

CHAPTER 1 – INTRODUCTION

INTRODUCTION

The report comprises five chapters, the background relating to water and wastewater treatment and reuse, the existing situation in Gaborone, case studies of reclamation facilities, the outlining of the available options and finally the conceptual design of a chosen option.

The main objective of the project is to:

Assess and design a treatment facility making use of existing infrastructure and resources for the treatment of the Gaborone wastewater to a sufficient quality for potable reuse.

The reuse of the wastewater generated by the city of Gaborone and surrounding areas for drinking will have a major impact socially and economically in that this water is currently utilised by various parties for construction, landscaping, dust control as well as subsistence and commercial farming. If this supply for agricultural purposes and other uses is in future restricted this could impact negatively on these 'downstream' users. This project does not address this issue directly but rather attempts to factor this into the design. Any negative impacts this creates on these communities would have to be addressed during the environmental impact assessment process.

This chapter gives an overview of water and wastewater treatment as well as issues regarding water reuse.

GENERAL OVERVIEW OF WATER, AND WASTEWATER TREATMENT

The reuse of wastewater, for drinking purposes (potable reuse) is not a new concept and is currently being utilised in many parts of the world including both developed countries, such as the United States, Singapore

and United Kingdom, as well as less developed countries such as Namibia. This type reuse has been viewed as new source of water and is rapidly developing in the United States in areas such as Florida, California and Arizona (Jansen, Stenstrom and de Koning¹).

Water reuse in many countries happens inadvertently with one population disposing of treated wastewater to streams and rivers with this effluent being abstracted, treated and used further downstream – unplanned reuse.

As this project deals with the reuse of wastewater for drinking purposes there is a need to understand the basic processes involved in both water and wastewater treatment.

There are many different treatment processes involved for both wastewater and water treatment with many of these processes being termed conventional due to these being commonly used although this is ambiguous as new technologies are becoming conventional continuously.

Each of the different levels of treatment have a related cost of treatment, with a general rule of thumb being that the smaller the particle size the more expensive it is to treat.

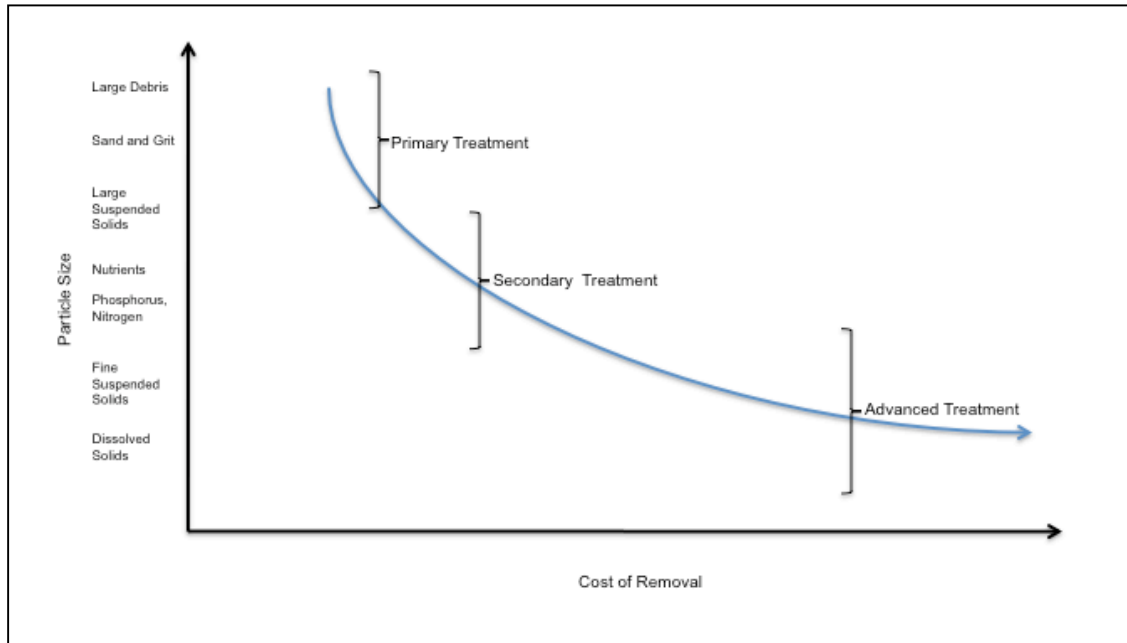


Figure 1 Theoretical cost of different treatment levels based on the removal of different particle sizes (Modified from Judd²).

With the ever-increasing analytical techniques being developed there is a constant improvement of the understanding of the constituents founding wastewaters and updating of the various standards and guidelines (Rowe and Abdel-Magid³). With these developments come changes in the standards required for the reuse of wastewater especially with regards to drinking water. The overall result of this is the development of more stringent water quality standards, and more expensive treatment processes being utilised to meet these.

Metcalf and Eddy⁴, outline five keys areas, which need to be understood in order to ensure there is protection of both public health and the receiving environment. This requires knowledge of the following points:

- The constituents of concern in the wastewater.

- The impacts these constituents can result in when discharged to the environment.
- The changes and fate of these constituents in the various treatment processes.
- The different treatment methods available for the removal or modification of these constituents.
- The various methods available for the disposal or beneficial use of solids generated from the various treatment processes.

Generally water treatment differs from wastewater treatment in that; water treatment processes are highly dependant on the inflow quality. Wastewater treatment process selection is influenced almost equally by influent quality and the environment to which the treated effluent will be discharged.

This is further emphasised by the difference in standards. For the most part water quality standards are similar throughout the world (obviously some countries do have more stringent standards than others) as they are designed to protect public health, which is universal. Wastewater standards on the other hand can vary based on many different 'external factors' such as:

- The sensitivity of the receiving environment.
- Dilution effects from other water bodies such as rivers or oceans.
- Nature of the wastewater influent, industrial versus domestic.
- The possible reuse/reclamation by downstream users.

A brief overview of the more conventional processes involved in water and wastewater treatment has been provided in the following section.

Wastewater Treatment - Overview

Wastewater treatment can be divided into four different levels of treatment preliminary, primary, secondary, and advanced. The level of treatment is situation dependant with the complexity of the treatment plant being based on many factors including among others budget limitations, discharge

standards, receiving environments, and reuse requirements. With each additional increase in level of treatment so there is an increase in the quality of effluent as well as an increase in the cost of treatment. Figure 2 has a detailed breakdown of the different treatment levels and the different processes common to each.

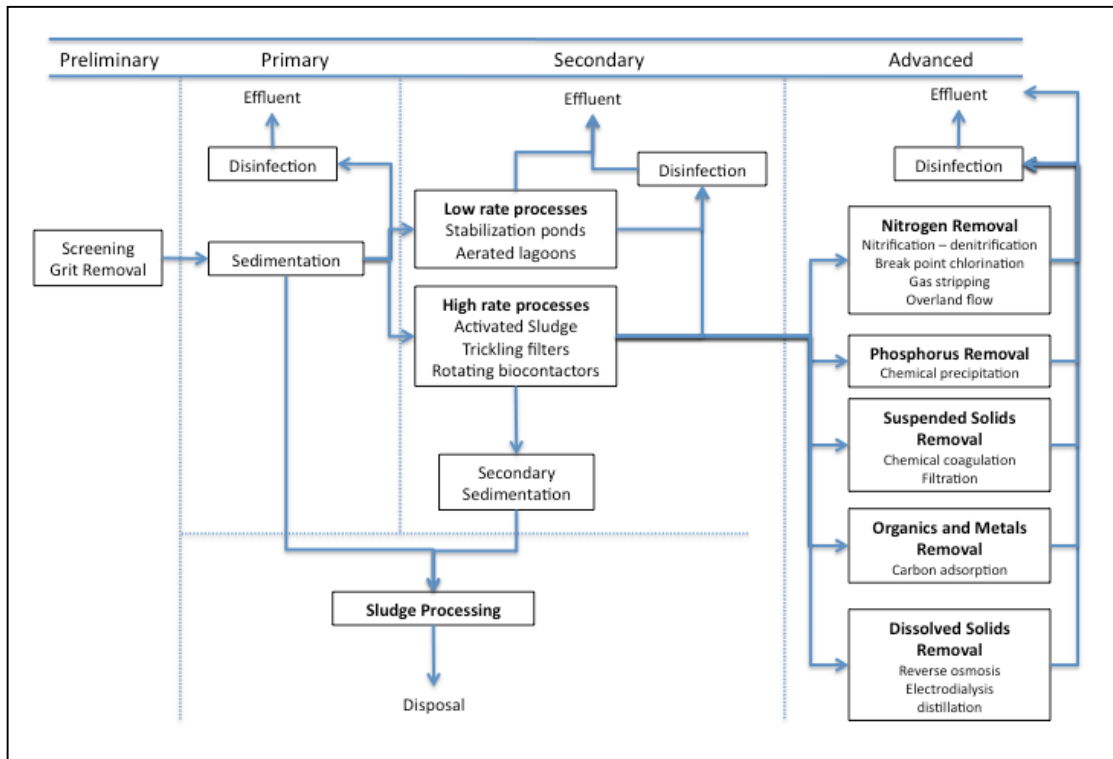


Figure 2 Outline of the levels of treatment and process involved (Modified from Asano⁵).

