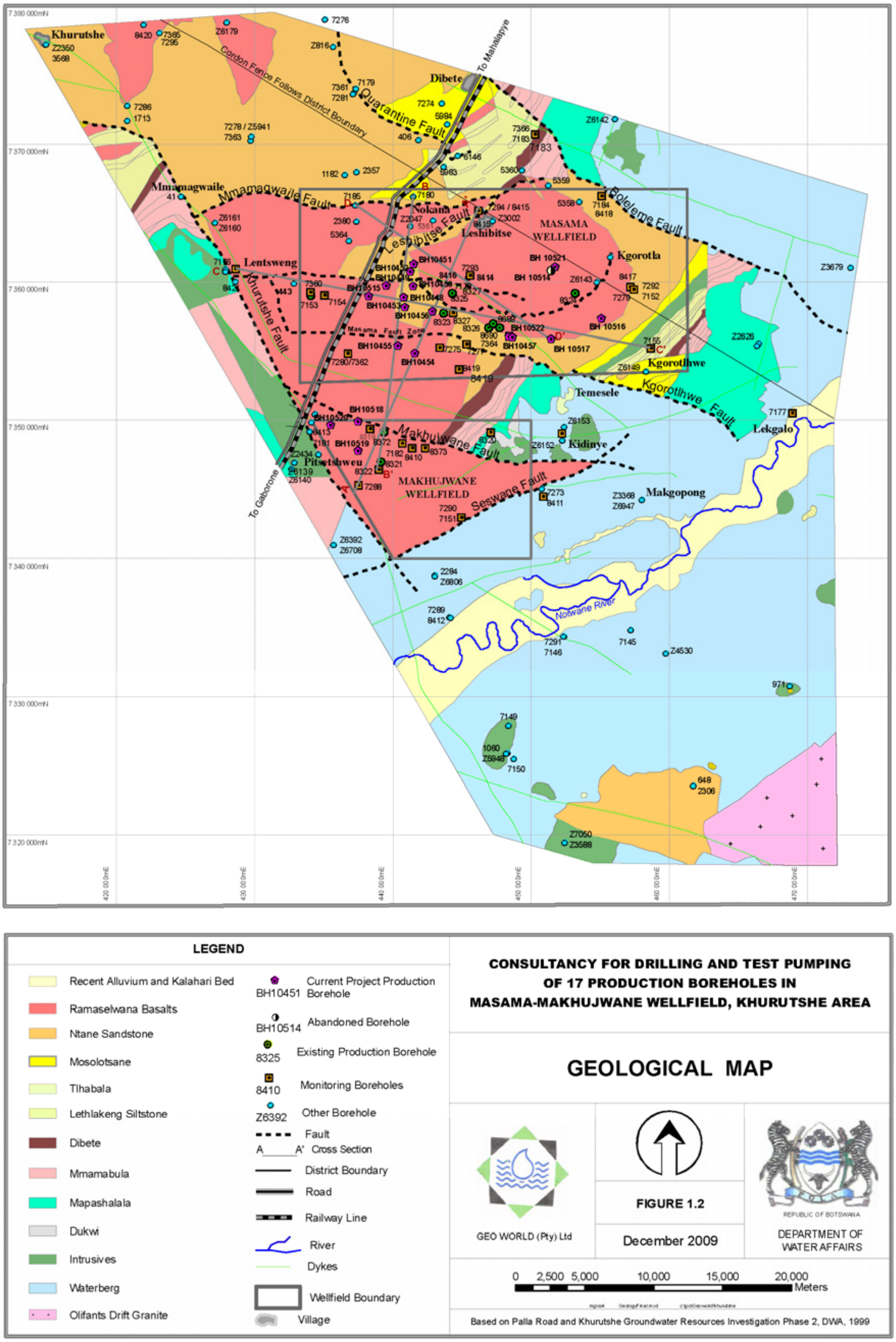


Figure 4.5. The geology of the Masama/Makhujwane Wellfields, Khurutshe area (Geo World, 2009).

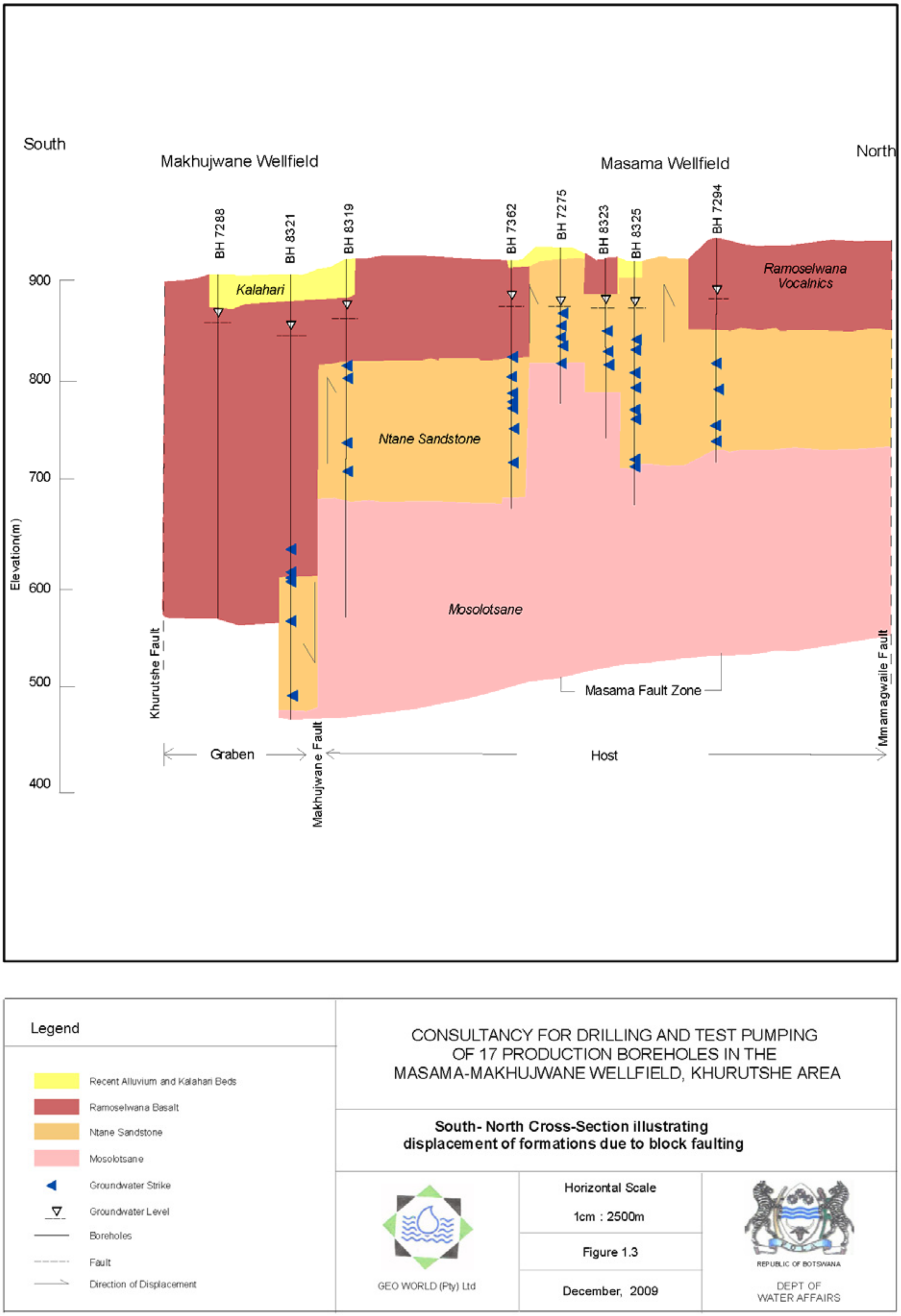


Figure 4.6. S-N hydrogeological cross-section (A-A´) of the Makhujwane and Masama Wellfields (Geo World). See Figure 4-5 for the location of the profile.

Regional groundwater flow and model boundaries

The regional groundwater flow in the area is from north to south, following the general topography and parallel to the Khurutshe and Boleleme Faults. The model area of the numerical model of the Masama Groundwater Resources Evaluation Project (Geo World, 2009) and the boundary conditions are shown in Figure 4.7 and a groundwater level contour map of the Ntane Aquifer is shown in Figure 4.8. The model covers an area of c. 1 100 km^2.

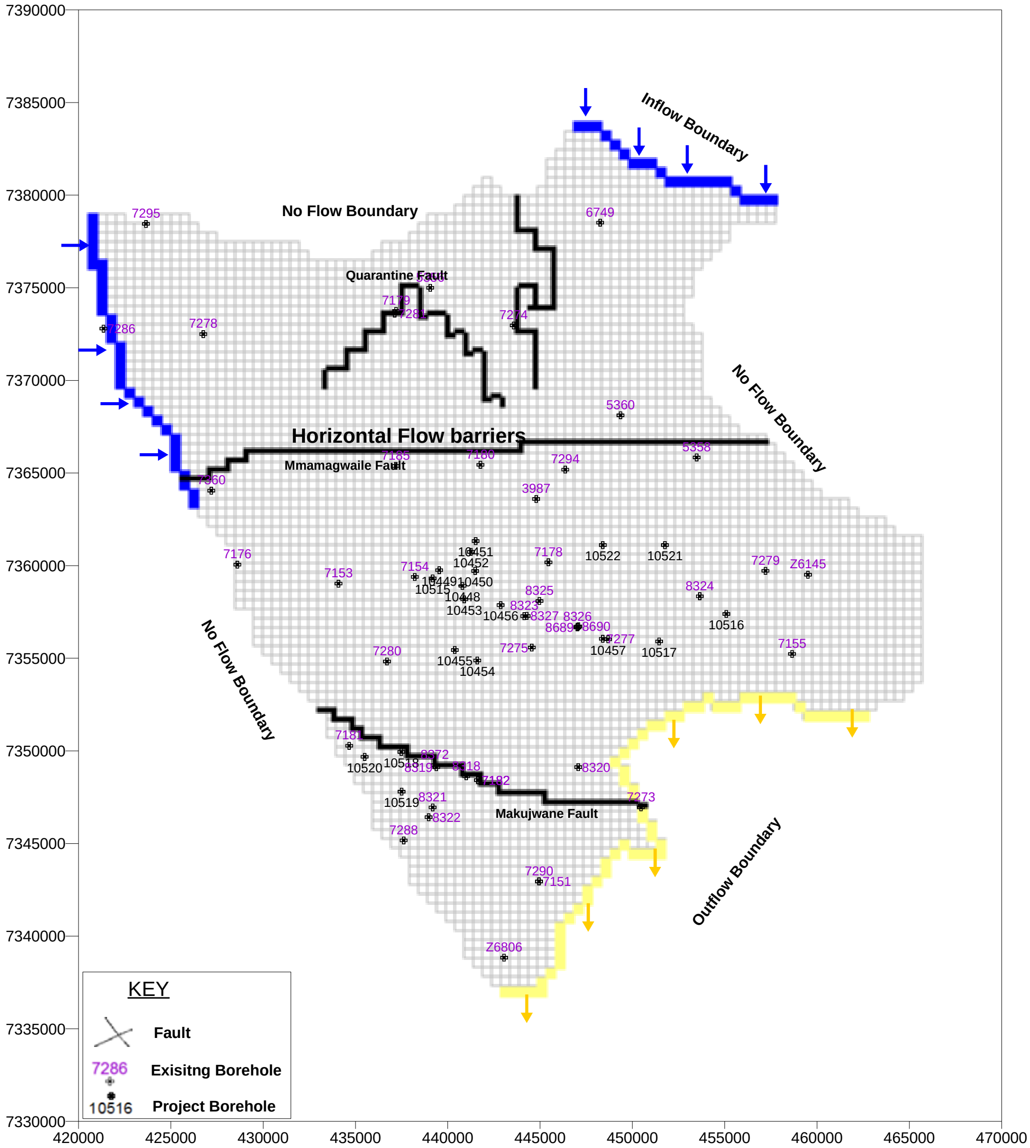


Figure 4.7. The model extent and boundary conditions of the numerical model of the Masama Groundwater Resources Evaluation Project (Geo World, 2009).

The northern boundary is a water divide caused by uplifted Ecca Mudstone and is set as a no-flow boundary for the Ntane Aquifer. The western boundary runs along the Khurutshe Fault and is considered as a no-flow boundary due to uplifted Ecca units to the west.

However, in the northern part of the western boundary NW-SE striking faults cut across the Khurutshe Fault allowing inflow to the Ntane Sandstone. The eastern boundary follows the Boleleme Fault. Groundwater flows parallel to the fault, defining a no-flow boundary. Some inflow occurs to the northeast across the fault. The southern boundary is an outflow boundary defined by the Ntane Sandstone and the Waterberg Group. Groundwater is discharged from the Ntane Aquifer to the fractured Waterberg Group. The vertical displacement, connected to the block faulting, has caused hydraulic discontinuities forming internal boundaries within the model area, along the Quarantine Fault, the Mmamagwaile Fault and the Makhujwane Fault. Due to possible leakage, the Makhujwane Fault has been simulated as a leaky horizontal flow barrier in the model.

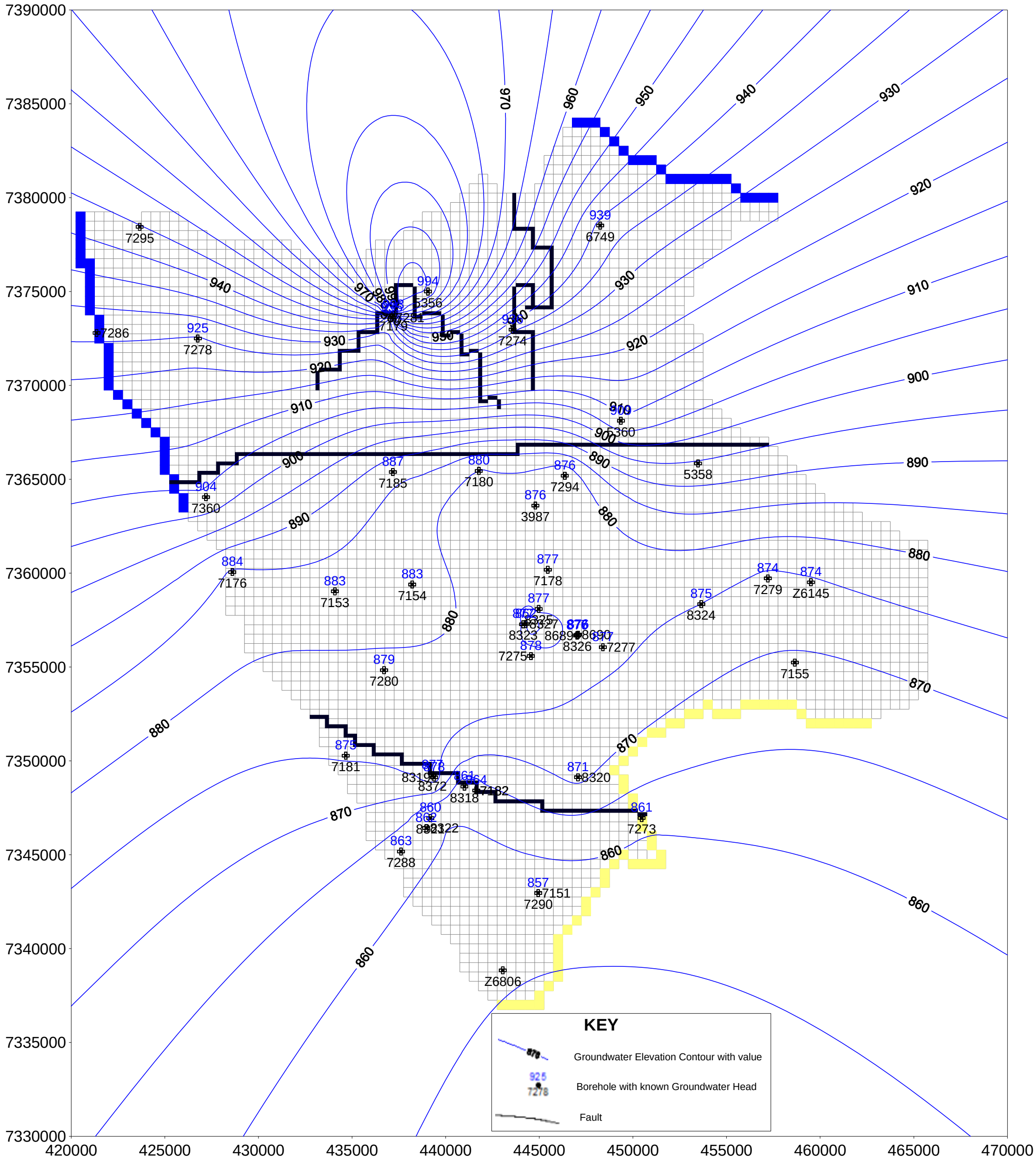


Figure 4.8. *Initial hydraulic head of the Ntane Sandstone Aquifer (Geo World, 2009).*

Groundwater recharge and discharge

Previous groundwater recharge studies in the area, based on remote sensing and GIS, isotopes, and chloride mass balance, have indicated recharge values in the range of 1-10 mm/year. In the calibrated model, values in the range of 0 to 3 mm/year was applied, with the higher values in areas where the Ntane Sandstone outcrops or sub-outcrops, and the lower values in areas with thick basalt cover as in the Makhujwane Wellfield. Groundwater discharge takes place to the Waterberg Group along the Seswane Fault in the south and further to Notwane River.

Water budget

The water budget for the steady-state calibration of the new numerical model (Geo World, 2009) is presented in Table 4.7.

Table 4.7. Water budget for the steady-state calibration of the numerical model of the Masama Groundwater Resources Evaluation Project (Geo World, 2009).

Direct recharge into the model domain	+3 372 m^3/d
Inflow across the Khurutshe Fault	+41 m^3/d
Inflow across the Boleleme Fault	+27 m^3/d
Outflow across the southern boundary	-3 440 m^3/d

Water quality

The majority of the water samples from the Ntane Aquifer has low mineral content with less than 450 mg/L of TDS. The major constituents are calcium, sodium, magnesium and bicarbonate. Sulphate and chloride levels are generally low. Like in the Palla Road/Chepete area some samples show higher TDS and chloride concentrations. These samples are interpreted as Ntane Aquifer water mixed with groundwater from underlying aquifers (probably the Ecca Aquifer) along fault zones.

Modelling scenarios used as basis for the water supply safety modelling

After calibration the Masama Groundwater Resources Evaluation Project Model (Geo World, 2009) was used for predictive modelling of selected abstraction scenarios. One of these scenarios (Scenario 3) and the results from the simulations were used to derive necessary input data to the MAR-scenario of the Masama/Makhujwane Wellfields in the water supply safety modelling.

In Scenario 3 abstraction of c. 21 500 m^3/d was simulated from 24 wells in the Masama Wellfield (total abstraction c. 17 800 m^3/d) and 5 wells in the Makhujwane Wellfield (total abstraction 3 700 m^3/d) every second year for five years and then every fifth year for 20 years with a 10 hours daily duty cycles. Only the first 5 years with abstraction every second year was used for derivation of input data to the water supply safety modelling. During this five year cycle, the total abstraction was c. 23.8 Mm^3 compared with the natural groundwater recharge of c. 6.2 Mm^3. The groundwater outflow across the southern boundary decreased from c. 3340 m^3/d in steady-state to c. 200 m^3/d during the last year of the five-year period. In total, the groundwater outflow during the five-year cycle was 2.7 Mm^3. This means that the groundwater storage was depleted by 23.8+2.7-6.2=20.3 Mm^3 during the cycle. This depletion resulted in simulated effective drawdowns (drawdowns in wells) of 16-21 m in the Masama Wellfield (c. 20 % of available drawdown) and 47-55 m effective drawdown in the Makhujwane Wellfield (c. 30 % of available drawdown). The five meter drawdown contour line reached the southern model boundary.

Since the drawdown after the storage depletion of c. 20 Mm^3 was only 20-30 % of the available drawdown it was assumed that also a depletion of 40 Mm^3 should give an acceptable drawdown. Therefore, 40 Mm^3 was chosen as the active storage in the baseline MAR sub-scenario of the water supply safety modelling, as well as for the extended MAR sub-scenario, see below. Since the groundwater abstraction in the area today is very small and the aquifer could be considered to be in steady-state, also the initial storage was set to 40 Mm^3.

An extended MAR sub-scenario for Masama/Makhujwane was defined on maximum and recommended abstraction rates of the 24 wells in the Masama Wellfield (31 200 m^3/d) and the 5 wells in the Makhujwane Wellfield (6 500 m^3/d) (Geo World, 2009). These abstraction rates are given for 18 hour daily duty cycle.

For more information on the Masama Groundwater Resources Evaluation Project Model the reader is referred to Geo World (2009).

The input data needed for the water supply safety modelling derived from groundwater model are summarized in Table 4.8 and Figure 4.9.

Table 4.8. Input data for the water supply modelling derived from the Masama Groundwater Resources Evaluation Project Model (Geo World, 2009).

	Masama/Makhujwane, baseline	**Masama/Makhujwane, extended**
Maximum active storage ($Mm^{3)}$	40	40
Initial storage (Mm^3)	40	40
Natural groundwater recharge (m^3/d)	3 379	3 379
Groundwater inflow (m^3/d)	0	0
Groundwater outflow (m^3/d)	see Figure 4.4	see Figure 4.4
Maximum abstraction and injection rates (m^3/d)	21 566	37 734

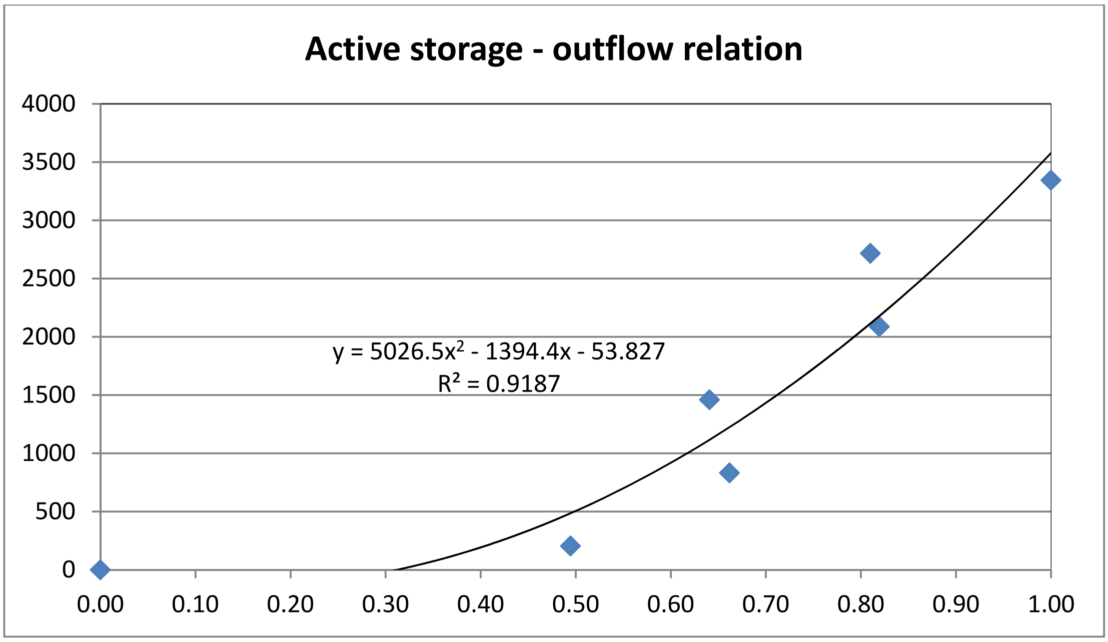


Figure 4.9. Active storage-groundwater outflow relationships for the Masama/Makhujwane Wellfield baseline and extended MAR sub-scenarios derived from the Masama Groundwater Resources Evaluation Project Model (Geo World, 2009).

4.3 Surface water dams and source water for MAR

Water from the surface water dams already included in the water supply system is the most obvious source of water for MAR, see Chapter 3 above.

Treated sewage water and storm water are also potential sources for recharge. However, an overview of the possibilities to use treated sewage and storm water as a source for artificial groundwater recharge for drinking water purposes, based on the NWMPR (DWA, 2006f) and updated information supplied by DWA and Dept. of Waste Management and Pollution Control (DWMPC) indicated that this is not feasible at present. Gaborone is the only city along the NSC, where large enough quantities of sewage water for large-scale artificial recharge are available (c. 90 000 m^3/d). However, major investments are needed in new sewage water treatment facilities to get water that is possible to inject in wells for artificial recharge for drinking water purposes. Furthermore, there are no aquifers suitable for artificial recharge within reasonable distance from the sewage water treatment works. The only possible aquifer is the Ramotswa Aquifer/Wellfield, but its hydrogeological and transboundary characteristics makes it less attractive for MAR (see section 4.2 abover). Furthermore, the aquifer already today has high nitrate concentrations due to contamination from settlements on top of it. Regarding storm water, a strategic decision was taken in the NWMPR to have local systems for the collection and infiltration instead of large centralized systems that could generate water quantities of interest for large-scale artificial recharge.

The conclusion in (DWA, 2006f), that reuse of treated sewage water for drinking purposes is not economically feasible, is considered to be still valid also for MAR purposes. However, reuse of treated sewage water for other purposes, which today are covered by potable water, but that do not require potable water quality, e.g. irrigation, environmental flows etc. should be given high priority.

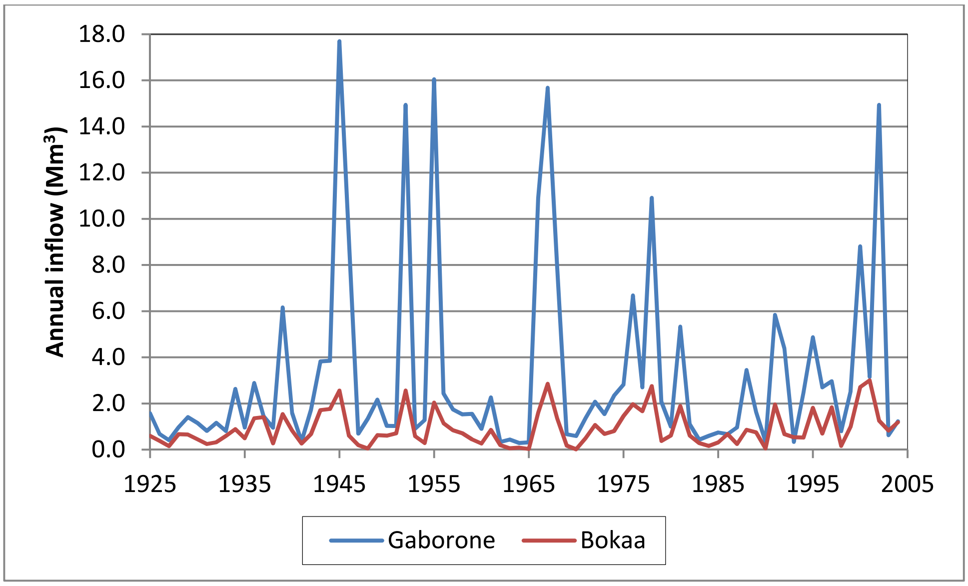
Only water from the surface water dams included in water supply system, as presented in Chapter 3, is considered as source water for MAR in the water supply safety modelling.

Time series of monthly values of the inflows to the dams for the 80-year period of 1925-2004 were compiled for the water development modelling performed in the NWMPR based on measurements and hydrological modelling (DWA, 2006d). These time series have been used in the present water supply safety modelling.

Catchment area sizes of the dams are shown in Table 4.9 together with average inflow for the 80-year period of 1925-2004. In Figure 4.10 the historic time series of annual inflow to the dams are presented. (The full time series are included in the Water Supply Safety Model delivered on CD together with the present report.)

Table 4.9. Catchment areas and average annual inflow to the five dams included in the water supply modelling (data from the WATHNET-modelling in the NWMPR, 2006).

Dam	**Catchment area (km2)**	**Annual mean runoff 1925-2004 (Mm3)**	**Annual mean runoff (mm)**
Gaborone	3 983	31.7	8.0
Bokaa	3 570	9.1	2.5
Letsibogo	5 480	57.7	10.5
Dikgatlhong	4 160	110.5	26.6
Shashe	3 650	84.3	23.1



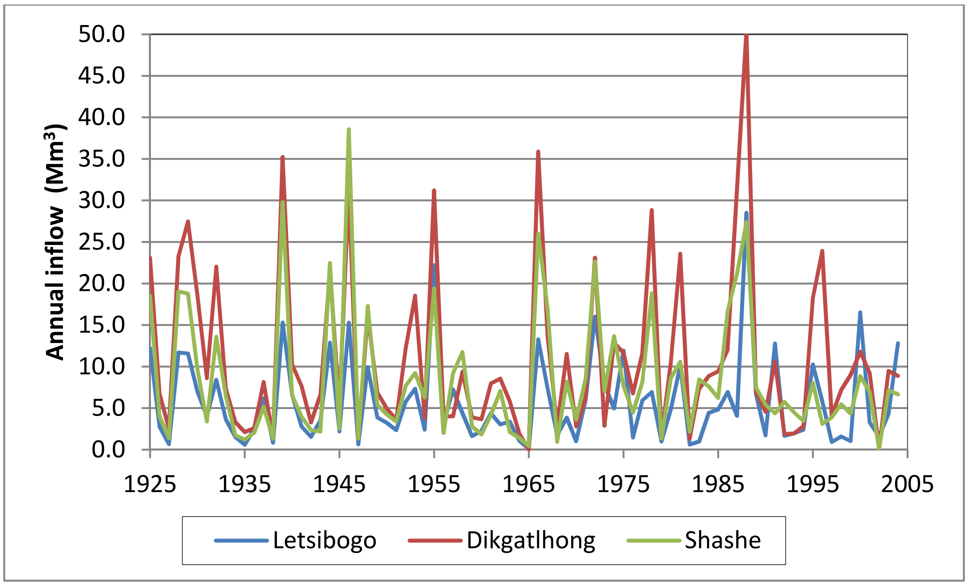


Figure 4.10. Historic inflow time series for the dam sites, 1925-2004 (data from the WATHNET-modelling of the NWMPR, 2006).

Water balance calculations of the storage in each dam are required for the water supply safety modelling:

$Storage_t$=$Storage_{t-1}$+inflow-evaporation-seepage-environmental flow-abstraction-spill over

The input data needed for the modelling are:

- Storage capacity (full supply level /FSL/)
- Minimum practical storage (minimum operation level /MOL/)
- Initial storage (initial condition)
- Area-storage relationship ("rating curves")
- Inflow time series (monthly values)

- Rainfall and evaporation (monthly values from nearby meteorological stations)
- Seepage rates
- Maximum pumping (abstractions) rates
- Spill over
- Loss of storage due to sedimentation
- Water delivery failure (technical problems coupled to the water intake, pumps and pipelines, frequency and duration)

4.3.1 Dam storage

The storage at full supply level (FSL), minimum operation level (MOL) and the initial storage of the dams at the start of the water supply safety modelling (Jan. 1, 2013) are shown in Table 4.10. In the table values are also given for seepage, environmental flows and sedimentation rates. The data is based on the input data used for the WATHNET-modelling in the NWMPR, 2006), but updated and revised according to new information from DWA and WUC. Information on seepage is missing for the Gaborone, Bokaa and Letsibogo Dams and is set to zero in the modelling.

