

OPTION 1 – INDIRECT POTABLE REUSE – SURFACE STORAGE

The indirect potable reuse option using surface water storage site would be best off using the Gaborone Dam as this dam has not reached 100% capacity and overflowed since the year 2000. This would reduce the risk of treating water, which would effectively not be used for drinking, due to overflows from the dam.

A flow diagram of this proposed option has been detailed in Figure 19.

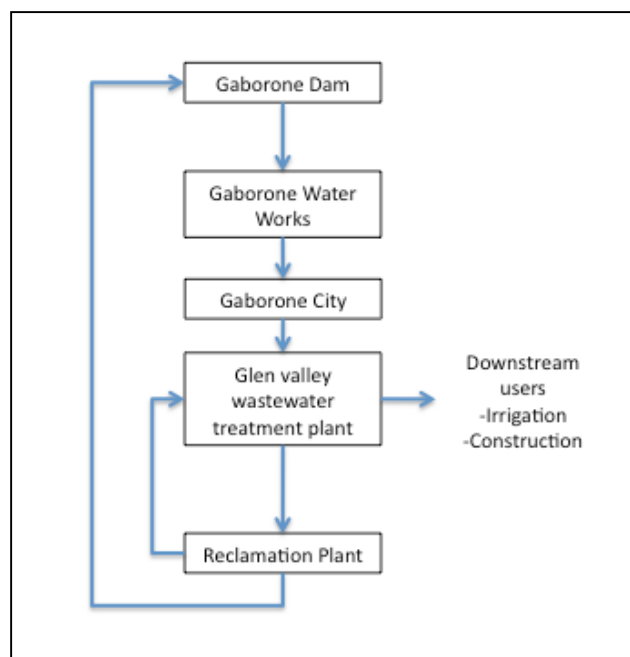


Figure 19 Overview of Indirect reuse process using surface water.

The process would involve secondary treated effluent being treated at a reclamation plant using at minimum microfiltration, reverse osmosis and UV disinfection in a similar arrangement to either Orange County or Singapore. Product water from the reclamation plant would then be pumped to the Gaborone Dam.

In order to achieve the maximum benefits of the dam, as an environmental barrier (i.e. storage for one year before reuse), the inlet to the dam would

need to be positioned a distance away from the outlet/wall. Evaporative losses during storage of this water would be substantial.

Factor	Value
Full capacity of Gaborone Dam (WUC Annual Report ⁵³)	141 400 000 m ³
Net average evaporation rate (Gibb/pula)	2000 mm/year
Approximate surface area of Gaborone Dam	9 350 412 m ² *
Approximate loss of surface water to evaporation per annum	13% or 18 700 824 m ³ approx. 51 235m ³ /day

Table 12. Evaporation rate of the Gaborone Dam

** Figure obtained using Google Earth – dam level not at full capacity.*

This means that 13% of all water delivered to the Gaborone dam will be lost to evaporation.

Over and above the evaporative losses this water would then have to be retreated making use of conventional treatment processes at the Gaborone treatment works, further increasing the cost of treatment.

OPTION 2 – INDIRECT POTABLE REUSE – GROUNDWATER RECHARGE

This option is very similar to option 1 having all the benefits of the environmental barrier and storage facilities without the risk of overflow or issues of evaporation. This is possibly the most suitable option for water reclamation in Botswana. The only reason why this option has not been selected for by this project is that there is no known suitable aquifer readily available for recharge. The Ramotswa well fields are a potential aquifer although these have been abandoned due to them being polluted (Gibb/Pula³¹). This would result in the reclaimed water stored in this well field being contaminated by both the existing waters in the well field and the source of pollution.

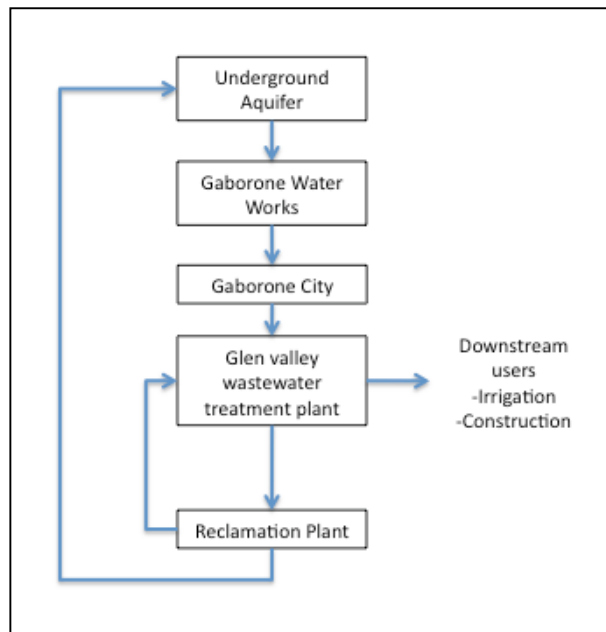


Figure 20 Overview of Indirect reuse process using groundwater recharge.

Another solution to this problem could be the acceptance that contamination will occur and then the upgrading of the Gaborone water works to enable it to treat this contaminated water. This would result in the reclaimed water undergoing advanced treatment twice, which would be expensive. This option would only be considered if pollution levels in the Gaborone dam force the upgrading of the Gaborone water works.

OPTION 3 - DIRECT RE-USE OPTION ADOPTED BY WUC

The current design for the proposed reclamation plant being adopted by the WUC involves the reuse of Gaborone treated wastewater effluent once it has passed through the maturation ponds. The plant is to have a capacity equal to 20% of the demand of the water demand of the Gaborone water works or approximately 20 000 m³/day and will be blended with surface water sources at the Gaborone water works (Gibb and Pula³¹).

The design process uses a multiple barrier approach with the following *treatment barriers*, being deemed sufficient:

1. One barrier is adequate for adjusting stability of water (reducing scale formation, or corrosiveness of water).
2. Two barriers are necessary for aesthetic parameters such as taste, odour, turbidity, and colour (parameter which do not have hazardous effects but are necessary for ensuring public confidence in the system)
3. Three barriers are required for the removal or inactivation of microbiological contaminants (such as *Cryptosporidium*, and *Giardia*).

In addition to *treatment barriers*, *non-treatment barriers* and *operational barriers* have also been included:

- *Non-treatment barriers* include activities designed to assist the treatment process an example would be: in Namibia the separation of industrial and domestic waste streams, or in California the source point source control of specific wastes, or in the case of Gaborone the issuing of trade effluent agreements.
- *Operational treatment barriers* providing necessary 'backup' in cases where additional treatment is required. A Namibian example could be the addition of Powdered Activated Carbon when influent waters have high organic carbon loads or odour problems. This treatment is not continuous but is based on the operational conditions.

The Gibb and Pula³¹ report reviews the use of different unit processes as well as comparing the Singapore, NEWater and Namibian, New Goreangab processes. Due to the influent from Gaborone being comprised of both domestic and industrial wastes the Namibian process alone was eliminated as suitable option. It was also established that in order to ensure complete removal of harmful constituents membrane processes in particular reverse osmosis should be used, along with the

necessary pre-treatment requirements for this process. Based on this a final process was designed as detailed below, Figure 22.

This design effectively covers the multiple barrier approach with there being more barriers than required for the various contaminants.

Parameter	Treatment
Stability of water	- Chemical dosing if need be - Blending with surface water sources
Taste, odour, and colour	Removal of organic materials - Nanofiltration (NF) - Reverse Osmosis (RO)
Dissolved Organic Carbon (DOC) Micro-pollutants	Three partial barriers - NF - RO - Cartridge filtration (CF)
Microbiological contaminants	<i>Cryptosporidium</i> two complete barriers, and one partial barrier - Ultrafiltration (UF) and CF – complete barriers - RO – partial barriers <i>Giardia</i> four complete barriers and two partial barriers - UF, NF, UV, and CF – complete barriers - RO and Chlorination – partial barriers Bacteria and viruses five complete barriers one partial barrier - UF, NF, UV, CF, and chlorination – complete barriers - RO – partial barrier

Table 13 Multiple barrier approach to treatment process selection – modified from Gibb and Pula³¹

Locations and Layouts

In terms of the location of the plant two options have been looked at, one with the plant positioned at the existing Gaborone water works and the other with the plant at the Glen Valley wastewater treatment works.

A decision has been made that it would be more cost effective to place the reclamation plant adjacent to the Glen Valley treatment works.

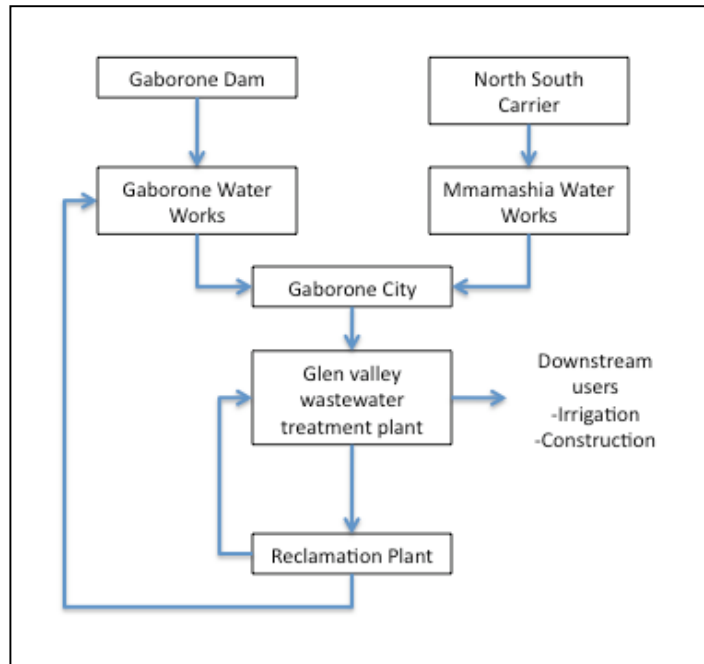


Figure 21 Simplified layout of Option 3

The second of the two options was preferred as this requires less distance of pipeline with only a supply pipeline of treated reclaimed water being needed as the waste stream would simply flow back to the Glen valley wastewater treatment plant. This option would also enable expansion of the reclamation plant to include distribution to Mmamashia water works as opposed to the development of a new reclamation plant at Mmamashia.

Overview of the process train

The process train is comprised of nine processes with some these undertaking the role of both treatment barrier and pre-treatment for a process to follow. Feed water for the plant is to be sourced from the maturation ponds effluent. This would provide disinfection of the secondary treated wastewater and would serve as an equalization tank, providing continuous flows to the reclamation plant.