Although there are many different treatment levels, most of the large wastewater treatment works (municipal scale) will only undertake the first four, up to secondary treatment with nutrient removal (Spellman⁶).

Advanced treatment is generally only used in the treatment of industrial wastes or for the wastewater reuse application requiring high quality product water.

Treatment level	Description
Preliminary	Removal of wastewater constituents such as rags, sticks, floatables, grit, and grease that may cause maintenance or operational problems with the treatment operations, processes, and ancillary systems
Primary	Removal of a portion of the suspended solids and organic matter from the wastewater
Advanced primary	Enhanced removal of suspended solids and organic matter from the wastewater. Typically accomplished by chemical addition or filtration
Secondary	Removal of biodegradable organic matter (in solution or suspension) and suspended solids. Disinfection is also typically included in the definition of conventional secondary treatment
Secondary with nutrient removal	Removal of biodegradable organics, suspended solids, and nutrients (nitrogen, phosphorus, or both nitrogen and phosphorus)
Tertiary	Removal of residual suspended solids (after secondary treatment), usually by granular medium filtration or microscreens. Disinfection is also typically a part of tertiary treatment. Nutrient removal is often included in this definition
Advanced	Removal of dissolved and suspended materials remaining after normal biological treatment when required for various water reuse applications

°Adapted, in part, from Crites and Tchobanoglous (1998).

Figure 3. Levels of Wastewater Treatment - Metcalf and Eddy⁴

Within each level of treatment various unit processes occur. Wastewater treatment can be broken down into three process types, which generally follow the each other in the following order:

1. Physical – this is usually the first stage of treatment involving screening, settling and floatation.
2. Biological – usually forming part of the secondary treatment process involving the use of bacteria and microorganisms in usually aerobic or anaerobic conditions to reduce the organic content of the wastewater effluent.
3. Chemical – these processes are usually associated with either the tertiary or advanced treatment levels or with disinfection. These processes invariably rely on the addition of a chemical to reduce specific contaminants.

Although treatment works differ from each other there are some basic unit processes, which are very similar in most 'conventional' treatment works. This process is best illustrated in Figure 4 below. This figure is typical of a wastewater treatment plant although considerable variation between works does occur.

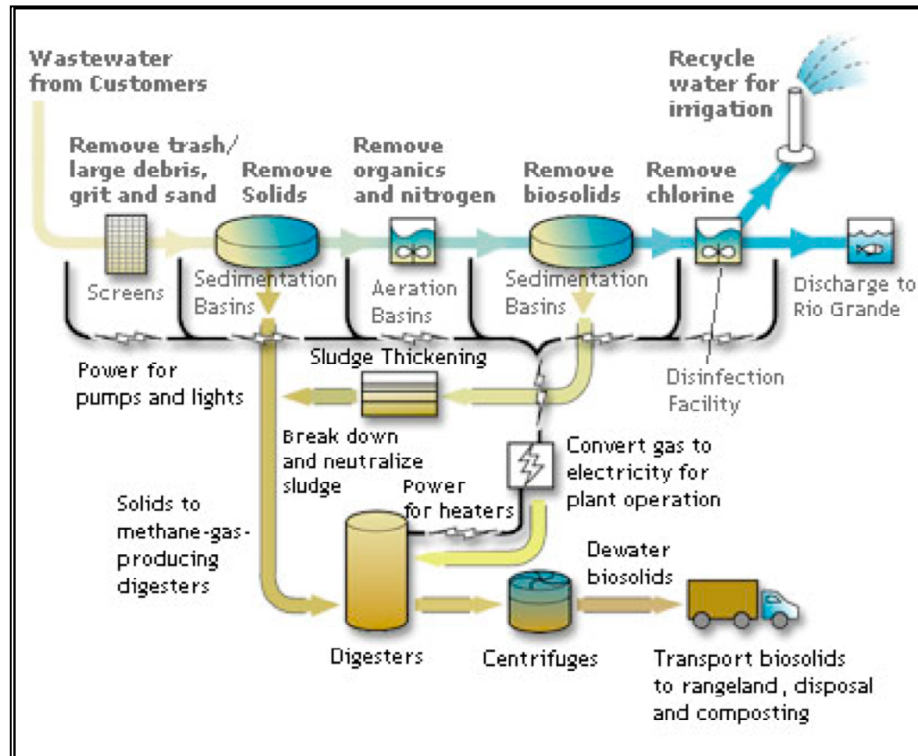


Figure 4. Outline of the basic processes involved in the treatment of Wastewater (City of Albuquerque⁷).

As this study is designed to focus on the Gaborone wastewater treatment processes only those treatment levels relevant to the study have been discussed in any great detail, as these are the main levels of treatment employed at the Gaborone, Glen Valley wastewater treatment works.

Primary Treatment

Primary Treatment is predominantly based on physical process types with the main focus being the removal of the larger pollutants from large particulate matter to suspended solids.

The initial stage (sometimes called Preliminary Treatment) involves the removal of the large particulate matter and most commonly makes use of some type of screen in order to remove materials, which could possibly damage the equipment or occupy capacity without actually being treated (Spellman⁶).

Screens can vary considerably from bars, to mesh, grating, to perforated plates. Other variations also include the size of openings of the different screens, ranging from bar or rack screens of >25 mm openings (Coarse) to mesh screens <6mm openings (Fine) (Stevenson⁸ and Geostar Publishing⁹).

The next stage involves the removal of sand and grit from the influent. Sand and grit removal is necessary as these particulates can cause excessive wear to pumps and pipes as well as interfere with the next stages of the treatment. The removal of this grit is particularly important in areas where the storm water and sewers are not separated, as often debris wash into the sewers with the storm water (USEPA¹⁰).

Grit and sand are most commonly removed by reducing the velocity of the flowing sewage to between 0.15 and 0.3m/s, which in turn allows the larger, heavier inorganic sands and grit (0.2mm and bigger) to settle on the bottom of the chamber whilst the lighter organic materials remain suspended (Geostar Publishing⁹ and Spellman⁶).

The final stage of Primary Treatment is the removal of the suspended solids and most often makes use of sedimentation tanks/basins (also referred to as primary settling). This stage sees the sewage separated into sludge and effluent, both of which require further treatment prior to final disposal (Spellman⁶).

The sludge component is then mechanically removed for further treatment making use of digesters to process this sludge.

Secondary Treatment

Secondary treatment involves the use of the bacteria to remove organic matter. This stage is often responsible for the removal of approximately

“85 percent of the organic matter” (USEPA¹⁰). This treatment stage aims at removing or reducing the five-day biochemical oxygen demand (BOD₅) and dissolved and colloidal suspended organic matter through biological action converting organics into stable solids, carbon dioxide and more organisms (Spellman⁶).

The two most common methods used in secondary treatment are either “attached growth” or “suspended growth” techniques (USEPA¹⁰). More recently, the use of activated sludge process has been preferred as this process is able to increase the speed of the plant by increasing the contact of air, bacteria and organic matter in the sewage (USEPA¹¹).

The configuration of the aeration and activated sludge mix can form various conditions of i.e. aerobic, anoxic or anaerobic (Metcalf and Eddy⁴). These conditions influence the ability to treat different constituents in addition to Biochemical Oxygen Demand (BOD) such as nitrogen and phosphorus. The removal of nitrogen and phosphorus is highly dependant on the inclusion of a combination of these different conditions (Metcalf and Eddy⁴).