Table 4.10. Storage properties and environmental flows for the five dams included the water supply safety modelling (data from the WATHNET-modelling (DWA, 2006d and updated information from DWA and WUC).

	Gaborone	Bokaa	Letsibogo	Dikgatlhong	Shashe
Maximum storage (at FSL), Mm^3	140.59	18.20	108.00	397.60	75.05
Minimum operational storage (at MOL), % of max. storage	15	3	5	4	15
Initial storage, Jan 1. 2013, Mm^3	49.65	7.08	31.00	198.80	59.62
Seepage, l/s	0.0	0.0	0.0	30.0	0.8
Environmental flow, Feb.; Nov.	0; 0*	0; 0*	2.49; 0.49**	5; 5*	0; 0*
Loss due to sedimentation, Mm^3/year	0.22	0.04	0.35	0.70	0.61

* %, ** Mm3, provided inflow >0

For calculation of the evaporation from the dams, as well as the rainfall on the dam surface, area-storage relationships are required. These relationships were taken from the WATHNET-modelling in the NWMPR, 2006. The equations for the relationships used in the WATHNET-modelling were expressed as:

$A=a+b*V^C$,

Where A=surface area of the dam, V=actual volume/maximum storage and a,b,c are parameters. The derived equation gave a very good fit to the actual relationships. The area at maximum storage (FSL) and the parameters for the five dams are shown in

Table 4.11, and the area-storage relationship for the Dikgatlhong Dam is shown in Figure 4.11 as an example.

Table 4.11. Dam surface area at maximum storage (FSL) and the parameters derived for the area-storage relationships (from the WATHNET-modelling in the NWMPR, 2006).

Dam	Area at FSL (km^2)	a	b	c
Gaborone	19.43	0.00	19.56	0.65
Bokaa	6.50	0.00	6.46	0.73
Letsibogo	108.00	0.00	20.19	0.84
Dikgatlhong	43.67	0.00	44.04	0.74
Shashe	14.23	0.00	14.78	0.67

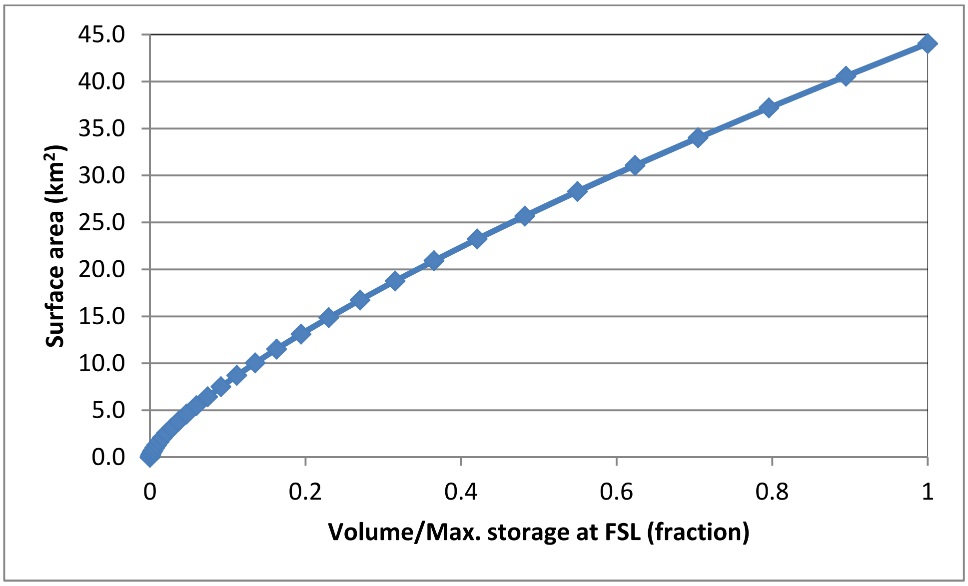


Figure 4.11. Surface area - volume relationship for the Dikgatlhong Dam (from the WATHNET-modelling of the NWMPR, 2006).

4.3.2 Rainfall and evaporation

The rainfall and evaporation data used for the water supply safety modelling were taken from the WATHNET-modelling in the NWMPR, 2006 and were from the meterorological stations at the Met. H.Q in Gaborone for the Gaborone and Bokaa Dams, and from Francistown Airport for the Letsibogo, Dikgatlhong and Shashe Dams.

The annual open water evaporation was calculated according to SMEC (1987) as:

E_a=2261-0.486·P, where

E_a=annual average open water evaporation and P=precipitation.

Annual rainfall and open water evaporation for the Gaborone and Francistown meteorological stations are summarized in Table 4.12. The full time series are included in the Water Supply Safety Model delivered on CD together with the present report.

Table 4.12. Annual rainfall and open water evaporation at Gaborone and Francistown. Mean, min. and max. values for the 80-year period 1925-2004 (data from the WATHNET-modelling in the NWMPR, 2006).

	Gaborone Met. H. Q.	**Francistown Airport**
Mean annual rainfall (mm)	531	460
Min annual rainfall (mm)	224	116
Max. annual rainfall (mm)	924	836
Mean annual evaporation (mm)	2003	2037
Min. annual evaporation (mm)	1812	1855
Max. annual evaporation (mm)	2152	2205

The calculated annual evaporation was distributed over the year for the modelling as shown in Table 4.13.

Table 4.13 Distribution over the year of calculated annual open water evaporation (from the WATHNET-modelling in the NWMPR, 2006).

Month	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
Fraction	0.105	0.091	0.092	0.072	0.060	0.048	0.054	0.071	0.092	0.109	0.103	0.103

The net evaporation losses from the dam surfaces were calculated monthly as:

Net loss = Surface Area · (E-(P-R)), where

E=open water evaporation, R=equivalent runoff from the inundated area prior to the construction of the dam (very small for Botswana Rivers).

The annual net loss due to evaporation for the 80-year period 1925-2004 is shown in Figure 4.12 for the Gaborone and the Bokaa Dams. The average net loss was 1480 mm/year, and the min. and max values were 915 and 1960 mm/year, respectively. For the Letsibogo, Dikgatlhong and Sashe Dams the average net loss was 1591 mm and the min. and max. values were 931 and 2090 mm/year. The full time series are included in the Water Supply Safety Model delivered on CD together with the present report.

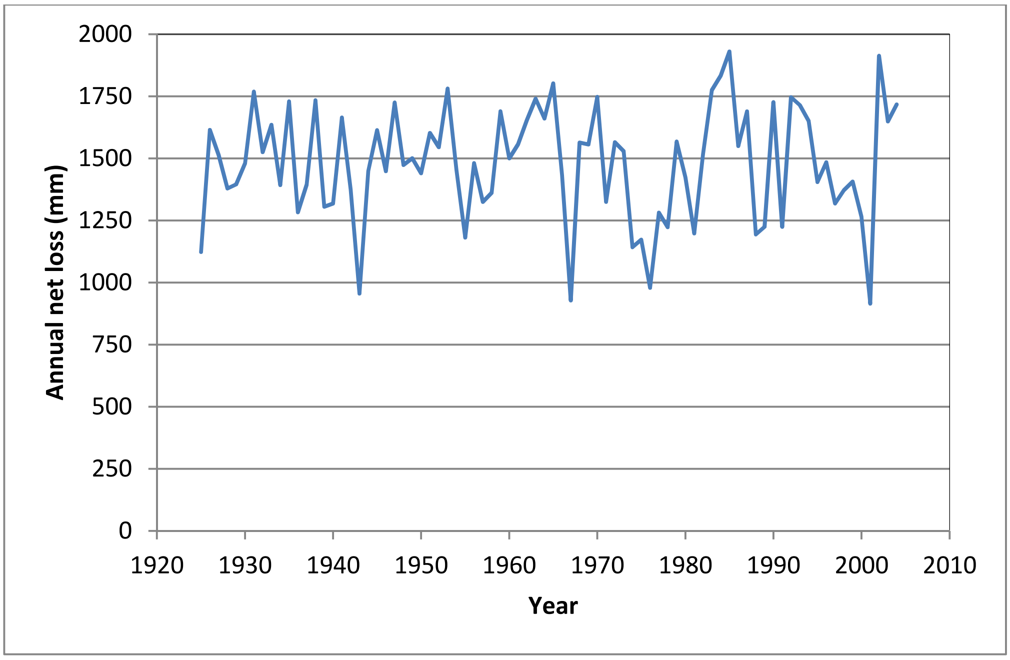


Figure 4.12. Annual net losses due to evaporation for the 80-year period 1925-2004 for the Gaborone and Bokaa Dams. (data from the WATHNET-modelling in the NWMPR, 2006).

4.4 Water transfer and treatment

Data on the abstraction capacities from the dams, the NSC-pipeline, the pumping stations, and the water works were supplied by WUC. At present, water in the NSC flows by gravity from south of Palapye and southwards. By the construction of Pumping Station 4 (PS4), when connecting the Dikgatlhong Dam to the NSC, the transfer capacity is doubled (see Figure 2.3 and **Fel! Hittar inte referenskälla.** for the location and position of PS4 in the water supply system). According to WUC, this means that the transfer capacity of the NSC will not be a limiting factor for the water supply in the water demand scenario applied in the water supply safety modelling. However, the maximum abstraction rates from the dams and the capacities of the water works may be limiting factors. The maximum abstraction rates from the dams and the water works capacities are show in Table 4.14 and Table 4.15.

Table 4.14. Maximum abstraction rates from the dams (m^3/d).

	Gaborone	Bokaa	Letsibogo	Dikgatlhong	Shashe (to WW)	Shashe (to mines)
Max. abstraction rate (m3/d)	84 000	31 000	88 128	175 000	52 000	24 000

Table 4.15 Maximum treatment capacities of the water works included in the water supply safety modelling.

Water works	Max. treatment capacity (m^3/d)	
	Current	After upgrade*
Sashe	52 000	52 000
Palapye	16 000	32 000
Selebi-Phikwe	38 000	38 000
Mahalapye	14 000	14 000
Gaborone	108 000	108 000
Mmamashia	110 000	155 000
Lobatse	2 500	2 500
Mabalane	1 200	1 200

* used in Scenarios 2-6 of the modelling, see Ch. 5.

Besides the maximum abstraction rates from the dams and the treatment capacities of the water works, there are some additional limitations in the water infrastructure that may affect the supply safety, see Table 4.16.

In the water supply safety model the transfer capacity from the Bokaa Dam to the Gaborone WW is considered since it is may be critical in situations when, for example, the Gaborone Dam cannot supply water to the WW but water from the NSC could be transferred via the Bokaa Dam. The transfer capacity from the Shashe Dam to Selebi-Phikwe is, however, not included since it is the same as the abstraction rate from the Shashe Dam and thus already considered in the model. Furthermore, the limitation related to transfer capacity from the Letsibogo Dam to Selebi-Phikwe is not limiting since the WW capacity is less than the transfer capacity. The limitations linked to the ability to transfer water from the Mmamashia and Gaborone WW to the demand centres are assumed to be solved when necessary and thus not included in the model.

Table 4.16. Additional water infrastructural limitations in the water supply system.

Link	Transfer capacity (m^3/d)
Bokaa Dam - Gaborone WW	23 000
Shashe Dam - Selebi-Phikwe	52 800
Letsibogo Dam - Selebi-Phikwe	172 800
Mmamashia WW - Gaborone	192 000
Gaborone WW - Lobatse	1 200

The limitations in abstraction rates and active storage for the Palla Road/Chepete and Masama/Makhujwane Wellfields were presented in Sections 4.2.1 and 4.2.2, and the sustainable yield of the other wellfields included in the water supply modelling in Table 4.4.

According to an international agreement there is a transfer of water from the Molatedi Dam in South Africa to the Gaborone Water Works. If the Molatedi Dam is more than 30 % full the maximum agreed transfer is 20 000 m^3/d and below that level 10 000 m^3/d. The Molatedi Dam is not included in the water supply safety modelling in the same way as the other five dams, but as a constant source of water at 80 % of the maximum transfer, i.e. 16 000 m^3/d (this is also how the Molatedi Dam was handled in the WATHNET-modelling in the NWMPR, 2006).

5 Scenario descriptions

DWA, WUC and Chalmers agreed to include six water supply scenarios in the present study:

1. Current system
2. Current system + Dikgatlhong Dam
3. Current system + Dikgatlhong Dam + Masama/Makhujwane Wellfields (Non-MAR)
4. Current system + Dikgatlhong Dam + Palla Road/Chepete Wellfields MAR (baseline and extended MAR sub-scenarios for the wellfields)
5. Current system + Dikgatlhong Dam + Masama/Makhujwane Wellfields MAR (baseline and extended MAR sub-scenarios for the wellfields)
6. Current system + Dikgatlhong Dam + Palla Road/Chepete Wellfields MAR + Masama/Makhujwane Wellfields MAR (baseline and extended MAR sub-scenarios for the wellfields)

Common for all scenarios are:

- The m^3-adjusted water demand scenario is used for all demand centres, see Section 4.1 and Table 4.2. However, comparison with a lower increase in water demand will be presented for some scenarios (linearly lower from 0 % at the start to 20 % lower the last year, 2035).
- Surface water availability was calculated based on the data and methodology described in Section 4.3. A set of 23-year long monthly time series of inflow data were generated for the simulation of each scenario based on the calculated 80-year long historical inflow time series (see Chapter 0).
- The limitations of the water infrastructure, as described in Section 4.4.
- Gaborone and connected demand centres are as default supplied to 60 % from the Gaborone WW and to 40 % from the Mmamashia WW. Water may be transferred from the Bokaa Dam if raw water availability is limiting for the Gaborone WW.
- Water to the NSC is to 60 % taken from the Dikgatlhong Dam and to 40 % from the Letsibogo Dam. If storage in either of the dam is below minimum operational storage, water is taken from the other dam if available (Scenarios 2-6).
- The wellfields included in the system, but not considered for MAR, deliver the below listed percentage of demand up to up to sustainable yield:
    - Palapye Wellfield to Palapye: 50 %
    - Serowe Wellfield to Serowe: 58 %
    - Paje Wellfield to the Morupule mine: 10 %
    - Palla Road Wellfield to Mahalapye & Shoshong: 50 %
    - Malotwane Wellfield to Mochudi: 0 %

    - Kanye Wellfield to Kanye & Mashupa: 60 % (only included in Scenarios 2-6 since the demand centres are not connected to the NSC system in Scenario 1)
    - Ramotswa Wellfield to Ramotswa & Lobatse: 50 % (only included in Scenarios 2-6)

- If full supply cannot be met, a reduction is calculated as a percentage of full supply which is the same for all demand centres with exceptions for Francistown and Selebi-Phikwe. For Francistown it is assumed that the possible abstraction rate from the Shashe Dam and the water works capacity will be updated to meet the water demand, i.e. the only limitation will be the minimum operational storage of the Shashe Dam. For Selebi-Phikwe it is assumed that the capacity of the water works will be increased to meet the water demand, i.e. the only limitations will be the minimum operational storages in the Letsibogo and Shashe Dams and in the transfer capacity from the Shashe Dam.
- NSC-failures can optionally be simulated. If included, 2-5 interruptions a year of 3-hour duration due to communication problems, and pipeline leakages 2-3 times year with a duration of 1 to 3 weeks.

Short descriptions of the specific features of the six scenarios are given below.

Scenario 1: Current system

In this scenario the current system is simulated according to the structure shown in **Fel! Hittar inte referenskälla.**.

Scenario 2: Current system + Dikgatlhong Dam

In addition to the features of Scenario 1, the Dikgatlhong Dam is connected to the NSC. Pumping Station PS4 is in operation, doubling the NSC-capacity south of the station. Kanye, Thamaga and Moshupa are connected to the NSC. The water works capacity is increased according to Table 4.15.

Scenario 3: Current system + Dikgatlhong Dam + Masama/Makhujwane Wellfields

In addition to the features of Scenario 2, the Masama/Makhujwane Wellfields are connected to the NSC as an emergency supply, with no limitation of the abstraction rate to sustainable yield. The maximum abstraction rate is set to c. 21 600 m^3/d and the maximum active storage to 40 Mm^3 (see Section 4.2.2 and Table 4.8 for more information on the wellfields). The abstraction rate is the same as for the Masama/Makhujwane Wellfields MAR baseline scenario, but for comparison also an increased abstraction rate of c. 38 000 m^3/d, as for the extended MAR-scenario, was simulated.

Scenario 4: Current system + Dikgatlhong Dam+Palla Road/Chepete Wellfields, MAR

In this scenario, in addition to Scenario 2, facilities for MAR are provided for the Palla Road/Chepete Wellfields. The existing transfer capacity from the wellfields to Mahalapye is upgraded to allow for reversed flow for supply of treated water from the Mahalapye Water Works to the wellfields for injection. For full scale abstraction and injection an additional pipeline is most likely needed as well as an upgrading of the capacity of the Mahalapye Water Works. There are two alternatives for transfer of water to the the NSC from the wellfields:

- The abstracted water is pumped back to Mahalapye in the pipeline used for injection and from there to the NSC in the existing pipeline between Mahalapye and the NSC used for the water supply today. Upgrading is necessary to allow for reversed flow.
- A new pipeline is constructed for transfer of abstracted water from the Palla Road/Chepete Wellfields directly to the NSC.

Scenario 4 has one baseline and one extended sub-scenario. The difference between the scenarios is the c. 50 % higher maximum abstraction rate and maximum active storage of the extended sub-scenario; abstraction rates of 21 300 m^3/d compared with 14 200 m^3/d for the baseline sub-scenario, and active storages of 43 Mm^3 compared with 26 Mm^3 for the baseline sub-scenario.

Scenario 5: Current system + Dikgatlhong + Masama/Makhujwane Wellfields, MAR

In this scenario, in addition to Scenario 2, facilities for MAR are provided for the Masama/Makhujwane Wellfields. Two alternatives are simulated:

- The connection to the NSC from the wellfields is upgraded to allow reversed flow to allow transfer of water from the NSC to the wellfields for injection, and for the extended scenario also for a higher transfer rate. A new water treatment plant is constructed for treatment of the water to be injected. When water is abstracted from the wellfields, it is transferred back to the NSC as in Scenario 3.
- A new pipeline is constructed from the Mmamashia Water Works to Masama for supply of treated water for injection. The same pipeline is used when water is abstracted from the wellfields and delivered directly to the water distribution system (if necessary after some minor treatment).

Like Scenario 4, Scenario 5 has one baseline and one extended sub-scenario. The difference between the sub-scenarios is the c. 75 % higher maximum abstraction rate of the extended sub-scenario, 37 800 m^3/d, compared with 21 600 m^3/d for the baseline sub-scenario.

Scenario 6: Current system + Dikgatlhong Dam + Palla Road/Chepete Wellfields, MAR + Masama/Makhujwane Wellfields, MAR

In this scenario, Scenario 2 is combined with the MAR-facilities of both Scenario 4 and 5. The same alternatives for treatment of the injection water and the connections to the NSC as for Scenarios 4 and 5 are included as well as the baseline and extended sub-scenarios.

More details on the outline of the MAR-scenarios at the Palla Road/Chepete Wellfields and at the Masama/Makhujwane Wellfields are presented in Chapter 0.

6 Water supply safety model

6.1 Overview

A water supply safety model was developed to enable a thorough assessment of the effects of implementing MAR and other measures in the water supply system. The aim of the model is thus to provide results that can be used to evaluate and compare the water supply safety of the current system and possible future scenarios. The developed model includes the area along the NSC as described in Chapter 3 and included components are available source water, groundwater aquifers, water supply infrastructure, water demand centres etc. The existing water supply system is the baseline and MAR options and coming upgrading of the system are included to enable a comparison to the present day situation in terms of incremental increase in water supply safety.

The model is a dynamic water balance model where statistically generated time series of the availability of source water are used, together with dynamic storages in dams and aquifers, and water demands to simulate the magnitude and probability of water supply shortages. Previous models, such as the WATHNET-model used in the NWMPR (DWA, 2006d, e), provide similar opportunities to analyse the supply system. The previous models were, however, not specifically developed to consider MAR-scenarios. Furthermore, the primary aim of the model developed as part of the present pre-feasibility study was to provide an easily accessible model that can be run without expert knowledge. The water supply safety model is therefore developed as a spreadsheet model in Excel. To enable statistical analysis considering uncertainties in results etc., an add-in software (Oracle Crystal Ball) is used to run Monte Carlo simulations. Monte Carlo simulation uses random numbers to sample values from probability distributions representing the input variables. This is performed iteratively in order to select values representing the entire probability distribution and obtain a probability distribution that represents the result.

The structure of the model and the applied technique is presented in the subsequent sections. Note that the analysed system is presented in Chapter 3 and the necessary input data and compilation are described in Chapter 4. A user's manual is provided in Appendix 3, including more details on how to run the model.

6.2 Structure

As noted above the model is a dynamic water balance model used to simulate (mainly) the NSC system and connected components from 2013 to 2035 (23 years). The simulations are performed with a time step of one month and for each month the demand, available storage in dams and aquifers as well as treatment capacities, water losses etc. are considered.

In Figure 6.1 a schematic illustration of the parameters considered in the model and the link between them and the model components are presented. Based on historical data on inflow to the dams, a large set (96 000) of possible time series are generated and used to sample from when running the model. The generated time series consider the correlation between the dams and each generated data set includes all five dams. The annual inflow data is transformed into monthly data based on the closest historical annual inflow and the monthly distribution that year. Since the dams are spatially correlated, the historical data for the Gaborone Dam is used when transforming the simulated annual data for the Bokaa and Gaborone Dams. In the same way the historical data for the Dikgatlhong Dam is used for the Letsibogo, Shashe and Dikgatlhong Dams.

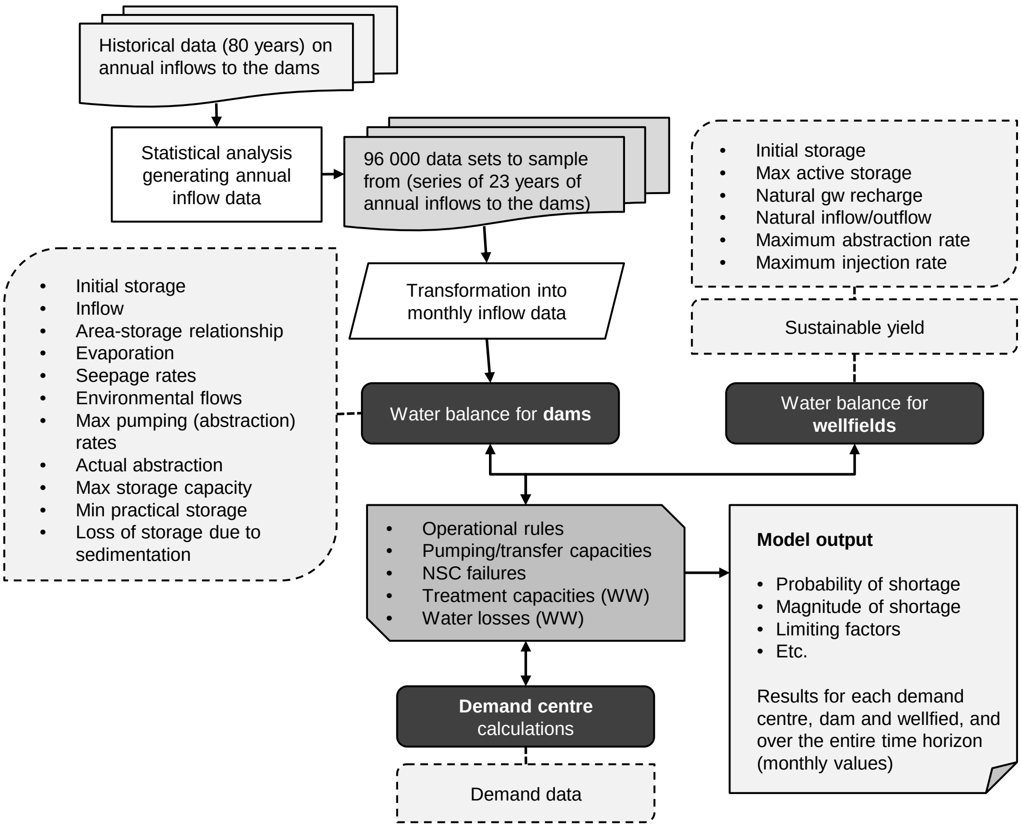


Figure 6.1. Overview of the parameters considered in the model and the link between them.

For each dam, water balance calculations are done for each month considering all parameters presented in Figure 6.1. The evaporation is calculated according to the description in Section 4.3.2. In the same way, water balance calculations are performed for the wellfields. However, for the wellfields not considered relevant for MAR only the sustainable yield is considered (i.e. abstraction is allowed up to sustainable yield). The water demand (see Section 4.1) is used to determine how much water must be abstracted from the dams and wellfields. A set of operational rules (see the grey shaded box in the middle of Figure 6.1) determine to what extend different sources are used and how much water can be transferred etc.

6.3 Generation of dam inflow time series

Based on historical data on inflow to the dams (Gaborone, Bokaa, Letsibogo, Dikgatlhong and Shashe) an analysis was made in order to generate future inflow time series that are used when running the model. Data consist of yearly inflow to the five dams for 80 years starting 1925 and ending 2004. This five-dimensional time series is modelled as a first order stationary Gaussian Auto-Regressive, AR(1), sequence,

$$y_t - \mu = \phi(y_{t-1} - \mu) + \epsilon_t$$

For t = -79, -78, …, 0 (t = 0 corresponds to year 2004). The row vectors μ and ϵ_t denote the long time yearly mean and white noise, respectively, the latter with covariance matrix Σ. In order to carry out a standard least squares (LS) estimation, the model is rewritten as follows,

$$y_t = \phi y_{t-1} + b + \epsilon_t$$

where $b = \mu - \phi\mu$. The parameters ϕ, b and Σ are estimated by the method of least squares. Also estimated is the spatial covariance matrix

$$\gamma = E y_t y_t' - \mu\mu'$$

(the prime ‘ denotes transpose). Future dam inflow values $y_1, y_2, \ldots, y_{25}$ are then repeatedly simulated from the estimated model, taking the uncertainty of the LS estimates into account. The reader is referred to Appendix 2 for details.

6.4 Calculation steps

The calculations in the model are performed in the main steps listed below. In all steps available abstraction rates (i.e. pump capacities), treatment capacities, water losses during treatment etc. are considered. The schematic illustration in Figure 3.1 shows how the different components of the system are connected and how water can be transferred.

1. Water from the Shashe Dam is abstracted and first supplied to Francistown and after that to the Tati and Mupani mines.
2. Water from the Letsibogo Dam is abstracted and supplied to Selebi-Phikwe and if the demand cannot be meet water is also (if available) abstracted and supplied from the Shashe Dam.
3. Intended local supply from wellfields (i.e. all wellfields except for Palla Road/Chepete and Masama/Makhujwane in Scenarios 3-6) based on the defined operational rules.
4. Water from the Molatedi Dam is used to supply water to the River Villages.
5. The total water demand for Gaborone and connected demand centres is calculated. Water is supplied in the following order (based on operational rules defining to what extent the different sources are intended to be used):
    a. From the Gaborone WW using water from the Molatedi Dam.
    b. From the Gaborone WW using water from the Gaborone Dam.
    c. From the Mmamashia WW using water from the Bokaa Dam.
    d. From the Mmamashia and Gaborone WWs using water from the NSC, abstracting water from the Letsibogo Dam (Scenario 1) or both the Letsibogo and Dikgatlhong Dams (Scenario 2-6).
    e. From the Mmamashia WW using water from the Bokaa Dam (if there is a remaining demand and water available in the dam).
    f. From the Gaborone WW using water from the Gaborone Dam (if there is a remaining demand and water available in the dam).
    g. From the Gaborone WW using water from the Bokaa Dam (if there is a remaining demand and water available in the dam).

6. Abstraction and supply from the Masama/Makhujwane Wellfileds (Non-MAR in Scenario 3 and MAR in Scenario 5 and 6) and the Palla Road/Chepete Wellfields (MAR in Scenario 4 and 6).
7. Injection of water at the MAR wellfields (Scenario 4-6) using (treated) water from the NCS.

The water supply safety model has an interface where the user can change the existing input data and adjust the settings so that the specific scenario of interest can be modelled. In Figure 6.2 the first part of the model is presented where the user selects the main scenario to simulate. Figure 6.3 shows how the settings related to the NSC are defined and in Figure 6.4 dam properties and related operational rules are defined. In Figure 6.5 and Figure 6.6 the required input related to the MAR and Non-MAR wellfields are defined. Finally, the demand data set to be used is defined as illustrated in Figure 6.7 and the properties for the water works are defined according to Figure 6.8.

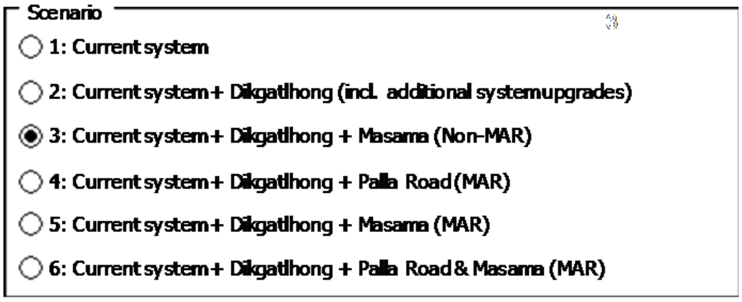


Figure 6.2. Selection of scenario in the water supply safety model.

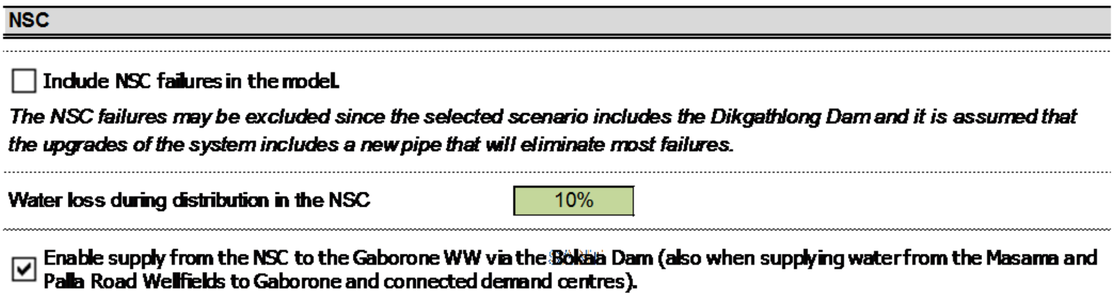


Figure 6.3. Settings related to the NSC.