1. Screening – this is the first step in the process with influent from the maturation ponds being screened to ensure no large particles are passed to the microfiltration units. Screening will consist of a 150 - 200 µm strainer or drum screen.
2. Membrane filtration – the type of membranes to be used will be based on pilot test results before being decided although the two different options include microfiltration (MF) or ultrafiltration (UF). Both of these are low-pressure membrane processes with ultrafiltration being able to produce slightly higher quality product water than microfiltration. It would be expected that both of these processes are able to achieve above 90% removal of *Giardia* and *Cryptosporidium*. The pore sizes of the selected membrane process will determine if it is necessary to include the step 3 of UV radiation. Microfiltration with larger pore sizes will require this step whilst UF will sufficiently remove bacteria and viruses such that these will not result in biological growths in the steps to follow.
3. Nanofiltration (NF) – is a pressure-driven process, requiring higher pressures than the MF and UF but less pressure than RO. This process is able to remove organic contaminants, bacteria, viruses as well as colour derived from organic sources. The use of NF for the removal of divalent compounds such as salts and organic material is not certain and would require pilot testing in order to determine if this is the case. The inclusion of NF is to be decided based on the pilot testing as this is expected to add a considerable amount to both the capital and operational costs.
4. Reverse osmosis (RO) – requires high pressures to remove dissolved solids, bacteria, and other organic contaminants. In this case the use of RO is principally to remove dissolved solids, whilst providing a barrier against pathogens and other organic materials that may have passed through earlier processes. By removing the salt from the feed water this results in a brine waste stream

containing a high total dissolved solids concentration. Typically 25% of the total feed water will be brine retentate (Gibb and Pula³¹).

5. Cartridge filtration (CF) – is to be used as a barrier against protozoa, including *Giardia* and *Cryptosporidium*. The CF would use 0.45-micron cartridge filters and could be placed either before or after the RO process, as they are not pressure intensive. Replacement of the cartridges is expected to be between 6 – 8 months. These filters have been preferred over the 1-micron filters as these can be subjected to integrity testing.
6. Ultraviolet radiation (UV) – UV radiation is to be used as a second barrier against viruses and bacteria by disinfecting anything that happens to pass through the RO stage. UV has been found to be an “effective bactericide and virucide of wastewater whilst not contributing to the formation of toxic by-products” (Metcalf and Eddy¹). UV is also effective in destroying *Cryptosporidium* oocysts, which are resistant to chlorine (Gibb and Pula³¹).
7. Chlorination – breakpoint gas chlorination will not only provide further disinfection but will also provide the residual disinfection in the distribution network.
8. Stabilisation – the RO product water is often found to be corrosive and once chlorinated will require stabilisation before being distributed. The blending of waters from surface water source will assist in this stabilisation.
9. Blending – product water from the reclamation plant will then be delivered to the Gaborone water works where it will be blended in a 80:20 ratio with surface water, 20% reclaimed water and 80% treated surface water. This will then be distributed for consumption.

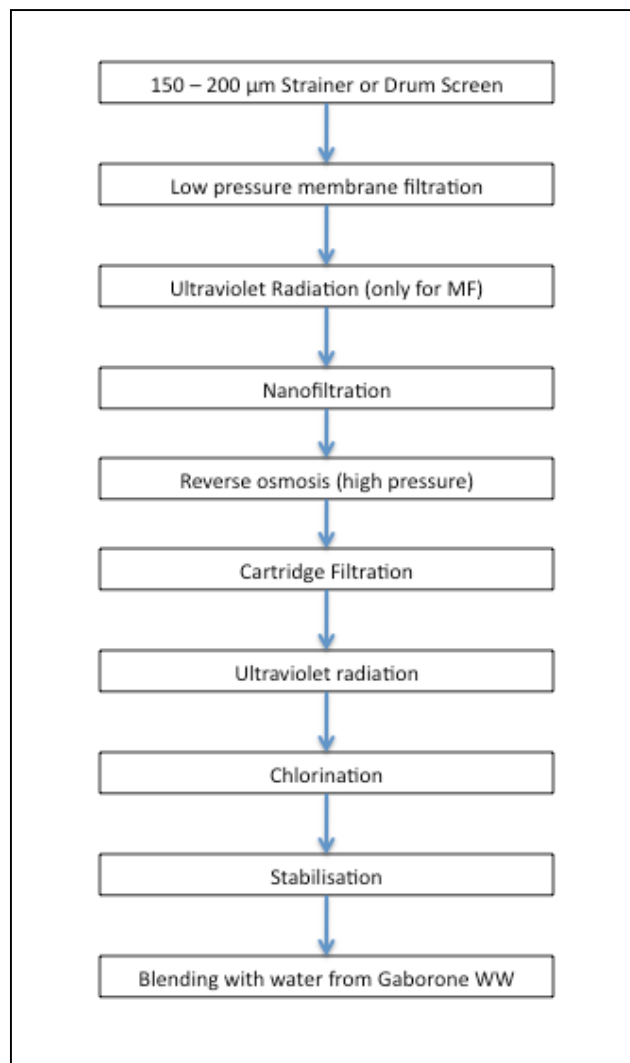


Figure 22. Process flow diagram – Gibb and Pula³¹

Waste handling

The majority of the different processes produce some form of waste stream or concentrate/retentate. This is often a problem for many reclamation plants to deal with, as this can be difficult to dispose of without eventually impacting on the quality of the feed water, as it is recycled. Many plants that have access to an ocean outfall make use of these especially when disposing of RO concentrate.

The waste stream from this option has been estimated to be in the region of 30% of the total influent water approximately 7350 m³/day of waste water (Gibb and Pula³¹). After considering the use of evaporation ponds it was established that if the waste stream underwent an secondary RO process this would reduce the concentrate to approximately 2600 m³/day and that evaporation ponds to treat this would need to have a surface area of 470 000 m² which is larger than the existing maturation ponds.

Based on this the design opts for disposing of the brine to the wastewater treatment plant without the use of a secondary RO process. As the wastewater treatment plant does not remove total dissolved solids (TDS) it would be expected that this concentration would accumulate to a point. Based on a large area of the town not being supplied with reclaimed water but discharging to the sewer system and the release of wastewater to downstream this should stabilise. This stabilisation point was calculated to be approximately 90 mg/l in the potable water supply and 820mg/l in the effluent from the wastewater treatment works. This is based on the treated wastewater from the ponds having 400 mg/l TDS concentration, 10% of the influent to the wastewater treatment works is discharged as waste and the RO process removed 95% of the salts. This calculation is based on the maximum upper limit (worst case scenario) of the expected concentration based on this disposal method. These concentrations are also expected to increase if there is an increase in the percentage of water reclaimed and is the motivation for the capacity of the plant (20% of demand on Gaborone waterworks) (Gibb and Pula³¹).

A diagram of the water system and the different TDS concentrations has been provided in Figure 23.

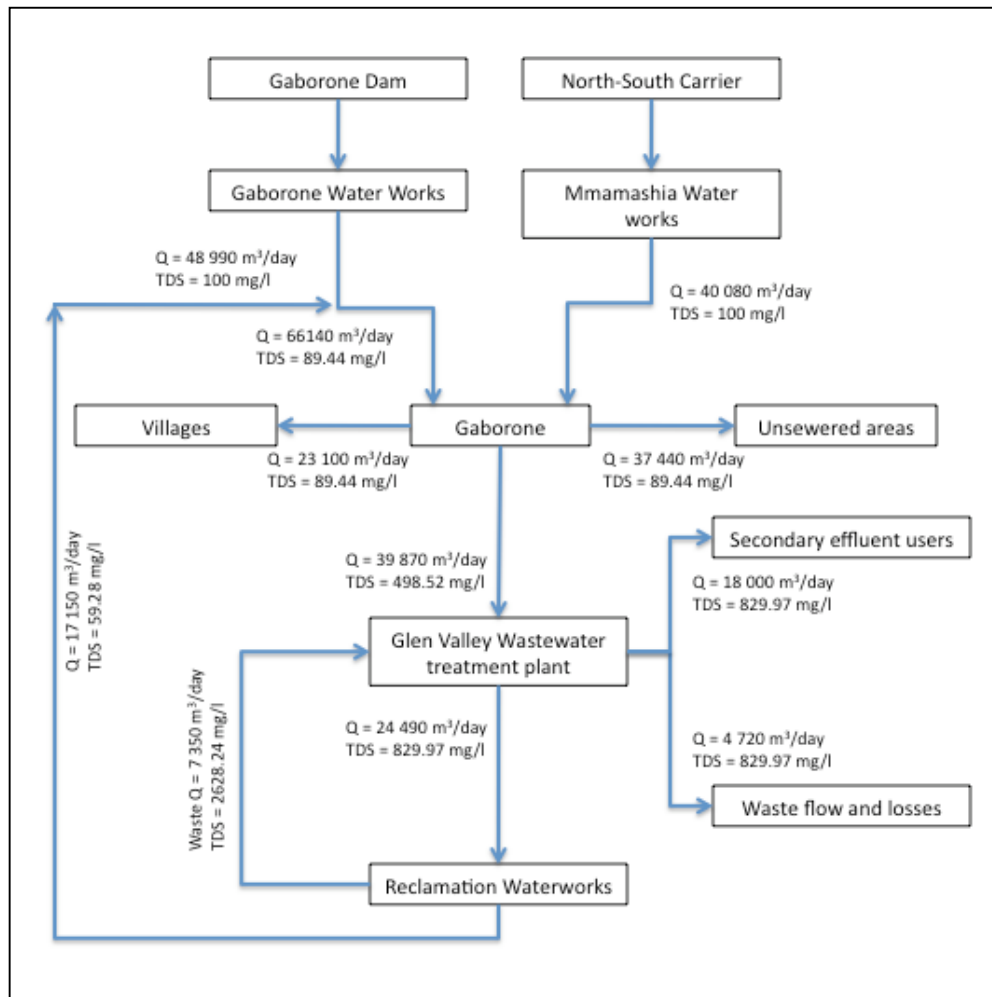


Figure 23 Schematic diagram of flow volumes and TDS balances – (Gibb and Pula³¹).

OPTION 4 – DIRECT REUSE - MODIFIED OPTION 3

This option essentially makes use of the existing Option 3 and suggests improvements by integrating the treatment of water and wastewater in the design.

This design is based on the existing wastewater treatment plant (currently being upgraded with phase 1) requiring the future expansion, Phase 2 in 2012 based on predicted influent volumes by Liebenberg & Stander and Rites³³ in Table 7, Chapter 2.

The design follows a similar process of Option 3 except that the future expansion to the wastewater treatment plant should be kept isolated from

the existing (including phase 1) plant. By providing this division the existing plant can be used for treating the waste stream generated by the reclamation plant without 'recycling' the total dissolved solids, see Figure 24.

The phase 2 expansions to the wastewater treatment works has been designed conceptually but due to budget constraints no detailed design or tender documentation was produced for this phase (Liebenberg & Stander and Rites³³).