From the aeration tanks the effluent is released to the secondary sedimentation tanks for further settling. The secondary sedimentation process results in the formation of sludge and water. Some of the sludge is sent to the digesters for further processing whilst the remainder is returned to the aeration chambers as activated sludge. The water component at this stage is discharged to lagoons for further polishing and then released to the environment or reused.

Disinfection

Chlorination is the most widely used means of disinfection (Spellman⁶). Disinfection making use of chlorine is common prior to final discharge but this is dependant on the receiving environment as residual chlorine can kill fish and other aquatic species, even in small concentrations (Geostar Publishing⁹). Various alternative sources of disinfection are also used such as ultraviolet radiation, ozonation, and bromide chloride additions

(Spellmans¹²). Ultimately chlorination is most commonly used in order to provide residual disinfection (Spellman¹²).

Sludge treatment

Sludge treatment can either involve anaerobic or aerobic processes to treat the solids removed from the wastewater during the treatment processes. This treatment aims to stabilise the sludge, inactivate pathogens and organisms, and reduce the volume through the removal of water (Spellman⁶).

Water Treatment for Drinking Water

Like wastewater treatment there is a large array of different treatment process that have been developed over the years for the treatment of water for drinking. Although every treatment plant differs from the next there are some relatively common treatment processes frequently used in the treatment of water for drinking. This is likely to change in the future as new techniques and processes, as well as standards are being continuously developed which tend to favour higher quality water (American Water Works Association¹³). One of the most important developments in the field of water treatment is that of membranes which are becoming increasingly popular for the treatment of waters for drinking purposes (MWH¹⁴).

For the most part the treatment of water for drinking purposes makes use of large bodies of water, dams, lakes, subsurface aquifers/groundwater, or rivers. As a result the source of the water influences the level of treatment required, with surface waters generally requiring higher levels of treatment than groundwater (Drinan¹⁵). Some of the main processes used in the treatment of water have been detailed below, although some of these may overlap at some plants, no plant would ever employ all of these (American Water Works Association¹³).

- 🔧 Pre-treatment – screening (large debris), micro screening (algae) and chemical pre-treatment (pH adjustment).

- 🔧 Aeration – cascade or other type of system to oxidise dissolved iron or manganese.
- 🔧 Coagulation and Flocculation – flash mixing, chemical addition and pH adjustment to increase settling, baffles or slow mixing to induce flocculation.
- 🔧 Sedimentation – gravity settling for 24 hours to separate out solids
- 🔧 Softening – lime-soda (most common), ion exchange, or membrane filtration.
- 🔧 Filtration – slow or rapid sand filters (most common), cartridge filtration or membranes.
- 🔧 Adsorption – Granular or powder activated carbon is most common means of adsorption.
- 🔧 Membrane technologies – Micro, Ultra and Nanofiltration and reverse osmosis.
- 🔧 Fluoridation – Increase fluoride in water supply to aid in teeth strengthening and prevent tooth decay.
- 🔧 Corrosion control – prevention of electrochemical reactions reducing corrosion of pipes, fittings and equipment.
- 🔧 Disinfection – Destruction of disease causing bacteria commonly using chlorine.

A conventional water treatment processes could comprise a basic six-stage process as described in Figure 5 below.

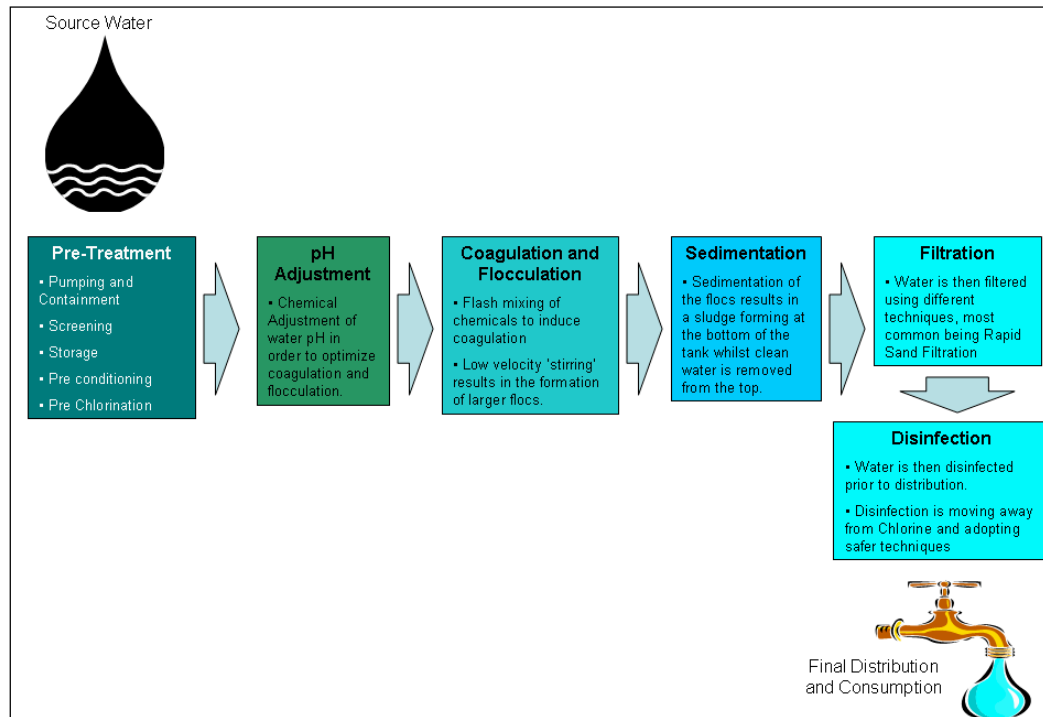


Figure 5. Outline of the different stages of potable water treatment (Modified from Drinan¹⁵).

Pre-treatment

The pre-treatment of the water varies tremendously from site to site and in many cases some of the following stages will be almost entirely eliminated. The entire pre-treatment stage focuses on the containment and conditioning of the water in order to ensure there is:

- A means of storing or ensuring a consistent head of water to be treated,
- No debris or large particulate matter which could result in clogging and blockages or impact on the treatment processes
- Minimal hardness in the water that can both impact on treatment processes and physically damage pipes and fittings,

→ Little chance of bacterial growth before the treatment begins

Pre-treatment essentially comprises 8 main unit processes, coarse screening, pumping, storage, fine screening, equalization, neutralisation, aeration and chemical pre-treatment (Gray¹⁶).

Additional processes common to traditional water treatment may include sedimentation, and aeration although these are largely determined by the influent source and quality (Binnie and Kimber¹⁷).

In some instances there will be more emphasis on one process whilst another may be almost excluded i.e. if the source water is from the ground then there would be little if any screening but there would more than likely be a need for pre-conditioning in order to reduce the hardness salts from the water (Drinan¹⁵).

More recently there has been a move away from the use of chlorine for primary disinfection due to both health risks associated with it, both by the plant operators (poisoning from chlorine gas) and the consumers (formation of Trihalomethanes that are carcinogenic)(Spellman¹²).

pH Adjustment

In order to enhance the effectiveness of the flocculation and coagulation process the pH of the influent waters must be adjusted based on what type of coagulant chemicals are to be used. Aluminium sulphate is a commonly used coagulant and is best suited to waters with a pH of between 5 and 7.5 (Spellman¹⁸).

The pH of the influent waters are adjusted based on the existing pH and the optimal pH requirements for the next process being undertaken.

Coagulation and Flocculation

Coagulation is the process of adding chemical reagents to a mixing device causing colloidal particles to destabilise and flocculate resulting in other suspended particles becoming more easily settled (Droste¹⁹). There are a number of coagulation mechanisms, such as double layer compression,

charge neutralisation and inter particle bridging with the water quality and dosing requirements largely deciding which mechanism is suitable (Parsons & Jefferson²⁰).

Flocculation is a slow mixing process following on from the flash mixing of coagulants, and designed to increase particle contact thereby forming larger particles which can be more easily settled (Droste¹⁹).

Sedimentation

From flocculation the water then moves to the sedimentation basins where through gravity the floccs are settled out and removed as sludge whilst the upper body of clean water is passed off for further treatment prior (Spellman¹⁸).