Dam properties

	Gaborone	Bokaa	Letsibogo	Dikgatlhong	Shashe (to WW)	Shashe (to mines)
Max abstraction rate (Ml/d)	84.0	31.0	88.1	175.0	91.0	24.0

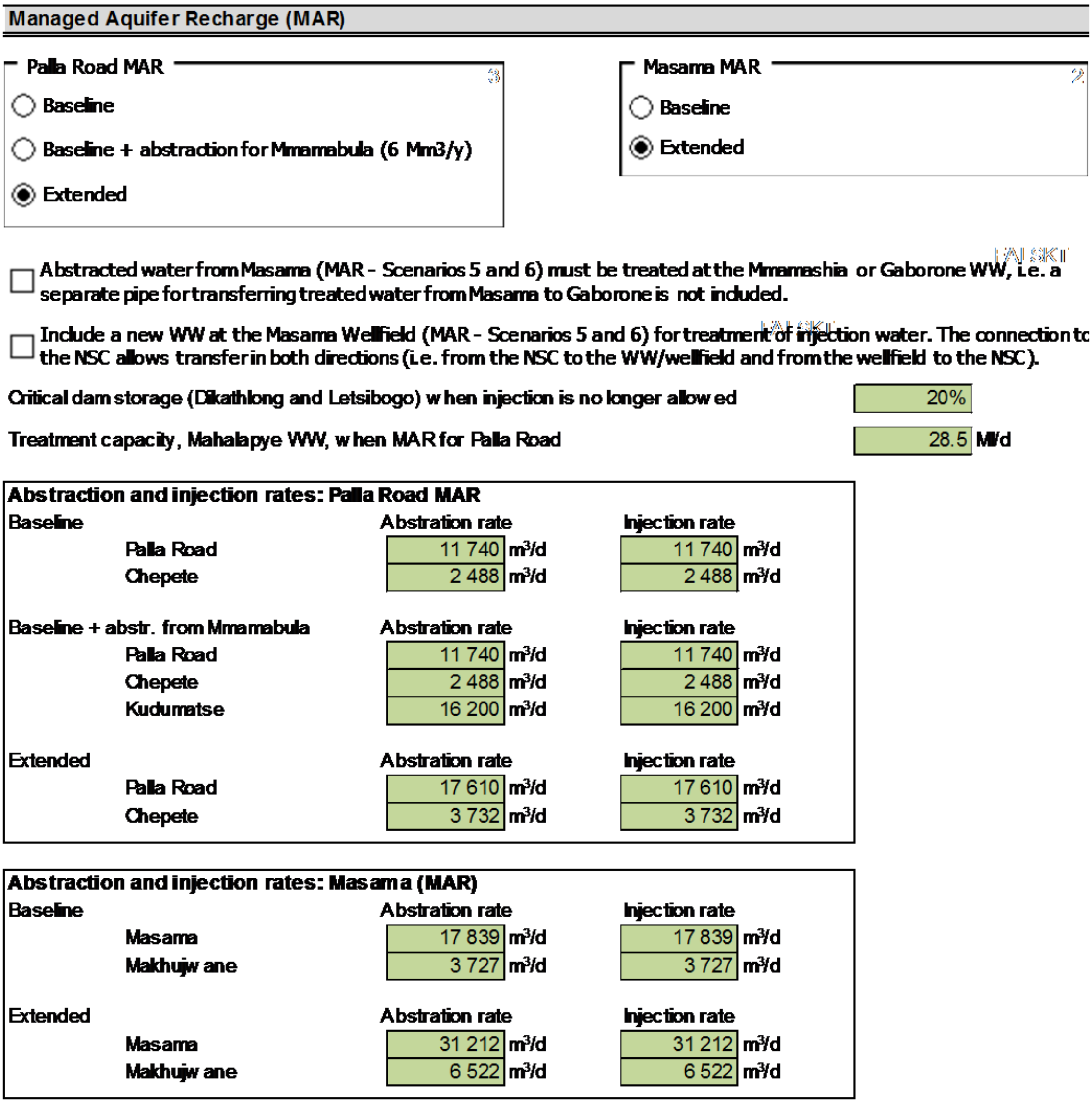
		Gaborone	Bokaa	Letsibogo	Dikgatlhong	Shashe
Initial storage (Mm^3)		49.65	7.08	31.00	198.80	59.62
Initial maximum storage Mm^3 (at full supply level)		140.59	18.20	108.00	397.60	75.05
Minimum operational level (% of maximum storage)		15%	3%	5%	4%	15%
Loss of storage due to sedimentation (Mm^3/year)		0.22	0.04	0.35	0.70	0.61
Seepage (l/s)		0.0	0.0	0.0	30.0	0.8
Environemntal flow s	Feb	0%	0%	2.49	5%	0%
	Nov	0%	0%	0.49	5%	0%
		% of inflow	% of inflow	Mm^3, provided inflow >0	% of inflow	% of inflow

Supply from Molatedi | 16 | Ml/d — *Default value is 80 % of 20 Ml/d, i.e. 16 Ml/d.*

Transfer capacity: Bokaa Dam to Gaborone WW | 23.0 | Ml/d

Intended supply to Gaborone and connected demand centres		
From Mmamashia WW	60%	of demand
From Gaborone WW	40%	of demand
Intended supply to the Mmamashia WW		
From the Bokaa Dam	30%	of demand
From the NSC	70%	of demand
Supply to NSC w hen the Letsibogo and Dikgathlong Dams are connected		
From the Letsibogo Dam	40%	of demand
From the Dikgathlong Dam	60%	of demand

Figure 6.4. Dam property settings and related operational rules in the model.



Managed Aquifer Recharge (MAR)

Palla Road MAR
- ○ Baseline
- ○ Baseline + abstraction for Mmamabula (6 Mm3/y)
- ◉ Extended

Masama MAR
- ○ Baseline
- ◉ Extended

☐ Abstracted water from Masama (MAR - Scenarios 5 and 6) must be treated at the Mmamashia or Gaborone WW, i.e. a separate pipe for transferring treated water from Masama to Gaborone is not included.

☐ Include a new WW at the Masama Wellfield (MAR - Scenarios 5 and 6) for treatment of injection water. The connection to the NSC allows transfer in both directions (i.e. from the NSC to the WW/wellfield and from the wellfield to the NSC).

Critical dam storage (Dikathlong and Letsibogo) when injection is no longer allowed	20%	
Treatment capacity, Mahalapye WW, when MAR for Palla Road	28.5	Ml/d

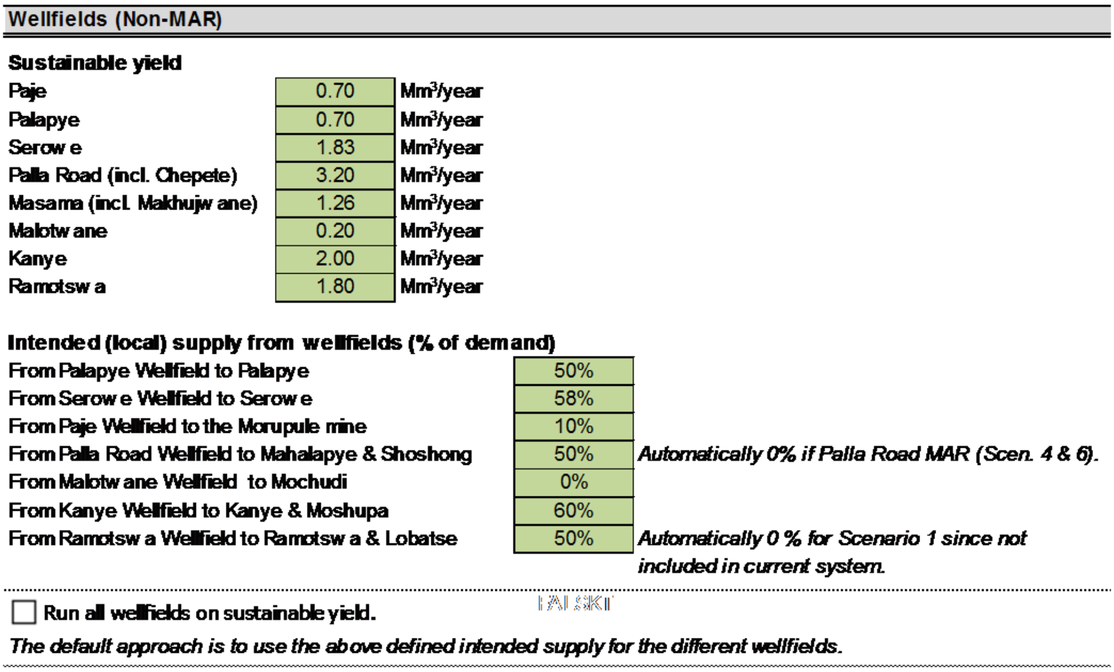
Abstraction and injection rates: Palla Road MAR

		Abstration rate		Injection rate	
Baseline					
	Palla Road	11 740	m³/d	11 740	m³/d
	Chepete	2 488	m³/d	2 488	m³/d
Baseline + abstr. from Mmamabula					
	Palla Road	11 740	m³/d	11 740	m³/d
	Chepete	2 488	m³/d	2 488	m³/d
	Kudumatse	16 200	m³/d	16 200	m³/d
Extended					
	Palla Road	17 610	m³/d	17 610	m³/d
	Chepete	3 732	m³/d	3 732	m³/d

Abstraction and injection rates: Masama (MAR)

		Abstration rate		Injection rate	
Baseline					
	Masama	17 839	m³/d	17 839	m³/d
	Makhujwane	3 727	m³/d	3 727	m³/d
Extended					
	Masama	31 212	m³/d	31 212	m³/d
	Makhujwane	6 522	m³/d	6 522	m³/d

Figure 6.5. Input data and settings for the MAR scenarios.



Wellfields (Non-MAR)

Sustainable yield

Paje	0.70	Mm³/year
Palapye	0.70	Mm³/year
Serowe	1.83	Mm³/year
Palla Road (incl. Chepete)	3.20	Mm³/year
Masama (incl. Makhujwane)	1.26	Mm³/year
Malotwane	0.20	Mm³/year
Kanye	2.00	Mm³/year
Ramotswa	1.80	Mm³/year

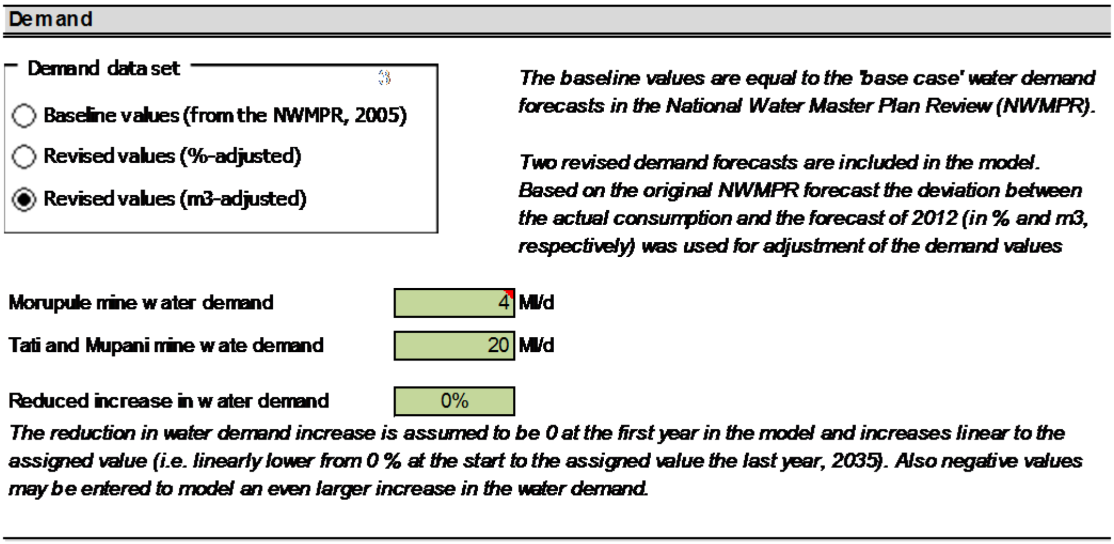
Intended (local) supply from wellfields (% of demand)

From Palapye Wellfield to Palapye	50%	
From Serowe Wellfield to Serowe	58%	
From Paje Wellfield to the Morupule mine	10%	
From Palla Road Wellfield to Mahalapye & Shoshong	50%	*Automatically 0% if Palla Road MAR (Scen. 4 & 6).*
From Malotwane Wellfield to Mochudi	0%	
From Kanye Wellfield to Kanye & Moshupa	60%	
From Ramotswa Wellfield to Ramotswa & Lobatse	50%	*Automatically 0 % for Scenario 1 since not included in current system.*

☐ Run all wellfields on sustainable yield.

The default approach is to use the above defined intended supply for the different wellfields.

Figure 6.6. Input data and operational rules for the (Non-MAR) wellfields.



Demand

Demand data set

○ Baseline values (from the NWMPR, 2005)

○ Revised values (%-adjusted)

◉ Revised values (m3-adjusted)

The baseline values are equal to the 'base case' water demand forecasts in the National Water Master Plan Review (NWMPR).

Two revised demand forecasts are included in the model. Based on the original NWMPR forecast the deviation between the actual consumption and the forecast of 2012 (in % and m3, respectively) was used for adjustment of the demand values

Morupule mine water demand	4	Ml/d
Tati and Mupani mine wate demand	20	Ml/d
Reduced increase in water demand	0%	

The reduction in water demand increase is assumed to be 0 at the first year in the model and increases linear to the assigned value (i.e. linearly lower from 0 % at the start to the assigned value the last year, 2035). Also negative values may be entered to model an even larger increase in the water demand.

Figure 6.7. Selection of demand data set and some additional demand figures.

Water Works

Treatment capacity and water losses

	Current	After upgrades *Scenario 2-6*		Water loss (%)
Sashe WW	52	91	Ml/d	5%
Palapye WW	16	32	Ml/d	5%
Selibe-Phikw e WW	38	50	Ml/d	5%
Mahalapye WW	14	14	Ml/d	5%
Gaborone WW	108	108	Ml/d	5%
Mmamashia WW	110	155	Ml/d	5%
Lobatse WW	2.5	2.5	Ml/d	4%
Mabalane WW	1.2	1.2	Ml/d	11%

Figure 6.8. Properties for the water works.

7 Modelling results

The water supply safety model provides a wide range of results which can be used to analyse and compare different scenarios. In this chapter the model results for the scenarios described in Chapter 5 are presented. The focus is on illustrating how the occurrence and magnitude of water shortage events differ between the scenarios.

7.1 Overview of included results

To provide guidance on how to interpret the results included in this chapter an overview is presented here. Since a probabilistic approach is used in the water supply safety model and, for example, inflow time series are simulated, the results are presented including uncertainties. In addition to mean values (corresponding to expected values) also percentiles are presented, most often the 10^{th} and 90^{th} percentiles (P10 and P90). A percentile represents the value below which a given percentage of model results fall. For example, P10 represents the value below which 10 % of the simulated results fall and P90 represents the value below which 90 % of the simulated results fall (i.e.10 % above).

As commonly done in risk analyses results such as maximum annual water shortage etc. are plotted against the cumulative or reverse cumulative probability. The cumulative probability plots can be used to determine, for example, that there is 30 % probability that the value will not exceed 10 Mm^3. The reverse cumulative probability plots can be used to determine, for example, that there is a 10 % probability of the values being at least 25 Mm^3.

The probabilistic approach is possible since the calculations are performed using Monte Carlo simulations. The results presented here have been calculated using 3,000 trials, which have been concluded to give sufficient low uncertainties in the results. Using this number of trials the uncertainties in the results are, thus, due to uncertainties defined for the input parameters and not due to an insufficient number of trials/calculations.

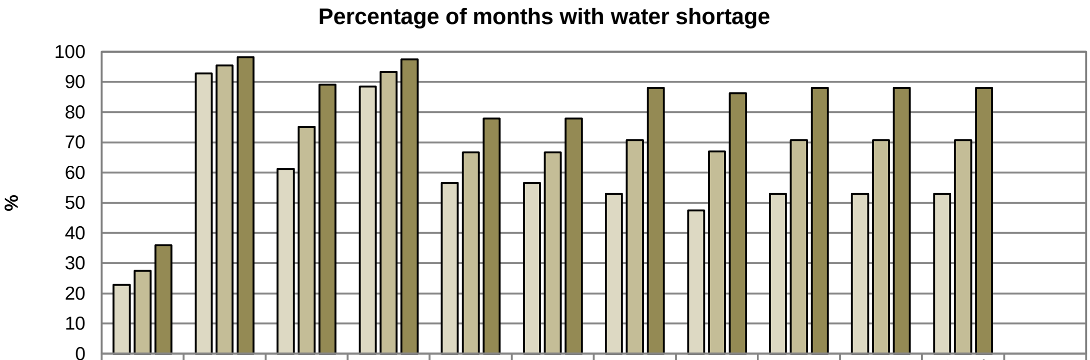
The following main results are included in the presentation and comparison of the different scenarios:

- Percentage of months with water shortage for each demand centre (P10; Mean; P90).
- Total water shortage (i.e. summed over the simulated 23 years) for each demand centre (P10; Mean; P90).
- Percentage of demand (per month) not met given water shortage for each demand centre (P10; Mean; P90).
- Number of months until first water shortage event for each demand centre (P10; Mean; P90).
- Maximum annual water shortage (Mm^3) within the simulated period (23 years) versus reverse cumulative probability.
- Total water shortage (i.e. summed over the simulated 23 years) versus reverse cumulative probability.
- Expected probability of annual water shortage of different magnitude (e.g. >2 Mm^3, >5 Mm^3, etc.) versus time.

- Total net evaporation loss savings versus reverse cumulative probability.
- Expected groundwater storage versus time.
- Groundwater storage at end of simulated period versus reverse cumulative probability.
- Proportion of limiting factors for different steps in the supply chain.

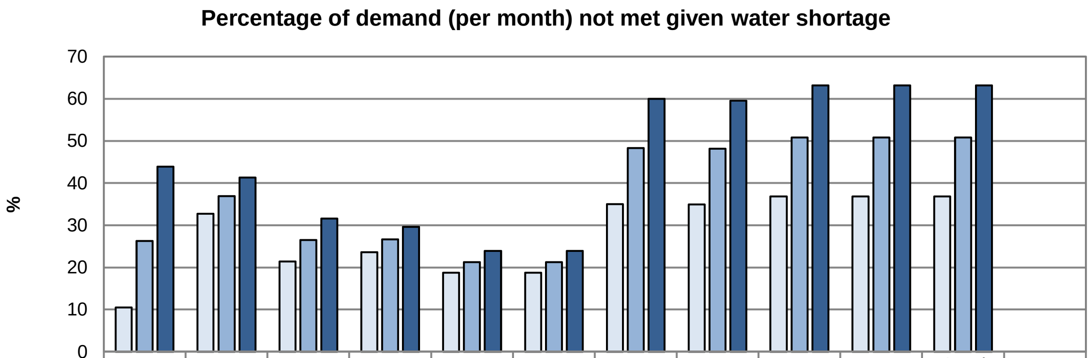
7.2 Current system (Scenario 1)

For the current system the model results show, as expected that there will be a great water shortage problem in the future and that the problems will start to arise almost immediately. Figure 7.1 shows that water shortage is expected in around 70 % (mean value) of the months for most demand centres. Only the River Villages will not experience any water shortage and this is because the supply from the Molatedi Dam is assumed to be constant in the model and demand will not exceed the possible supply within the simulated period. Given a month with water shortage the deficit varies between c. 20-60 % of the demand according to Figure 7.2. In total, i.e. over the simulated 23 years, up to year 2035, the total deficit is estimated to be 340 Mm^3 (mean value) only for Gaborone, see Figure 7.3. Note that the results presented for Scenario 1 does not include Kanye, Moshupa and Thamaga. This is because these demand centres are not connected to the NSC system in Scenario 1 but they are included in Scenarios 2-6.



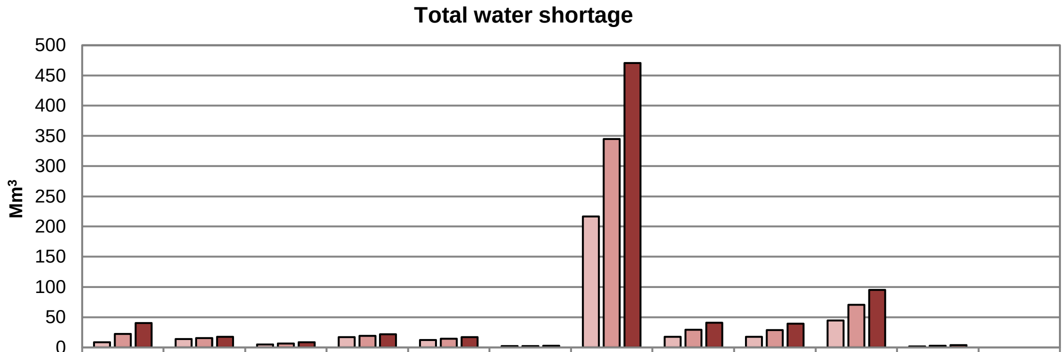
	Selebi-Phikwe	Palapye	Morupule mine	Serowe	Mahalapye	Shoshong	Gaborone	Mochudi	Ramotswa	Lobatse	Good Hope Cluster	River Villages
P10	23	93	61	88	57	57	53	47	53	53	53	0
Mean	27	95	75	93	67	67	71	67	71	71	71	0
P90	36	98	89	97	78	78	88	86	88	88	88	0

Figure 7.1. Percentage of months with water shortage for the demand centres included in Scenario 1.



	Selebi-Phikwe	Palapye	Morupule mine	Serowe	Mahalapye	Shoshong	Gaborone	Mochudi	Ramotswa	Lobatse	Good Hope Cluster	River Villages
P10	10	33	21	24	19	19	35	35	37	37	37	0
Mean	26	37	26	27	21	21	48	48	51	51	51	0
P90	44	41	32	30	24	24	60	60	63	63	63	0

Figure 7.2. *Percentage of monthly demand not met given water shortage for the demand centres included in Scenario 1.*

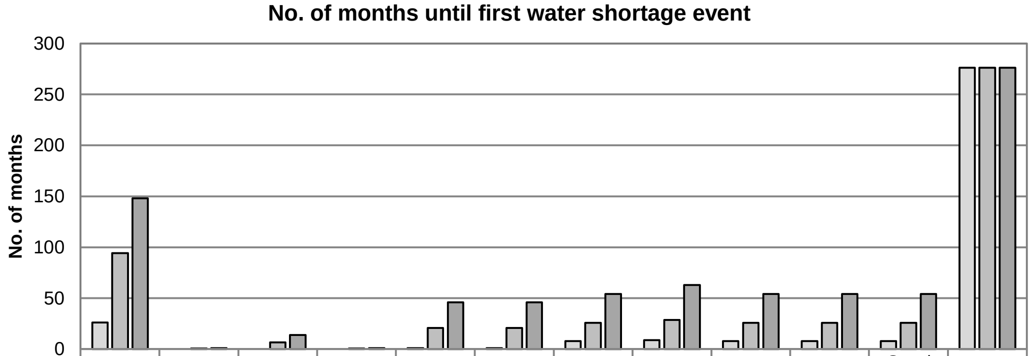


	Selebi-Phikwe	Palapye	Morupule mine	Serowe	Mahalapye	Shoshong	Gaborone	Mochudi	Ramotswa	Lobatse	Good Hope Cluster	River Villages
P10	8.6	14.0	4.9	17.0	12.3	2.1	216.3	17.6	17.8	44.4	1.8	0.0
Mean	22.4	15.8	6.7	19.3	14.6	2.5	344.7	29.5	28.7	70.3	2.9	0.0
P90	40.2	17.6	8.6	21.8	17.0	2.9	470.5	41.1	39.4	95.3	3.9	0.0

Figure 7.3. *Total water shortage (i.e. summed over the simulated 23 years) for the demand centres included in Scenario 1.*

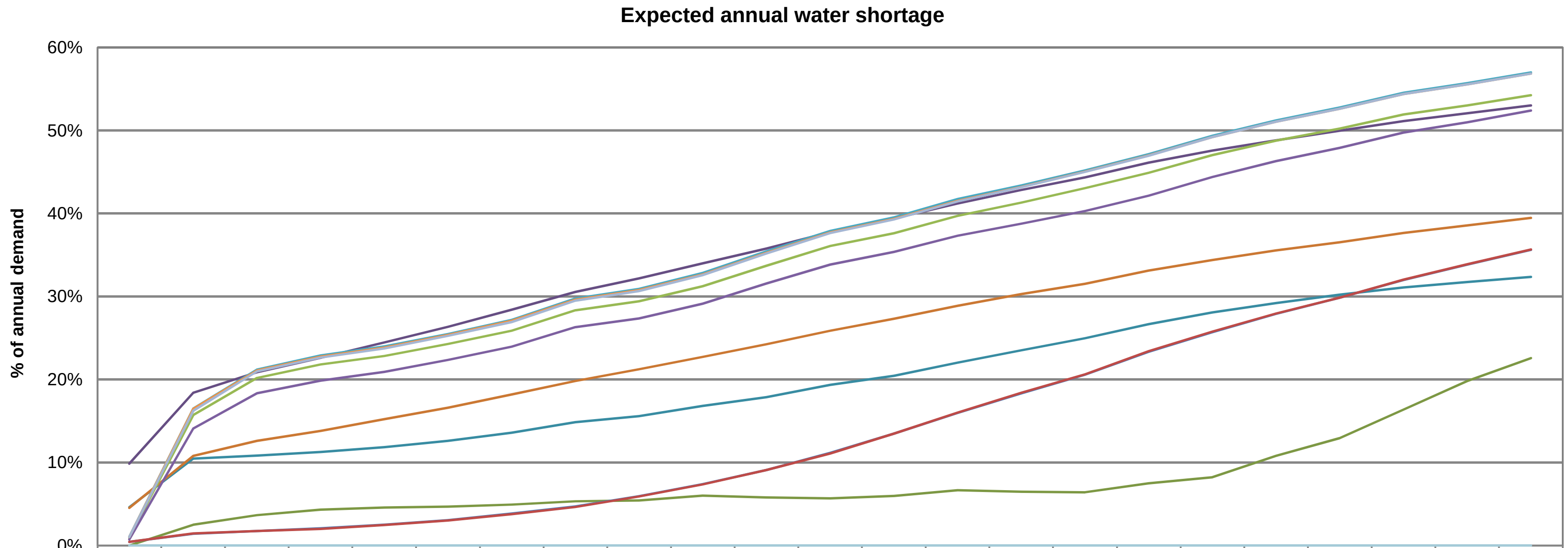
Since the water demand is increasing, the water shortage events will become more frequent in the future and the actual deficit will increase. As presented in Figure 7.4, water shortage events are expected to occur within less than 3 years for most demand centres. The effect of the increasing water demand can be seen in the results in Figure 7.5 where the annual water shortage (in percent) is presented for each demand centre for each year. At the end of the simulated period (i.e. year 2035) the deficit will be up to 50 % for some of the demand centres, including Gaborone.

The results presented here are based on the m^3-adjusted water demand data (see Chapter 4.1). Since the water demand is a key factor affecting the results, the model was also run with a lower increase in the water demand as a sensitivity test. The adjusted/reduced demand data are linearly lower from 0 % at the start to 20 % the last year, 2035. The results are presented in Figure 7.6 and show that water shortage will still be a major problem even if the demand will not increase as much as expected.



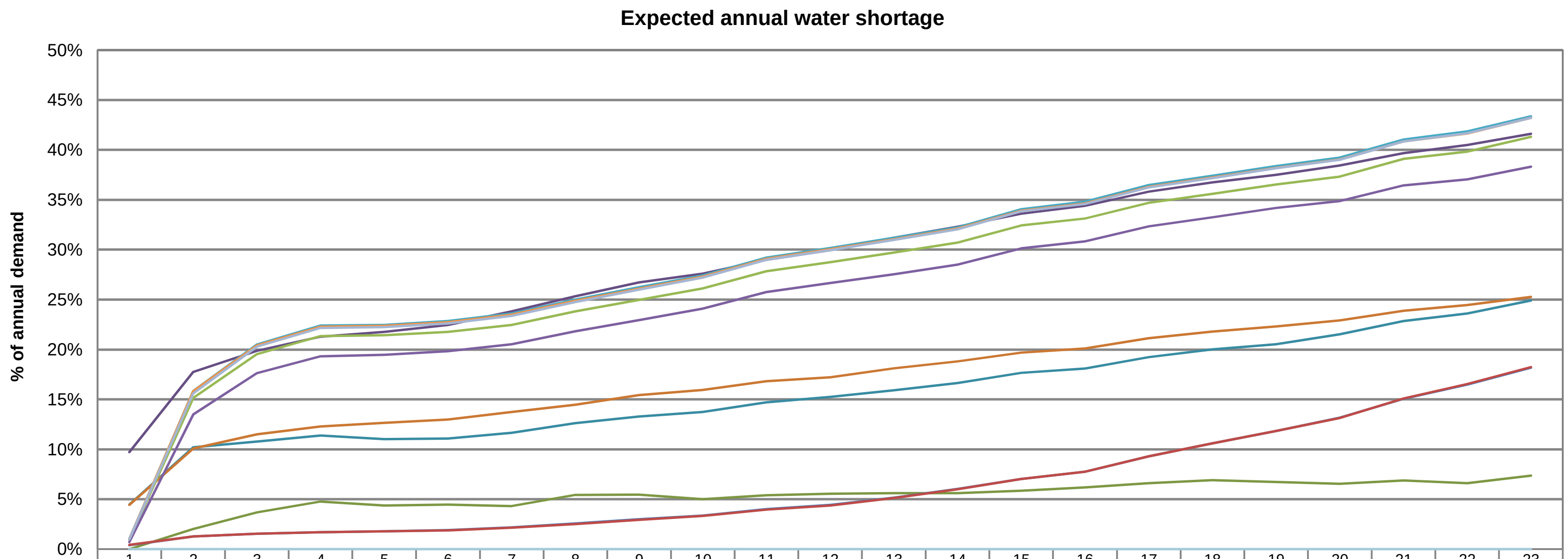
	Selebi-Phikwe	Palapye	Morupule mine	Serowe	Mahalapye	Shoshong	Gaborone	Mochudi	Ramotswa	Lobatse	Good Hope Cluster	River Villages
P10	26	0	0	0	1	1	8	9	8	8	8	276
Mean	94	1	7	1	21	21	26	29	26	26	26	276
P90	148	1	14	1	46	46	54	63	54	54	54	276

Figure 7.4. *Number of months until first water shortage event for the demand centres included in Scenario 1.*



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Selebi-Phikwe	0%	2%	4%	4%	5%	5%	5%	5%	5%	6%	6%	6%	6%	7%	6%	6%	7%	8%	11%	13%	16%	20%	23%
Palapye	10%	18%	21%	23%	24%	26%	28%	31%	32%	34%	36%	38%	39%	41%	43%	44%	46%	48%	49%	50%	51%	52%	53%
Morupule mine	5%	10%	11%	11%	12%	13%	14%	15%	16%	17%	18%	19%	20%	22%	24%	25%	27%	28%	29%	30%	31%	32%	32%
Serowe	5%	11%	13%	14%	15%	17%	18%	20%	21%	23%	24%	26%	27%	29%	30%	32%	33%	34%	36%	37%	38%	39%	39%
Mahalapye	0%	1%	2%	2%	2%	3%	4%	5%	6%	7%	9%	11%	13%	16%	18%	21%	23%	26%	28%	30%	32%	34%	36%
Shoshong	0%	1%	2%	2%	2%	3%	4%	5%	6%	7%	9%	11%	13%	16%	18%	21%	23%	26%	28%	30%	32%	34%	36%
Gaborone	1%	16%	20%	22%	23%	24%	26%	28%	29%	31%	34%	36%	38%	40%	41%	43%	45%	47%	49%	50%	52%	53%	54%
Mochudi	1%	14%	18%	20%	21%	22%	24%	26%	27%	29%	32%	34%	35%	37%	39%	40%	42%	44%	46%	48%	50%	51%	52%
Ramotswa	1%	16%	21%	23%	24%	25%	27%	30%	31%	33%	35%	38%	40%	42%	43%	45%	47%	49%	51%	53%	55%	56%	57%
Lobatse	1%	16%	21%	23%	24%	25%	27%	30%	31%	33%	35%	38%	39%	42%	43%	45%	47%	49%	51%	53%	54%	56%	57%
Good Hope Cluster	1%	16%	21%	23%	24%	25%	27%	29%	31%	33%	35%	38%	39%	41%	43%	45%	47%	49%	51%	53%	54%	56%	57%
River Villages	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 7.5. Expected annual water shortage as % of annual demand over time (year 1-23) for the different demand centres included in Scenario 1, representing the current system.