The Liebenberg & Stander and Rites³³ report also suggests the option of a Membrane Bioreactor (MBR) for the expansion of the treatment works. This option was not selected for the phase 1 of the upgrading, with the chosen option being conventional biological reactors.

Option 4 includes a conceptual design for the expansion of the wastewater treatment plant using MBR's as the main treatment process. This technology is able to treat effluent to a quality equal to that of a "combination of secondary clarification and effluent microfiltration" Metcalf and Eddy 2003⁴. By making use of this technology it would not be necessary to make use of the maturation ponds for further disinfection enabling a "pipe-to-pipe" design.

The rest of the process train used in the reclamation follows that of Option 3 enabling these two options to be comparable.

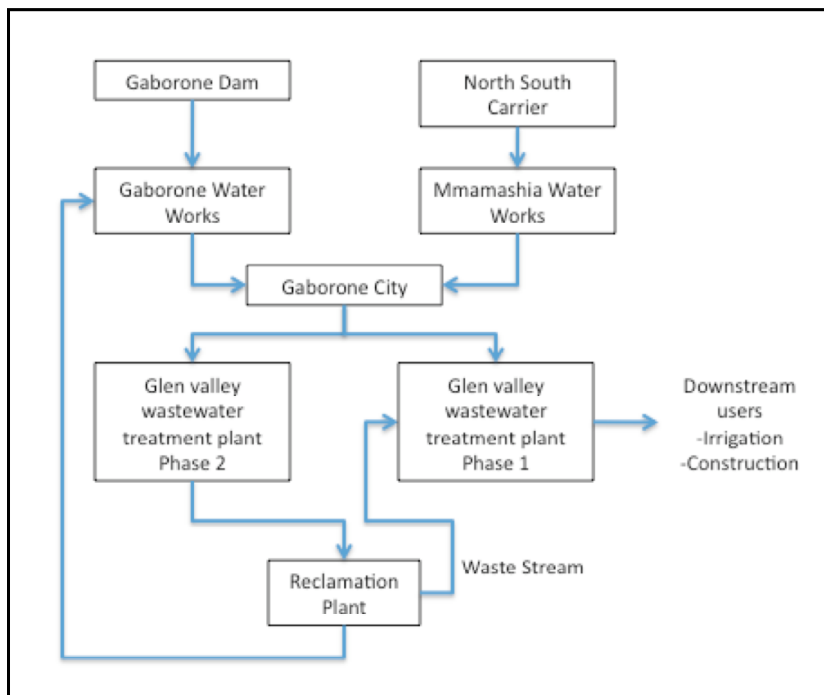


Figure 24 Overview of option 4 direct potable reuse

SELECTED OPTION

Based on this brief assessment of the four options for reuse, option 4 has been chosen for the assessment and design, as this option is realistically comparable to option 3.

CHAPTER 5 – OPTION 4 DESIGN

This chapter includes an assessment and design of option 4 comparing this to option 3 for which a preliminary design and feasibility study have already been undertaken.

🔧 Option 3 – has been proposed by the Water Utilities Corporation (WUC) and is the result of a consultancy by Gibb and Pula³¹.

🔧 Option 4 – is an alternative to option 3 being explored by this project.

This chapter details option 4 and compares this to option 3. In order to compare the options particularly the cost implications of each, the unit processes selected in option 4 have been kept the same to those of option 3, where possible.

BACKGROUND TO THE DESIGN

Option 4 integrates the planned expansion for the existing Glen Valley wastewater treatment plant as well as the existing effluent reuse agreements.

Both the Bergstan & Liebenberg³² and the Gibb & Pula³¹ reports acknowledge the current capacity of 65 000 m³/day will be reached and that phase 2 of the Glen Valley treatment plant expansion should occur by 2012.

The Gibb & Pula³¹ report also outlines that if the existing effluent reuse agreements with downstream users are to be fully utilised then only in 2014 would there be sufficient water to begin reclamation (at a rate of 20% of Gaborone water treatment works).

Option 4 is designed to commence once the inflow to the Gaborone wastewater treatment works exceeds the current expanded capacity of 65 000 m³/day. This limit has been set so as to provide for the use of new technologies in the expansion of the Glen Valley treatment works as well as to fulfil the existing water reuse agreements.

Currently agreements exist with various downstream users for the abstraction of a total of 37 000 m³/day (Gibb & Pula³¹). These agreements are however are not being fully utilised and two of the agreements are renewable annually (totalling 10 000m³/day) with one of these two businesses being closed down (Fabulous Flowers, 2000m³/day).

Based on these findings, the target supply for downstream use, for option 4, has been set at 27 000 m³/day, provided the Gaborone City Council (GCC) and Water Allocation Board (WAB) do not issue any further agreements. The Gibb and Pula³¹ report highlights that although these agreements are in place the actual current downstream abstraction is only 1811.2 m³/day.

By ensuring 27 000m³/day is released for downstream use there should be no conflict between these users and the reclamation plant.

Regarding the expansion of the Glen Valley wastewater treatment, this is currently being expanded by 25 000 m³/day in the first of two expansion phases.

Phase 1 expansion is two fold with the inlet works (screening, grit removal and lifting station) and sludge handling facilities being expanded to have a capacity of 140 000 m³/day whilst the remainder of the plant (settling tanks and biological reactors) being expanded by only 25 000 m³/day to total of 65 000 m³/day (Bergstan and Rites Afrika³²). Based on the Liebenberg & Stander and Rites Afrika³³ evaluation report this expanded capacity would be met in 2021 for the inlet works and sludge handling expansions whilst the remainder of the plant will require further expansion in 2012.

The Bergstan and Rites Afrika³³ report also goes on to offer alternative technologies for the upgrading and expansion of the plant using Membrane Biological Reactor (MBR) technology. This option was not selected for by the client for phase 1 of the expansion but could be selected and implemented in phase 2.

OVERVIEW

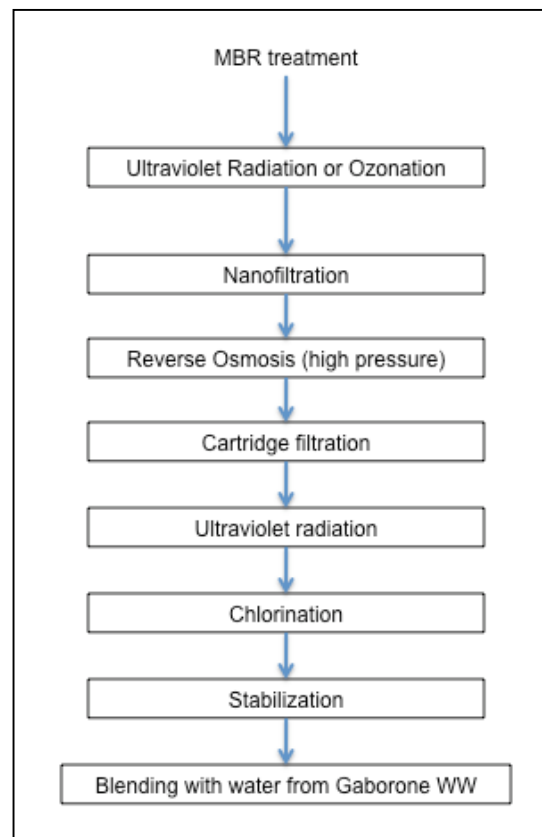
The unit processes selected for option 4 are similar to those of option 3, with the largest difference being the source of the water for reclamation. Option 3 uses the outflow of the existing maturation ponds as the feed water for the reclamation plant. The maturation ponds serve both as a means of disinfection as well as a balancing/equalization tank for the supply, providing continuous feed water for the reclamation plant.

Option 4 does not use the existing (including current expansions) Glen Valley wastewater treatment plant. The option looks to the next phase of the expansion of this plant and the installation of a Membrane Biological Reactor (MBR) for this future expansion.

The feed water for the reclamation plant will come directly from the MBR section of the Glen Valley plant not making use of the maturation ponds. MBR processes will incorporate submerged ultrafiltration membranes, ensuring a high quality feed water is delivered to the reclamation plant.

By utilising MBR treatment the effluent quality is expected to be comparable if not better than 'conventional' ultrafiltration. Supply from the MBR process is set at a constant rate removing the need for a balancing tank after the MBR process but there

would possibly be a need to install a balancing tank prior to the MBR process to ensure a constant feed rate. Although the exact configuration of this process would be determined during a pilot testing period, this



process should include nitrogen and phosphorus removal prior to the MBR process.

As option 4 aims to provide a higher quality feed water to the reclamation plant, effectively the screening or microfiltration process of option 3 will not be necessary. In the reclamation plant the following processes will be used:

- 🔧 Initial disinfection: This could consist of either UV or ozonation. Experiences in Namibia with ozonation have been problematic and in order to compare the two options UV has been selected as the preferred means of disinfection.
- 🔧 Cartridge filtration: Will provide an additional barrier as well as ensuring the complete removal of synthetic organic compounds such as pesticides or herbicides. This unit process should be reviewed during the pilot testing stage in order to monitor its effectiveness in the process train. This process was placed downstream of reverse osmosis in option 3 but it is felt that due to the cartridges being disposable it would be better suited upstream to the pressurised membrane processes. This should be assessed with regards to the issue of cartridge replacement and fouling.
- 🔧 Nanofiltration: This process is essentially the same as that of option 3. Nanofiltration would be an additional barrier and pre-treatment stage prior to the reverse osmosis process ensuring there is no risk of fouling and reducing the possibility of micro contaminants moving to the next stage.
- 🔧 Reverse osmosis: This process is expected to account for the largest consumption of energy whilst at the same time being the single most effective barrier against many contaminants as well as reducing the salt or total dissolved solid concentrations of the product water. The waste stream from this process should be where possible treated separately due to the high total dissolved solids concentrations.

- 🔧 Ultraviolet radiation: This will provide the primary disinfection of the reclaimed waters and will also provide a barrier to some of the more obscure contaminants such as *N*-Nitrosodimethylamine (NDMA). Disinfection using UV will also help prevent disinfection by-products developing, by reducing the amount of chlorine required for disinfection.
- 🔧 Chlorination: Chlorination will be used to provide residual disinfection of the product waters whilst being distributed. This process is the same as that of option 3.
- 🔧 Stabilization: The final product water is likely to be extremely acidic due to the UV disinfection and RO process and will possibly require stabilization. It is foreseen that blending with conventionally treated waters would be the most cost effective means of stabilizing these waters. Should the product water be corrosive, and there would be a need to adjust pH and/or add lime, CaCO_3 . This can only be accurately determined once a pilot study has been undertaken.
- 🔧 Blending: Aside from the role of stabilizing the product waters, blending will also both reduce the chances of contamination and ensure aesthetic qualities such as odour and taste are maintained.