Sedimentation basins can either be rectangular or circular and are large in volume so as to increase the retention time of the water. The sludge removal is typically a combination of a mechanical tank cleaner, which ensures sludge is moved to the discharge point and a pump, which removes the sludge from the tank. A typical retention time in sedimentation tanks is 2-3 hours (Parsons & Jefferson²⁰).

Filtration

Filtration is the final step in clarifying water and is aimed at removing particulate matter including “clays and silts, microorganisms, precipitates of organics and metal ions” (Parsons & Jefferson²⁰). Many different types of filtration systems exist for this treatment process although sand filtration is one of the oldest and most widely used (Parsons & Jefferson²⁰).

Simply put the water passes through the granular filter media, often sand or activated carbon, at a relatively slow velocity leaving the physical impurities behind in the media (Hendricks²¹). The sand section of the filter is dependent on suspended floc particles and becoming trapped in the pores between the sand (straining) and adhering to the sand particles (depth filtration) (Hendricks²¹). This property ensures that filtration occurs through the depth of the sand layer. These filters will require routine

cleaning which will include backwashing and air scouring by forcing water and air respectively backwards through the filter and discarding the backwashed water (Parsons & Jefferson²⁰).

Membrane filtration has become more popular as cost of production decreases and water quality standards increase (Rautenbach and Albrecht²²) especially with the increase in competitively priced desalination operations (American Water Works Association¹³).

Disinfection

Disinfection is achieved by both effectively filtering out harmful microbes and bacteria, followed by the addition of chemicals to inactivate any remaining micro-organisms (Hendricks²¹).

Disinfection can be generally broken into two stages, disinfection during treatment or primary disinfection and secondary or residual disinfection.

Traditionally primary disinfection during treatment made use of Chlorine based chemicals (Hendricks²¹). Nowadays chlorination is mainly used to disinfect fully treated waters or high quality groundwater (Binnie and Kimber¹⁷). Disinfection in the treatment plant may make use of one or more of the following common processes, chlorination, ozonation, UV radiation, or chlorine dioxide (Binnie and Kimber¹⁷ and Hendricks²¹). Ozonation and UV radiation however do not have any residual disinfecting properties and this type of disinfection must be undertaken separately (Stevenson⁸).

Residual disinfection is concerned with the disinfection of the water whilst in the distribution network. Residual disinfection is almost always chlorine based, such as chlorine (gas or hypochlorite solution), chlorine dioxide (Hendricks²¹ and Spellman¹²), or chloramine (Binnie and Kimber¹⁷).

Water wastes and sludge handling

Clarification and filtration processes produce the bulk of the wastes from water treatment works (Binnie and Kimber¹⁷). Previously sludge was disposed of into water bodies where it caused environmental problems

although today these sludges are treated prior to disposal (Drinan¹⁵). Based on what type of sludge is being handled, these wastes are often disposed of either to sewers, lagoons or landfill (Drinan¹⁵). Sludge waste is predominantly generated from clarification processes and is mainly disposed of in lagoons or thickened, dewatered and sent to landfill sites provided the solid contents is more than 20% (Binnie and Kimber¹⁷).

Treatment and Reuse

The reuse of wastewater and the design of the treatment process for treating wastewater are highly dependant upon each other, and should be planned and developed in conjunction (Water Research Commission²³).

If for example wastewater were to be reused for landscaping or agricultural purposes the quality of the effluent would not have to be as high as the quality of the effluent to be reused for drinking purposes. This would mean that in designing the wastewater treatment plant, fewer treatment processes and stages required compared to a plant, which was to reuse the water for drinking purposes. This will also have economical benefits as treating effluent to standards suitable for drinking is costly.

This report focuses primarily on the potable reuse options available although it must be mentioned that the non-potable reuse options can be extremely effective in reducing the demand on potable water supplies.

Potable reuse options can be generally broken into two distinctive categories Direct Potable Reuse (DPR) and Indirect Potable Reuse (IPR).

This is best illustrated in the figure 6, below.

- **Direct Potable Reuse (DPR)** is “the introduction of highly treated reclaimed water either directly into the potable water supply distribution system downstream of a water treatment plant, or into the raw water supply immediately upstream of a water treatment plant “(Metcalf and Eddy & AECOM²⁴).

- **Indirect Potable Reuse (IPR)** is described as “the planned incorporation of reclaimed water into a raw water supply such as in potable water storage reservoirs or a groundwater aquifer, resulting in the mixing and assimilation, thus providing an environmental buffer” (Metcalf and Eddy & AECOM²⁴).

The above definition of IPR was found to be rather vague in that there is no definition of the retention time or dilution factor of the reclaimed water. Another definition of IPR by Jensen, Stenstrom and Koning¹ defines IPR as a “method of reusing treated waters and wastewaters for potable use through at least one environmental barrier that serves to isolate, as well as protect, consumers. Examples of barriers include a groundwater basin or reservoir providing more than 1-year retention time”.

Treatment processes and new technologies

This report focuses on potable reuse and as such deals only with some of the common treatment process options for advanced treatment of wastewater. There are many different treatment processes for treating wastewater using a vast array of different unit processes. The most common factor regarding the treatment of reclaimed water for potable reuse is the ‘multiple barrier’ approach. A multiple barrier approach essentially means that for any specific contaminant of concern there is more than one barrier (Du Pisani⁵⁴). In many cases each barrier covers a number of different contaminants helping in reduce the number of unit processes. These barriers can be in different forms such as the Namibian reclamation project, making use of treatment barriers, non-treatment barriers and operational barriers (Du Pisani⁵⁴).

- 🔧 Treatment barriers would form part of the existing process train. An example would be disinfection.
- 🔧 Operational barriers being additional treatments performed in response to a specific change i.e. powdered activated carbon dosing to reduce taste issues.

🚧 Non-treatment barriers are activities undertaken to ensure the best quality of wastewater is received at the reclamation plant. Activities such as policing effluent discharges, waste separation activities etc. A combination of these different types of barriers assists in the formation of a multiple barrier effect on the various contaminants of concern. By incorporating these sequential and redundant processes into the multiple barrier design this provides for a high degree of reliability (Metcalf and Eddy & AECOM²⁴).

Many different unit processes exist for the reclamation of wastewaters although many of the new reclamation facilities are making use of membrane technologies (Baker⁶⁴). Membrane technologies have been advancing and becoming increasingly more popular for the reuse of industrial wastewater (Judd and Jefferson²⁵).

This technology has been used in many different advanced and reclamation treatment works worldwide, and generally results in reducing the number of unit processes involved in the reclamation of wastewater as seen in Figure 6.

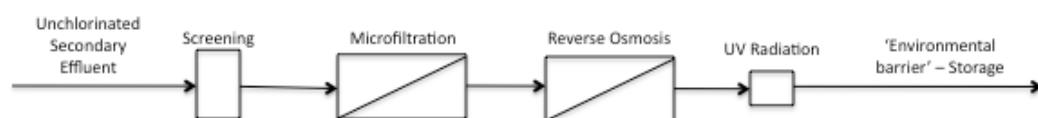


Figure 6. Simplified treatment process for indirect potable reclamation plant using membrane technology (Metcalf and Eddy⁴).

The use of the membranes and ultraviolet (UV) radiation in this treatment process provides for an effective multiple barrier approach. Microfiltration providing a pre-treatment stage for the RO process as well as eliminating any suspended solids and bacteria. The RO process further eliminates viruses, synthetic organics and most other contaminants whilst the UV radiation disinfects any remaining viruses or contaminants. Although this treatment process may appear simple it is effective in treating water for

indirect potable reclamation and is very similar to the process currently being implemented in Singapore, Bedok and California, Orange County.

Membrane bioreactor (MBR) technology is also being increasingly used for the treatment of wastewater in numerous facilities around the world (Hillis²⁶ and Metcalf and Eddy & AECOM²⁴). The main reasons for this increase in MBR usage are that membrane life spans has increase from 3 to 8 years and the increase in number of manufacturers has resulted in decreased fabrication costs (Hillis²⁶).

Hillis²⁶ has described some of the membrane bioreactors advantages and disadvantages compared to conventional activated sludge treatment processes:

Advantages	Disadvantages
They produce higher quality effluent with greater removal of microorganisms compared to conventional wastewater treatment techniques.	Higher pressure requirements resulting in higher operating costs
Smaller plant footprint as no sedimentation tanks are required.	Higher capital costs due to membrane costs.
Better control of biological conditions, as all sludge is recycled and sludge age is dependant on hydraulic retention time.	Fouling of membranes can occur in some wastewaters.
Less sludge production.	