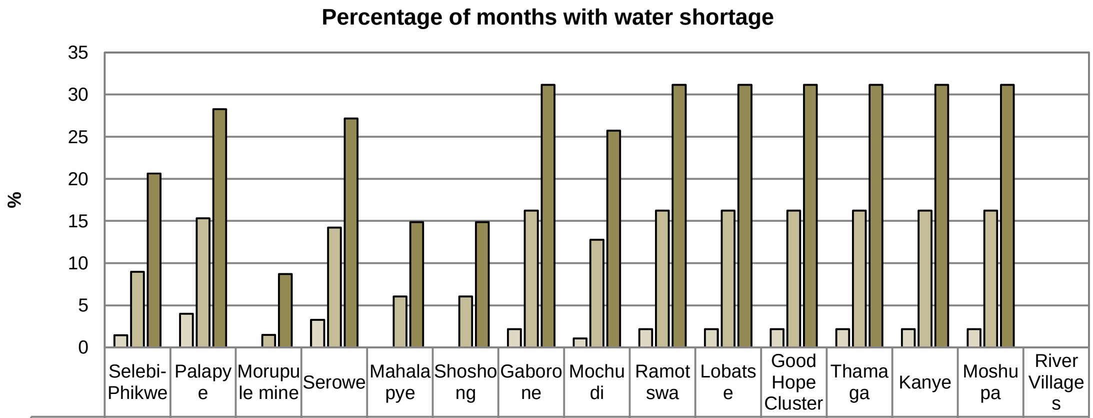


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Selebi-Phikwe	0%	2%	4%	5%	4%	4%	4%	5%	5%	5%	5%	6%	6%	6%	6%	6%	7%	7%	7%	7%	7%	7%	7%
Palapye	10%	18%	20%	21%	22%	22%	24%	25%	27%	28%	29%	30%	31%	32%	34%	34%	36%	37%	37%	38%	40%	40%	42%
Morupule mine	4%	10%	11%	11%	11%	11%	12%	13%	13%	14%	15%	15%	16%	17%	18%	18%	19%	20%	21%	22%	23%	24%	25%
Serowe	4%	10%	12%	12%	13%	13%	14%	14%	15%	16%	17%	17%	18%	19%	20%	20%	21%	22%	22%	23%	24%	24%	25%
Mahalapye	0%	1%	2%	2%	2%	2%	2%	3%	3%	3%	4%	4%	5%	6%	7%	8%	9%	11%	12%	13%	15%	16%	18%
Shoshong	0%	1%	2%	2%	2%	2%	2%	3%	3%	3%	4%	4%	5%	6%	7%	8%	9%	11%	12%	13%	15%	17%	18%
Gaborone	1%	15%	20%	21%	21%	22%	22%	24%	25%	26%	28%	29%	30%	31%	32%	33%	35%	36%	37%	37%	39%	40%	41%
Mochudi	1%	14%	18%	19%	19%	20%	21%	22%	23%	24%	26%	27%	28%	29%	30%	31%	32%	33%	34%	35%	36%	37%	38%
Ramotswa	1%	16%	21%	22%	22%	23%	24%	25%	26%	27%	29%	30%	31%	32%	34%	35%	36%	37%	38%	39%	41%	42%	43%
Lobatse	1%	16%	20%	22%	22%	23%	23%	25%	26%	27%	29%	30%	31%	32%	34%	35%	36%	37%	38%	39%	41%	42%	43%
Good Hope Cluster	1%	16%	20%	22%	22%	23%	23%	25%	26%	27%	29%	30%	31%	32%	34%	35%	36%	37%	38%	39%	41%	42%	43%
River Villages	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 7.6. *Expected annual water shortage as % of annual demand over time (year 1-23) for the different demand centres included in Scenario 1 but with a lower increase in the water demand.*

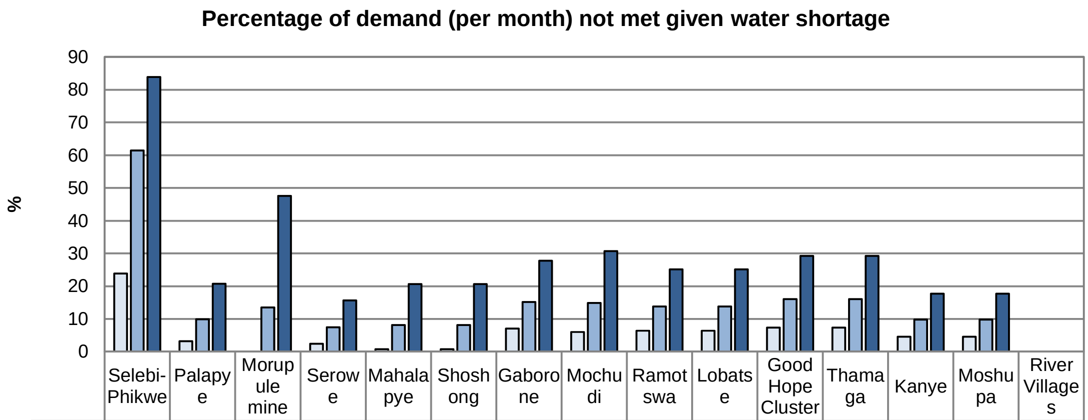
7.3 Connecting Dikgatlhong (Scenario 2)

Scenario 2 includes the Dikgatlhong Dam and a set of other upgrades of water works etc. (see Section 4.4 and Chapter 5). The connection of the Dikgatlhong dam to the NSC, and the increased treatment capacity in the Mmamashia WW included in Scenario 2, increases the supply safety to a large. The expected percentage of months with water shortage (Figure 7.7) is reduced by 70 % from by Scenario 1 for Gaborone (cf. Figure 7.1). In general water shortage occurs in 2-16 % of the months in Scenario 2 compared to 70 % for most demand centres in Scenario 1. Also the magnitude of the deficits is reduced and is expected to be around 10-20 % per month (given shortage) in Scenario 2 (Figure 7.8). In Scenario 1 the corresponding figures were 20-60 % (Figure 7.2).



	Selebi-Phikwe	Palapye	Morupule mine	Serowe	Mahalapye	Shoshong	Gaborone	Mochudi	Ramotswa	Lobatse	Good Hope Cluster	Thamaga	Kanye	Moshupa	River Villages
P10	1	4	0	3	0	0	2	1	2	2	2	2	2	2	0
Mean	9	15	1	14	6	6	16	13	16	16	16	16	16	16	0
P90	21	28	9	27	15	15	31	26	31	31	31	31	31	31	0

Figure 7.7. Percentage of months with water shortage for the demand centres included in Scenario 2, i.e. when the Dikgatlhong Dam has been connected and additional upgrades of water works etc. have been made.

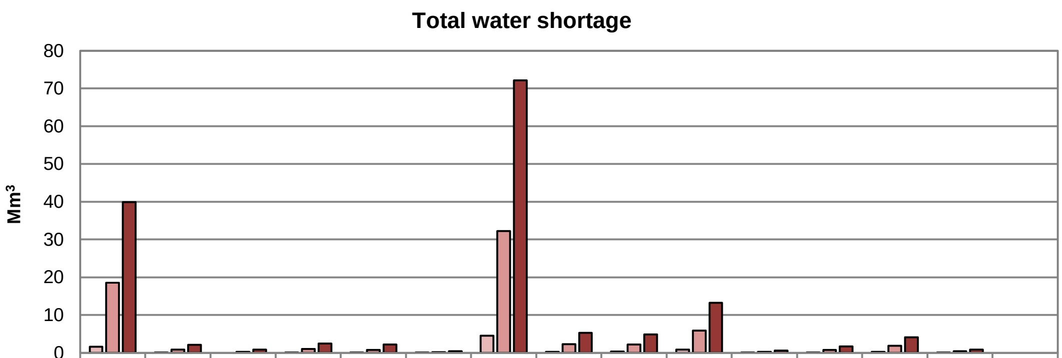


	Selebi-Phikwe	Palapye	Morupule mine	Serowe	Mahalapye	Shoshong	Gaborone	Mochudi	Ramotswa	Lobatse	Good Hope Cluster	Thamaga	Kanye	Moshupa	River Villages
P10	24	3	0	2	1	1	7	6	6	6	7	7	5	5	0
Mean	61	10	14	7	8	8	15	15	14	14	16	16	10	10	0
P90	84	21	48	16	21	21	28	31	25	25	29	29	18	18	0

Figure 7.8. Percentage of demand (per month) not met given water shortage for the demand centre included in Scenario 2.

The total deficit of water, i.e. summed over the simulated 23 years, is presented in Figure 7.9 (mean total deficit c. 50 Mm^3). In Figure 7.10 the results for Scenarios 1 and 2 are presented as a reverse cumulative plot for Gaborone and the connected demand centres. In Scenario 1 there is a probability of 0.5 of having a deficit of at least 450 Mm^3 which is reduced to 35 Mm^3 in Scenario 2. The results are also presented for a case with a lower increase in the demand (linearly lower from 0 % at the start to 20 % the last year, 2035). In Scenario 2 the probability of having a deficit greater than 13 Mm^3 is 0.2.

As shown in Figure 7.9 the total deficit for Selebi-Phikwe in Scenario 2 is not reduced to the same extent as for the other demand centres (mean total deficit is reduced from 25 to 19 Mm^3, cf. Figure 7.3). The percentage of months with water shortage is, however, not higher for Selebi-Phikwe compared to the other demand centres in Scenario 2 (Figure 7.7). In the modelled scenarios it is assumed that the water treatment capacity is increased at the Selebi-Phikwe WW to meet the increased demand (i.e. current capacity of 38 Ml/d is increased to 50 Ml/d in Scenario 2-6). Similarly, the abstraction rate for the Shashe dam (and the treatment capacity for the Francistown WW) is increased to meet the water demand in Francistown. The abstraction rate for the Shashe Dam (in Scenario 2) is, however, not increased to meet also the demand in Selebi-Phikwe. The effect of additional increased abstraction rate is presented in Section 7.5.



	Selebi-Phikwe	Palapye	Morupule mine	Serowe	Mahalapye	Shoshong	Gaborone	Mochudi	Ramotswa	Lobatse	Good Hope Cluster	Thamaga	Kanye	Moshupa	River Villages
P10	1.6	0.1	0.0	0.1	0.0	0.0	4.6	0.2	0.3	0.8	0.0	0.1	0.3	0.1	0.0
Mean	18.6	0.9	0.2	1.0	0.8	0.1	32.2	2.2	2.2	5.9	0.2	0.8	1.8	0.4	0.0
P90	39.9	2.1	0.8	2.5	2.2	0.4	72.2	5.3	4.9	13.3	0.5	1.7	4.1	0.9	0.0

Figure 7.9. Total water shortage (i.e. summed over the simulated 23 years) for the demand centre included in Scenario 2.

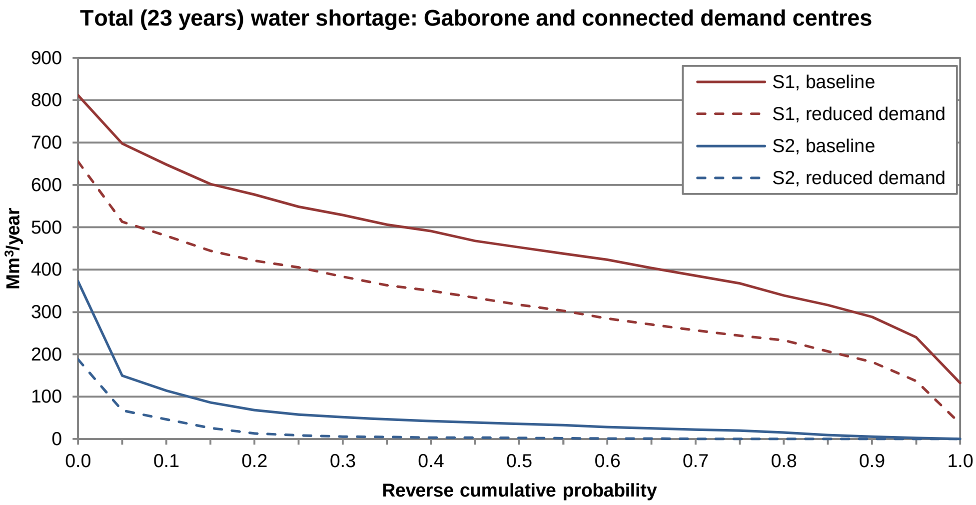


Figure 7.10. Total water shortage summed over the 23 years for Gaborone and connected demand centres.

A similar graph as presented in Figure 7.10 is presented in Figure 7.11 but for the maximum annual water shortage for Gaborone and connected demand centres. The results illustrates how likely different (annual) worst case scenarios are. In Scenario 1 the maximum annual shortage is at least 40 Mm^3 with a 0.95 probability. The corresponding figure for Scenario 2 is approximately 2 Mm^3. In Scenario 2 there is probability of 0.25 of having a shortage of at least 20 Mm^3.

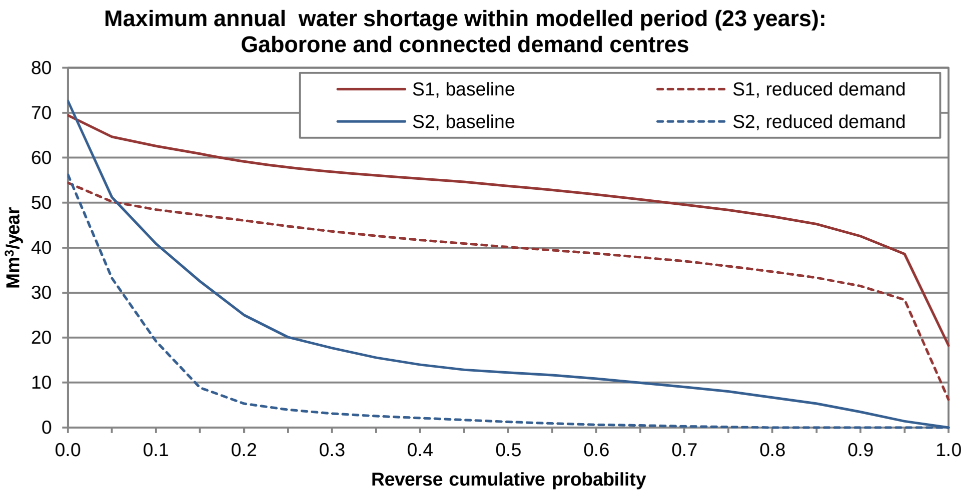


Figure 7.11. Maximum annual water shortage for Gaborone and connected demand centres.

To illustrate the effect of Scenario 2, Figure 7.12 and Figure 7.13 present the expected probability of annual shortage for Gaborone and the connected demand centres in Scenarios 1 and 2, respectively. In Scenario 1 water shortage events occur almost immediately, but in Scenario 2 the problem seems to occur after approximately 11 years, and the probability of shortage is reduced in general.

An overview of how the problem of water shortage (expressed as percent of annual demand) develops over the simulated period is also presented in Figure 7.14.

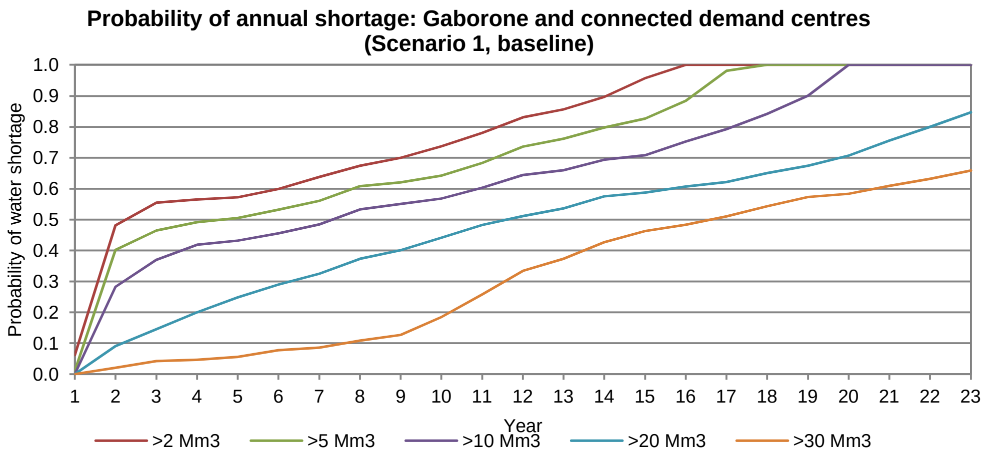


Figure 7.12. Expected probability of annual water shortage of different magnitudes for each year in Scenario 1, i.e. current system.

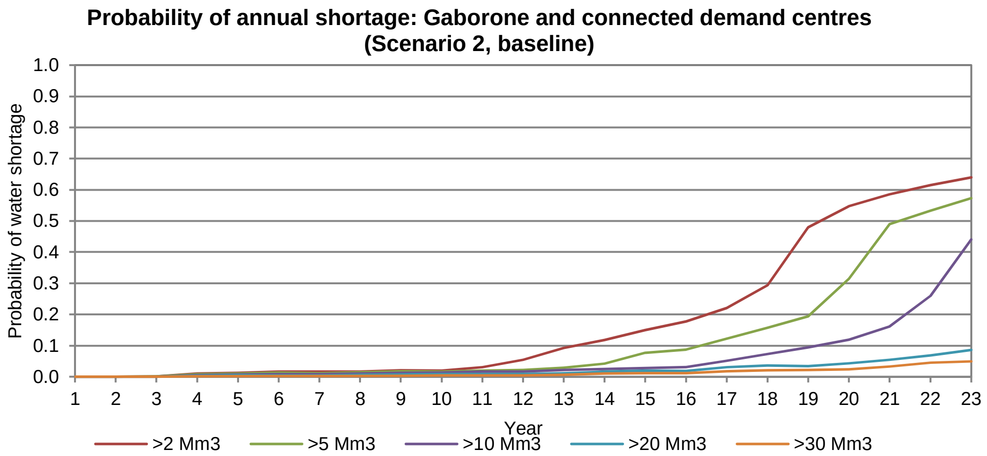
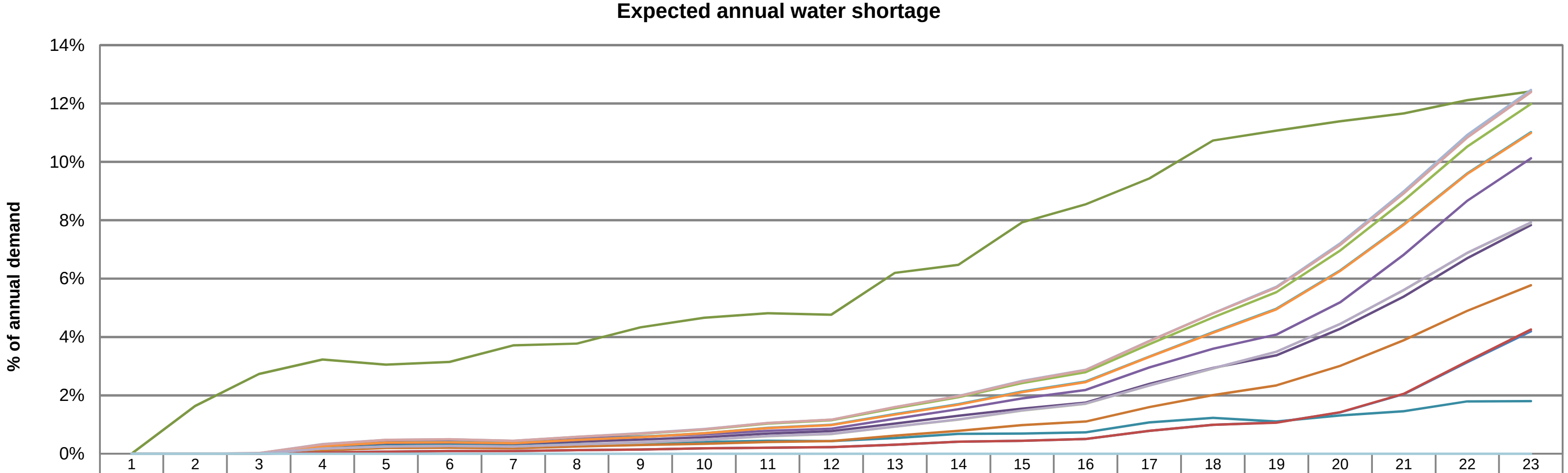


Figure 7.13. Expected probability of annual water shortage of different magnitudes for each year in Scenario 2 including the Dikgatlhong Dam.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Selebi-Phikwe	0%	2%	3%	3%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	8%	9%	9%	11%	11%	11%	12%	12%	12%
Palapye	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	2%	2%	2%	3%	3%	4%	5%	7%	8%
Morupule mine	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	1%	1%	1%	1%	2%	2%
Serowe	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	2%	2%	2%	3%	4%	5%	6%
Mahalapye	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	2%	3%	4%
Shoshong	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	2%	3%	4%
Gaborone	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	2%	2%	2%	3%	4%	5%	6%	7%	9%	11%	12%
Mochudi	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	1%	2%	2%	2%	3%	4%	4%	5%	7%	9%	10%
Ramotswa	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	2%	2%	2%	3%	4%	5%	6%	8%	10%	11%
Lobatse	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	2%	2%	2%	3%	4%	5%	6%	8%	10%	11%
Good Hope Cluster	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	2%	2%	2%	3%	4%	5%	6%	7%	9%	11%	12%
Thamaga	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	2%	2%	2%	3%	4%	5%	6%	7%	9%	11%	12%
Kanye	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	2%	2%	3%	3%	4%	6%	7%	8%
Moshupa	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	2%	2%	3%	4%	4%	6%	7%	8%
River Villages	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 7.14. Expected annual water shortage as % of annual demand over time (year 1-23) for the different demand centres included in Scenario 2.

7.4 Connecting Masama/Makhujwane (Non-MAR & MAR) and/or Palla Road/Chepete (MAR)

The use of Masama/Makhujwane Wellfields in a MAR or Non-MAR scenario and Palla Road/Chepete Wellfields in a MAR scenario will further increase the water supply safety. In Figure 7.13 the probability of different water shortages were presented for Gaborone and connected demand centres in Scenario 2. The same results are presented in Figure 7.15 and Figure 7.16 for Scenario 3 (including Masama/Makhujwane as a Non-MAR) and Scenario 6 (including Masama/Makhujwane and Palla Road/Chepete as MAR), respectively. Figure 7.15 shows that the probability of water shortage is low up to year 15 in Scenario 3, compared to year 11 for Scenario 2 (cf. Figure 7.13). The probability of the smaller deficits is not reduced from Scenario 2 to 3 but is reduced for the larger ones.

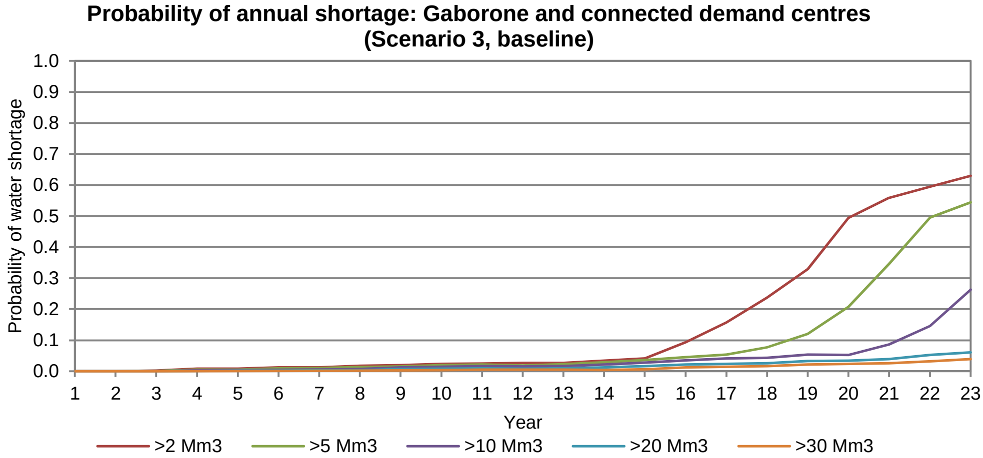


Figure 7.15. Expected probability of annual water shortage of different magnitudes for each year in Scenario 3, i.e. including Masama/Makhujwane (Non-MAR).

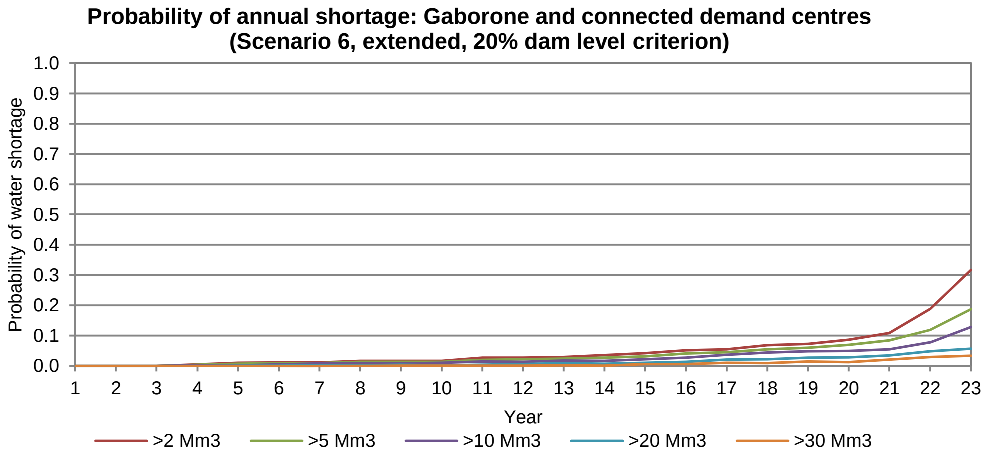


Figure 7.16. Expected probability of annual water shortage of different magnitudes for each year in Scenario 6, i.e. including Masama/Makhujwane and Palla Road/Chepete, MAR.

For Scenario 6, when running the model with the extended sub-scenarios for the MAR wellfields (see Chapter 4.2), the shortage probabilities are markedly reduced (Figure

7.16). The probability of a water shortage of more than 10 Mm^3 (12 % of demand) in the last year of the simulated period (i.e. 2035) is c. 0.1, compared to probabilities of 0.4 and 0.25 for the same deficits in Scenario 2 and 3, respectively. If the baseline sub-scenarios are used for the MAR wellfields, the results show shortage probabilities between the results presented in Figure 7.15 and Figure 7.16.

The difference between Scenarios 3 and 6 (extended) is also presented in Figure 7.17 and Figure 7.18. In the former figure the maximum annual deficit is presented and in the latter the total deficit summed over the simulated 23 years (up to 2035). The results are presented for the m^3-adjusted demand data (see Chapter 4.1) as well as for a case with reduced increase in the demand (demand data are linearly lower from 0 % at the start to 20 % the last year, 2035). The difference with respect to maximum annual water shortage is primarily that for Scenario 3 the probability of deficits around 10 Mm^3 is higher relatively to Scenario 6. This is also the case for the total shortage, i.e. the probability of having a shortage of 20 Mm^3 or more is 0.6 in Scenario 3 whereas the same probability is 0.25 for Scenario 6.

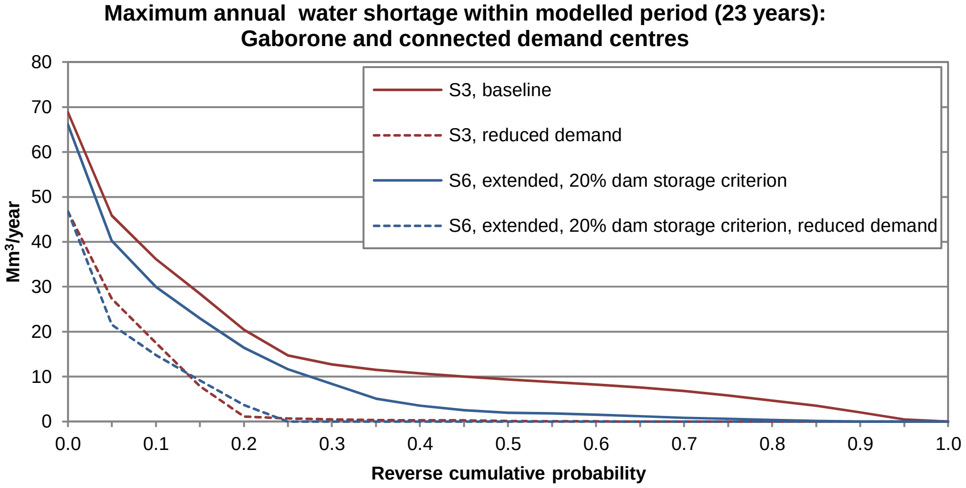


Figure 7.17. Maximum annual water shortage for Gaborone and connected demand centres.