DETAILED CONCEPTUAL DESIGN

This design involves two core components:

1. The treatment of raw sewage to the level of secondary treatment or greater, at the Glen Valley wastewater treatment plant.
2. The treatment of the secondary effluent to drinking water quality at the reclamation plant.

The first component deals with the expansion of the Glen Valley wastewater treatment works, which will occur in approximately 2012, once the capacity of 65 000 m³/day is reached.

The second component focuses on the treatment in the reclamation plant of the final effluent from the Glen Valley wastewater treatment works. For the purposes of comparing costs and designs the unit processes employed by option 3 have been left unchanged although it is felt some of these should be considered during the pilot testing stage of the project.

Wastewater Treatment

By the end of 2009 the Glen Valley wastewater treatment plant will have an inlet works (screening and grit removal) and sludge handling capacity of 140 000 m³/day, whilst the settling tanks, and biological reactors will only have 65 000 m³/day capacity. The expansion of the settling tanks and biological treatment works being expanded by 2012 in Phase 2 of the expansion program.

Option 4 makes use of Membrane Biological Reactors (MBR) for the expansion of the treatment works using the existing inlet works and sludge handling facilities without the need to develop either primary or secondary settling tanks.

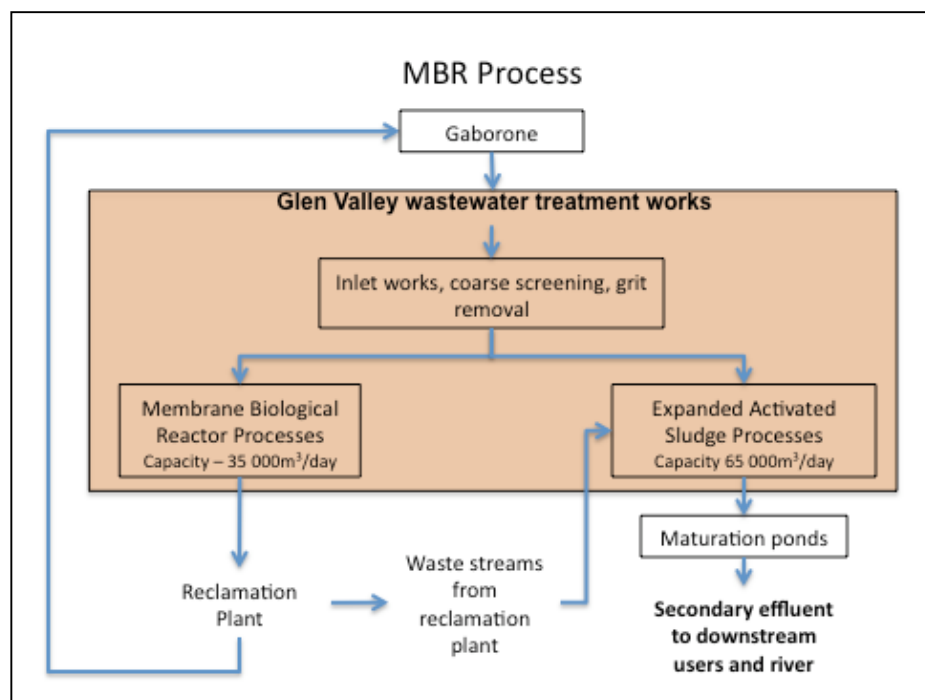


Figure 25 Membrane Bioreactor schematic layout.

Membrane Bioreactor (MBR)

The Membrane Bioreactor is simply put a system “integrating biological degradation of wastewater with membrane filtration” (Naghizadeh, *et al*⁵⁵). MBR technology was chosen against the conventional activated sludge treatment process because MBR’s have the advantages of “a smaller foot print, reduced sludge production, and consistently high quality of effluent in the treatment of domestic sewage over activated sludge process” (Qin *et al*⁵⁶ and Metcalf and Eddy & AECOM²⁴). MBR effluent is able to produce effluent which is comparable in quality to that of secondary treated wastewater which has undergone microfiltration (Metcalf and Eddy & AECOM²⁴ and Metcalf and Eddy⁴).

MBR processes have been used in many parts of the world including Australia, the United States, Japan, Canada, Egypt and Singapore. A recent survey showed that there are over 1000 facilities in the world using MBR processes (Metcalf and Eddy & AECOM²⁴). Many of these countries using MBR technology both for the treatment and reuse of wastewater. The configuration of the MBR plants can vary with many plants incorporating biological nutrient removal prior to the membrane stage whilst the actual type of membrane can also vary with ultrafiltration and microfiltration membranes being more common (Metcalf and Eddy & AECOM²⁴). The actual design and configuration of these plants vary between manufacturers; some being pressure driven and other operate on a vacuum. For the most part pressure driven membrane units are located externally from the bioreactor (External MBR) and are more commonly a tubular configuration (Metcalf and Eddy & AECOM²⁴). Vacuum driven MBR units are usually submerged in the bioreactor utilising coarse bubble diffusers to reduce fouling (Metcalf and Eddy & AECOM²⁴).

It has been stated “membrane biological reactor technology promises to be one of the most important treatment devices for wastewater treatment and water reclamation and reuse” (Metcalf and Eddy & AECOM²⁴).

Singapore’s Public Utilities Board (PUB) has recently conducted a successful pilot study using MBR technology and is now implementing this

technology at the various reclamation plants on the island with a possible reduction on the number of steps utilised in the production of NEWater (Judd²).

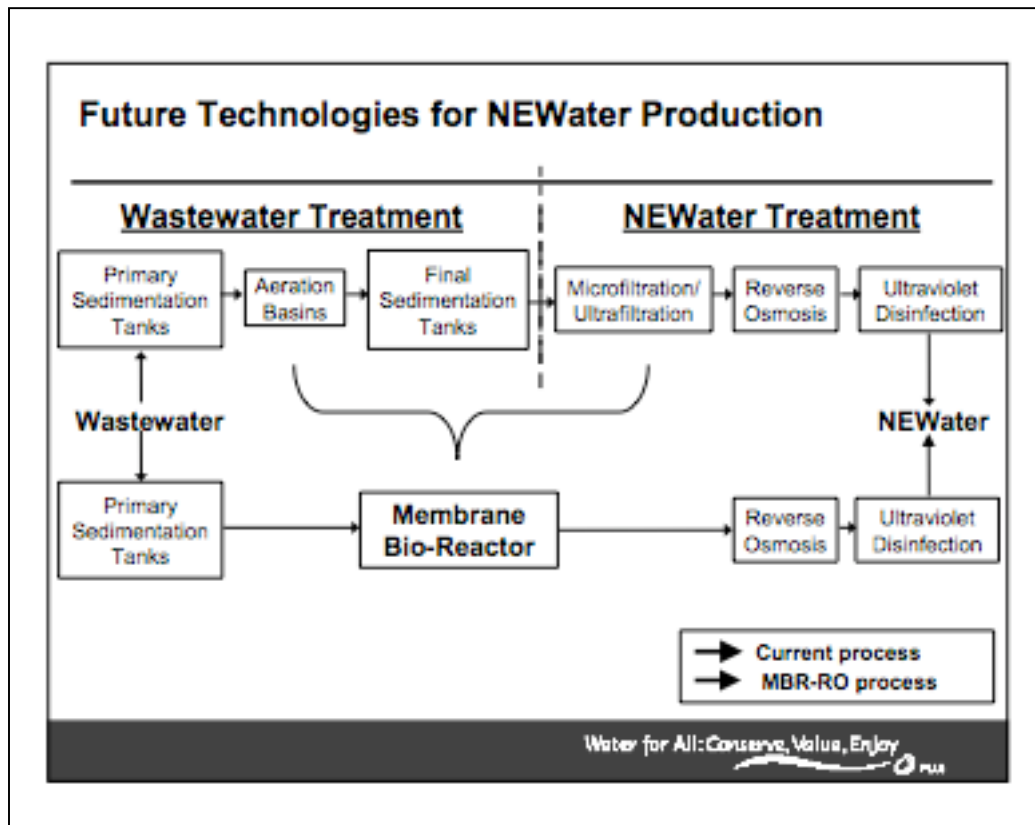


Figure 26. Proposed new process train for the production of NEWater - Lee Mun Fung⁴⁶.

The process involved uses primary settled wastewater treated through submerged MBR processes using three different membranes manufacturers for comparison. The product water from the MBR processes is then treated using reverse osmosis prior to reuse. The findings of showed the product waters produced by the MBR + RO process to be slightly better than that of the conventional MF/UF + RO treatment process (Judd²).

Membrane bioreactors have been shown to produce higher quality product water than that produced by conventional activated sludge treatment processes and “appears to be adequate feedwater to the reverse osmosis process” (Adham, *et al*⁵⁷).

As Gaborone city has no separation of industrial and domestic sewage, there is a need to ensure a multiple barrier approach to treatment is maintained. The process described in Figure 26 above does not include sufficient multiple barriers for treating combined wastewaters for drinking purposes. The MBR will however enable a reduction in the number of unit processes required for the reclamation of wastewater.

By utilising the MBR technology there are many distinct advantages as well as a few disadvantages associated with it.

Pros

- Smaller overall footprint of the plant
- Less sludge production.
- Effluent from the MBR process is of high enough quality to be used in the nanofiltration
- The MBR process will treat raw sewage (not taking effluent from the maturation ponds) thereby reducing the loading of the maturation ponds.
- Reduction in the number of unit processes at the reclamation plant as screening and micro/ultrafiltration would not be necessary.

Cons

- Any leakage from the MBR process would mean possible fouling of the following processes. In order to prevent this cartridge filtration and nanofiltration are to be used as pre-treatment for the reverse osmosis. This should be looked into in the pilot testing stage.
- Higher total life costs due to operational costs from aeration and pumping pressures on membranes
- High costs of membranes, which need to be, replaced approximately every five to ten years.

Traditionally MBR processes have been considered more expensive than activated sludge processes although more recently this has been refuted.

The costs associated with the MBR technology has also been shown to be competitive against that of activated sludge processes with the final

effluent being of a higher quality (Adham, *et al*⁵⁷). Some controversy does exist in this regard with a study of an MBR wastewater treatment plant in the Netherlands has concluded that the energy consumption in the MBR plant is only 15% higher than that of a conventional activated sludge with sand filtration plant (Van Bentem⁵⁸). As the MBR process produces a higher quality effluent any increase in costs would be factored out through the reduction in the number of downstream unit processes.

The exact design and configuration of the MBR system would be developed during the pilot testing stage although the basic components of this have been outlined below. One of the key factors to be addressed during the piloting period is that of energy consumption.

Pre-treatment

The main pre-treatment processes required are grit removal, screening and balancing/equalization. The grit removal will be undertaken by the existing inlet works whilst screening and balancing/equalization need to be designed and constructed.