Table 1. Advantages and disadvantages of Membrane Bioreactors (Information taken from Hillis²⁶ and Metcalf and Eddy & AECOM²⁴).

Reuse Options

The reuse of wastewater can be generally classified into two main classes, *potable reuse* or *non-potable reuse*.

Non-potable reuse options offer larger amount of diversity regarding the different options available for reuse. Non-potable reuse involves substantially lower treatment costs, as many options will only require treatment of effluent to a level of conventional secondary wastewater treatment (reclaimed water).

Reclaimed water can be utilised for many different purposes based on the effluent quality. Some of the more common uses include:

1. Agricultural irrigation. This reportedly the largest use of reclaimed water and is likely to hold significant opportunity for future reuse (Al Baz, *et al*²⁷ and Metcalf and Eddy⁴).
2. Landscaping and Gardening. Landscaping usually involves communal areas and public open spaces such as parks, city gardens, and roadsides. In Botswana however recent water restrictions forced companies and the general public to purchase reclaimed water for private gardens both private residences and office and industrial complexes.
3. Industrial purposes. Cooling processes are the single biggest reuse option in industry in the USA (Metcalf and Eddy⁴) although this has not yet been explored in Botswana.

Effluent quality is the key determinant of the options available for reuse. Some standards do occur for the reuse of wastewater although to a large degree these are often simply guidelines and are not enforced, as often the case in developing countries.

General Uses	Disinfected tertiary*	Disinfected secondary – 2.2**	Disinfected secondary – 23***	Undisinfected secondary****
All uses except potable use, groundwater recharge or food preparation.	Allowed	Not allowed	Not allowed	Not allowed
Irrigation – Parks, playgrounds, residential yards, school yards, golf courses with residences.	Allowed – spray, drip or surface irrigation	Not allowed	Not allowed	Not allowed
Irrigation – Restricted access golf courses, cemeteries, freeway landscapes.	Allowed – Spray, drip, or surface irrigation	Allowed – Spray, drip, or surface irrigation	Allowed – Spray, drip, or surface irrigation	Not allowed
All food crops	Allowed – spray, drip or surface	Not allowed	Not allowed	Not allowed
Food crops above ground and not contacted by reclaimed water	Allowed – spray, drip or surface	Allowed – drip or surface	Not allowed	Not allowed
Pasture for milking and other animals	Allowed – spray, drip or surface	Allowed – spray, drip or surface	Allowed – spray, drip or surface	Not allowed
Fodder, fibre, and seed crops not eaten by humans	Allowed – spray, drip or surface	Allowed – spray, drip or surface	Allowed – spray, drip or surface	Allowed – drip or surface
Flushing toilets and urinals	Allowed	Not allowed	Not allowed	Not allowed
Industrial processes with exposure to workers <i>(Industrial process does not generate mist or involve facial contact with reclaimed water).</i>	Allowed	Not allowed	Not allowed	Not allowed
Industrial processes with exposure to workers	Allowed	Allowed	Allowed	Not allowed
Fire fighting <i>(other than dumping from aircraft).</i>	Allowed	Not allowed	Not allowed	Not allowed

General Uses	Disinfected tertiary*	Disinfected secondary – 2.2**	Disinfected secondary – 23***	Undisinfected secondary****
Dampening of soil for compaction or dust control at construction sites, landfills and other sites	Allowed	Allowed	Allowed	Not allowed

Table 2. Different uses and methods for application of reclaimed water based on California Code of Regulations. Modified from Metcalf and Eddy⁴

* - Filtered through filter media, sand, diatomaceous earth. Less than 2.2 Total coli form most probable number (MPN) per 100ml, Turbidity – average 2 NTU, and maximum 5 NTU.

** - Less than 2.2 Total coli form MPN per 100ml, Turbidity – not applicable

*** - Less than 23 Total coli form MPN per 100ml, Turbidity – not applicable

**** - Total coli form and Turbidity – not applicable. Organic matter is stabilised, non putrescible, and contains dissolved oxygen.

Concerns for Reuse

Advancements in treatment technologies has resulted in wastewater being viewed more and more as a resource rather than a waste, with technology being available to treat wastewater to meet drinking water standards. Although this is the case DPR is only really practiced continuously in Namibia on a municipal scale (Metcalf and Eddy & AECOM²⁴) with the USA reporting that the DPR is not “practicable” (Metcalf and Eddy⁴).

There are a number of concerns regarding the DPR with the main concern being that of trace contaminants, which have been discovered through the recent advances in analytical techniques for the measurement of these. The lack of comprehensive long-term studies on the impacts of trace contaminants on human health is of concern (Metcalf and Eddy & AECOM²⁴) and Metcalf and Eddy⁴). It must be noted that this lack of knowledge extends to almost all sources of waters and is not reserved for direct potable reuse applications.

Metcalf and Eddy⁴ have also classified constituents in three types, described in Table 3 below.

Classification	Description	Constituent
Conventional constituents	Conventional constituents are measured in mg/L and are predominantly removed through conventional wastewater treatment processes.	- Total suspended solids - Colloidal Solids - Biochemical oxygen demand - Chemical oxygen demand - Total organic carbon - Ammonia - Nitrate - Nitrite - Total nitrogen - Phosphorus - Bacteria - Protozoan cysts and oocysts (value per 100ml) - Viruses (Plaque-forming units/100ml)
Non-conventional constituents	Constituents provide the focus for advanced water treatment processes, and need to be removed before water can be reused for drinking purposes.	- Refractory organics - Volatile organic compounds - Surfactants - Metals - Total dissolved solids
Emerging constituents	Measured in micrograms or nanograms per litre and little is known about the long term health effects of these. Often these constituents are not effectively removed through advanced water treatment.	- Prescription and non-prescription drugs (Pharmaceutically active substances) - Home care products - Veterinary and human antibiotics - Industrial and household products - Sex and steroidal hormones - Other endocrine disrupters

Table 3. Classification of constituents found in wastewaters (Modified from Metcalf and Eddy⁴)

Within this classification system three types of constituents are of concern when planning for potable reuse and these include enteric viruses, organic constituents (including industrial chemicals, home products, and medicine), and heavy metals with these three types of constituents being poorly understood (Metcalf and Eddy⁴).

Treatment Issues

The reuse of wastewater is not only dependant on the quality requirements of the final product water but is also determined by the treatment processes involved in obtaining the desired water quality. Some of the unit processes themselves are limited not by the quality of product water they produce but rather by the waste stream generated from the process.

Reverse osmosis has in the past become one of the main unit processes involved in the treatment of wastewaters for potable reuse and is currently being used in many parts of the world. Although this treatment process does have many benefits in producing high quality waters it is limited by three main factors; costs, discharge permits and waste stream dissolved solid concentrations (Duranceau²⁸).

A survey of treatment works utilising reverse osmosis processes in the states showed the majority of these plants to discharge the waste streams to fresh water surfaces (48%) and sewers (17%), whilst only 9% made use of land application (Duranceau²⁸).

It has also been stated, “salinity is the single most important parameter in determining the suitability of a water for agricultural irrigation” (Rowe and Abdel-Magid³). A guideline for the interpretation of water quality for agricultural irrigation is given below:

TDS concentration (mg/l)	Degree of restriction on reuse
< 450	None
450 – 2000	Moderate
> 2000	Severe

Table 4. Guide for the interpreting TDS concentrations for agricultural reuse (Rowe and Abdel-Magid³)

This is highly relevant to Botswana as there is little fresh water available to dilute these salt concentrations.

CHAPTER 2: EXISTING SITUATION IN BOTSWANA

This chapter looks at the existing situation in Gaborone, Botswana with regards to existing infrastructure, institutional, location, climatic and geographic contexts.

LOCATION, CLIMATIC, GEOGRAPHIC AND DEMOGRAPHIC CONTEXT

Gaborone is the capital of Botswana, situated in the southern part of Botswana in close proximity ($\leq 30\text{km}$) to the South African border. The city has been growing rapidly over the last 40 years since independence in 1966.