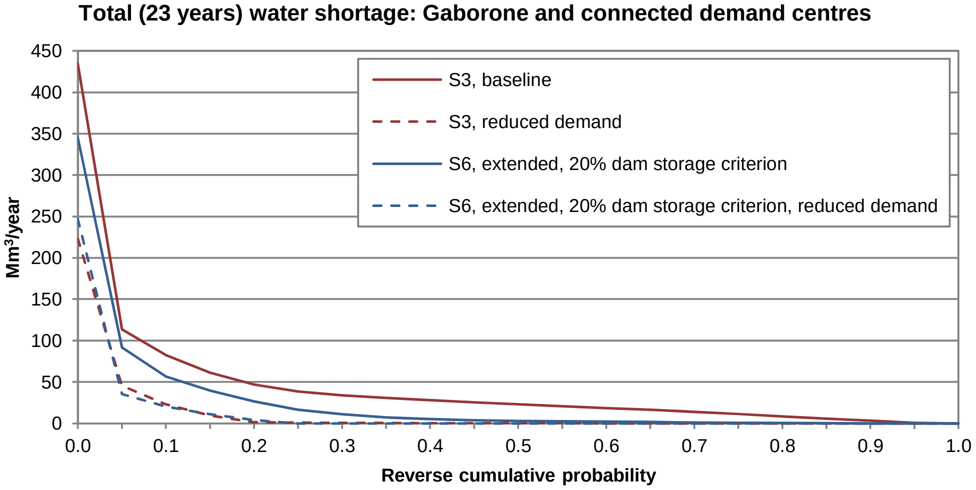
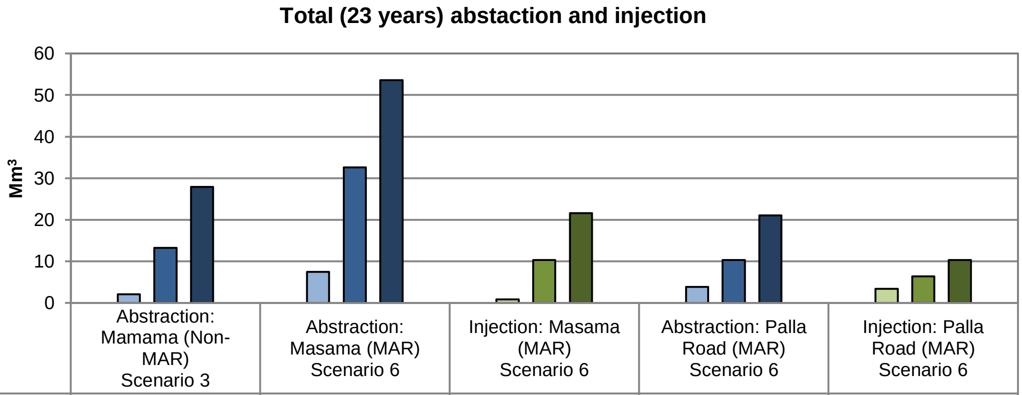


Figure 7.18. Total water shortage summed over the 23 years for Gaborone and connected demand centres.

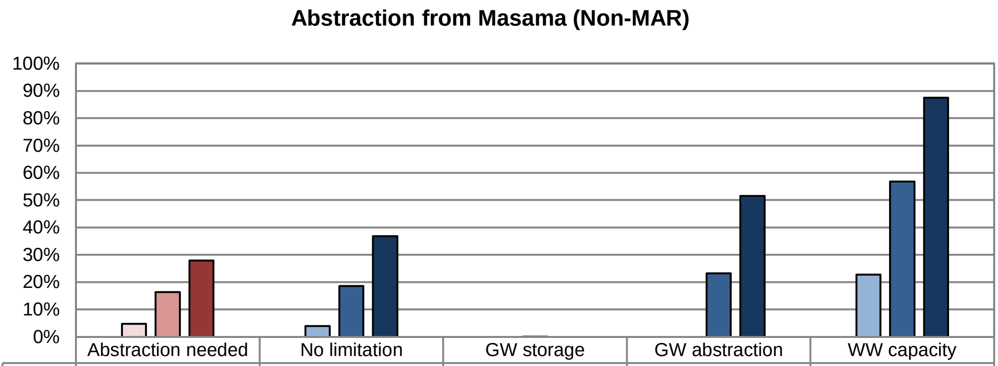
The total abstraction and injection for Masama/Makhujwane and Palla Road/Chepete Wellfields is presented in Figure 7.19 for Scenarios 3 and 6. The larger abstraction for Masama/Makhujwane in Scenario 6 is partly because of the increased abstraction rates (extended settings are used). The factors limiting the abstraction in Scenario 3 are presented in Figure 7.20. It can be concluded that abstraction from Masama/Makhujwane is needed in 16 % of the months and it is possible to obtain the needed injection water in 19 % of these cases (mean values). In 23 % of the cases the available abstraction rate is too low. However, it is primarily the capacity of treating the abstracted water at the Mmamashia WW or the Gaborone WW that is limiting (57 % of the cases). The mean values in Figure 7.20 sum up to 100 % but note that it is not possible to sum the percentiles since they represent the uncertainties in the results.

Detailed analysis of the model results show that Masama/Makhujwane is needed when the Gaborone Dam level is low and only a minor part of the Gaborone WW capacity can be used due to the limited capacity of the pipeline transferring water from the Bokaa Dam (possibly from the NSC) to the Gaborone WW. In such cases more or less the full capacity of the Mmamashia WW must be used to supply water to the demand centres and limited extra capacity is available for treating water abstracted from Masama/Makhujwane Wellfields.



	Abstraction: Mamama (Non-MAR) Scenario 3	Abstraction: Masama (MAR) Scenario 6	Injection: Masama (MAR) Scenario 6	Abstraction: Palla Road (MAR) Scenario 6	Injection: Palla Road (MAR) Scenario 6
P10	2.1	7.5	0.9	3.9	3.4
Mean	13.2	32.6	10.3	10.3	6.4
P90	27.9	53.6	21.6	21.1	10.3

Figure 7.19. Total volumes (entire model period of 23 years) abstracted and injected for Masama/Makhujwane and Palla Road/Chepete Wellfields.

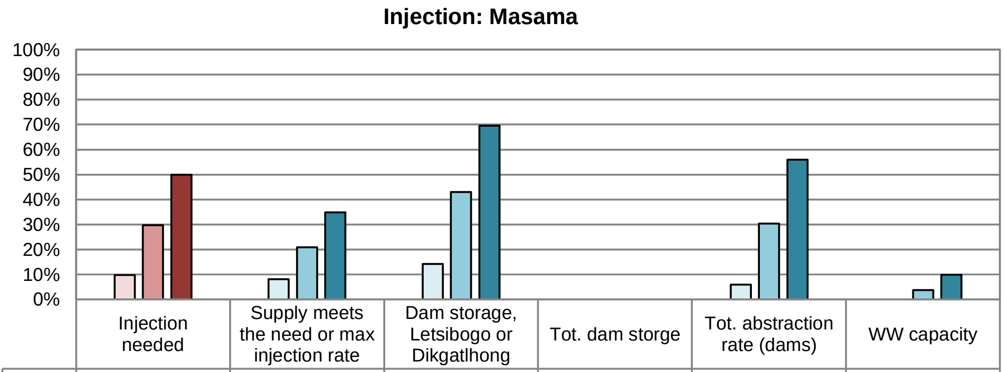


	Abstraction needed	No limitation	GW storage	GW abstraction	WW capacity
P10	5%	4%	0%	0%	23%
Mean	16%	19%	0%	23%	57%
P90	28%	37%	0%	52%	88%

Figure 7.20. Factors limiting the abstraction from Masama/Makhujwane Wellfield in Scenario 3 (Non-MAR). The left set of bars (red) show the percentage of months when abstraction is needed and the remaining set of bars (blue) show if there is anything limiting the abstraction.

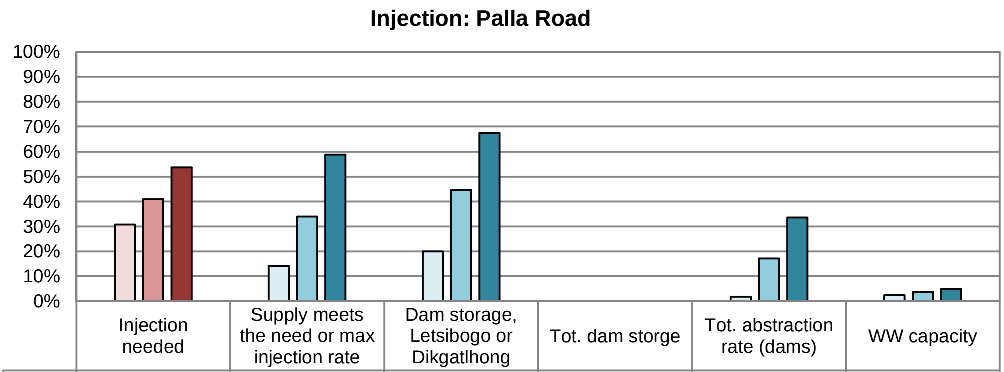
In Scenario 6 an additional pipeline supplying water to and from Masama/Makhujwane Wellfields is included (optional) in the model which erases the WW capacity limitation. In Scenario 6 it is instead the abstraction rate that is the main limitation for Masama/Makhujwane abstraction. However, it is possible to meet the needed abstraction in 70 % of the cases. For Palla Road/Chepete it is possible to meet the needed abstraction (for supply to Mahalapye and Shoshong) in 100 % of the cases, but the WW capacity at Mmamashia is limiting the for additional supply to Gaborone.

In Figure 7.21 and Figure 7.22 the factors limiting the injection at the Masama/Makhujwane and Palla Road/Chepete Wellfields are presented. Injection is expected to be needed in 30 and 41 % of the months for Masama/Makhujwane and Palla Road/Chepete, respectively. Injection up to full storage or up to maximum injection rate is obtained in 21 % of the months for Masama/Makhujwane Wellfields and 34 % of the months for Palla Road/Chepete Wellfields (mean values). The scenarios presented in the figures are run with a criterion saying that the dam storages in both the Letsibogo and Dikgatlhong Dams must be at least 20 % in order to allow abstraction of water for injection. The results show that the dam storages and also the abstraction rates are limiting the possibility to inject the needed amount of water (up to maximum injection rate). The results presented here are for the m^3-adjusted demand data and it can be concluded that the increased demand results in limited spare capacity, i.e. even if there is water available in the dams, the abstraction rate for the dams is not enough to supply water to both the demand centres and the MAR wellfields for injection. In Section 7.5 results are presented showing how the effect of the MAR alternatives etc. can be improved by upgrading, for example, abstraction rates for the dams and transfer capacities of pipelines.



	Injection needed	Supply meets the need or max injection rate	Dam storage, Letsibogo or Dikgatlhong	Tot. dam storge	Tot. abstraction rate (dams)	WW capacity
P10	10%	8%	14%	0%	6%	0%
Mean	30%	21%	43%	0%	30%	4%
P90	50%	35%	70%	0%	56%	10%

Figure 7.21. Factors limiting the injection at Masama/Makhujwane Wellfields in Scenario 6 (extended sub-scenario). The left set of bars (red) show the percentage of months when injection is needed and the remaining set of bars (blue) show if there is anything limiting the injection.



	Injection needed	Supply meets the need or max injection rate	Dam storage, Letsibogo or Dikgatlhong	Tot. dam storge	Tot. abstraction rate (dams)	WW capacity
P10	31%	14%	20%	0%	2%	2%
Mean	41%	34%	45%	0%	17%	4%
P90	54%	59%	67%	0%	34%	5%

Figure 7.22. Factors limiting the injection at Palla Road/Chepete Wellfields in Scenario 6 (extended settings). The left set of bars (red) show the percentage of months when injection is needed and the remaining set of bars (blue) show if there is anything limiting the injection.

The groundwater storage at the end of the simulated period (end of 2035) is presented for Masama/Makhujwane Non-MAR (Scenario 3), Masama/Makhujwane MAR (Scenario 6) and Palla Road/Chepete MAR (Scenario 6) in Figure 7.23, Figure 7.24 and Figure 7.25, respectively. Note that the actual supply safety with respect to water shortage events, total deficits etc. differs between Scenario 3 and 6 and thus also the total abstraction that was done (see Figure 7.19). In Scenario 3 Masama/Makhujwane (Non-MAR) will have a storage of at least 30 Mm^3 with a probability of approximately 0.5 (Figure 7.23). The reason the storage has not been reduced further is due to the above described limiting factors.

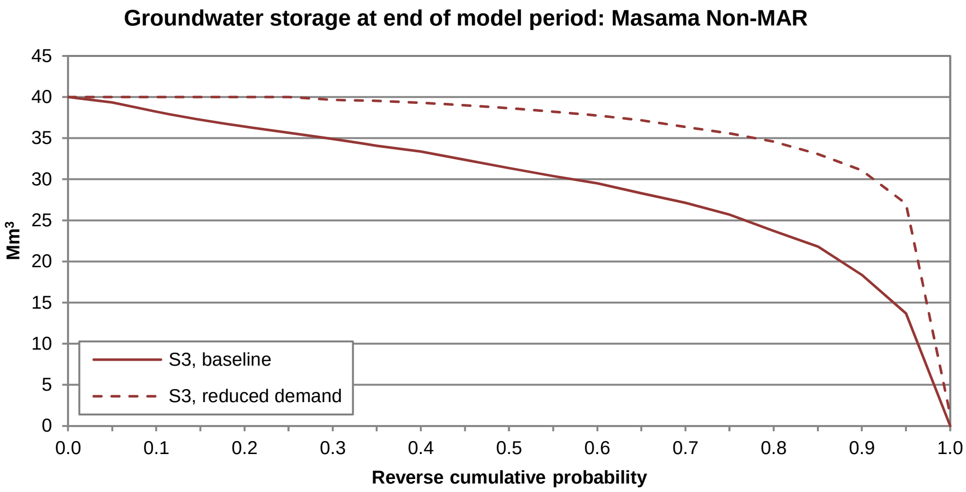


Figure 7.23. Groundwater storage at the end of the model period (year 2035) for Masama in Scenario 3.

For Masama/Makhujwane (MAR) in Scenario 6 the storage is reduced further compared to Scenario 3 and the likelihood of having a full storage (40 Mm^3) is about 0.2, while the 0.5 probability storage is 25 Mm^3 (Figure 7.24). However, if a reduced demand data set is used the storage will be full (40 Mm^3) with a probability of around 0.7. For Palla Road/Chepete, the probability of having a reduced storage is small with both demand data sets (Figure 7.25).

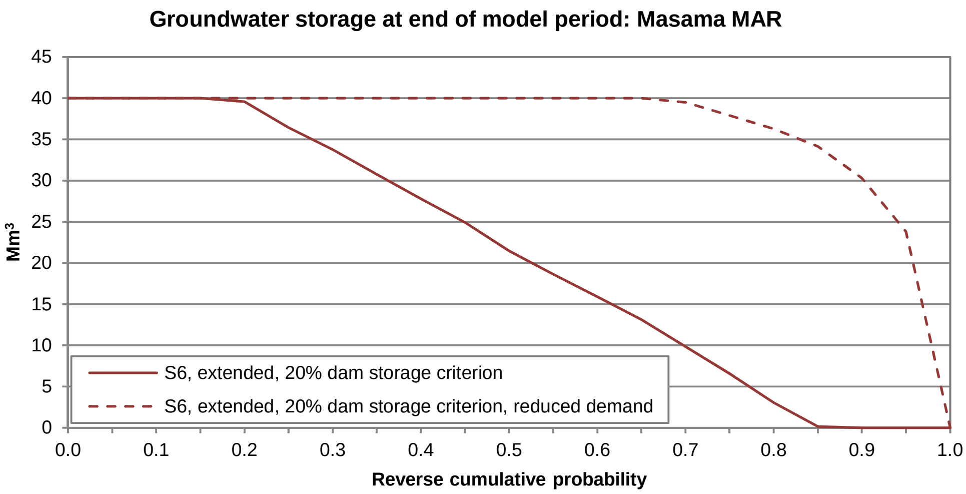


Figure 7.24. Groundwater storage at the end of the model period (year 2035) for Masama/Makhujwane Wellfields in Scenario 6 (extended sub-scenario).

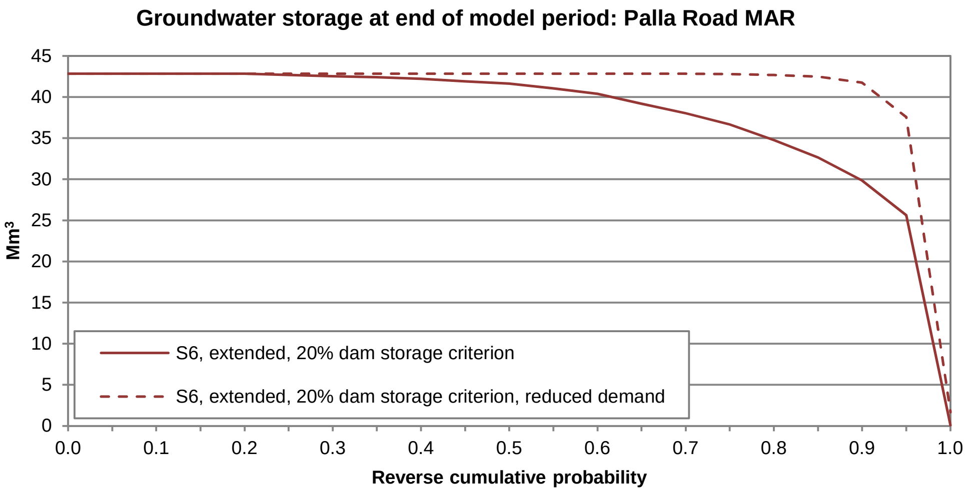


Figure 7.25. Groundwater storage at the end of the model period (year 2035) for Palla Road/Chepete Wellfields in Scenario 6 (extended sub-scenario).

One of the primary aims of applying MAR is to be able to recharge the aquifers faster than if only relying on natural recharge. To illustrate the difference between the MAR and Non-MAR scenarios, the theoretical development of the storage from 0 Mm^3 at the start are presented in Figure 7.26 and Figure 7.27. Hence, the simulation results presented in the two figures are based on the assumption that the storage is 0 Mm^3 at the start of the period, no abstraction is done, for the Non-MAR scenarios only natural recharge is included and for the MAR-scenarios full injection is used (see Section 4.2). Both the Masama/Makhujwane and Palla Road/Chepete Wellfields reach a full storage after 5-6 year in the MAR scenarios, whereas for the Non-MAR scenarios full storage is not reached within the simulated 23 years. It can thus be concluded that if the storage is heavily reduced in a Non-MAR scenario the time to for recharging the aquifers will be long.

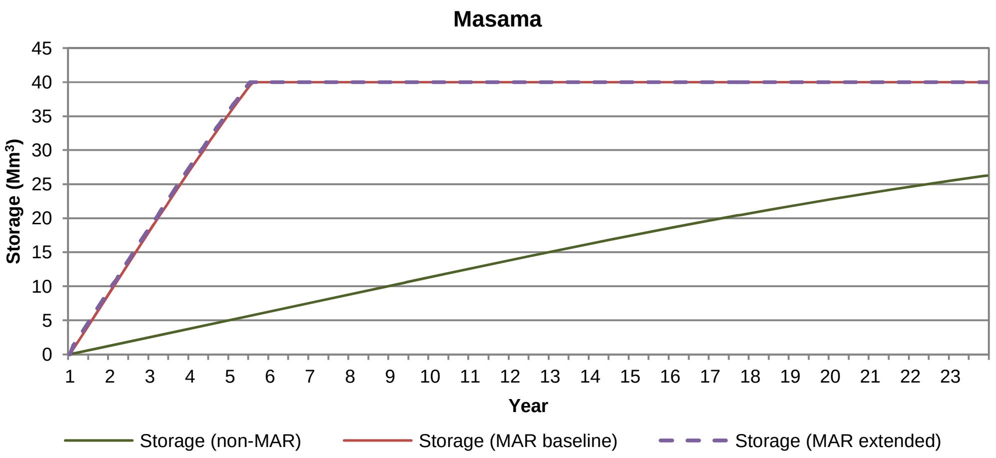


Figure 7.26. Masama/Makhujwane Wellfields storage over time assuming empty storage at start, no abstraction, and only natural recharge or natural and artificial recharge.

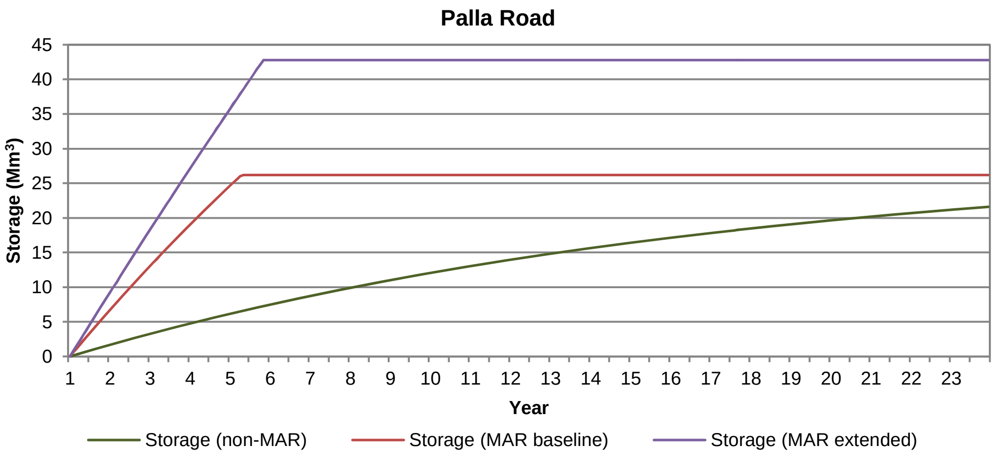


Figure 7.27. Road/Chepete Wellfields storage over time assuming empty storage at start, no abstraction, and only natural recharge or natural and artificial recharge.

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7.5 Effects of possible system improvements

In this section the effect of upgrading, for example, abstraction rates for the dams, increased transfer capacity of specific pipes etc. are illustrated. The aim is to illustrate how limiting factors can be eliminated and the effect of, for example, the MAR-scenarios be increased.

7.5.1 Selebi-Phikwe and Francistown

As noted in Section 7.3, the water shortage problems for Selebi-Phikwe are not eliminated in Scenario 2. Furthermore, Scenarios 3-6 do not provide any improvements for Selebi-Phikwe since the additional water sources supply the southern parts of the system. It could, however, be possible to allocate a larger percentage of the supply from the Letsibogo Dam to Selebi-Phikwe and use a larger default supply from the Dikgatlhong Dam to the NSC. The presented model results are based on the assumption that water to the NSC is to 60 % taken from the Dikgatlhong Dam and to 40 % from the Letsibogo Dam (if storage in either of the dam is below minimum operational storage, water is taken from the other dam if available). If a larger percentage of water is taken from the Dikgatlhong Dam to the NSC, water is saved to Selebi-Phikwe and the water shortage events are reduced. However, since the storage in the Letsibogo Dam occasionally is below the minimum operational level, within the simulated period, the access to an additional water source if of great importance to obtain a reliable supply.

In Figure 7.28 the effect of an additional increased abstraction rate for the Shashe Dam is illustrated for Selebi-Phikwe and Francistown. The abstraction rate is assumed to be 91 Ml/d for the baseline scenario and 145 Ml/d for the scenario with increased abstraction rate. The latter abstraction rate is assumed to enable full supply to both Francistown and Selebi-Phikwe at the end of the simulated period (i.e. 2035). The lower (baseline) abstraction rate enables full supply to Francistown at the end of the period. However, there is no spare capacity to supply water to Selebi-Phikwe at the end of the period when the demand for Francistown has increased. In the scenarios it is assumed that also necessary upgrading is made of the pipelines for transferring the water.

From the results presented in Figure 7.28 it can be concluded that an increased abstraction rate is not enough to substantially reduce the water shortage problems for Selebi-Phikwe. With an abstraction rate of 91 Ml/d it is possible to supply the needed water to Selebi-Phikwe in 25 % of the months (when supply from the Shashe Dam is needed) and when the abstraction rate is increased to 145 Ml/d the corresponding figure is 42 %. It should be noted that also Francistown will experience water shortage problems. The reason for these problems is that when the demand increases, the Shashe Dam will be not be able to supply all needed water within the simulated period (it will occasionally be emptied).

Another possibility to improve the safety of the supply to Selebi-Phikwe is, as noted above, to allocate a larger proportion of the supply from the Letsibogo Dam to Selebi-Phikwe and to a larger extent use the Dikgatlhong Dam for supplying water to the NSC. In Figure 7.28, a scenario where 90 % of the needed water to the NSC is abstracted from the Dikgatlhong Dam and 10 % from the Letsibogo Dam is presented. This scenario has a positive effect on the water shortage, mainly during the first part of the simulated period.

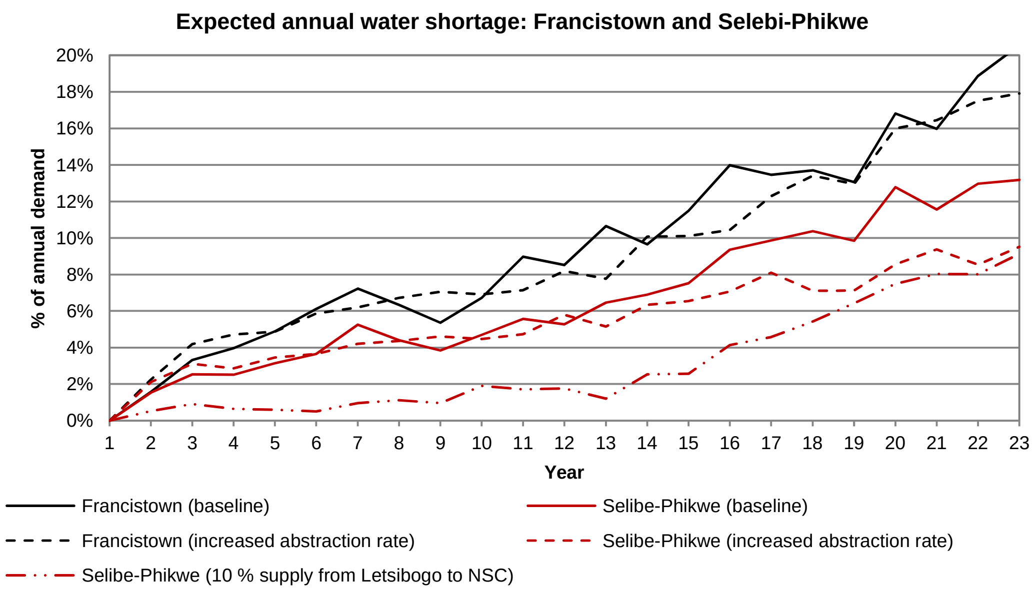


Figure 7.28. Annual water shortage as % of annual demand over time for Francistown and Selebi-Phikwe for different abstraction rates for the Shashe Dam and one scenario with reduced supply from the Letsibogo Dam to the NSC.

7.5.2 Masama/Makhujwane Non-MAR (Scenario 3)

The results presented in Figure 7.20 show that it is the abstraction rate and the ability to treat the abstracted water that is limiting the abstraction from the Masama/Makhujwane Wellfields in Scenario 3 (i.e. Non-MAR). To illustrate the effect when reducing these limiting factors, a scenario was run based on the following assumptions:

- The same abstraction rate as used in the extended sub-scenario of Scenario 6 is used for the Non-MAR case (see Chapter 5).

- All abstracted water from the Masama/Makhujwane Wellfields can be treated and supplied to Gaborone and the connected demand centres, i.e. no limitations related to treatment and transfer capacities.

The results presented in Figure 7.29 show the resulting probability of annual shortage of different magnitudes for Gaborone and connected demand centres. When compared to the baseline Scenario 3 (Figure 7.15) it can be concluded that the shortage probabilities have been reduced. Hence, an improved capacity of treating and transferring water from the Masama/Makhujwane Wellfields results in a higher abstraction in the simulations of Scenario 3. The total expected abstraction is 27 Mm^3 compared to 13 Mm^3 in the baseline case for Scenario 3. The total deficit during the 23-year period has thus also been reduced by around 14 Mm^3.

The increased abstraction from the Masama/Makhujwane Wellfields can also be seen in Figure 7.30. At the end of the simulated period the probability of having a storage less than 15 Mm^3 will be approximately 0.5.

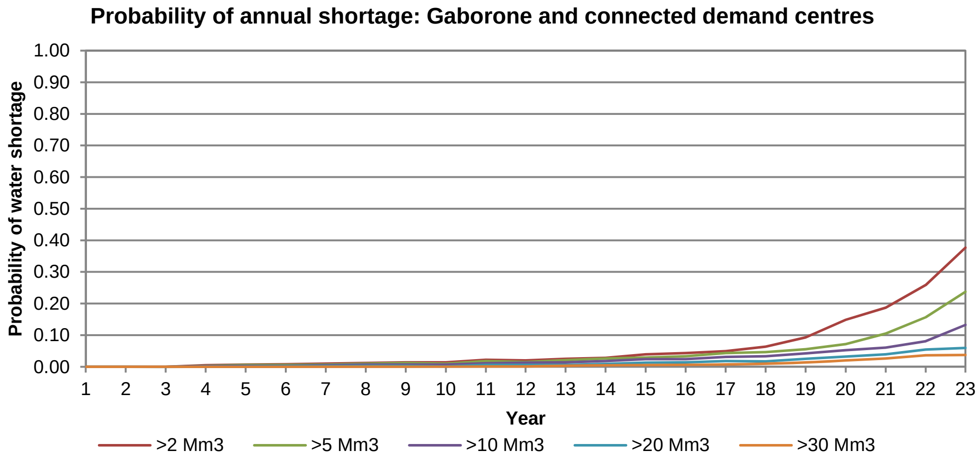


Figure 7.29. Expected probability of annual water shortage of different magnitudes for each year in Scenario 3 but with no limitations regarding treatment and transfer capacity for the water abstracted from the Masama/Makhujwane Wellfields and the extended sub-scenario for the abstraction rate (Non-MAR).

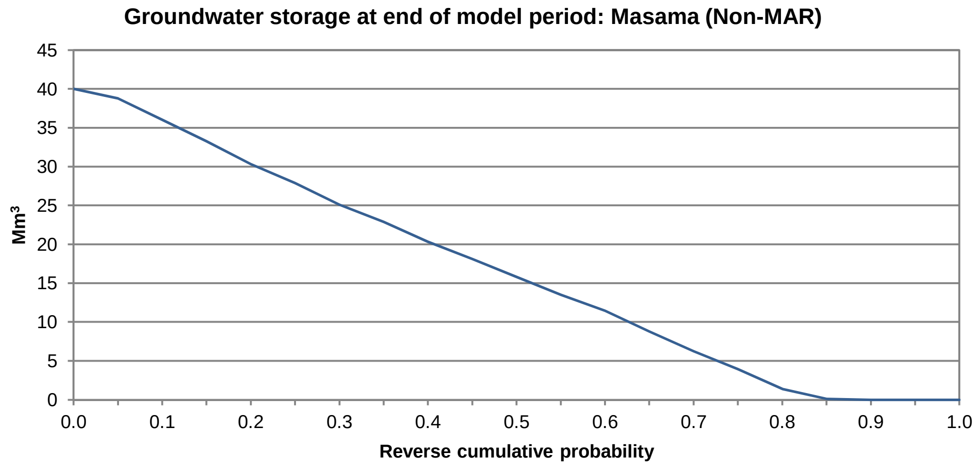


Figure 7.30. Storage for the Masama/Makhujwane Wellfields in Scenario 3 (Non-MAR, extended sub-scenario) with reduced limitations regarding treatment and transfer capacity for the abstracted water.