Screening of the influent waters needs to be undertaken using a fine screen with a diameter of approximately 3mm. Different options exist for undertaking this and these should be decided on during the pilot testing stage.

Balancing/equalization can be achieved either internally or externally. Internal equalization is suited towards dampening minor fluctuations and is often used in situations where space is an issue and the overall footprint needs to be reduced. External equalization requires the construction of a separate basin ahead of the MBR basin.

One other pre-treatment requirement, which could be used based on influent quality, is an oils and fats removal system. Oils and fats have been known to build up in the MBR processes resulting in a lowering of the membrane efficiency. This should be considered during the pilot testing stage although at this is not seen as a problem.

MBR

The MBR will be configured to include three main sections, an anoxic zone, an aerobic zone and a membrane (UF) bubble aerated zone. The anoxic and aerobic zones providing denitrification and nitrification, whilst the bubble aeration in the membrane tank is designed to prevent fouling.

The process involves feed water initially passing through the anoxic zone, which would require stirring to prevent any settling occurring.

The next stage involves aeration resulting in nitrification. This can be stage can either be undertaken inside the membrane separation unit or can be performed in a separate unit prior to the membrane separation unit. Different manufacturers have different configurations and this would best be decided during the pilot testing. The removal of phosphates should also be considered in this design although this should be based on pilot testing.

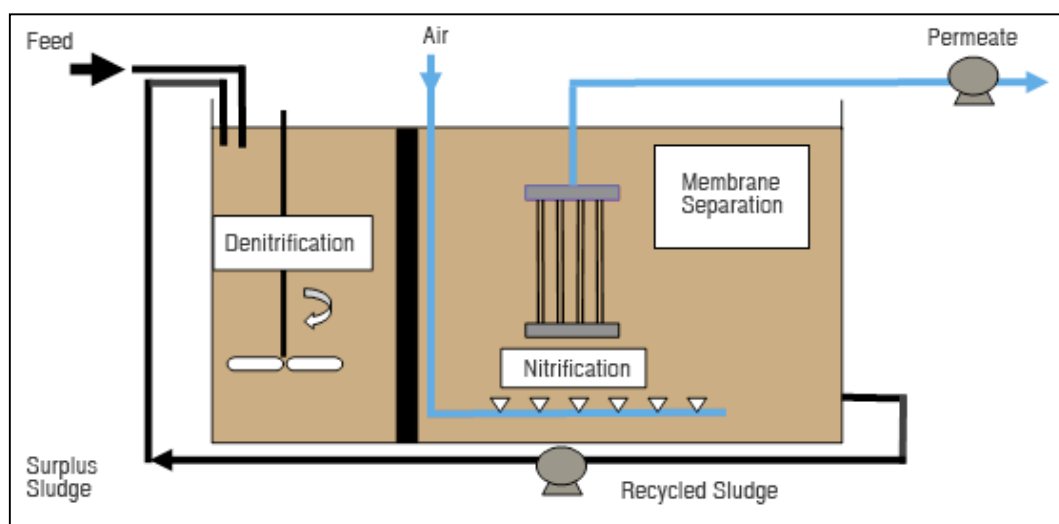


Figure 27 Basic outline of typical MBR process (United Envirotech⁵⁹)

Fouling and energy consumption are possibly the most important factors to be considered in the selection criteria, with other factors to be considered being, ease of cleaning or removal of membrane cassettes, aeration system, and sludge recycling system.

The final quality of effluent from the MBR process should be similar to that of ultrafiltration of secondary treated wastewater.

Although the MBR effluent quality is expected to be sufficient for reverse osmosis, cartridge filtration and nanofiltration have been included as additional barriers. This will serve to both reduce the risk of fouling of the reverse osmosis membranes should a leak occur as well as provide a barrier against bacteria, viruses and some salts.

An additional process of disinfection has been recommended for the effluent of the MBR process in order to reduce the risk of biological fouling in the reclamation plant.

Disinfection

In order to reduce the chances of biological fouling of the membrane units in the reclamation plant, disinfection should take place prior to delivery.

Disinfection can be achieved using a variety of different techniques with some of the more common processes for water treatment and water reuse including chlorination, ultraviolet (UV) radiation and ozonation. A table below describes the pros and cons of each of these different applications.

Process	Description	Cons	Pros
Chlorination	Chlorine gas is currently being used to disinfect treated surface waters at the Gaborone water works prior to distribution	▪ Poisonous gas, operational risks ▪ Formation of disinfectant by-products in waters with high organic contents ▪ Some membranes have adverse reaction to chlorine	▪ Cheap and effective disinfectant ▪ WUC has previous experience with the operations and handling of this process.
UV Radiation	Commonly used in high quality waters with low turbidity. Used to for disinfection of final product waters in both Orange County and Singapore	▪ Can only be used to treat one influent stream. ▪ No residual disinfection is formed.	▪ Does not impact negatively on membranes ▪ No disinfectant by-product formation

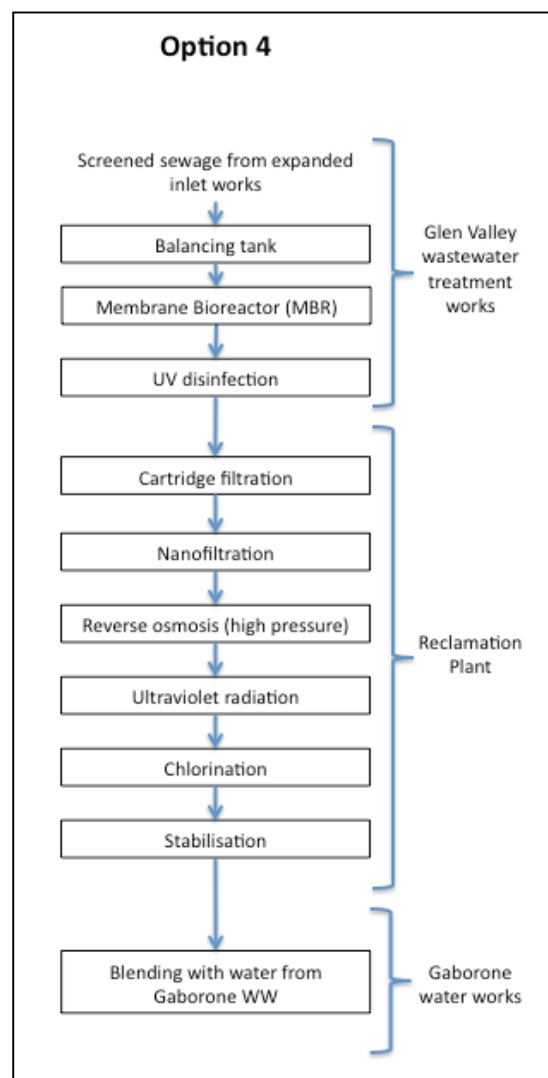
Ozonation	Ozonation involves the generation of ozone from oxygen. Ozone is bubbled through the water through diffusers. Used in Namibia.	- Namibia has had problems with the plant, resulting in a reduction in operational capacity. - No residual disinfection is formed.	- No disinfectant by-product formation - One plant can be used to produce ozone for various applications or influent streams.
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The Gibb and Pula design does not specify whether microfiltration or ultrafiltration will be the selected process but does highlight that should microfiltration take place then UV disinfection downstream of microfiltration should occur in order to prevent biological fouling of the membrane processes that follow. Ultrafiltration would not require the additional disinfection step as this process effectively removes biological contaminants.

UV disinfection has been chosen opposed to ozone disinfection due to previous bad experiences with ozone disinfection, by the New Goreangab Reclamation Plant in Windhoek, Namibia.

Conventional UV is a highly effective disinfectant, and does not

produce disinfectant by-products (Singer⁶⁰). The largest disadvantage of using this process is that it is limited to one treatment stream and cannot be utilised for alternative applications.



Based on the current 'best' practices of Orange County, California and Singapore and the unfavourable experiences of the Windhoek, Namibians it is suggested that UV disinfection be used.

Water Reclamation/Advanced water treatment

The reclamation plant feed water is expected to be of a high quality, ultrafiltration. Due to the feed water being of such high quality, fewer unit processes are required in the reclamation plant.

The process train used in the option 4 design has been kept similar to that of option three in order to enable these two options to be comparable. Some minor changes have been recommended although for the most part the designs are similar.

Cartridge filtration

Cartridge filtration will be the first process downstream of the disinfection and will provide both a pre-treatment for the RO and a barrier for organic micro pollutants, and pathogens including *Cryptosporidium*, *Giardia*.

This unit process would use the same technologies as option 3 and will consist of a 0.45-micron cartridge filter encased in a stainless steel housing. Cartridges would need to be replaced every 4-6 months. The life expectancy of the cartridges will need to be assessed based on the pilot testing. The main reason for the selection of this type of filter, opposed to cheaper 1-micron filters, is that this system can be integrity tested.

Many different types of cartridges exist and selection of these cartridges should focus on the removal of dissolved organic carbon (DOC) or total organic carbon (TOC).

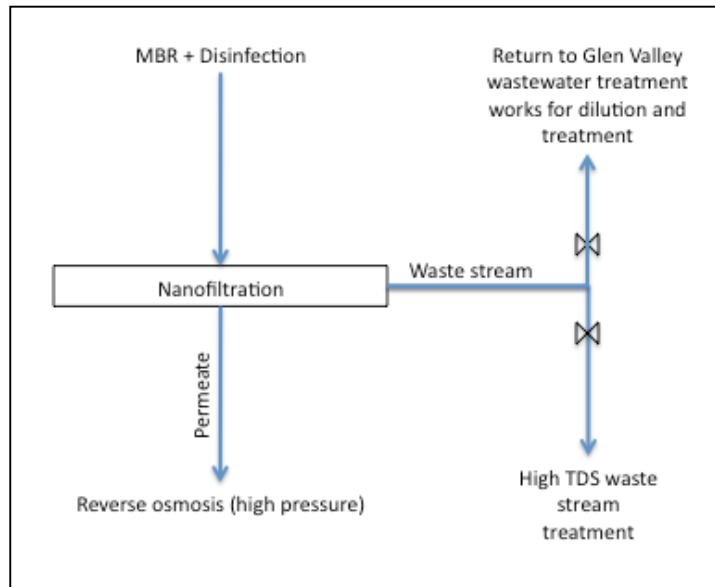
This process generates no waste stream as contaminants are attached to the filters and disposed of with the filters. Low pressure is also required for this process reducing the operational costs involved.

An alternative or additional process to this cartridge filtration is the inclusion of a granular activated carbon step. This would reduce odour and taste issues as well as removing refractory organics such as aromatic solvents, pesticides, high molecular weight hydrocarbon (petrols and

dyes), and chlorinated no aromatics (carbon tetrachloride) thus reducing the DOC concentrations.