Gaborone is the largest city in Botswana with a population in the region of 208,493 in 2006 and is expected to grow to 295,454 by 2026 (Central Statistics Office 2005²⁹). Some distortion of these figures could be expected due to political instability in the region (Zimbabwe), which has resulted increased immigration to Botswana.

Gaborone falls in a sub-tropical climate zone and is prone to high temperatures in summer months and cold temperatures including frosts during the winter months. The majority of the rainfall is experienced during the summer months of November through to February, with annual rainfall varying from between 353mm to 915 mm per annum based on figures from 1991 through to 2001 from Department of Meteorological Services (Gaborone City Council 2003³⁰). An average rainfall has been recorded as being 537mm (Gibb and Pula 2007³¹). This tremendous variation in rainfall creates challenges for planning for the city and has in the past resulted in water restrictions due to the lack of water in the Gaborone Dam.

Evaporation has been recorded as approximately 2000mm per annum (Gibb and Pula 2007³¹), making this a serious factor to consider for the storage of water.

EXISTING PLANNING AND INSTITUTIONAL DETAILS – WATER RESOURCES AND WASTEWATER TREATMENT

Water as a resource in Botswana falls under the responsibility of the Ministry of Minerals, Energy and Water Affairs (MMEWA) with regards to planning, assessments, developments, management and protection. The Department of Water Affairs (DWA) is the primary department overseeing the responsibilities of the MMEWA throughout Botswana and this applies to all surface and ground water resources.

In terms of water supply the responsibility is split between the DWA, which is responsible for the supply to various major villages throughout Botswana whilst the Water Utilities Corporation (WUC) is responsible for the supply to most major urban centres including Gaborone (Gibb and Pula 2007³¹).

Wastewater has historically not been viewed as a resource throughout the world and Botswana is no exception. The Ministry of Environment Wildlife and Tourism is responsible for the management of the Department of Waste Management and Pollution Control (DWM&PC) responsible for the implementation and regulation of wastewater treatment. The actual treatment of wastewaters from the major urban areas in Botswana is the responsibility of the various individual local authorities namely city or town councils. In the case of Gaborone the Gaborone City Council (GCC), Sewage Department, is responsible for the operation of the treatment works also known as the Glen Valley Treatment Works.

OVER VIEW OF EXISTING INFRASTRUCTURE

This section looks at the existing infrastructure available in Gaborone for water supply and treatment as well as wastewater treatment. Much of the existing infrastructure is in the form of water supply and treatment.

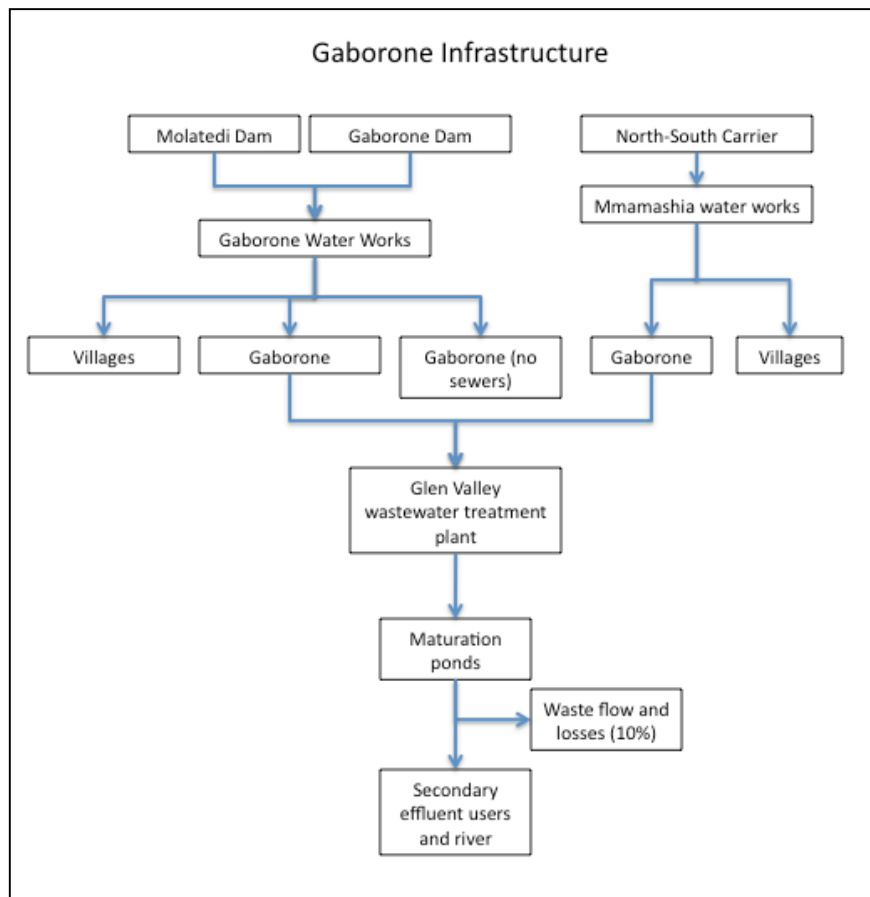


Figure 7. Existing water infrastructure (Information from Gibb and Pula 2007³¹)

Water Treatment Works

Two water treatment works, the Mmamashia and the Gaborone water works service Gaborone. Although these two works treat different source waters their treatment processes are essentially identical.

The Gaborone water works is located adjacent to the Gaborone Dam and is the older of the two works. Feed water for the Gaborone water works comes from two sources, either the Gaborone dam (including the Bokaa transfer waters) and the Molatedi transfer scheme.

This treatment plant has been extended over the years and now consists of three separate plants with a current capacity of between 94 000 (nominal capacity) and 109 030 (overload capacity) m³/day (Gibb and Pula 2007³¹).

The Mmamashia water works treats water from the North South Carrier as well as from Bokaa Dam, if required. This plant has a maximum design capacity 117 600 m³/day Gibb and Pula 2007³¹ although this plant is scheduled for expansion once phase 2 of the North South Carrier comes on line.

The basic processes involved for water treatment at these plants include has been outlined in

Figure 8, these include:

1. Chemical mixing – this is based on operational testing and includes either dosing with lime in the to correct pH if too acidic or the addition of powder activated carbon if odour becomes an issue.
2. Flash mixing – of coagulant to improve flocculation and clarification.
3. Clarification – settlement of floccs, removal of upper body of water for filtration.
4. Filtration – gravity fed sand filtration removes any remaining floccs and suspended solids. Backwashing is undertaken every 72 hours with backwash waste being sent to a recovery tank.
5. Disinfection – either chlorine gas or sodium hypochlorite are used for disinfection. Sodium hypochlorite is produced on site whilst chlorine gas is only used when necessary.
6. Sludge handling – sludge is gravity thickened with the supernatant being recycled back to the head of the works whilst sludge component is pumped to drying beds.

The treatment of water is fairly conventional whilst these are the main components of the water treatment works with only minor differences occurring between the two plants.