One possible measure to improve the ability to treat all abstracted water from the Masama/Makhujwane Wellfields, i.e. the actions simulated in the scenario presented here, is to increase the abstraction rate from the Bokaa Dam and the transfer capacity of the pipe from the Bokaa Dam to the Gaborone WW. This action would make it possible to transfer more water to the Gaborone WW when there is available treatment capacity due to low levels in the Gaborone Dam. This action would of course also improve the supply safety in scenarios not including MAR and Non-MAR scenarios.

7.5.3 Masama/Makhujwane and Palla Road/Chepete MAR (Scenario 6)

The factors limiting the injection in Scenario 6 is mainly the dam storage and the abstraction rate for the Letsibogo and Dikgatlhong Dams (see Figure 7.21 and Figure 7.22). Furthermore, as concluded in Section 7.5.2 the ability to treat the abstracted water (from the Masama/Makhujwane and Palla Road/Chepete Wellfields in a MAR/Non-MAR scenario) limits the possibility to fully use the wellfields.

To simulate the overall effect on the system if the abstraction rates are increased and the limitations for using the MAR wellfields are reduced an additional scenario was run based on the following assumptions:

- The abstraction rates for the Letsibogo and Dikgatlhong Dams are increased by 50 %.
- The abstraction rate for the Bokaa Dam is doubled and the same capacity is used for the pipe connecting the Bokaa Dam and Gaborone Water Works. This upgrading aims to enable a better capacity for treating the water from Palla Road if there is no spare capacity in the Mmamashia Water Works. The water from the Masama/Makhujwane Wellfields is in this scenario assumed to be supplied using a separate pipe from the wellfields to Gaborone.
- A 0 % criterion is used for the minimum storage needed in both the Letsibogo and Dikgatlhong Dams to allow abstraction for injection in the MAR wellfields. In previouse scenarios presented here a 20 % criterion has been used.

The probability of annual shortage is presented in Figure 7.31 and shows, when compared to Figure 7.16, that the simulated improvements of the system has an effect on the supply safety. The higher abstraction rates will of course make it possible to supply all needed water from the NSC to a larger extent. However, the ability to recharge the MAR wellfield has also increased. The expected total abstraction for the Masama/Makhujwane Wellfields is 7.7 Mm^3 and injection 5.5 Mm^3. Hence, in this scenario was possible to inject 71 % of what has been abstracted. The corresponding figure for the Scenario 6 presented in Section 7.4 was 30 % (see Figure 7.19). For the Palla Road/Chepete Wellfields the total abstraction is 7.4 Mm^3 and injection 7.7 Mm^3. The injection is higher than the abstraction since the storage is not full when the simulations start for the Palla Road/Chepete Wellfields.

The storage to the Masama/Makhujwane and Palla Road/Chepete Wellfields is presented in Figure 7.32 and Figure 7.33. The results show that the storage is full with a probability of c. 0.8 for both MAR wellfields.

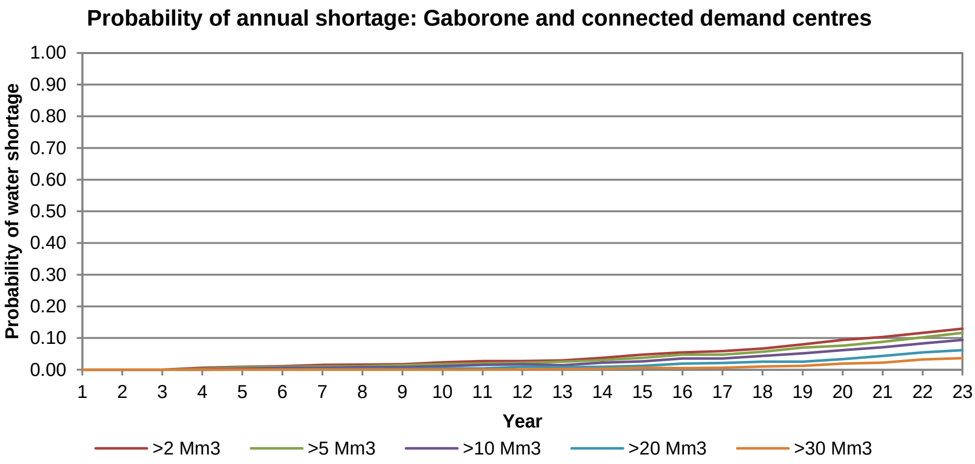


Figure 7.31. *Expected probability of annual water shortage of different magnitudes for each year in Scenario 6 with increased abstraction rates for the dams etc.*

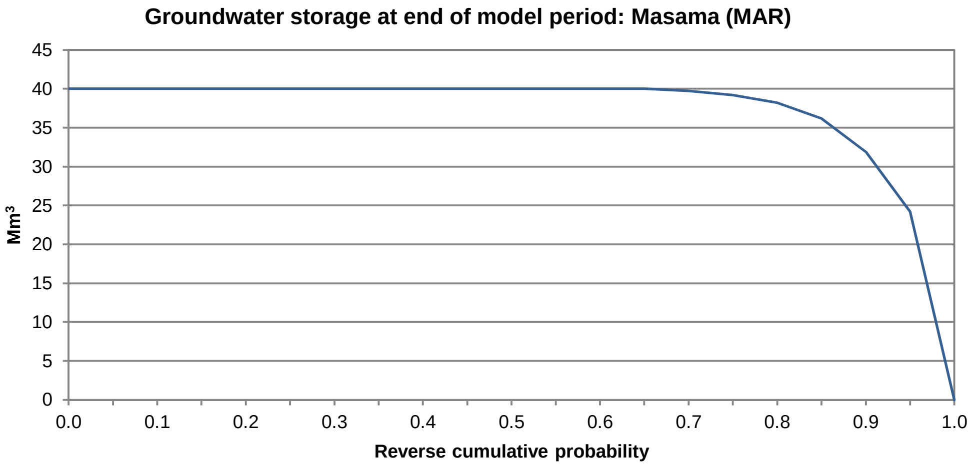


Figure 7.32. *Groundwater storage at the end of the simulated period (year 2035) for Masama/Makhujwane Wellfields in the presented adjusted version of Scenario 6.*

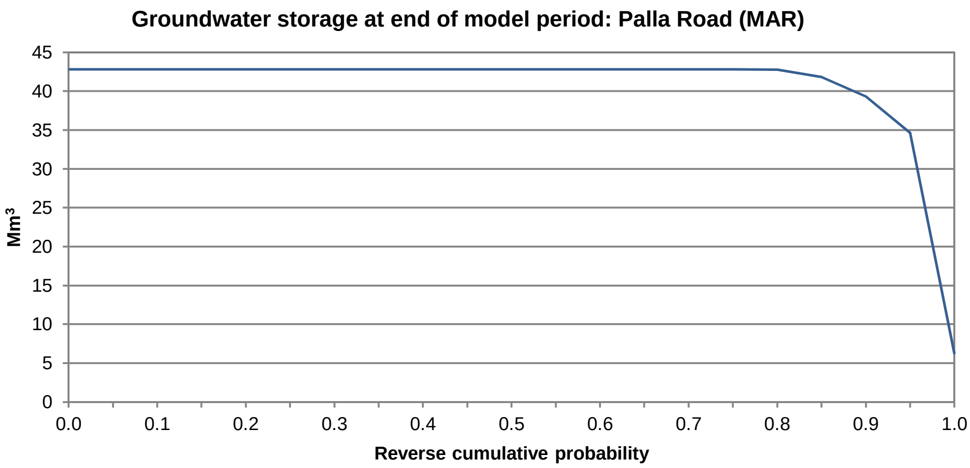


Figure 7.33. *Groundwater storage at the end of the simulated period (year 2035) for Palla Road/Chepete Wellfields in the presented adjusted version of Scenario 6.*

7.5.4 Palla Road/Chepete MAR (Scenario 4)

A possible scenario would be to combine MAR for the Palla Road/Chepete Wellfields and Non-MAR for the Masama/Makhujwane Wellfields, i.e. a combination of Scenario 3 and 4. This combination has not been analysed in detail but the results from an adjuster version of Scenario 4 (i.e. MAR including Palla Road/Chepete Wellfields) is presented here. Note that for the specific Scenario 4 presented here, all limitations with respect to treatment and transfer capacities for the water supplied to Gaborone and connected demand centres are eliminated. Also the extended sub-scenario is used in order to allow a higher abstraction and injection rate. However, the abstraction rates for the dams are not increased as in Section 7.5.3.

The total abstraction from the Palla Road/Chepete Wellfields is 28.8 Mm^3 and the injected volume 15.3 Mm^3 (53 % of the abstracted volume). It is thus possible abstract considerably more water from these wellfields compared to what is done in Scenario 6 when the primarily the Masama/Makhujwane Wellfields are used to supply water to Gaborone and connected demand centres (cf. Figure 7.19). Limitations affecting the ability to inject water are mainly related to dam properties, i.e. actual storage and abstraction rates which in the end of the simulated period is not enough to supply both water to the demand centres and water for injection.

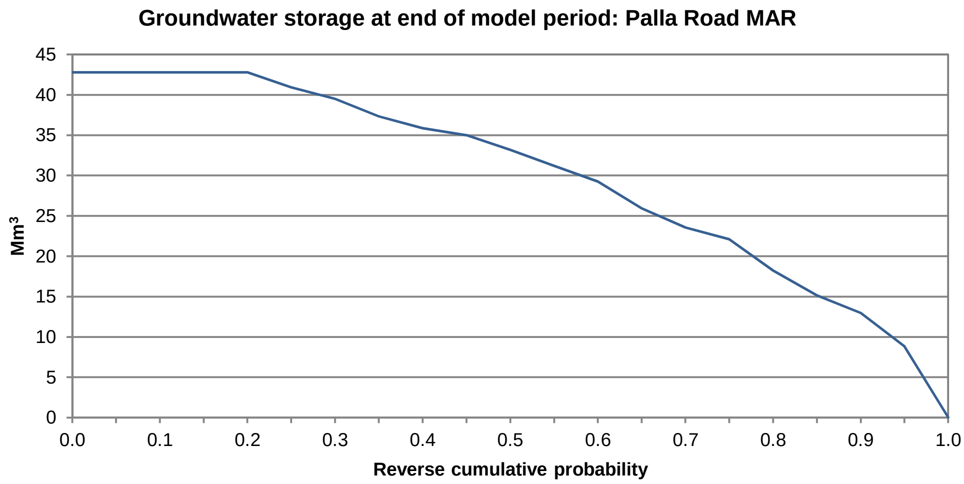
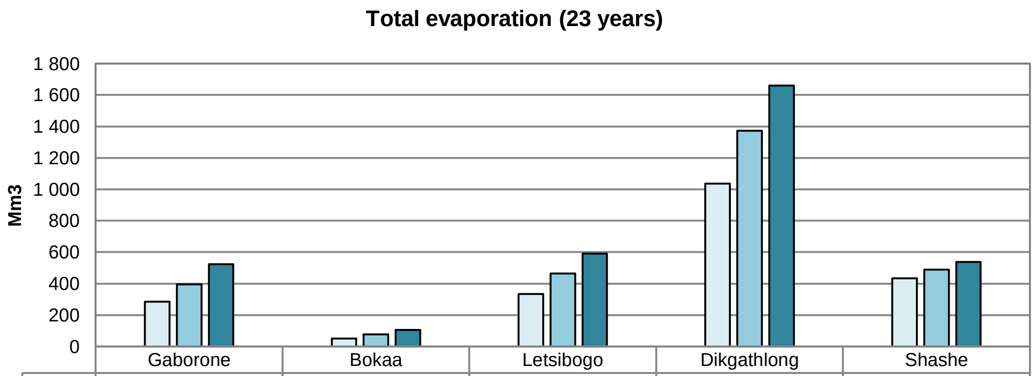


Figure 7.34. Groundwater storage at the end of the simulated period (year 2035) for Palla Road/Chepete Wellfields in the presented adjusted version of Scenario 4.

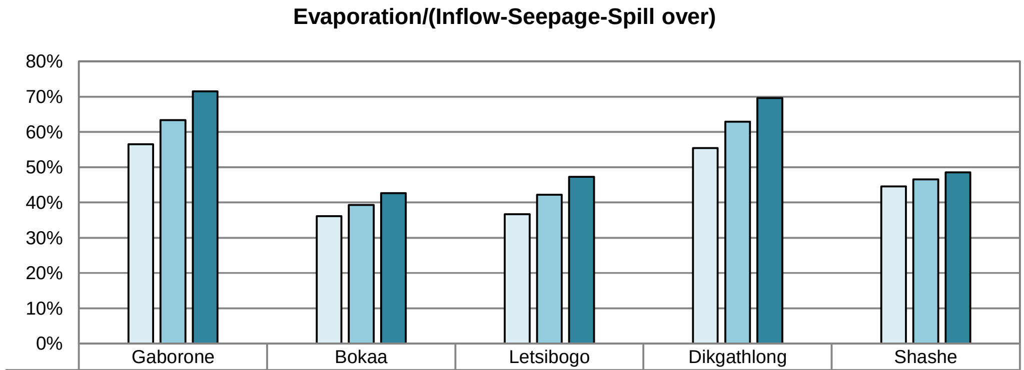
7.6 Evaporation losses

An advantage of MAR is the possibility to reduce evaporation losses by storing water in the aquifers instead of in surface water dams. The total evaporation losses for each dam throughout the model period (23 years) are presented for Scenario 2 in Figure 7.35. In Figure 7.36 the total evaporation is presented for each dam as the percentage of inflow minus seepage and spill over. It can be concluded that a large proportion of water is lost due to evaporation (expected values between 40-60 % for the dams).



	Gaborone	Bokaa	Letsibogo	Dikgathlong	Shashe
P10	285	51	335	1 036	434
Mean	395	78	465	1 373	488
P90	524	107	591	1 659	538

Figure 7.35. *Total (i.e. summed) evaporation for the five dams.*



	Gaborone	Bokaa	Letsibogo	Dikgathlong	Shashe
P10	56%	36%	37%	55%	45%
Mean	63%	39%	42%	63%	47%
P90	71%	43%	47%	70%	48%

Figure 7.36. *Percentage of evaporation per available water in terms of inflow to the specific dam minus seepage and spill over.*

Although the evaporation losses are high the MAR-alternatives are not able to reduce the losses to any great extent. In Figure 7.37 the total net loss saving (i.e. compared to Scenario 2) is presented for Scenario 6. The results show that when injection of water is allowed as long as the dam storage in both the Letsibogo and Dikgatlhong Dams are ≥20 % of full storage (FSL), the water saving is insignificant. If there is no limitation, with respect to dam storage, for when abstraction for injection is allowed, then a saving of c. 5 Mm^3 is likely. The reason for the minor reduction in evaporation is that there are other factors (e.g. abstraction rates for the dams and dam storage) limiting the possibility to inject water to the Masama/Makhujwane and Palla Road/Chepete Wellfields.

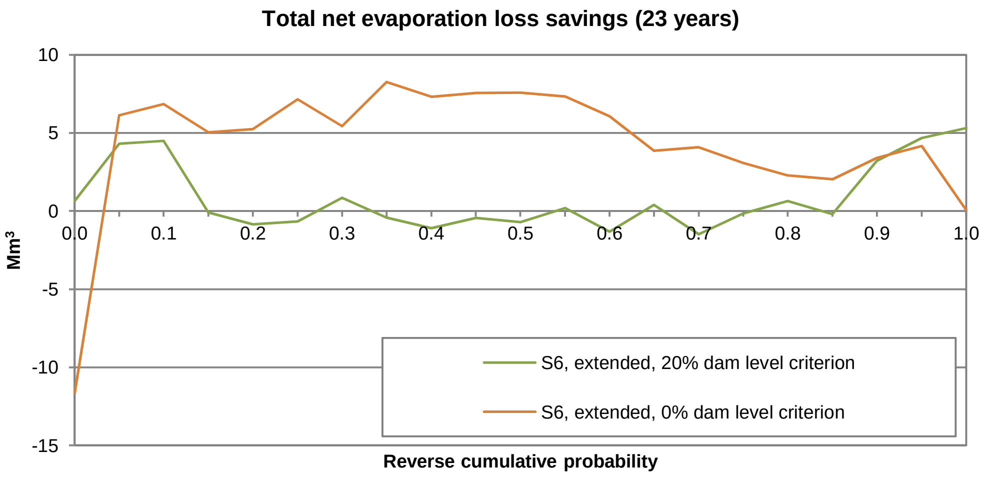


Figure 7.37. Reduced evaporation losses for two variant of Scenario 6 compared to Scenario 2. The difference between the two Scenario 6 alternatives is if water from the dams (Letsibogo and Dikgatlhong) can be abstracted for injection in the MAR wellfields until the dams storage reaches 20 % or if there is no limit with respect to the dam storage (0 %).

8 Economic valuation

In order to assess the economic viability of including MAR in the NSC system a comparison of the increased safety to the costs for implementing, operating and maintaining MAR is needed. An economic assessment should be performed for selected MAR and Non-MAR scenarios (see Chapter 5) to provide a relevant decision support and basis for prioritization regarding future investments for improving water supply safety.

It was not possible within the scope of this study to perform a quantitative economic valuation of MAR. However, forms to be applied for quantification of MAR cost items were developed and are presented in Appendix 4. Some of the costs have been obtained from DWA and other organizations during the study and to proceed with quantification of remaining cost items is necessary for a relevant economic valuation.

It is suggested that the economic valuation is performed as a cost-effectiveness analysis (CEA), see e.g. Levin & McEwan (2001) and Lindhe et al. (2011). The main steps of the CEA are:

- Scenarios that are considered to provide acceptable water supply safety are identified.
- A time horizon is selected. In this study a 23-year time horizon was applied, but other time horizons may be found justified. It is important that the selected time horizon is agreed upon among all parties involved in the decision-making process.
- Investments and the streams of operation and maintenance costs over the selected time horizon are quantified for each scenario, using the developed forms in Appendix 4.
- A present value (PV) is calculated for the total cost for each scenario, using the selected time horizon and discount rate.
- Prioritization of scenarios is performed, based on the relationship between the increase in water safety and the total cost (PV) for each alternative, i.e. the cost-effectiveness.

If MAR is considered as a feasible option to increase water supply safety, field investigations and field tests are necessary to show that the MAR-scenarios outlined in Chapter 5 are realistic in terms of abstraction and injection rates and sizes of active storage. Furthermore, the tests are needed to ensure that injection water quality is appropriate as well as the quality of the abstracted water. The field tests will also give experience of practical issues, for example if well clogging may cause a problem. If problems emerge, solutions have to be tested.

Preliminary outlines of field tests and full-scale schemes are presented below as a basis for cost estimates.

8.1 Field MAR-test at Palla Road Wellfield

The Palla Road Wellfield seems to be the most feasible site for a first MAR field test depending on existing infrastructure. The Mahalapye Water Works has at present spare treatment capacity to allow for treatment of injection water. By upgrading of the existing pipeline from the wellfield to Mahalapye to allow for reversed flow, injection water will be available at the wellfield with only minor investments, and during the abstraction phase the water could be pumped to Mahalapye to be used for water supply. A preliminary outline for field investigations and a MAR field test with abstraction and injection of c. 2 500 m^3/d, at least three abstraction and injection cycles, and a total duration c. 1.5 years, are given below and a cost estimation form for the outlined field investigations and field test is given in Appendix 4.

- Detailed planning and design, and procurement (investigation and test programme, including mathematical groundwater modelling of field test and full-scale scenarios).
- Source water for injection can be supplied from the Mahalapye Water Reservoir. The treatment capacity of Mahalapye Water Works is c. 14 000 m^3/d and present water demand is c. 9 500 m^3/d.
- Water can be transferred from the Mahalapye Water Reservoir by reversed flow in the existing pipeline to the Palla Road Wellfield. A new connection is needed at the reservoir as well as new valves etc. along the pipeline. Booster pumping is needed if 2 500 m^3/d can't be transferred by gravity flow.
- Three dual-purpose wells are proposed for injection and abstraction. Two options exist: (i) use of existing abstraction or monitoring wells, or (ii) drilling of new wells. For both cases, the wells should be checked and tested by borehole camera, step drawdown and injection tests, pumping tests and water sampling. These tests should be repeated at the end of the test period.
- Depending on which wells will be chosen for the test, additional infrastructure will be needed at the wellfield in the form of connecting pipelines, injection pipes, electrical and automatic control works etc.
- Monitoring of abstraction and injection rates and groundwater levels, and water sampling for chemical and microbial analysis.

8.2 Cost estimate for a full-scale MAR-scheme at Palla Road/Chepete Wellfields

A preliminary programme outline of a full-scale MAR scheme at the Palla Road and Chepete Wellfields, based on the descriptions in Section 4.2.1 and Chapter 5, Scenarios 4 and 6, are presented below as a basis for a cost estimate. A cost estimation form is given in Appendix 4. Only additional costs for the MAR-scheme is considered (i.e. already planned upgrading by new wells etc. is not included).

- Procurement of the planning and design of a full-scale MAR-scheme.
- Detailed planning and design of a full-scale MAR scheme based on the results from the field test, including mathematical groundwater modelling.
- Procurement of a phased implementation of the MAR-scheme.
- Source water for injection will be supplied from the Mahalapye Water Reservoir. The treatment capacity of Mahalapye Water Works has to be upgraded to supply an additional c. 14 300 or 21 300 m^3/d, for MAR-injection in the baseline and extended sub-scenarios, respectively (present capacity and demand are c. 14 000 m^3/d and c. 9 500 m^3/d, respectively).

- Water can be transferred from the Mahalapye Water Reservoir by reversed flow in the existing pipeline to Palla Road Wellfield. A new connection is needed at the reservoir. Maximum capacity of the existing pipeline has to be evaluated to see if an upgrading of the pipeline is an alternative (facilities for reversed flow, booster pumping etc.). If the capacity after upgrading will still too low, an additional pipeline is necessary.
- Dual-purpose wells are proposed for injection and abstraction: 15 existing wells + 3 new wells in Palla Road Wellfield + 6 existing wells in Chepete Wellfield. The wells should be checked and tested by borehole camera, step drawdown and injection tests, pumping tests and water sampling.
- Additional infrastructure will be needed at the wellfield in the form of a new water reservoir for the injection water, a chlorination station, connecting pipelines, injection pipes, electrical and automatic control works etc.
- Two options are identified for the transfer of the abstracted water: (i) the water is pumped to the Mahalapye Water Reservoir and used for the water supply of Mahalapye. The surplus is transferred to the NSC from the Mahalapye Water Reservoir, which requires upgrading to allow for reversed flow in the existing pipeline, or (ii) water is pumped to Mahalapye Water Reservoir for the water supply of Mahalapye and the surplus is transferred to the NSC by means of a new pipeline directly from the wellfields.
- Operation costs should be estimated for water treatment, pumping, and monitoring, and maintenance costs for wells, pumps, pipelines etc. (expressed as annual costs in 2014 prices).

8.3 Cost estimate of field test and full-scale MAR-scheme at Masama/Makhujwane Wellfields

As for the Palla Road/Chepete Wellfields, a preliminary programme was outlined for a field test and a full-scale MAR-scheme at the Masama/Makhujwane Wellfields.

- Procurement and execution of the field investigation and test programme.
- Detailed planning, design and execution of field investigation and test programme, including mathematical groundwater modelling of field test and full-scale scenarios.
- Procurement of the planning and design of a full-scale MAR scheme.
- Detailed planning and design of a full-scale MAR scheme based on the results from the field test, including mathematical groundwater modelling.
- Procurement of a phased implementation of the MAR-scheme.
- Two options have been identified for the supply of treated source water for injection: (i) a new water treatment plant is constructed to treat water from the NSC at the wellfields with a capacity of c. 21 600 or 37 700 m^3/d for the baseline and extended sub-scenarios, or (ii) construction of a new pipeline from the Mmamashia WW to the wellfields.
- For option (i) above water is transferred in the pipeline to be constructed from the wellfields to the NSC, but facilities are needed to allow for reversed flow.

For option (ii) a new pipeline has to be constructed from the Mmamashia WW to the wellfields. The pipeline should allow for flow in both directions.

- Dual-purpose wells are proposed for injection and abstraction: 24 wells in the Masama Wellfield + 5 wells in the Makhujwane Wellfield. The wells should be checked and tested by borehole camera, step drawdown and injection tests, pumping tests and water sampling.
- Additional infrastructure will be needed at the wellfields in the form of a chlorination station, connecting pipelines, injection pipes, electrical and automatic control works etc. The water reservoir planned for the connection of the Masama Wellfield to the NSC, will be adequate also for a MAR-scenario and should not be considered as a MAR-cost.
- Coupled to the two options for supply of treated water for injection specified above, there are two alternatives for transfer of the abstracted water: (i) water is transferred in the pipeline to be constructed from the wellfield to the NSC, or (ii) the water is transferred by reversed flow in the pipeline constructed for the supply of injection from the Mmamashia WW. If the water from the wellfields is of good quality it can be delivered directly into the water distribution system at an existing reservoir. Minor treatment may be necessary.
- Operation costs should be estimated for water treatment, pumping, and monitoring, and maintenance costs for wells, pumps, pipelines etc. (expressed as annual costs in 2014 prices).

9 Conclusions and recommendations

The development of the water supply safety model and performed simulations provide an increased knowledge of the possibilities for improving the water supply safety in the NSC system. It facilitates modelling of effects from implementing MAR in groundwater aquifers, as well as effects from other upgrades of the system. A number of scenarios have been studied within the scope of this study, but the model can also be used for analysing other scenarios that may be identified and considered to be of interest. It should be noted that the model includes information on the NSC system, water demand, water availability, etc. as known today, but as new information becomes available the model should be updated accordingly to provide relevant results.

The following major conclusions were drawn from this study:

- The current supply system is, as expected, clearly insufficient to meet the water demand within the simulated period of 23 years. Water shortage is likely to be a problem already early in the simulated period (2013-2035).
- The connection of the Dikgatlhong Dam to the NSC and additional upgrades (including water works upgrading, an additional pipeline down to Palapye, and installation of Pump Station 4) will have a large positive effect on the supply safety and reduce the expected total water shortage (summed over the 23 years) by approximately 90 %. However, the model results show that there still will be a probability of 0.25 of having a maximum annual water shortage ≥20 Mm^3 for Gaborone and connected demand centres.
- The connection of Masama/Makhujwane Wellfields as a Non-MAR scheme will further increase the supply safety. However, the effect is limited by the abstraction rate and the possibility to treat the water from the wellfields. Based on the expected development of the demand, it is clear that abstraction from Masama will be needed often and groundwater mining is likely since there will not be enough time for recovery.
- The modelled Palla Road/Chepete and Masama/Makhujwane MAR-scenarios provide additional water supply safety. In the extended MAR sub-scenario, a total storage capacity of 80 Mm^3 is added to the system, i.e. an increased storage corresponding to an additional dam of the same size as the Shashe Dam. However, as for the Masama/Makhujwane Non-MAR scenario, the effects of MAR are to some extent limited by different system properties.
- The active storages of the MAR wellfield aquifers, as defined in the present study, have average recovery times from empty to full by natural recharge of 25 and 42 years for the baseline and extended MAR sub-scenarios, respectively, at Palla Road/Chepete Wellfields. The recovery time for Masama/Makhujwane is 35 years for both baseline and extended MAR-scenarios. With continuous injection at maximum rates, the corresponding recovery times are 5 and 6 years for the baseline and extended MAR sub-scenarios, respectively, for Palla Road/Chepete Wellfields, and 5-6 years for Masama/Makhujwane.

- The Masama/Makhujwane Non-MAR scenario and Palla Road/Chepete and Masama/Makhujwane MAR-scenario delays the risk for substantial water storage by c. 5 and 10 years, respectively.
- The Palla Road/Chepete and Masama/Makhujwane MAR-scenario reduces the probability of having a 10 % (8 Mm^3) water shortage in Gaborone and connected demand centres in 2035 to 10 %, compared to c. 25 % for the Masama Non-MAR scenario and c. 40 % for scenario with only connecting the Dikagathlong Dam.
- The impact of the MAR-scenarios are limited by:
    - availability of water for injection in the dams
    - abstraction rates from the dams
    - water works capacities
    - transfer capacities
    - maximum abstraction and injection rates and active storages for the wellfields
- The MAR-scenarios with the baseline water demand forecast show a considerable risk for groundwater storage deficits at the end of the simulated period (2035), i.e. groundwater is mined in this time perspective. The major reason for this is that there is not sufficient time for injection, given the maximum abstraction rates from the dams and the limitations in injection rates, especially during the last years of the simulated period when the demand is high. The mining is much lower in the simulations with a reduced increase in demand.
- The MAR-scenarios have only a marginal influence on the evaporation losses from the dams, i.e. only relatively insignificant volumes of water are saved. The reason is that only relatively small volumes are abstracted extra from the dams for injection due to infrastructural limitations in abstraction rates from the dams, treatment capacities of the water works and injection rates at the wellfields.
- The total abstraction in the Non-MAR scenario of Masama/Makhujwane can be doubled from 13 to 27 Mm^3 over the 23-year period if the abstraction in this scenario is increased to the same rate as for the extended MAR-sub-scenario (from c 21 500 to 37 500 m^3/d) and if the limitations in treatment and transfer capacities are eliminated. However, this will give 50 % probability of a storage deficit of 25 Mm^3 or more at the end of the period compared to the same probability for a 10 Mm^3 or more deficit in the baseline Non MAR-scenario.
- The water safety provided by the MAR-scenarios may be further increased if combined with other NSC-system improvements. A 50 % increase of the abstraction rates from the Letsibogo and Dikgatlhong Dams, a doubling of the transfer capacity from NSC to Gaborone WW via Bokaa, and allowing wellfield injection down to the minimum operational levels of the dams, will reduce the probability for a 2.5 % (2 Mm^3) water deficit for Gaborone and connected demand centres to c. 10 % in 2035. This increase will be reached without any substantial risk for mining the wellfields.