Nanofiltration

This process is the same as option 3 with the only difference being that the feed water has been treated by both the MBR and cartridge filtration thus there is no need for drum screening, or low-pressure membrane filtration.



Nanofiltration and reverse osmosis both require very high quality feed waters. Metcalf and Eddy⁴ suggest the some of the following pre-treatment options for the secondary effluent:

- Chemical clarification and multimedia filtration or multimedia filtration and ultrafiltration
- Cartridge filtration with pore sizes between 5 -10 µm
- Disinfection of feed water using chlorine, ozone or UV
- Exclusion of oxygen to prevent oxidation, of iron, manganese, and hydrogen sulphide. Iron and manganese may need to be removed completely to reduce scaling.
- Removal of chlorine and ozone may also be required based on membrane characteristics.
- pH adjustment to between 4 – 7.5 to inhibit the formation of scale.

Option 4 makes use of some of these options including MBR ultrafiltration, disinfection using UV and possibly pH adjustment (this will be determined during the pilot stage).

Nanofiltration would be a pressure driven process aimed at providing part of the barrier against bacteria, viruses, organic contaminants as well as divalent salts and organic compounds. The performance of nanofiltration membranes is however not easily predicted and manufacturers recommend pilot testing in order to ascertain the efficiency of the process (Gibb and Pula³¹).

Recovery rates vary considerably with some manufacturers claiming recovery rates above 90%. Metcalf and Eddy⁴ report that recovery rates for nanofiltration vary from between 80 – 85%.

It is expected that the feed water to the nanofiltration process will be better than ultrafiltration quality and should have a recovery rate of approximately 85%.

Nanofiltration is also able to reduce TDS concentrations although by comparison to the reverse osmosis process this is not expected to be substantial. The rate of removal is highly variable and dependent on the influent quality. For the purposes of this study a TDS removal rate of 20% has been selected based on the influent waters having been through ultrafiltration and that the feed water TDS is approximately 498.52 mg/l (Gibb & Pula³¹). This percentage would need to be verified during the pilot testing period.

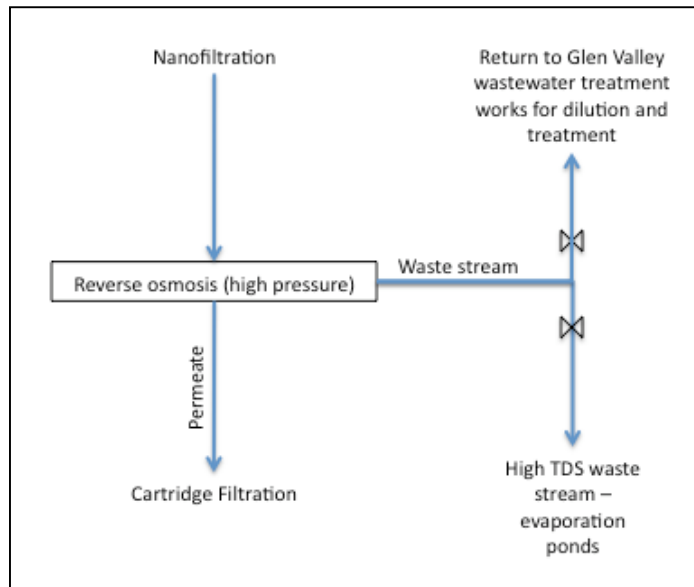
As this process is likely to remove some salts it is recommended that this waste stream be designed such that it can be separated, and treated separately if necessary.

The Gibb and Pula design (option 3) provides the optional exclusion of this unit process based on the findings of the pilot testing and the efficiency of this unit process. This is not an option for option 4, which would rely on this barrier, as a back up should there be a breakage in the MBR seals. In order to maintain the “multiple barrier” approach it would be necessary to ensure this unit process was utilised.

Reverse Osmosis

Reverse osmosis is essentially a pressure driven membrane process where the concentration of dissolved material is proportional to the pressure needed to drive the process. This process would provide a complete barrier against the majority of the contaminants including suspended matter and pathogens that may have past the previous membrane processes. Up to 99% of the dissolved solids would also be removed.

In order to reduce operational costs, energy efficient technologies should be utilised where possible



for this unit process. Some of these technologies include, larger diameter membrane elements (16-inch), integrated flow distributor, electro magnetic field device, pre-treatment including pH adjusting, and anti-scaling additives.

The exact details of the types of units to be used would be based on the pilot stage.

Recovery rates from this process vary considerably with typical values ranging from between 70 – 85% (Metcalf and Eddy⁴). Singapore and Orange County have a recovery rate of approximately 75% and with the removal of more than 95% of the total dissolved solids (TDS).

Some manufacturers do however offer far better recovery rates with possibly the best recovery rate being the GE Water and Process technologies “HERO” (High Efficiency Reverse Osmosis) system claiming a recovery rate of greater than 90%. These systems should be considered

during the pilot testing stage in order to increase the efficiency of the process and reduce the volume of waste generated.

As this design includes nanofiltration prior to the reverse osmosis process it is expected that the recovery rate would be greater than that of Singapore and Orange County. This design has assumed an approximate recovery rate of 80% with a 95% removal of TDS.

Energy inputs for the reverse osmosis process are expected to be high and influenced by many different variables including the TDS concentrations. Increased TDS concentrations in the influent water result in an increase in the osmotic pressure, thus requiring a greater pumping pressure. This increased pressure will cause an increase in operational costs due to increased energy consumption from pumping.

The result of the RO process is the formation of a brine waste effluent from, which needs to be disposed of. The WUC design has proposed directing this to the head of the Glen Valley wastewater treatment works where it would be diluted with influent from Gaborone.

Option 4 looks to reduce the TDS concentration of the influent to the RO process by diverting this waste stream to the head of the Glen Valley wastewater treatment works but not to the MBR section so as not to recycle this effluent. By not recycling this effluent there is less dilution of the TDS concentration resulting in an increase of TDS concentrations in the effluent from the maturation ponds. This value is however seen to be marginally above that of Option 3 and to be well below the World Health Organisation drinking water guidelines see Figure 29.

By separating this waste stream this would make it easier to treat separately if future complications regarding TDS accumulation from irrigation arise.

Disinfection

Disinfection would be the same as option 3 using UV disinfection. Option 3 makes use of the UV process being undertaken using low pressure, low intensity lamps submerged in a channel leading to the chlorination contact

tank. Option 4 makes use of UV disinfection although the actual design of the UV process should be reviewed during the pilot testing. Some of factors to be considered in the design of this process include:

- 🔧 space requirements – low intensity lamps and channel designs often have a larger footprint
- 🔧 Micro-pollutants - combined disinfection using hydrogen peroxide and UV has been found to decompose aromatic and chlorinated compounds as well as NDMA and 1,4-dioxane more effectively (Parsons⁶¹).

This process should be used as a barrier for both the more common pathogens as well as micro-pollutants.

Chlorination and Stabilisation

Chlorination will be undertaken using chlorine (most probably gas) in order to provide residual disinfection. As the influent water will have low organic carbon concentrations there is little chance for the formation of disinfectant by products. Chlorination will require the use of a contact tank, which will be used as the feed sump for reclaimed water.

This will feed the pump station pumping reclaimed water to the Gaborone water works where it will be blended. The blending of reclaimed water with conventionally treated surface water is expected to sufficiently stabilise the product water although this blending will only occur approximately 10 km away. For this reason stabilisation prior to blending would be possibly be required this may have to be determined during the pilot testing stage. Based on findings from Orange County, California stabilisation would involve pH adjustment and/or the addition of lime, CaCO_3 .

Blending

Blending of the reclaimed water with the conventionally treated surface water will not only provide stabilisation of the water but will also provide an additional barrier through dilution. Taste and odour should effectively be controlled through blending although the addition of a GAC process would also eliminate the possible impact these contaminants could have.

The maximum ratio of blended water would be 35% reclaimed water and 65% conventional water. The details regarding this selected ratio are based on the experience of the Namibians and is discussed under the section dealing with capacity.

Summary of Barriers

Option 4 has adopted the multiple barrier approach of option 3. The framework developed by Gibb and Pula³¹ has outlined the following treatment barriers, which need to be adhered to.

1. One barrier is adequate for adjusting stability of water (reducing scale formation, or corrosiveness of water).
2. Two barriers are necessary for aesthetic parameters such as taste, odour, turbidity, and colour (parameter which do not have hazardous effects but are necessary for ensuring public confidence in the system)
3. Three barriers are required for the removal or inactivation of microbiological contaminants (such as *Cryptosporidium*, and *Giardia*).

Option 4 meets all of these requirements and in some areas exceeds them. The table below outlines the requirements and the various treatment barriers employed:

Parameter	Treatment
Stability of water (1 barrier required)	- Chemical dosing if required. - Blending with surface water sources (if possible)
Taste, odour, and colour (2 barriers required)	Removal of organic materials - Nanofiltration (NF) - Reverse Osmosis (RO)
Dissolved Organic Carbon (DOC) Micro-pollutants (no specific requirement)	Three partial barriers - NF - RO - Cartridge filtration (CF)
Microbiological contaminants (3 barriers required)	<i>Cryptosporidium</i> two complete barriers, and one partial barrier - Membrane Bioreactor - Ultrafiltration (MBR-UF) and CF – complete barriers - RO – partial barriers <i>Giardia</i> four complete barriers and two partial barriers - MBR-UF, NF, UV, and CF – complete barriers - RO and Chlorination – partial barriers Bacteria and viruses five complete barriers one partial barrier - MBR-UF, NF, UV, CF, and chlorination – complete barriers - RO – partial barrier

Table 14. Outline of the different treatment barriers

In addition to these requirements one area of concern is that of micro-pollutants, specifically synthetic organic compounds often used in industries. In order to ensure these do not pose future health risks additional processes need to be incorporated into this design. These include:

- Cartridge filtration should make use of filters, which are able to reduce DOC or TOC levels, either through activated carbon adsorption or some alternative media. These filters should form a complete barrier to organic micro-pollutants.

- UV disinfection should incorporate hydrogen peroxide in order to ensure thorough disinfection.

Waste Streams and Downstream Impacts

The waste streams from the reclamation plant with the MBR treating raw sewage from the inlet works whilst all waste streams from the reclamation plant could be directed to the existing activated sludge section of the Glen Valley treatment plant. By separating the waste stream from the reclamation plant this would have various impacts on the entire system, and these include;

1. Reduction in the TDS concentration of the feed water to the reclamation plant. This would result in a lower operating cost due to less energy requirement being needed for reverse osmosis.
2. Higher quality final product water with a lower TDS concentration being produced by the reclamation plant.
3. Reduced risk of TDS accumulation in the system especially once future expansions include the Mmamashia distribution network, resulting in all of Gaborone being supplied a percentage of reclaimed water.