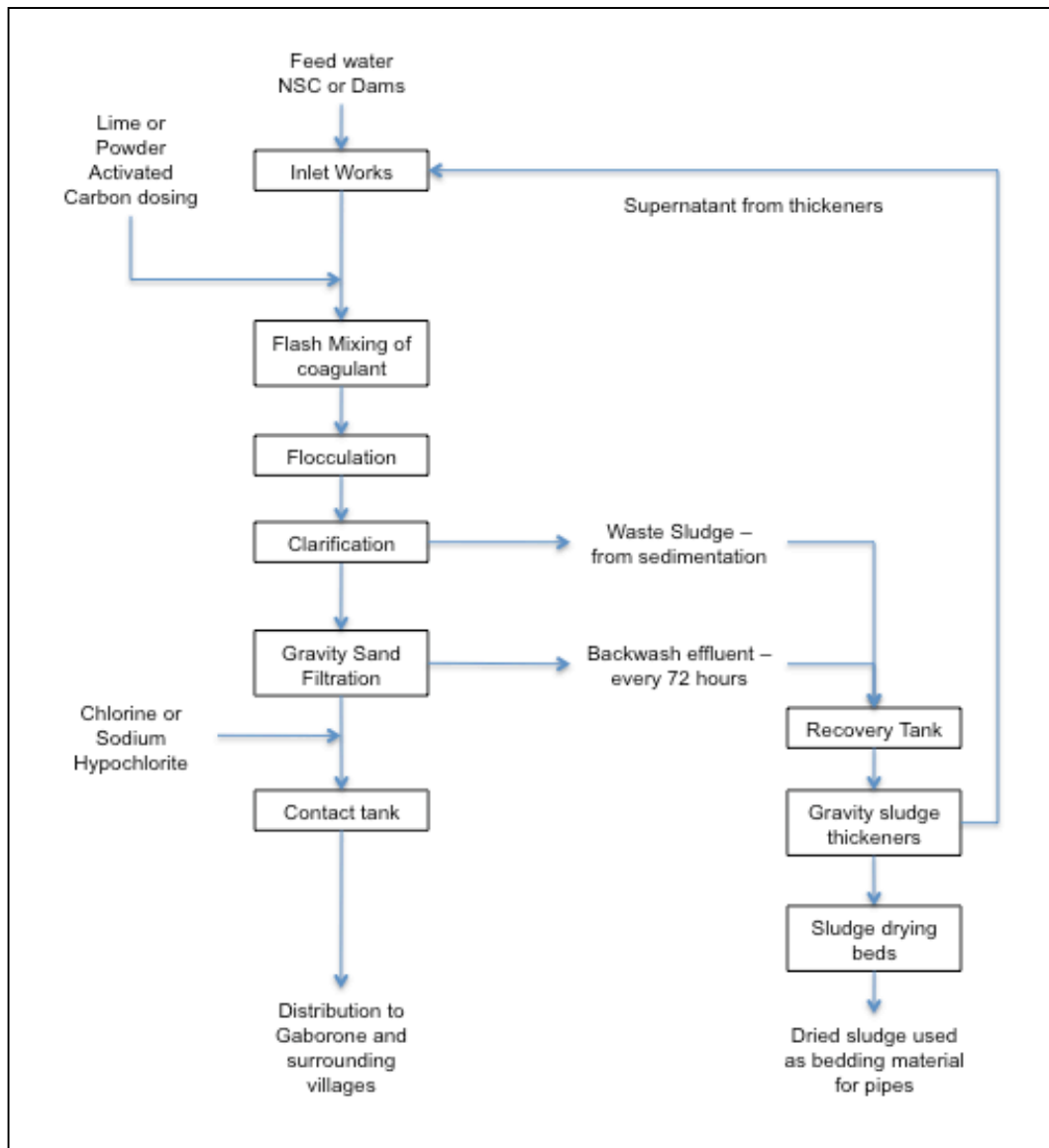


Figure 8 Flow diagram of key treatment processes at the Gaborone water works.

Storage and Supply

Gaborone has various sources of water including local catchments, cross border imports, and supply from eastern Botswana. Overall water demand is expected to increase as can be seen in Table 5.

Year	2006	2010	2020	2030
Demand (m ³ /day)	69 336	80 447	108 375	131 313

Table 5. Average day demand projections from 2005 Water Master Plan Review – Gibb and Pula 2007³¹

The Gibb and Pula 2007³¹ report justifies the need for the developing additional sources of water by highlighting that even with water reclamation, tight management practices (distribution losses currently 15%), and the current development Dikgathong Dam (eastern Botswana) demand will exceed supply by 2035.

Gaborone and Bokaa Dam

The Gaborone Dam is located on the Notwane River and is the primary feed for the Gaborone water works. The full supply capacity of the dam is 141.4 million cubic meters making it the largest dam in Botswana (WUC 2008¹³). In recent years the dam has been extremely low, below 20%, due to erratic rainfall in the catchment area. The catchment area for the Gaborone dam is large and incorporated some large villages including Ramotswa, Taung, and Mokolodi and as a result pollution from upstream is an issue, which can be expected in the future.

The Gaborone Dam has a 99/95% yield of 25 753 m³/day (Gibb and Pula 2007³¹). In order to increase this yield the Bokaa Dam was developed along with a transfer scheme. The Bokaa Dam is situated on the Metsemothlaba river north east of Gaborone. The dam is comparatively shallow and is used to transfer water to Gaborone dam. Overall the dam provides an additional 13 425 m³/day thus increasing the overall yield of the Gaborone Dam to 39 178 m³/day (Gibb and Pula 2007³¹).

Molatedi Dam

Molatedi Dam is located in South Africa and has been providing water to the Gaborone water works for almost twenty years based on a twenty-year agreement entered into between Botswana and South Africa in 1989.

The agreement is based on the Molatedi Dam level with 17 260 m³/day being made available when the dam is more than 26% full and 8 630 m³/day when less than 26% full (Gibb and Pula 2007³¹). In order to prevent the spread of aquatic plants this scheme has supplied water directly to the head of the Gaborone water works rather than the Gaborone Dam.

North South Carrier

The North South Carrier (NSC) phase one, is a transfer scheme transferring water from Letsibogo Dam in north east over 350 km away for supply to Gaborone and major villages (Palapye and Mahalapye).

The pipeline is approximately 360 km with two small treatment plants in Mahalapye and Palapye and a final treatment plant just north of Gaborone in Mmamashia.

The second phase of the scheme is to include extensions to the Mmamashia treatment plant, the construction of the Dikgatlhong Dam and a duplicate pipeline from this dam to Mmamashia.

Sub-surface Storage and Supply

Ramotswa wellfield has in the past been used as a source of supply but has been abandoned due to pollution issues. The pipeline that used to serve this wellfield has also been utilised for pumping treated water to Lobatse.

Currently no sub-surface storage of water occurs in Botswana although studies are being conducted to identify suitable aquifers for recharge.

Distribution Networks

The water works distribute water in a ratio of approximately 60:40 with Mmamashia providing the greater balance (Gibb and Pula 2007³¹). Many cross connections do occur between the two different distribution areas although generally Mmamashia supplies the area south of the railway line including Phakalane, Gaborone north and surrounding villages whilst the Gaborone water works supplies the areas north of the railway line including those villages to the south of the city. Figure 9 shows the two different areas more clearly.