- Due to the increasing water demand and the fact that the abstraction from the MAR wellfields cannot meet the full demand of Gaborone and connected demand centres, the abstraction from the wellfields should start before the dam storages are too low to achieve an extended period of simultaneous abstraction from surface water dams and wells. (It is not considered realistic to increase wellfield abstraction rates substantially relatively to the extended MAR-scenarios.
- The modelling highlights the impact of the assumed drastic increase in water demand. The NWMPR water demand “base case” forecast is used in the model, but adjusted for actual consumption 2012. According to this forecast the water demand is assumed to increase from c. 72 Mm3/year in 2012 to c. 144 Mm3/year in 2035 for the water demand centres included in the water supply system, i.e. an increase by 100 %. The present study focused on the resource component of the water supply, but the results show that the certainty/reliability of the demand forecast is crucial for assessment of the probabilities of water shortage, especially for the years 10 and onwards during the 23-year simulation period. Comparative simulations were performed with a reduced increase in water demand, linearly lower from 0 % at the start to 20 % at the end. With this reduction in the water demand increase, the risk of substantial water shortage is delayed by c. five years.

The present study addresses the possible effects of implementing MAR in the NSC system. It is concluded that the current NSC system with the Dikgatlhong dam connected but without MAR is not likely be able to provide a safe water supply over the studied time period. The study further shows that connection of the Masama/Makhujwane Wellfields to NSC and implementation of MAR at Palla Road/Chepete and Masama/Makhujwane Wellfields will not completely eliminate the risk of future water shortage. However, implementation of these scenarios may still be of significant importance in managing the water supply situation in Eastern Botswana over the next 23 years.

Based on the results of this study, we recommend the following future work:

Definition of acceptable risk for water supply shortage

To enable an analysis of the cost-effectiveness of options to increase water supply safety, the goal for the improvements of the system needs to be clearly defined, i.e. an acceptable risk level has to be defined. The acceptable risk needs to be defined with respect to the acceptable number of occasions of shortage, the acceptable magnitude of shortages, and the acceptable durations of shortages.

Review of water demand forecast reliability

The performed water supply safety modelling highlights the impact of the assumed drastic increase in water demand. The NWMPR water demand “base case” forecast is used in the model, but adjusted for actual consumption 2012. According to this forecast the water demand is assumed to increase by 100 % from 2013 to 2035. The pre-feasibility study focuses on the resource component of the water supply, but the results show that the certainty/reliability of the demand forecast is crucial for assessment of the probabilities of water shortage, especially for the years 10 and onwards during the 23-year simulation period.

Simulation of preliminary full-scale MAR schemes by existing groundwater models

The necessary parameters for the water supply modelling of the MAR-scenarios are derived from the results of the groundwater modelling report of the Masama Groundwater Resources Evaluation Project (Geo World, 2009) and the recent Post-Auditing of the Palla Road Ground Water Model (WRC, 2013). The preliminary outline of field tests and full-scale MAR-schemes, proposed in the pre-feasibility study, should be modelled by the existing groundwater models to confirm that the assumed maximum storages and injection and abstraction rates are possible and imply acceptable groundwater level drawdowns.

Revisions of the model to allow abstraction from the MAR-wellfields based on prognoses of water shortages

The impact of the MAR-scenarios is to some extent limited by the maximum abstraction rates from the wellfields. It is not considered realistic to increase these rates substantially above the rates used in the pre-feasibility study. However, the pre-feasibility modelling results indicate that the number of water shortages may be decreased if abstraction from the MAR-wellfields is started well before the water shortage appear. The water supply safety model should thus be revised to allow simultaneous abstraction from the dams and the MAR wellfields based on a water shortage prognosis. Rules have to be set for when to start abstracting water from the MAR-wellfields, to what extent etc. After revision the model can be used to evaluate the impact on water supply safety, e.g. the risk for groundwater mining.

Inclusion of an additional scenario in the model

In the pre-feasibility study six different scenarios were identified and analysed. According to the results it is indicated that another scenario should be of interest from both a technical and economic point of view: Current system + Dikgatlhong Dam + Masama/Makhujwane Wellfields Non-MAR + Palla Road/Chepete Wellfields MAR. It is possible that this scenario could be more cost-effective than the scenario with MAR also at Masama/Makhujwane Wellfield, i.e. provide substantial reduction in the risk for water shortage but at a considerably lower cost, maybe in combination with elimination of some other infrastructural limitations.

Identification of scenarios providing acceptable risk levels

Based on the definition of acceptable risk performed according to the first item above, the scenarios providing the desirable water supply safety among the modelled scenarios in the pre-feasibility study the supplementary scenarios proposed above are identified.

Completion of cost estimations for all scenarios providing acceptable risk levels

Estimations of cost items related to modelled scenarios need to be completed, using the forms developed in the pre-feasibility study. Cost estimations are also necessary for upgrades of the system identified as necessary to facilitate the implementation of modelled MAR and Non-MAR scenarios. In order to provide a well-founded decision support on implementation of MAR in the NSC, comparisons of modelled scenarios with other options to improve water supply safety, e.g. connection to the Chobe River, need to be performed. It is therefore necessary to compile previously performed cost estimations of such options.

Evaluation of cost-effectiveness of scenarios providing acceptable risk levels

The aim of performing a cost-effectiveness analysis (CEA) is to provide a combined assessment of both the cost of implementing a specific measure and the effect in terms of reduced water shortage risk. The analysis is performed for the scenarios identified to provide an acceptable water shortage safety. Important steps of the CEA are to: (i) select time horizon (23 years) and discount rate; (ii) quantify investments and the streams of operation and maintenance costs over the selected time horizon for each scenario; (iii) calculate for each scenario a present value (PV) for the total cost for each scenario; and (iv) prioritize scenarios based on the relationship between increase in water safety and the total cost (PV) for each alternative, i.e. the cost-effectiveness.

Comparison of MAR-scenarios with respect to water management options

A number of management options are possible to improve the water supply safety in the NSC system, e.g. measures to reduce the water demand, including reduction of technical losses of water and implementation of water saving technologies.

Advanced course on Water Supply Safety Model

To secure knowledge transfer of the water supply safety model and to make it possible for the DWA staff to operate and develop the model in accordance with future developments of the NSC system, advanced training for future modelling experts at DWA is necessary. The training should be made for 2-3 dedicated future operators of the water supply safety model.

Possible pilot-scale field test of MAR

The already performed pre-feasibility study and the execution of the supplementary items above will give the necessary information for evaluation of the economic viability of MAR for increased water supply safety along the NSC. Given economic viability a pilot-scale field test should be carried out. The Palla Road Wellfield seems to be the most feasible site for a first MAR field test, because of existing infrastructure. The Mahalapye Water Works has presently spare treatment capacity to allow for treatment of injection water. By upgrading of the existing pipeline from the wellfield to Mahalapye to allow for reversed flow, injection water will be available at the wellfield with only minor investments, and during the abstraction phase the water could be pumped to Mahalapye to be used for water supply. A preliminary outline for field investigations and a MAR field test with abstraction and injection of approximately 2 500 m^3/d, at least three abstraction and injection cycles, and a total duration approximately 1.5 years, is presented in this pre-feasibility study as well as a form for cost estimation.

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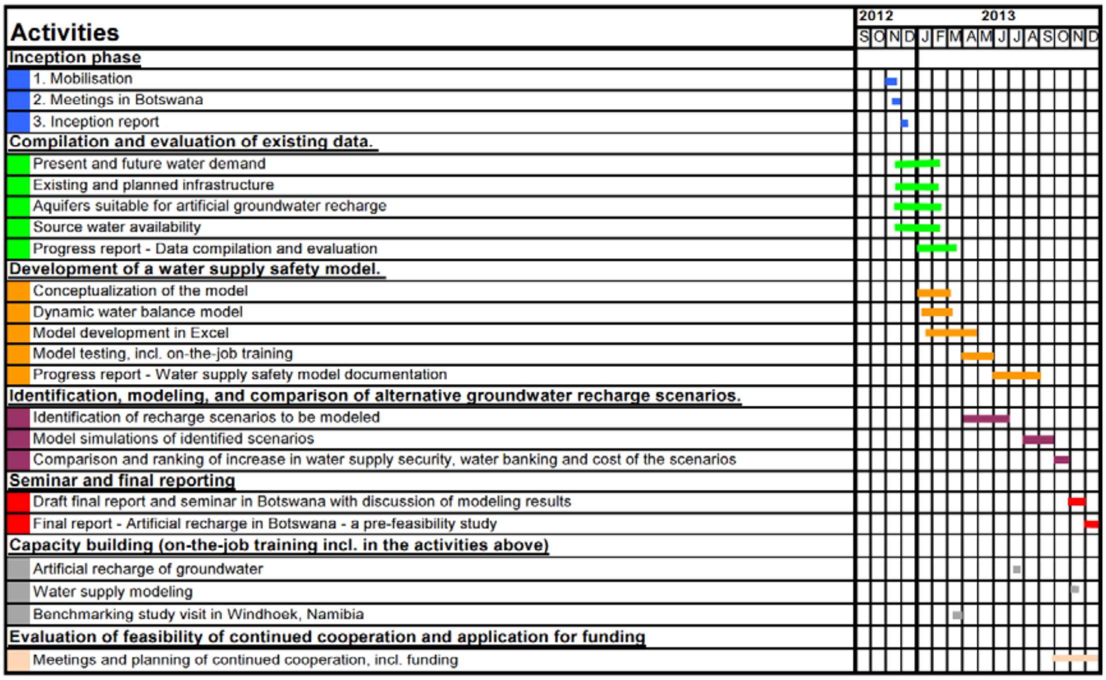
Appendix 1: Project work plan



Appendix 2: Water supply safety model – theory

Data consists of yearly inflow to the five dams Gaborone, Bokaa, Letsibogo, Dikgatlhong and Shashe for 80 years starting 1925 and ending 2004. This five-dimensional time series is modelled as a first order stationary Gaussian Auto-Regressive, AR(1), sequence,

$$y_t - \mu = \phi(y_{t-1} - \mu) + \epsilon_t$$

for $t = -79, -78, \dots, 0$ ($t = 0$ corresponds to year 2004). The row vectors μ and ϵ_t denote the long time yearly mean and white noise, respectively, the latter with covariance matrix Σ. In order to carry out a standard least squares (LS) estimation, the model is rewritten as follows,

$$y_t = \phi y_{t-1} + b + \epsilon_t$$

where $b = (I - \phi)\mu$ (I denotes the identity).

The spatial covariance matrix $\gamma = E y_t y_t' - \mu\mu'$ is estimated by the method of moments.

The parameters ϕ, b and Σ are estimated by ordinary least squares (LS), i.e., minimization of the least squares sum

$$\sum_t ||y_t - \phi y_{t-1} - b||$$

Note that the standard Gaussian theory of least squares estimation is not applicable here, since it requires independence between the response and predictor variables y_t and y_{t-1}, respectively. Instead we resort to a resampling technique, usually referred to as the bootstrap, since it allows us to verify assumptions on the covariance and correct for bias in the least squares estimates. By repeatedly simulating 80 years of data according to the estimated model and calculating new LS-estimates, we can (1) correct for bias and (2) verify that the bias corrected estimates behave as predicted from the standard LS theory. It is furthermore seen in the bootstrap that it is reasonable to assume that the estimate of Σ follows a Wishart-distribution with the degrees of freedom ν estimated from the bootstrap. We refer to Gelman et al. (2004) for exact definitions of all distributions mentioned in this appendix.

The result of the bootstrap serves well as a motivation for defining a joint uncertainty distribution (posterior) for the AR(1) parameters ϕ, b and Σ as follows:

1. Let Σ be inversely Wishart with parameters ν and the LS estimate of Σ.
2. Let the covariance matrix C of ϕ be inversely Wishart with $n - k(k + 1)$ degrees of freedom and the LS estimate of C and independent of Σ.
3. Let ϕ, b, conditional on C, be multi-variate normal with the LS estimates as means and covariance C.

Note that the unconditional distribution of ϕ, b is a translated and scaled multi-variate t-distribution.

The ultimate purpose of this analysis of the dam inflow data, is to simulate future inflow values to the five dams. So, after making a random draw of ϕ, b and Σ, independent white noise observations $\epsilon_1, \epsilon_2, \dots, \epsilon_T$ are simulated from a multi-variate normal distribution with zero mean and covariance matrix Σ. Then the future values $y_1, y_2, \ldots, y_T$ are recursively calculated from the drawn model $y_t = \phi y_{t-1} + b + \epsilon_t$. This is then repeated a suitably large number of times.

Reference:

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Appendix 3: Water supply safety model – User's manual

Introduction

This manual includes a description of how to select and adjust scenarios and run the model. Furthermore, the files needed to run the water safety model as well as other important aspects are described. Details on how the input data has been compiled and how water balance calculations etc. are done, are presented in the main text of the report. This manual is focused on providing a step by step description of how to run the model.

The model is a dynamic water balance model where statistically generated time series of the availability of source water are used, together with dynamic storages in dams and aquifers, and water demands to simulate the magnitude and probability of water supply shortages. The primary aim of developing the model was to provide an easily accessible model that can be run without expert knowledge. The water supply safety model is therefore developed as a spreadsheet model in Excel. To enable statistical analysis considering uncertainties in results etc., an add-in software (Oracle Crystal Ball) is used to run Monte Carlo simulations.

Overview

The water supply safety model is compiled to simulate (mainly) the NSC system and connected components from 2013 to 2035 (23 years). The simulations are performed with a time step of one month and for each month the demand, available storage in dams and aquifers as well as treatment capacities, water losses etc. are considered.

In Figure 1 a schematic illustration of the parameters considered in the model and the link between them and the model components are presented. Based on historical data on inflow to the dams, a large set (96 000) of possible time series are generated and used to sample from when running the model. The generated time series consider the correlation between the dams and each generated data set includes all five dams. The annual inflow data is transformed into monthly data based on the closest historical annual inflow and the monthly distribution that year. Since the dams are spatially correlated, the historical data for the Gaborone Dam is used when transforming the simulated annual data for the Bokaa and Gaborone Dams. In the same way the historical data for the Dikgatlhong Dam is used for the Letsibogo, Shashe and Dikgatlhong Dams.

For each dam, water balance calculations are done for each month considering all parameters presented in Figure 1. In the same way, water balance calculations are performed for the wellfields. However, for the wellfields not considered relevant for MAR only the sustainable yield is considered (i.e. abstraction is allowed up to sustainable yield). The water demand is used to determine how much water must be abstracted from the dams and wellfields. A set of operational rules (see the grey shaded box in the middle of Figure 1) determine to what extend different sources are used and how much water can be transferred etc.

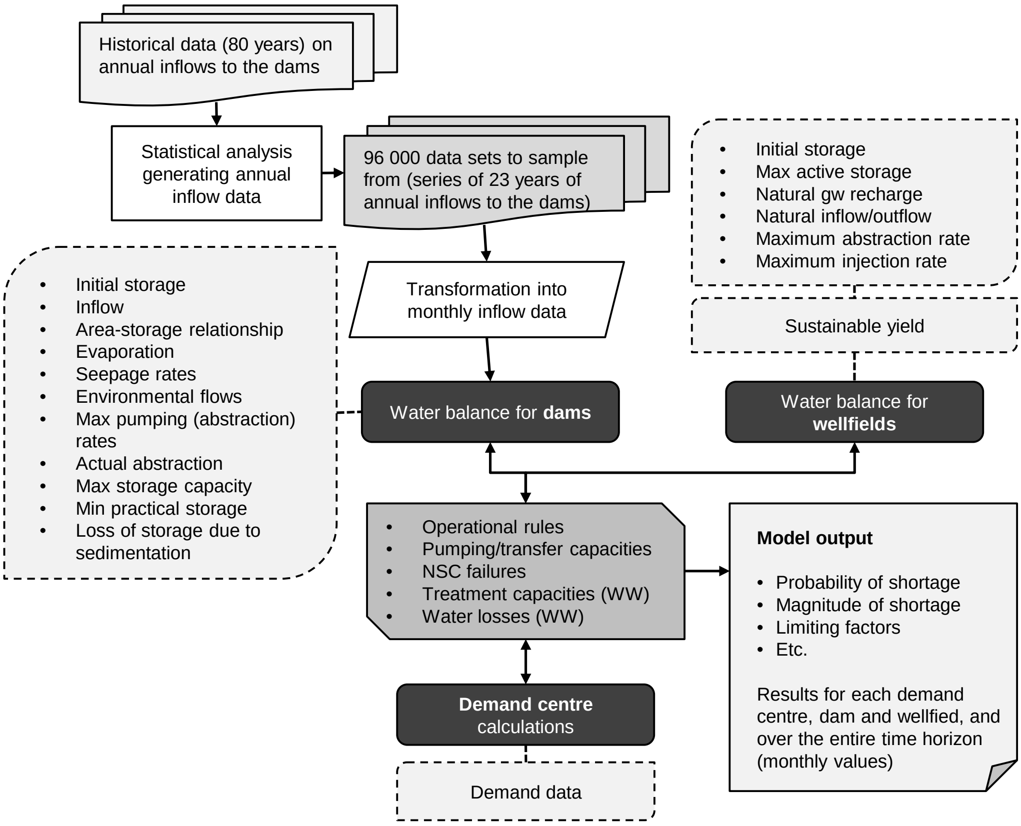


Figure 1. Overview of the parameters considered in the model and the link between them.

System structure and components

The model is focused on the area along the North-South Carrier (NSC) in eastern Botswana. The model layout is described in Chapter 0, an overview of the study area is presented in Chapter 2 and Figure 2.3 illustrates the location of the dams, wellfields and demand centres included in the system. The main focus of the model is to evaluate the possible effects of MAR-scenarios including the Palla Road/Chepete and/or the Masama/Makhujwane Wellfields.

In Figure 2 below, a schematic illustration of the water supply system is presented and the model includes the following components:

- 6 surface water dams
  - Shashe
  - Letsibogo
  - Dikgatlhong
  - Bokaa
  - Gaborone
  - Molatedi
- 8 wellfields
  - Paje
  - Serowe
  - Palapye

    - Palla Road/Chepete
    - Masama/Makhujwane
    - Malotwane
    - Kanye
    - Ramotswa
- 18 demand centres
    - Francistown, incl. Tati Siding and Tonota
    - Tati mine
    - Mupani mine
    - Selebi-Phikwe, incl. Mmadinare, excl. Bobonong and BCL-mine
    - Palapye
    - Moropule mine
    - Serowe
    - Mahalapye, incl. Palla Road
    - Shoshong, incl. Mmutlande, Kalamare and Bonwapitse
    - Mochudi, incl. Bokaa, Oodi, Metsimotlhaba, Rasesa, Morwa, Modipane, Mmopane
    - Gaborone, incl. Tlokweng and Mogoditshane
    - Ramotswa, incl. Ramotswa stn., Mmankgodi and Manyana
    - Lobatse, incl. Mogobane and Otse
    - Kanye, incl. Lotlakane
    - Thamaga, excl. Mmankgodi and Manyana
    - Moshupa, excl. Mmankgodi and Manyana
    - River Villages, incl. Sikwane, Dikwididi, Malolwane, Mabalane, Mmathubudukwane and Ramonaka
    - Goodhope Cluster, incl. Goodhope, Kgoro, Lejwana, Gamajaalela and Gathwane
- 7 water works (WW)
    - Francistown WW
    - Selebi-Phikwe WW
    - Palapye WW
    - Mahalapye WW
    - Mmamashia WW
    - Gaborone WW
    - Mablane WW

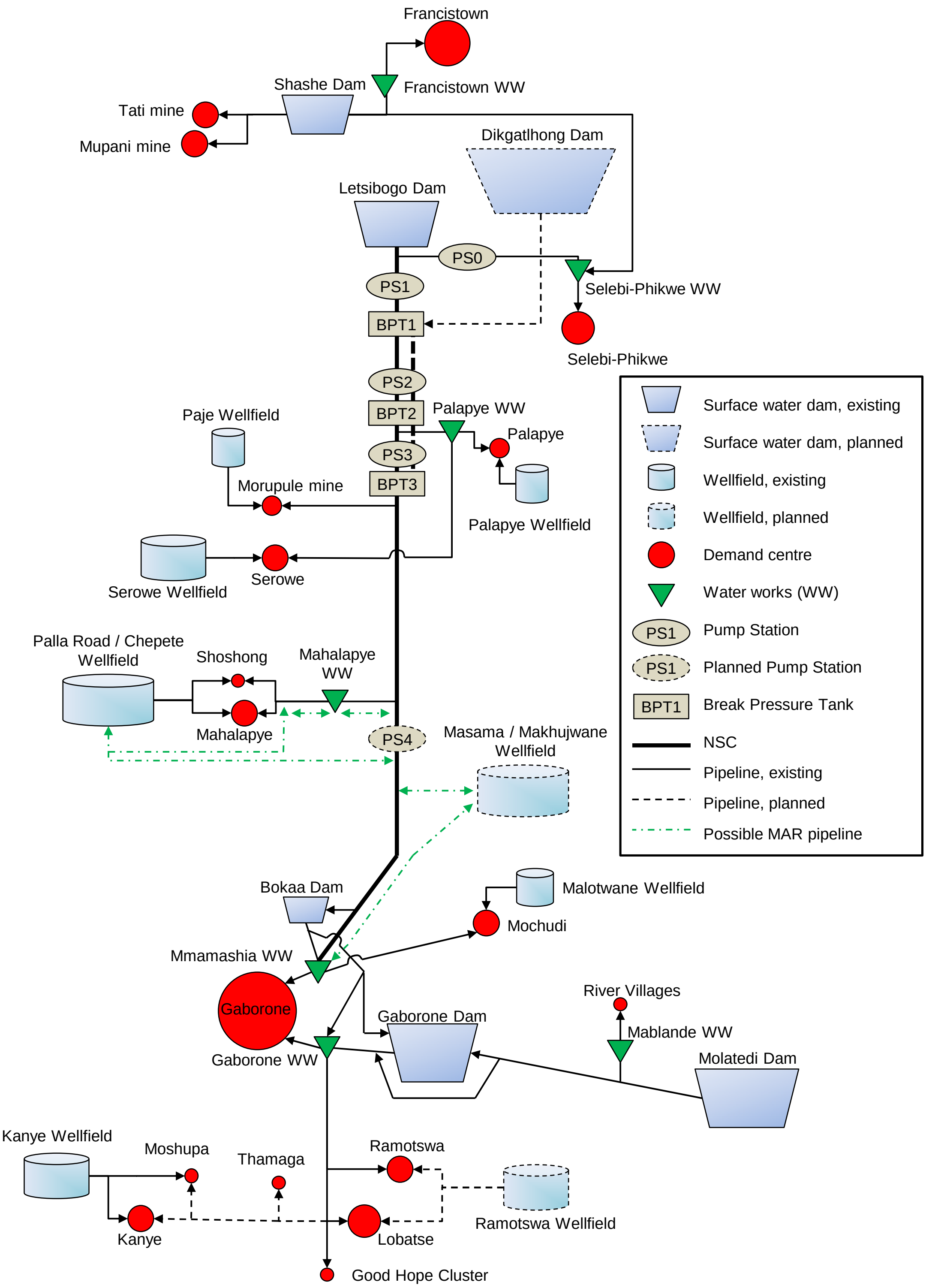


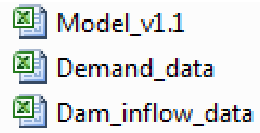
Figure 2. Schematic illustration of the water supply system linked to the NSC.

What is needed to run the model?

The water supply safety model is developed as a spreadsheet model in Excel. In order to view the model the only requirement is therefore to have Microsoft Excel installed on the computer (version 2010 or later should be used to make sure all functions are working correctly). However, to be able to run the model (i.e. simulate scenarios) also Oracle Crystal Ball must be installed. This is an add-in software to Excel that makes it possible to run Monte Carlo simulations in spreadsheet models. To download a trial version of the software or purchase a copy, go to www.oracle.com and search for Crystal Ball. Instructions on how to run the model etc. are provided below.

Model and input data files

The water supply safety model calculations and the automatically generated results are included in one Excel file (Model_v1.1.xlsx). Two input data files are also needed to be able to run the mode (Demand_data.xlsx and Dam_inflow_data.xlsx). The three files must be kept in the same folder since the model file uses data from the input files when simulations are performed. Thus, when copying the files to another computer, make sure they are placed in the same folder.



The model file is described in detail below. The demand data file (Demand_data.xlsx) includes the different demand data sets that can be selected in the model. Monthly demand values are listed for each demand centre for the simulated 23 years (2013-2035). Necessary changes in the demand data should be done in this file but the structure cannot be changed since the data is linked to the model file. However, it is possible to adjust the predicted increase in demand also in the model file (this is further described below). Changes in the demand data file should thus only be done If a new demand data set is compiled. See Section 4.1 for further description of the demand data.

The second input data file (Dam_inflow_data.xlsx) includes a set of 96 000 possible future time series of inflow to the dams. These data sets have been generated based on historical data and are used to sample from when running the model. See Section 6.3 for further details on how the times series were generated. The time series are organised according to the example in Table 1. The time series should not be changed. If, for example, additional inflow data becomes available a new analysis as described in Section 6.3 and Appendix 2 must be performed.

Table 1. Structure of the time series in Dam_inflow_data.xlsx.

Year	Gaborone	Bokaa	Letsibogo	Dikgatlhong	Shashe
0	5.00	4.30	52.79	78.28	91.72
1	19.46	23.23	93.15	216.23	183.61
2	258.24	26.97	43.80	138.99	92.63
3	57.45	14.27	11.53	67.42	35.28
4	99.38	20.57	42.43	97.25	72.49
5	349.89	62.27	98.55	114.34	64.07
6	413.45	18.24	58.99	36.68	55.09
7	7.87	6.68	122.63	350.05	494.20
8	17.31	2.57	3.21	0.97	4.12
9	10.83	6.45	6.22	15.07	6.26
10	32.37	6.78	9.10	40.06	40.34
11	9.28	4.52	28.97	11.25	30.92
12	10.65	3.34	60.85	19.35	37.23
13	34.71	12.73	244.91	485.70	351.70
14	34.65	16.55	19.89	26.22	24.35
15	72.65	9.30	92.73	89.40	124.97
16	11.86	2.33	58.64	108.88	76.41
17	40.83	19.47	138.89	264.27	185.84
18	127.52	13.82	74.32	218.15	191.95
19	88.49	12.34	64.68	239.82	142.50
20	61.74	5.44	11.18	3.14	10.13
21	1.65	0.49	97.68	64.65	171.92
22	5.86	1.77	73.63	159.49	121.74
23	4.90	5.49	28.68	8.56	12.57

Monte Carlo simulations using Oracle Crystal Ball

To enable statistical analysis considering uncertainties in input data and results, an add-in software (Oracle Crystal Ball) is used to run Monte Carlo simulations. The main input parameters for which uncertainties are considered are the dam inflows. Monte Carlo simulation uses random numbers to sample values from probability distributions representing the input variables. Hence, calculations are performed iteratively a large number of times to select values representing the entire probability distribution for each input parameter and obtain a probability distribution that represents the result (Figure 3).

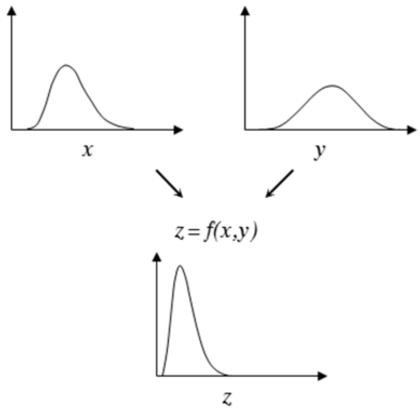


Figure 3. Illustration of how uncertainties in input parameters (x and y) are considered and used in Monte Carlo simulations to calculate results (z).

Crystal Ball is accessed in a specific tab (named Crystal Ball) in the menu bar in Excel (if installed on the computer), see Figure 4. The user of the model does not have to use the software to define uncertainties. The user only needs to define the number of trials/iterations (i.e. the number of times the calculations are repeated to make sure uncertainties in input parameters are well represented) and click the Start-button to start the simulations (i.e. run the model).

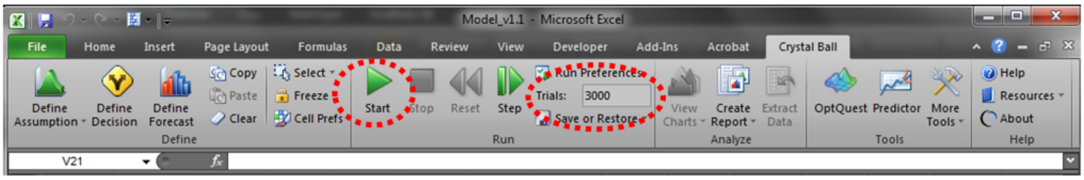


Figure 4. The Crystal Ball tab in the Excel menu bar.

How to run the model (model file and interface)

To start/open the model the file named Model_v1.1.xlsx is opened. On most computers, Crystal Ball is started automatically when Excel is started. However, if the Crystal Ball tab in the start menu bar (Figure 5) does not appear you should first start the Crystal Ball software, which will open Excel, and you can then open the model file.

In order to run the model you must do the following five basic steps (further described below):

1. Select and adjust the scenario to be analysed in the worksheet named "Start".
2. Define the number of trials/iterations for the Monte Carlo simulations (Figure 5). It is recommended to use 3,000 for detailed analysis but when testing the model 300-500 trials can be used to reduce the simulation time.
3. Click the start-button (Figure 5) to run the model (go to the worksheet "Start" before running the simulations to make the simulation process as fast as possible).
4. Evaluate the results using the graphs in "Results – All graphs" and other worksheets.

The above steps are described in more detail below, starting with the worksheets included in the model file.