The waste stream generated by the reverse osmosis process is by far the key area of concern and this waste stream should be design such that in future it can be treated separately if necessary.

The MBR process is the only process, which would produce sludge. This process would be located in the Glen Valley treatment plant and would be connected to the existing sludge handling facilities, making use of both anaerobic and aerobic digestion and belt filter pressing with treated sludge being disposed of at the landfill site.

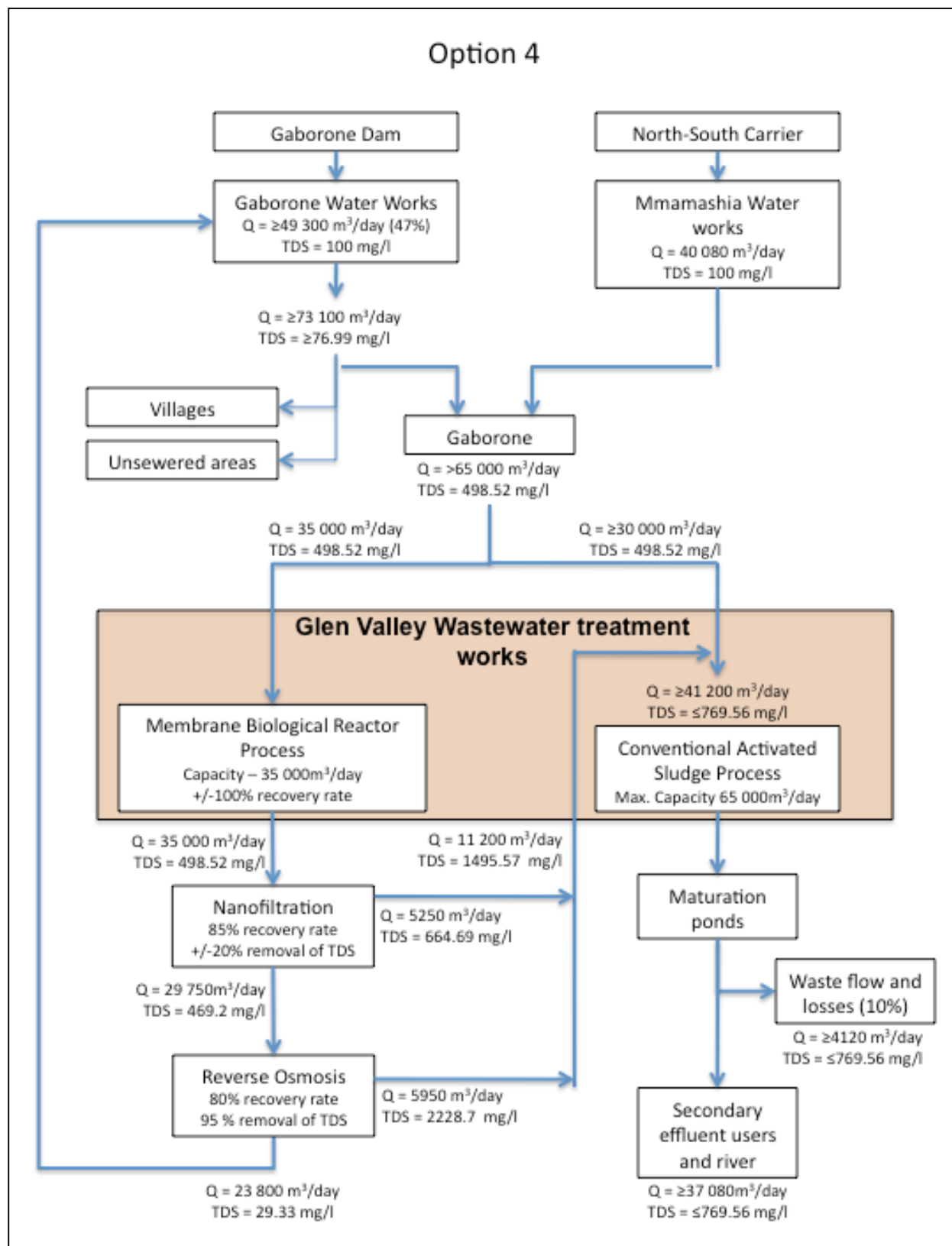


Figure 28. Schematic diagram of entire system volumes and TDS balances

It was initially anticipated that by separating the waste stream from the reclamation plant and treating it separately this would reduce the total dissolved solid concentrations in the system and reduce the TDS concentrations in the final effluent discharged to the maturation ponds. This however is not the case, as seen in Figure 29, with the downstream TDS concentration in option 3 (with separation of waste streams) being slightly higher than that of option 4 (recycling waste stream).

The TDS concentration of the final product water produced by option 4 will be lower than that of option 3. Option 3 essentially recycles the waste stream from the reclamation plant resulting in an increase in the TDS concentration being delivered to the Gaborone Water Works. As this process is not a complete cycle in that water is still being discharged and half of the Gaborone water supply comes from an entirely different source, there is no concern regarding long term build up of TDS concentrations. However if the future expansion plans come into effect and the Mmamashia distribution network is also augmented by the reclamation plant then there will be a real threat of TDS accumulation in the system.

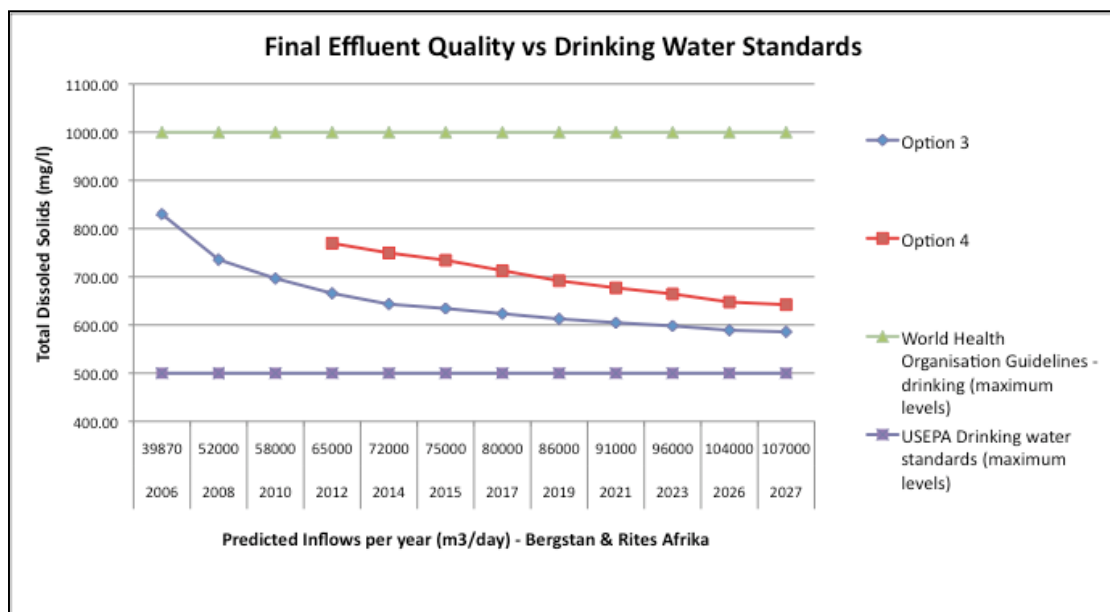


Figure 29 Secondary effluent total dissolved solid (TDS) concentrations over time.

This effluent TDS concentration is however below both the Botswana Bureau of Standards (BOS 93:2004) wastewater discharge standards (2000 mg/l) and WHO guidelines for drinking water (1000 mg/l). The Gibb and Pula³¹ report also identifies TDS concentrations but maintains that a concentration of 829.97 mg/l is within the standards although it must be recognised that long term irrigation using this water can have negative impacts on certain crops sensitive to high TDS concentrations. The report also notes that this level should decrease in time as greater inflows occur and more dilution takes place.

Although this is not an immediate issue, long term the reuse of this effluent water for irrigation can result in accumulation of salts at the root zones of plants thus reducing productivity (Metcalf and Eddy⁴).

Wastewater generally contains more salts than municipal water supplies, with salt concentration ranging from between 200 – 500 mg/l (Barnes and Bliss⁶²). Barnes and Bliss⁶² go on to identify three different effects on plant production due to high TDS concentrations;

1. Osmotic effects due to TDS concentrations in soil water resulting in more energy being spent obtaining water leaving less available energy for growth.
2. Specific ion toxicity from certain concentrations of specific ions.
3. Poor physical soil conditions from high sodium and low salinity.

Option 4 maintains the separation of waste streams in order to ensure that there is a constant water quality both inflow to the MBR and effluent for reclamation. By not treating the RO waste stream in the MBR the TDS concentration of the effluent for reclamation is substantially reduced resulting in lower energy consumption in the RO unit due to the lower osmotic pressure of the effluent (lower TDS concentration).

The dissolved solid concentration of the RO waste is the biggest barrier preventing the reuse of this waste stream (Duranceau²⁸). The management of this RO concentrate is possible through the reduction of

volumes through incorporating additional RO or membrane stage, and by reducing the ammonia toxicity through biological nitrification (Duranceau²⁸).

This design aims at reducing the dissolved solid concentration through dilution with the effluent from the existing biological treatment plant, which at the same time should assist in nitrification of the RO waste stream thus reducing issues relating to ammonia toxicity.

Location

The location of the reclamation is the same as that of Option 3 with the plant being located in close proximity to the existing Glen valley wastewater treatment plant. This reduces the amount of pipeline required, as only a single pipe to the Gaborone water works is required along with the waste and feed pipes to and from the wastewater treatment plant. This location would also enable the expansion of the reclamation plant by possibly supplying Mmamashia water treatment works in the future.

Capacity

The Gibb and Pula³¹ report highlights that although there is enough water available for reclamation if full abstraction rights of the current users are to be catered for then reclamation would only be viable until approximately 2014. The report also aims at reclaiming approximately 20% of the demand of the Gaborone water works with 17 150 m³/day being delivered for blending at the Gaborone water works. This figure has been selected for reclamation due to the issue of increased total dissolved solids concentrations and the availability of water for reclamation by option 3.

As option 4 would only be implemented in approximately 2012 with the phase 2 of the upgrading and expansion of the Glen Valley wastewater treatment works, the issues of water availability is reduced. Based on the Liebenberg & Stander and Rites Afrika³³ report average dry weather flows should be approximately 65 000 m³/day.

Option 4 has not been restricted by the availability of water for reuse but rather looks at current best practice as a means of deciding what quantity can be reclaimed.