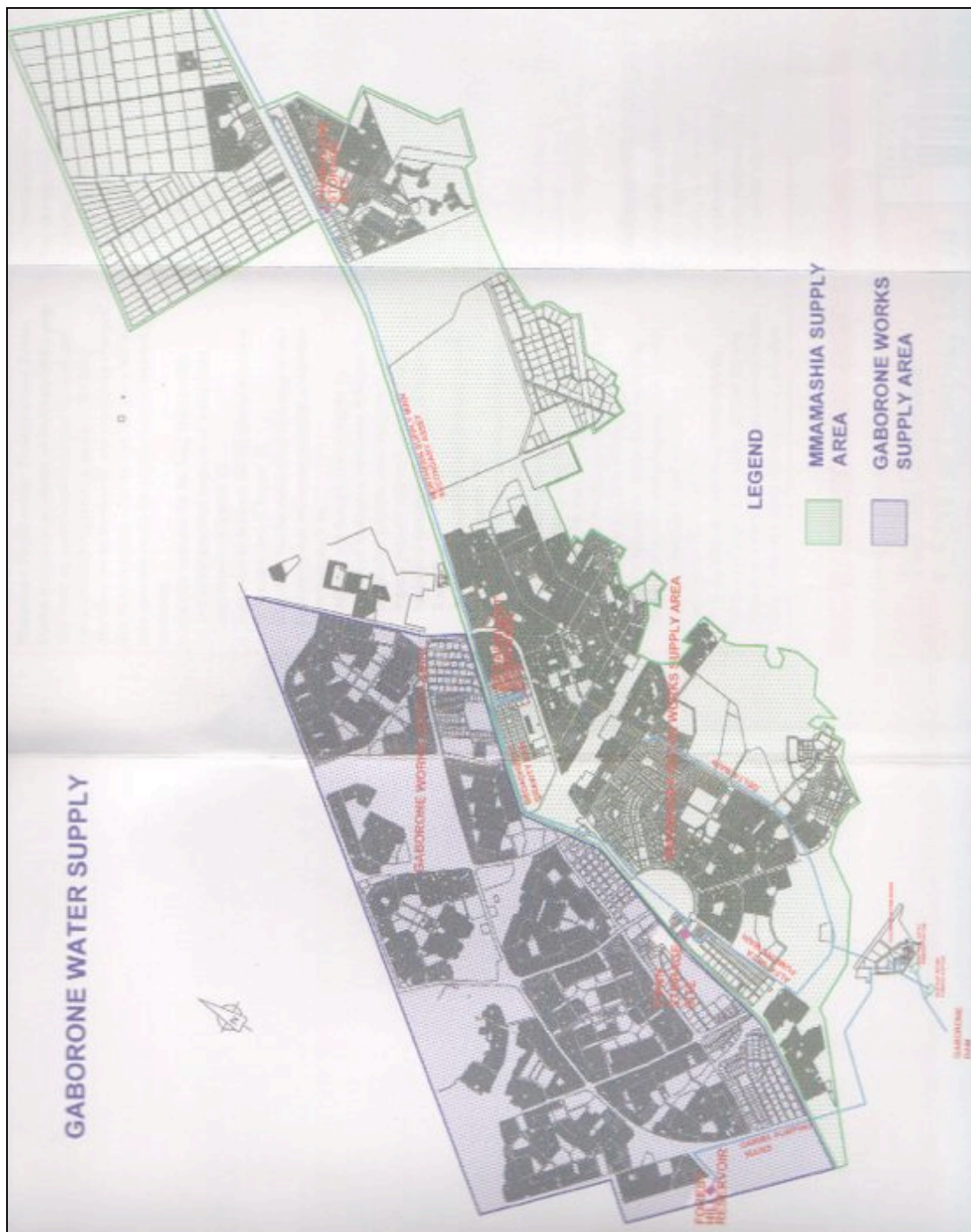


Figure 9 Overview of Gaborone water distribution networks - Gibb and Pula 2007³¹

Sewage Infrastructure

Currently the Glen Valley Wastewater treatment works collects sewage from the largest catchment area in Gaborone. This facility is serviced by four main sewer lines, which are connected throughout Gaborone by various trunk sewer lines. No distinction is made between industrial and domestic wastewater making any separation costly.

Separation of the different waste streams would be highly beneficial for the potable reuse of wastewater, and should be looked into for future developments.

Wastewater Treatment

The existing Glen Valley Wastewater Treatment Works has a designed capacity to treat 40 000m³/day of both industrial and domestic wastewater to a level of secondary treatment (Bergstan and Rites 2004³²).

The plant treats wastewater to both primary and secondary treatment levels before being sent to the maturation ponds. A detailed flow diagram of the plant can be seen in

Figure 10 although the five main treatment components include:

- ◆ Preliminary treatment – screening using belt screens and aerated grit removal, to remove larger debris, sand and grit from the influent wastewaters.
- ◆ Primary treatment – circular Primary Settling Tanks (PST) separating out suspended solids and other larger solids through settling, by reducing the velocity to the current Average Dry Weather Flow of 0.9 m/h (Liebenberg & Stander and Rites 2003³³). The sludge component is then pumped to the sludge treatment section whilst the water effluent is sent for further treatment.
- ◆ Secondary treatment – an activated sludge process in a Modified Ludzack-Ettinger (MLE) System configuration using 16 motor driven surface aerators. This configuration involves the activated sludge, from the Secondary Settling Tanks (SST), being returned to the head of the secondary treatment process where it is blended with

the effluent water from primary settling. The MLE configuration makes use of two distinct zones, an anoxic zone and an aerobic zone, both of similar volumes. Mixed Liquor is recycled from the aerobic zone back to the anoxic zone Bergstan and Rites 2004³². All excess sludge from the SST is sent to the sludge thickening process whilst effluent water undergoes secondary sedimentation at the circular SST's. The SST's velocity is determined by the mixed liquor suspended solids concentration, return activated sludge recycled ration and sludge settleability with velocities ranging from about 0.9 m/h to 2.2m/h based on these parameters (Liebenberg & Stander and Rites 2003³³).

- ◆ Maturation ponds – effluent from the SST's is then gravity fed to the ponds which have a total volume of 378 000m³ (Liebenberg & Stander and Rites 2003³³) and a surface area of 365 000 m² (Gibb and Pula 2007³¹) creating a retention time of between 5 - 11 days based on flows of between 35 000m³/day and 75 000m³/day respectively (Bergstan and Rites 2004³²). This assists in the disinfection process through exposure of the effluent to natural UV radiation.
- ◆ Sludge treatment has various components from the pumping of sludge from the PST and SST to the sludge thickening tanks. Gravity thickeners are used to thicken sludge prior to primary digestion. Once thickened the sludge undergoes primary and secondary digestion, with methane being harvested from the anaerobic conditions. This methane harvesting has not been extremely effective in the past. The majority of the harvested methane is then used for providing energy to keep the digesters at a constant temperature. Sludge retention time is approximately 15 days, which is considered the minimum time, required to adequately digest municipal wastewater (Liebenberg & Stander and Rites 2003³³). Drying beds are then used to dewater the sludge after digestion, and once dewatered it is sent to landfill sites. Any

excess liquid waste from the sludge works is returned to the head of the inlet works.

These processes are not all operating as efficiently as described with there being periodic breakdowns in the system resulting poor quality effluent water being released the maturation ponds. Although sludge handling has been identified as being the largest cause of these 'malfunctions' (Liebenberg & Stander and Rites 2003³³), part of the cause of these break downs is that the treatment works is reaching its maximum capacity.

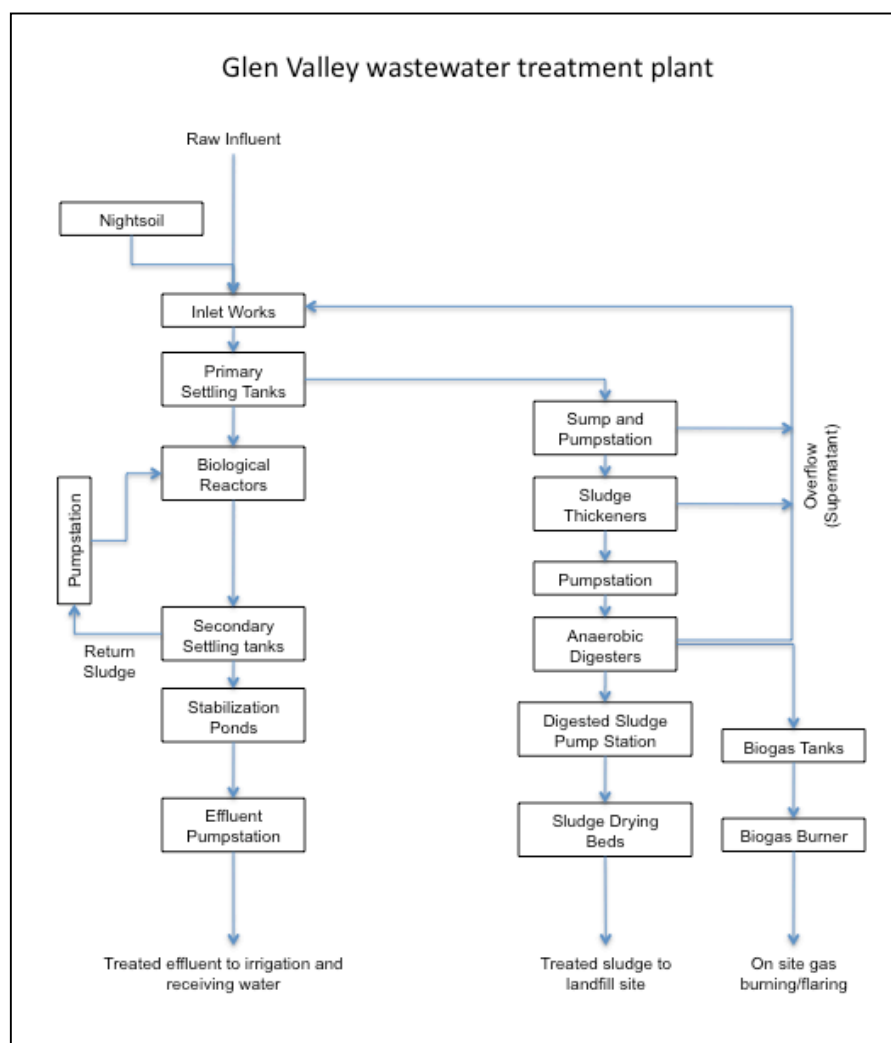


Figure 10. Flow diagram of existing Glen Valley wastewater treatment works – source Liebenberg & Stander and Rites 2003³³