Included worksheets

Some of the worksheet tabs in the model file are shown at the bottom in Figure 5 ("Start", "Results – All graphs", "Supply to demand centres", etc.). In total, the model file includes 24 worksheets:

- 1 for selecting and adjusting the scenario to be simulated
- 1 where all graphs (results) are presented
- 1 for calculating the actual supply and shortages for each demand centre
- 2 for performing the water balance calculations (dams and wellfields)
- 1 for sampling dam inflow data

- 2 including historical inflow data
- 2 for calculating evaporation losses
- 1 for calculating the supply from the Molatedi Dam
- 5 including system properties (capacities etc.)
- 8 including results

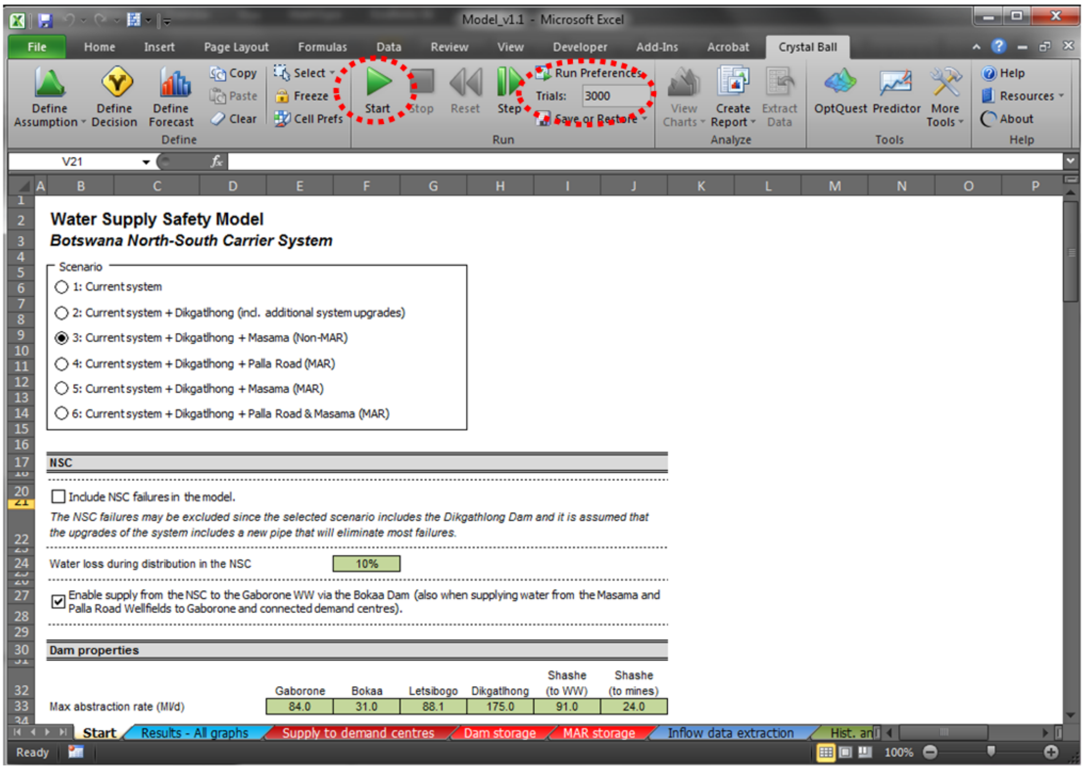


Figure 5. *The model file (Model_v1.1.xlsx) opened in Excel. The worksheet "Start" is selected and in the menu bar the Crystal Ball tab is showed.*

For each of the 24 worksheets a short description of the content is provided here (note that properties listed in some of the worksheets are defined by the user in "Start" and should thus not be changed in each worksheet):

- *Start*: The scenario to be modelled is selected and adjusted in this worksheet.
- *Results – All graphs*: All graphs including results are placed here to make it simple to view and print them.
- *Supply to demand centres*: The actual supply, including possible water shortage etc., is calculated here for each demand centre based on operational rules and other input data.
- *Dam storage*: Includes water balance calculations for the dams.
- *MAR storage*: Includes water balance calculations for the wellfields (Masama Non-MAR, Masama MAR and Palla Road MAR).
- *Inflow data extraction*: The annual inflow time series from the dam inflow data file (Dam_inflow_data.xlsx) are sampled and inserted here. Furthermore, the annual values are transformed into monthly values based on the closest historical value and the monthly proportions that year.

- *Hist. annual inflow (sorted)*: Includes historical annual inflows to the dams. This data is used when identifying the closest historical value for the sampled data in “Inflow data extraction”.
- *Hist. monthly inflow data*: Includes historical monthly inflows to the dams. This data (the proportions) is used when transforming the annual values to monthly values in “Inflow data extraction”.
- *Eva_Gab_Bok*: Here the evaporation losses are calculated for the Gaborone and Bokaa Dams based on a relationship between the surface area and the volume.
- Eva_Let_Dik_Sash: Here the evaporation losses are calculated for the Letsibogo, Dikgatlhong and Shashe Dams based on a relationship between the surface area and the volume.
- *Molatedi*: Includes the monthly inflows to the Molatedi Dam. The inflow is defined by the user in “Start”.
- *Dam properties*: Includes data on the maximum abstraction rate for each dam.
- *WW properties*: Includes data on maximum treatment capacity and water losses for each water works.
- *Wellfield properties*: Includes data on sustainable yield and thus maximum abstraction rate for each Non-MAR wellfield.
- *NSC failures*: Here the possible NSC failures are defined including uncertainties. Pipeline leakages causing interruptions in the supply are assumed to occur in the order of 2-3 times in a year interruptions with duration of 1 week to 3 weeks.
- *MAR properties*: Wellfield properties such as maximum abstraction and injection rates, maximum active storage and initial storage for the different MAR-scenarios are listed here.
- *Results – Probability plots*: Includes data and graphs showing, for example, the maximum annual water shortage plotted against the reverse cumulative probability.
- *Results – Summary*: Includes data on, for example, the total volume not supplied for each demand centre.
- *Results – Dams*: Includes data and graphs for the dams, e.g. storage over time.
- *Results – WW*: Includes data and graphs showing the remaining treatment capacity for the Mmamashia and Gaborone water works.
- *Results – Demand centres*: Includes data and results showing water shortages etc. for the demand centres.
- *Results – Limiting factors*: Includes data and graphs for the system properties limiting the supply.
- *Demand vs. Capacity*: Includes a comparison of demand, WW capacity and abstraction rates for some of the dams to illustrate what is limiting the capacity.

Selecting and adjusting scenarios

The worksheet named “Start” has been compiled to provide a user-friendly interface where the user can select and adjust the scenario to be modelled. The worksheet is divided into seven main parts where different setting can be made related to the components etc. included in the system. The first step is to select one of the six scenarios included in the model (Figure 6). For further details on the different scenarios, see Chapter 5 in the report.

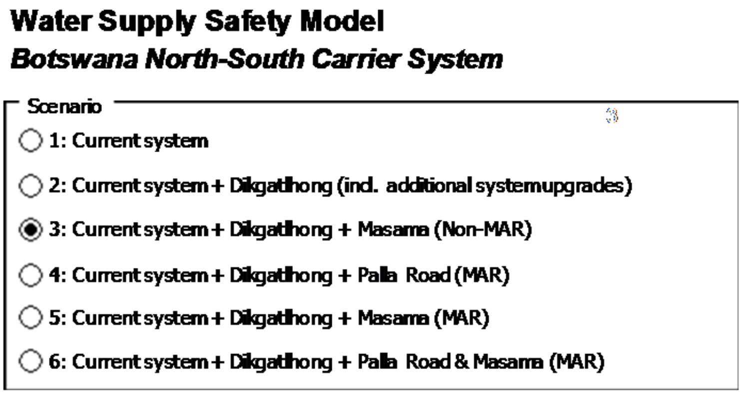


Figure 6. Selection of scenario in the water supply safety model.

In the remaining part of the worksheet “Start” it is possible to adjust settings and define input data for the dams, wellfields etc. In Figure 7 the possible settings that can be done for the NSC is shown. It is suggested that NSC failures are included when Scenario 1 (Current system) is modelled but when the Dikgatlhong Dam is connected to the NSC and a new pipe from the Break Pressure Tank 1 (BPT1) down to Pump Station 3 (PS3) is installed, the NSC failures (pipe breaks) are assumed to not affect the supply in the same manner and may thus be excluded (i.e. in Scenario 2-6).

The probability of NSC failure is modelled using a discrete probability function (1/6 monthly probability) and the duration of failure is modelled using a uniform probability distribution (7-21 days).

Furthermore, the water losses in the NSC are defined and it is selected if the possibility to supply water from the NSC to the Gaborone WW via the Bokaa Dam should be included.

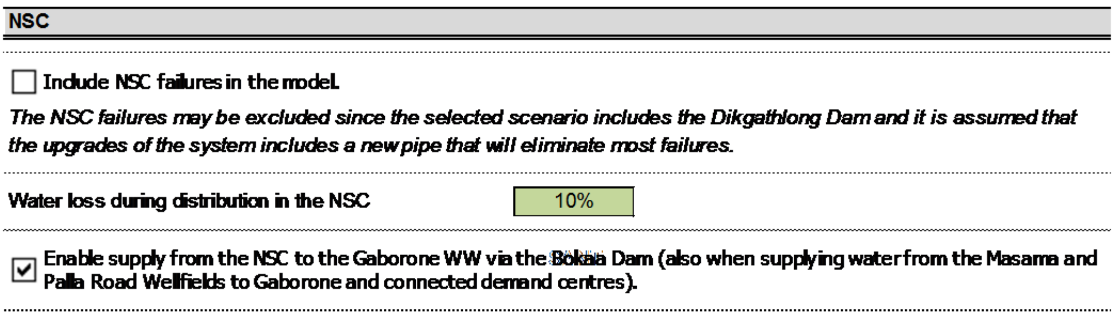


Figure 7. Settings related to the NSC.

The maximum abstraction rate, initial storage, etc. for each of the surface water dams are dined in the part shown in Figure 8. In addition to specific dam properties also the transfer capacity for supplying water from the Bokaa dam to the Gaborone WW is defined. Also the intended supply from the some of the water works to the connected demand centres, and the dams supplying water to the NSC, should be defined here.

Dam properties

	Gaborone	Bokaa	Letsibogo	Dikgatlhong	Shashe (to WW)	Shashe (to mines)
Max abstraction rate (Ml/d)	84.0	31.0	88.1	175.0	91.0	24.0

		Gaborone	Bokaa	Letsibogo	Dikgatlhong	Shashe
Initial storage (Mm³)		49.65	7.08	31.00	198.80	59.62
Initial maximum storage Mm³ (at full supply level)		140.59	18.20	108.00	397.60	75.05
Minimum operational level (% of maximum storage)		15%	3%	5%	4%	15%
Loss of storage due to sedimentation (Mm³/year)		0.22	0.04	0.35	0.70	0.61
Seepage (l/s)		0.0	0.0	0.0	30.0	0.8
Environemntal flow s	Feb	0%	0%	2.49	5%	0%
	Nov	0%	0%	0.49	5%	0%
		% of inflow	% of inflow	Mm³, provided inflow >0	% of inflow	% of inflow

Supply from Molatedi: 16 Ml/d — *Default value is 80 % of 20 Ml/d, i.e. 16 Ml/d.*

Transfer capacity: Bokaa Dam to Gaborone WW: 23.0 Ml/d

Intended supply to Gaborone and connected demand centres		
From Mmamashia WW	60%	of demand
From Gaborone WW	40%	of demand
Intended supply to the Mmamashia WW		
From the Bokaa Dam	30%	of demand
From the NSC	70%	of demand
Supply to NSC w hen the Letsibogo and Dikgathlong Dams are connected		
From the Letsibogo Dam	40%	of demand
From the Dikgathlong Dam	60%	of demand

Figure 8. Settings related to the surface water dams are defined in this part.

The possible settings for the MAR wellfields are shown in Figure 9. First of all it is selected if a baseline or extended sub-scenario should be modelled (see Chapter 5 for further description). The two properties related to Masama MAR are included to consider the following to possibilities:

- A new pipeline is constructed from the Mmamashia Water Works to Masama for supply of treated water for injection. The same pipeline is used when water is abstracted from the wellfields and delivered directly to the water distribution system (if necessary after some minor treatment).
- The connection to the NSC from the wellfields is upgraded to allow reversed flow to allow transfer of water from the NSC to the wellfields for injection, and for the extended scenario also for a higher transfer rate. A new water treatment plant is constructed for treatment of the water to be injected. When water is abstracted from the wellfields, it is transferred back to the NSC.

Managed Aquifer Recharge (MAR)

Palla Road MAR
- ◯ Baseline
- ◯ Baseline + abstraction for Mmamabula (6 Mm3/y)
- ◉ Extended

Masama MAR
- ◯ Baseline
- ◉ Extended

☐ Abstracted water from Masama (MAR - Scenarios 5 and 6) must be treated at the Mmamashia or Gaborone WW, i.e. a separate pipe for transferring treated water from Masama to Gaborone is not included.

☐ Include a new WW at the Masama Wellfield (MAR - Scenarios 5 and 6) for treatment of injection water. The connection to the NSC allows transfer in both directions (i.e. from the NSC to the WW/wellfield and from the wellfield to the NSC).

Critical dam storage (Dikathlong and Letsibogo) when injection is no longer allowed	20%	
Treatment capacity, Mahalapye WW, when MAR for Palla Road	28.5	Ml/d

Abstraction and injection rates: Palla Road MAR

		Abstration rate		Injection rate	
Baseline					
	Palla Road	11 740	m³/d	11 740	m³/d
	Chepete	2 488	m³/d	2 488	m³/d
Baseline + abstr. from Mmamabula		Abstration rate		Injection rate	
	Palla Road	11 740	m³/d	11 740	m³/d
	Chepete	2 488	m³/d	2 488	m³/d
	Kudumatse	16 200	m³/d	16 200	m³/d
Extended		Abstration rate		Injection rate	
	Palla Road	17 610	m³/d	17 610	m³/d
	Chepete	3 732	m³/d	3 732	m³/d

Abstraction and injection rates: Masama (MAR)

		Abstration rate		Injection rate	
Baseline					
	Masama	17 839	m³/d	17 839	m³/d
	Makhujwane	3 727	m³/d	3 727	m³/d
Extended		Abstration rate		Injection rate	
	Masama	31 212	m³/d	31 212	m³/d
	Makhujwane	6 522	m³/d	6 522	m³/d

Figure 9. Input data and settings for the MAR scenarios.

The critical dam storage (Figure 9) defines when injection is no longer allowed, i.e. the MAR wellfields are (if needed) injected until the dam storage reaches the critical level. Abstraction and injection rates are defined for the two MAR alternatives and for a baseline and an extended sub-scenario.

The demand data set to be used is selected in the part shown in Figure 10. Descriptions of the different data sets and the possibility to adjust them are also shown in Figure 10.

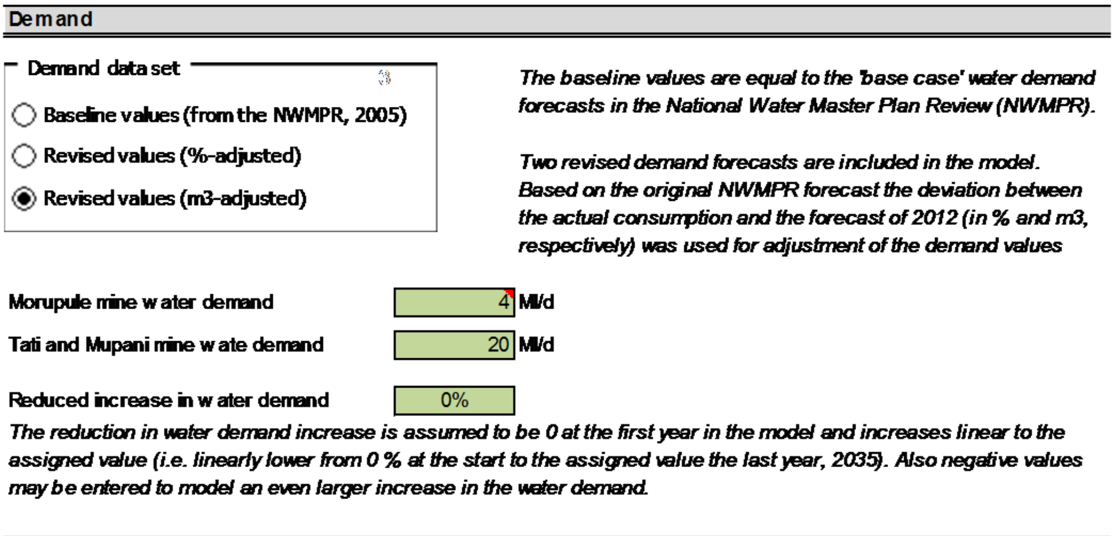


Figure 10. Selection of demand data set and some additional demand figures.

For each water works the treatment capacity and the water losses during treatment are defined (Figure 11). The treatment capacity is defined for the current system (Scenario 1) and after coming upgrades that are assumed to be implemented in Scenario 2-6.

Water Works

Treatment capacity and water losses

	Current	After upgrades *Scenario 2-6*		Water loss (%)
Sashe WW	52	91	Ml/d	5%
Palapye WW	16	32	Ml/d	5%
Selibe-Phikw e WW	38	50	Ml/d	5%
Mahalapye WW	14	14	Ml/d	5%
Gaborone WW	108	108	Ml/d	5%
Mmamashia WW	110	155	Ml/d	5%
Lobatse WW	2.5	2.5	Ml/d	4%
Mabalane WW	1.2	1.2	Ml/d	11%

Figure 11. Properties for the water works.

For the Non-MAR wellfields the sustainable yield is used as the maximum abstraction rate and this is defined in the part shown in Figure 12. Also the intended supply from the wellfields to the demand centres is defined. The intended local supplies are used for all wellfields except for Palla Road/Chepete and Masama/Makhujwane in Scenarios 3-6.

Wellfields (Non-MAR)

Sustainable yield

Paje	0.70	Mm^3/year
Palapye	0.70	Mm^3/year
Serowe	1.83	Mm^3/year
Palla Road (incl. Chepete)	3.20	Mm^3/year
Masama (incl. Makhujwane)	1.26	Mm^3/year
Malotwane	0.20	Mm^3/year
Kanye	2.00	Mm^3/year
Ramotswa	1.80	Mm^3/year

Intended (local) supply from wellfields (% of demand)

From Palapye Wellfield to Palapye	50%	
From Serowe Wellfield to Serowe	58%	
From Paje Wellfield to the Morupule mine	10%	
From Palla Road Wellfield to Mahalapye & Shoshong	50%	*Automatically 0% if Palla Road MAR (Scen. 4 & 6).*
From Malotwane Wellfield to Mochudi	0%	
From Kanye Wellfield to Kanye & Moshupa	60%	
From Ramotswa Wellfield to Ramotswa & Lobatse	50%	*Automatically 0 % for Scenario 1 since not included in current system.*

☐ Run all wellfields on sustainable yield.

The default approach is to use the above defined intended supply for the different wellfields.

Figure 12. Input data and operational rules for the (Non-MAR) wellfields.

The calculations in the model are performed in the main steps listed below. In all steps available abstraction rates (i.e. pump capacities), treatment capacities, water losses during treatment etc. are considered. The calculations can be followed in the worksheet “Supply to demand centres” (start from left and continue to the right) that is organised with headings describing what is done.

1. Water from the Shashe Dam is abstracted and first supplied to Francistown and after that to the Tati and Mupani mines.
2. Water from the Letsibogo Dam is abstracted and supplied to Selebi-Phikwe and if the demand cannot be meet water is also (if available) abstracted and supplied from the Shashe Dam.
3. Intended local supply from wellfields (i.e. all wellfields except for Palla Road/Chepete and Masama/Makhujwane in Scenarios 3-6) based on the defined operational rules.
4. Water from the Molatedi Dam is used to supply water to the River Villages.
5. The total water demand for Gaborone and connected demand centres is calculated. Water is supplied in the following order (based on operational rules defining to what extent the different sources are intended to be used):
    a. From the Gaborone WW using water from the Molatedi Dam.
    b. From the Gaborone WW using water from the Gaborone Dam.
    c. From the Mmamashia WW using water from the Bokaa Dam.
    d. From the Mmamashia and Gaborone WWs using water from the NSC, abstracting water from the Letsibogo Dam (Scenario 1) or both the Letsibogo and Dikgatlhong Dams (Scenario 2-6). If not enough water is available, the demand in the centres are met to the same degree. For

example, if 80 % of the needed water is available all receive 80 % of their demand.

e. From the Mmamashia WW using water from the Bokaa Dam (if there is a remaining demand and water available in the dam).

f. From the Gaborone WW using water from the Gaborone Dam (if there is a remaining demand and water available in the dam).

g. From the Gaborone WW using water from the Bokaa Dam (if there is a remaining demand and water available in the dam).

6. Abstraction and supply from the Masama/Makhujwane Wellfileds (Non-MAR in Scenario 3 and MAR in Scenario 5 and 6) and the Palla Road/Chepete Wellfields (MAR in Scenario 4 and 6).

7. Injection of water at the MAR wellfields (Scenario 4-6) using (treated) water from the NCS.

Start the simulations

As previously described Oracle Crystal Ball, an add-in software to Excel is used when running the model in order to perform Monte Carlo simulations. Before starting a simulation the number of trials/iterations has to be defined, see Figure 5. It is recommended to use 3,000 trials when the results should be used for a detailed analysis or comparison between different scenarios. When testing the model 300-500 trials can be used to reduce the simulation time. A simple way to see if the number of trials is enough is to run the same scenario a couple of times and see how much specific result varies. The results will always vary a bit between different simulations but when the number of trials is big enough the difference is sufficiently low.

When the number of trials has been defined, a simulation can be started by clicking the Start-button in the Crystal Ball ta in the menu bar (Figure 5). It is recommended to go to the worksheet "Start" before running the simulations to make the simulation process as fast as possible. When the simulation is started a control panel is shown (Figure 13). When the simulations are done the results can be viewed in, for example, "Results – All graphs".

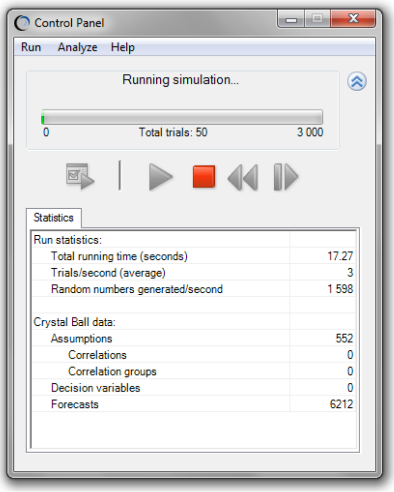


Figure 13. Control panel shown when a simulation is started.

Results

The model provides a large number of pre-defined graphs presented in the sheet named “Results – All graphs”. Furthermore the data etc. used to create the graphs are presented in eight result sheets:

- Probability plots
- Summary
- Dams
- WW
- Wellfields
- Demand centres
- Limiting factors
- Demand vs. Capacity

Except for the sheet “Results – All graphs” the user does only need to use the other sheets if, for example, the data should be exported or additional results should be added. The sheet “Results – All graphs” is organised (page brakes etc.) so that all graphs can be printed (or stored as a pdf) to create one report including all results (tot. 27 pages).

In addition to mean values (corresponding to expected values) also percentiles are presented in the results. Most often the 10^{th} and 90^{th} percentiles (P10 and P90) are presented. A percentile represents the value below which a given percentage of model results fall. For example, P10 represents the value below which 10 % of the simulated results fall and P90 represents the value below which 90 % of the simulated results fall (i.e.10 % above).

As commonly done in risk analyses results such as maximum annual water shortage etc. are plotted against the cumulative or reverse cumulative probability. The cumulative probability plots can be used to determine, for example, that there is 30 % probability that the value will not exceed 10 Mm^3. The reverse cumulative probability plots can be used to determine, for example, that there is a 10 % probability of the values being at least 25 Mm^3.

The following main results are included in “Results – All graphs”:

- Percentage of months with water shortage for each demand centre (P10; Mean; P90).
- Total water shortage (i.e. summed over the simulated 23 years) for each demand centre (P10; Mean; P90).
- Percentage of demand (per month) not met given water shortage for each demand centre (P10; Mean; P90).
- Number of months until first water shortage event for each demand centre (P10; Mean; P90).

- Maximum annual water shortage (Mm^3) within the simulated period (23 years) versus reverse cumulative probability.
- Total water shortage (i.e. summed over the simulated 23 years) versus reverse cumulative probability.
- Expected probability of annual water shortage of different magnitude (e.g. >2 Mm^3, >5 Mm^3, etc.) versus time.
- Total net evaporation loss savings versus reverse cumulative probability.
- Expected groundwater storage versus time.
- Groundwater storage at end of simulated period versus reverse cumulative probability.
- Proportion of limiting factors for different steps in the supply chain.

Add components etc. to the model

The above description is focused on how to select and adjust the currently included scenarios in the model. All choices and possible adjustment of the included scenarios are done in the worksheet named “Start”. However, in order to add additional components such as new demand centre, dams, wellfields, etc. the user has to adjust the calculation in some of the other worksheets. The worksheet “Supply to demand centres” includes a stepwise calculation of the possible supply to each demand centre and is the main worksheet to study to understand in detail how the calculations are done. By following the calculation (from left to right) in “Supply to demand centres” it is possible to understand how the calculations are done, how data from other worksheets are used and how to update the model in order to include additional components etc.

Appendix 4: Cost Estimation Forms for MAR field tests and full-scale schemes

MAR Field Test at Palla Road Wellfield **Cost Estimation Form**			
Item	**Specification**	**Cost, excl. VAT (P)**	**Comment**
Detailed planning, design and procurement.	Consultancy of planning and design, incl. gw-modelling. Procurement for additional infrastructure and for the performance and evaluation of the field investigations and test.	1 654 000	Consultancy for supervision of drilling, test pumping, and project reporting.
Source water.	Water treatment, 2 500 m3/d, 250 d.	Estimate missing	250 days of injection.
Transfer of water to the wellfield	New connection at the water reservoir, valves etc. along the pipeline, booster pumping?	Estimate missing	To allow for reversed flow from the Mahalapye Water Reservoir to the wellfield.
Injection and abstraction in existing production or monitoring wells (option 1).	3 wells, borehole camera logging, step drawdown test, step injection test, pumping test, water sampling and analysis (standard groundwater analysis, 2 samples per well at the end of step drawdown test and pumping test).	1 228 500	Specify wells to be used.
Injection and abstraction in new wells (option 2).	3 wells, well drilling and construction (dimension, depth, casing, screening?), borehole camera logging, step drawdown test, step injection test, pumping test, water sampling and analysis (standard groundwater analysis, 2 sample per well at the end of step drawdown test and pumping test)	4 630 000	Specify well design and duration of pumping tests used in cost estimate.
Additional infrastructure, existing production or monitoring wells (option 1).	Pipelines for connection of wells, pumps, injection pipes, taps for water sampling, electrical and automatic control works etc.	Estimate missing	
Additional infrastructure, new wells (option 2).	Pipelines for connection of wells, pumps, injection pipes, electrical and automatic control works, etc.	18 000 000	Assuming 3 km of pipeline inter-connection between boreholes
Abstracted water.	Pumping cost minus value of supplied water.	Estimate missing	250 days of pumping.
Operational and maintenance costs.	Other than water treatment and pumping costs.	Estimate missing	For a test period of 18 months.
Monitoring costs.	Flow meters, automatic and manual groundwater level measurements, field measurements of EC and temp., chemical and microbial analysis, sampling frequency?	120 000	Chemical analysis, injected and abstracted water,160 samples (EC, pH, Turbidity, Total suspended solids, Cl, Fe, Mn, Ca,Mg, Na, K, SO4, TOC, Hardness. Additional for injected water: Daily: Turbidity, Weekly: Dissolved oxygen, chlorine residual. Microbial analysis, injected and abstracted water, 160 samples: Heterotrophic plate count, total and fecal coliforms. Isotope analysis (D,Tritium,O-18, He-3)?

MAR Full-scale Scheme at Palla Road/Chepete Wellfields Cost Estimation Form			
Item	**Specification**	**Total cost, excl. VAT (P)**	**Comment**
Detailed planning, design, procurement and supervision.	Consultancy on detailed planning and design, incl. procurement of planning and design and a phased implementation.	9 339 000	Includes 18 months supervision.
Source water.	Increased treatment capacity at the Mahalapye WW, +14 500 m3/d.	105 454 545	The plant will be used to supply drinking water to Mahalapye, but with spare capacity so that injection water also can be supplied to the MAR scheme.
Transfer of water to the wellfield.	Increased capacity of the existing infrastructure needed (i.e. compared to field test), 14 500 m3/d.	Estimate missing	
Wells.	No additional wells are needed. Borehole camera loggning, step drawdown test, step injection test, pumping test, and water sampling before start.	3 185 700	
Additional infrastructure.	New reservoir at the wellfield, equipment for chlorination, pipelines for connection of wells, pumps, injection pipes, taps for water sampling, electrical and automatic control works etc.	Estimate missing	
Abstracted water, use of existing distribution system (option 1).	Required changes in existing pipes, pumps etc. to enable transfer of water to Mahalapye and further to the NSC.	Estimate missing	
Abstracted water, new pipe to the NSC (option 2).	New pipe connecting the wellfield to the NSC.	360 000 000	
Operation and maintenance.	Treatment cost, pumping cost, monitoring costs, maintenance costs etc. Total annual cost.	Estimate missing	Operation costs for treatment and pumping should be calculated per m3. Maintenance costs (incl. monitoring) should be calculated as percentages of the additional investment costs for MAR. Express as total annual cost in 2014 prices.

MAR Full-scale Scheme at Masama Cost Estimation Form			
Item	**Specification**	**Cost, incl. VAT (P)**	**Comment**
Detailed planning, design and procurement of field investigations and field test.	Consultancy on planning and design, incl. gw-modelling. Procurement for additional infrastructure and for the performance and evaluation of the	Estimate missing	Consultancy for supervision of drilling, test pumping, and project reporting.
Field investigation and field test.	Same programme as for Palla Road. Water for injection by reversed flow in pipeline from NSC, treatment in a provisional plant for the test, 2 500 m3/d.	Estimate missing	
Detailed planning, design, procurement and supervision.	Consultancy on detailed planning and design, incl. procurement of planning and design and a phased implementation.	26 550 000	Includes 18 months supervision.
Source water, new treatment plant at the Masama Wellfield (option 1).	Design and costruction of new treatment plant. Capacity 38 000 m3/d. Treated water quality requirement = drinking water. Transfer of water from NSC to the treatment plant.	276 000 000	
Source water, treated water from Mmamashia WW (option 2).	The capacity after the planned upgrading of Mmamashia (155 000 m3/d) is assumed to be suffiecient also for supply of injection water to the MAR scheme.		Only additional operation and maintenance costs.
Transfer of water to the wellfield from the NSC to new treatment plant at the Masama Wellfield (option 1).	Upgrading needed to enable reversed flow in existing infrastructure.	Estimate missing	
Transfer of water to the wellfield from the Mmamashia WW (option 2).	New pipeline from the Mmamashia WW to the Masama Wellfield, including possibility for reversed	480 000 000	
Wells	No additional boreholes are required for the MAR scheme.		No extra MAR costs assumed.
Additional infrastructure.	Pipelines for connection of wells, pumps, injection pipes, taps for water sampling, electrical and automatic control works etc.	18 000 000	The water reservoir planned for the connection of the Masama Wellfield to NSC considered to be adequate also for the MAR-scenarios.
Abstracted water, new treatment plant at the Masama Wellfield (option 1).	Required changes in existing pipeline, pumps etc. to enable transfer of water to the NSC.	Estimate missing	
Abstracted water, transfer of water to the Mmamashia WW from the wellfield (option 2).	Connections to allow bypass flow directly to the water distribution system.	Estimate missing	Cost for reversed flow in the new pipeline connecting Mmamashia and Masama included under transfer, option 2, see above.
Operation and maintenance.	Treatment cost, pumping cost, monitoring costs, maintenance costs etc. Total annual cost.	Estimate missing	Operation costs for treatment and pumping should be calculated per m3. Maintenance costs (incl. monitoring) should be calculated as percentages of the additional investment costs for MAR. Express as total annual cost in 2014 prices.