Namibia is the only country currently making use of direct potable reuse with reclaimed water being blended with conventionally treated water. Reclaimed water was originally limited to a maximum of 35% of the total potable water supplied to the city but due to low levels of dissolved organic carbon (DOC) (below 5 mg/l) this has been increased to 50% (Lahnsteiner and Lempert⁴⁸).

Option 4 involves the blending of reclaimed waters with conventionally treated waters at the Gaborone dam water works as further barrier through dilution. Gaborone differs from Windhoek in that there is no separation of industrial and domestic wastewater resulting in a larger diversity of contaminants in the wastewater to be treated. For this reason this design makes use of the 35% maximum blending ratio, with no more than 35% of the final blended water being reclaimed water.

In order to prevent the 35% level from being exceeded the capacity of the Gaborone water works has been assessed. This facility has a nominal capacity of 94 000 m³/day and an overload capacity of 109 300 m³/day (Gibb and Pula 2007³¹).

Plant	Nominal Capacity (m ³ /day)	Overload Capacity (m ³ /day)
Plant 1 (1981)	24 000	27 300
Plant 2 (1987)	20 000	22 000
Plant 3 (1991)	50 000	60 000
Total	94 000	109 300

Table 15 Treatment capacities at the Gaborone water treatment works (Gibb and Pula³¹).

The Gaborone water distribution network is divided into two supply areas one from the Gaborone dam water treatment works and the second from the Mmamashia water treatment works. These two supply areas are interlinked as various cross connections occur between the two. These cross connections will further increase the blending of reclaimed and conventional waters although this dilution ratio cannot be easily calculated as little is documented about the extent of these cross connections.

The capacity of this plant is limited by two factors, the availability of water for reclamation and the minimum operating capacity of the Gaborone water works in order to ensure that no more than 35% of the reclaimed water is present once blending has occurred.

Based on the capacities of the Gaborone water treatment works 25 000 m³/day reclaimed product water delivered for blending would be sufficient to provide approximately 25% of the Gaborone water treatment works capacity whilst also ensuring that in the event that the largest plant was taken out of operation the 35% ratio would still not be exceeded, see Table 16.

Gaborone Water Works Capacity	Capacity m³/day	Reclaimed Water m³/day	Reclaimed water after blending
47% Overload Capacity, assuming the largest plant (Plant 3) was completely out of service	49300	25000	33.65%
60% Nominal Capacity	56400	25000	30.71%
75% Nominal Capacity, assuming second largest plant is out of service.	70000	25000	26.32%
80% Nominal Capacity, assuming smallest plant is out of service.	74000	25000	25.25%
100% Nominal Capacity	94000	25000	21.01%
Overload Capacity	109300	25000	18.62%

Table 16 Capacities and ratios of reclaimed with for blending (Information from Gibb and Pula³¹).

This ratio of reclaimed versus conventionally treated water will only be delivered to a specific area of Gaborone. In order for reclaimed water to account for a significant percentage of the entire water demand for Gaborone reclamation plant would need to be expanded and a supply line to Mmamashia water treatment plant developed. This should be looked into in the future once more wastewater is available for reclamation.

The availability of water for reclamation is not entirely certain with the Gibb and Pula³¹ highlighting that although many formal agreements exists between the Gaborone City Council and the Water Allocation Board and downstream users, much of this allocated water is not being utilised. The report also mentions that if all abstraction rights are to be acknowledged then only in 2014 will there be enough water for reclamation.

The Gibb and Pula³¹ report makes an assumption that the total allocation to downstream users is approximately 38 770 m³/day and the current abstraction of this is only 1811,2 m³/day and based on this there is sufficient water available for reclamation from 2006 to meet 20% of Gaborone water treatment works.

Option 4 is based on the next expansion phase of the Glen Valley wastewater treatment plant, which is due to commence in 2012 when the existing plant reaches maximum capacity (Liebenberg & Stander, and Rites Afrika³³). By the time the expansion comes on line a greater amount of water will be available for reclamation (provided no further allocation rights are given by either the Water Allocation Board or Gaborone City council).

The option aims to supply approximately 25 000 m³/day to the Gaborone water treatment works. In order to achieve this volume the reclamation plant will have to be able to treat a larger amount as some of the influent is lost as waste during the different processes. The Gibb and Pula³¹ report predicts losses due to the different membrane processes as being 30% of the total influent. This value is a conservative measure and would be better assessed during the pilot testing stage.

Based on a 70% recovery rate the reclamation plant would have to have a capacity of 35 000 m³/day with approximately 25 000 m³/day of product water and 10 000 m³/day of waste water being produced.

Distribution losses have been identified as a concern with losses of approximately 15% occurring (Gibb and Pula³¹). This factor has been noted but it is expected that these losses will occur after the two waters (reclaimed and treated surface) have been blended and as such will not influence the blending ratio.

These losses are of concern regarding the economic feasibility of the project.

COST COMPARISON

A comparison has been made between the WUC option 3 and the alternative option 4, in order to ascertain if the option is viable and cost effective. This assessment uses the existing values provided by the Gibb and Pula³¹ report.

The Gibb and Pula³¹ report (relating to option 3) concludes, “the project is viable from an economic point of view”. This is based on a preliminary costing of the project over a twenty-year period. It is acknowledged that the financial analysis is based in information from manufacturers and suppliers and previous experience, and that some inaccuracies could occur due to factors such as exchange rate fluctuations, and exact specifications for pumps, blowers and building dimensions, which have been approximated.

The costing is based on a 10-year replacement period for electrical and mechanical equipment whilst UV lamps, and membrane module replacement periods are based in supplier recommendations.

Based on this option 3 has a average cost of production of P 5.98/m³ with the initial capital cost of P 220 million (Gibb & Pula³¹).

Options 3 and 4 although similar, do have different processes. In order to compare the cost effectiveness of the two options the costs involved in developing, operating and maintaining each of the different unit processes has been given below. These figures given below in Table 17, are the capital and maintenance costs of the different unit processes over an eleven year period (1 year of pilot testing and 10 years of regular operation and development) for option 3.

Unit Process	Capital Costs	Maintenance Costs	Total Value	Percentage of Total Costs
Pre - Filtration (250 micron)	P 2,700,000.00	P 360,000.00	P 3,060,000.00	1.28%
Ultrafiltration	P 46,002,844.80	P 21,640,608.00	P 67,643,452.80	28.33%
Nanofiltration	P 47,393,280.00	P 12,614,400.00	P 60,007,680.00	25.14%
Reverse Osmosis	P 47,393,280.00	P 30,560,302.08	P 77,953,582.08	32.65%
Cartridge filtration	P 3,513,854.52	P 16,112,844.00	P 19,626,698.52	8.22%
UV Disinfection	P 8,900,000.00	P 1,549,539.74	P 10,449,539.74	4.38%
Totals	P 155,903,259.32	P 82,837,693.82	P 238,740,953.14	100.00%

Table 17 Costs involved in different unit processes over 11 year period (1 year pilot testing and 10 years operation) – Information taken from Gibb and Pula³¹.

Option 4 has been separated into two sections, wastewater treatment and reclamation. The wastewater treatment is to take place at the Glen Valley wastewater treatment plant and the expansion of this plant will occur in the future (around 2012). The expansion of this plant (phase 2) has already been provisionally budgeted for, irrespective of what type of process is selected for the expansion.

As this expansion has been budgeted for already the costs of the MBR processes have been excluded from this comparison, as these costs will be incurred irrespective of whether the reclamation plant is developed or not.

Based on this separation of the different sections option 4 has fewer unit processes than option 3 making it a more cost effective means of reclaiming water.

Based on the above table both the pre-filtration (1.28% of total cost) and ultrafiltration costs (28.33% of total cost) can be eliminated from the design of option 4 whilst an additional UV process (4.38%) should be

required. The overall effect of this is that there would be an approximate saving of 25% on the costs involved in development and maintenance of the various unit processes.

As these values represent approximately 62% of the total costs (approximately P 384 million) to be incurred during the 11 years, an overall saving of approximately 15% or P 57.6 million could be realised.

These figures have been based on the quantities of product water being the same. It would be expected that there would be an increased saving per cubic meter, generated when a greater quantity of water is reclaimed.

Option 4 should also incur additional savings due to higher quality influent waters being used in the reclamation plant. More specifically feed water would have lower TDS concentrations, resulting in lower operational and maintenance costs particularly lower energy costs.

One factor, which has not been included in these costs, is the installation of an equalisation tank. This would be a cost incurred by the wastewater section of the treatment plant and it is not expected that this cost would exceed the amount saved through the use of the MBR technology. Alternatively this tank could be excluded from the design although this could result in the need for more membrane surface area in the MBR process to cater for the peaks and troughs in flow. This would need to be assessed at the pilot stage in order to ascertain which alternative is more cost effective.

CONCLUSION

Based on this study, the integration of the wastewater treatment processes into the overall design increases the efficiency of water reclamation, reducing the number of processes and costs involved in development and maintenance.

Provided that there is not an urgent requirement to begin reclamation and that the project could be developed between now and 2012, option 4 would have the benefit of reduced costs, and increased efficiency. This period could also be used to undertake a pilot project testing some of the technologies.

The main conclusions regarding this design include:

1. The reclamation of Gaborone wastewater should adopt an integrated approach to the design including the actual treatment of wastewater.
2. The option 4, design would only be operational once the flow to the Glen Valley treatment plant has inflows greater than 65 000 m³/day. The MBR treatment processes would need to undergo a pilot testing period prior to development.
3. This design would reduce the inflow to the maturation ponds thus giving the ponds a longer life span.
4. The downstream effluent TDS values would be similar or slightly higher than option 3, although these values are expected to be less than 770 mg/l. This concentration is not seen as a problem although an accumulation of TDS concentrations in irrigated areas with poor drainage could be a problem in the future.
5. Option 4 does not recycle the effluent thus keeping the influent quality consistent. This will effectively ensure there is no future build up of salts in the system, particularly once the project is expanded to incorporate the entire Gaborone supply area.
6. By operating the MBR – UF process this effectively reduces the costs involved in developing and operating the reclamation plant.

Although designs have been drafted for the reclamation of Gaborone wastewater for potable reuse there are still many other areas, which need to be addressed prior to this project being implemented. Some of these include:

1. The development or adoption of national standards for the reuse of water (for all aspects of reuse, potable reuse, irrigation, construction and landscaping etc).
2. No further allocation of water rights to downstream users should be made and the existing rights need to be monitored and redefined.
3. The monitoring and control of discharge into the sewer network particularly by industry needs to be addressed. Trade effluent agreements need to be reinstated, redefined, and policed.
4. The institutional arrangements for this project need to be sorted out to effectively give one institution the operational control whilst other institutions monitor compliance.
5. A thorough pilot test of the system needs to be undertaken over a minimum of a year in order to gain information regarding the best technologies to be implemented.

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