



Water minimisation at the power station using process integration

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Dissertation submitted in partial fulfilment of the requirements
for the degree [Master of Science in Chemical Engineering](#) at
the North-West University

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Examination: Graduation 19 July 2019

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DECLARATION BY CANDIDATE

I, Namashishi Dorian Mokhonoana, declare that unless indicated, this dissertation is my own and that it has not been submitted for a degree at another University or Institution.

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November 2018

ACKNOWLEDGEMENTS

The author gratefully acknowledges: I thank God for blessing me with this opportunity. I would like to express my heart felt gratitude and deepest appreciation to my Industrial supervisor Mr Gerhard Gericke and my Academic supervisor Prof. Frans Waanders, for their valued guidance, interest, assistance and encouragement in reaching this milestone.

My deepest gratitude to Kriel Power Station personnel who assisted me with the information for conducting this study.

DEDICATION

I dedicate this thesis to my late mother Sophy Mokhonoana and my sister Prof Eva Manyedi who always encouraged to study.

ABSTRACT

WATER USE MINIMISATION AT COAL FIRED POWER STATION APPLYING PROCESS INTEGRATION

The primary objective of this study is to determine the reduction of the raw water intake of an existing power station by applying process integration techniques to optimise the use of water available in the system. The secondary objective is to reduce the waste water produced within the process, hence reducing the cost of water, reducing the amount of chemicals and reducing the energy needed to treat water. This will be achieved by considering a system as a whole (i.e. integrated or holistic approach) to improve its design and/or operation which exploit the interactions between different units to employ resources effectively and minimise costs.

Process integration as technique for water minimization is initiated by identifying the water sources (providers) and sinks (users) in the water network, thereafter matching appropriate sources and sinks as water quality allows. The water network therefore first must be compiled and flow and quality data can subsequently be allocated to process units in the network.

Based on preliminary runs of the model, three role players in the Kriel water utilisation network were identified:

- Wastewater treatment plant water re-use
- The possibility of blow down water re-use due to different water chemistry in the respective cooling towers
- The ability to use any water to wash floors

Three different objective functions were set for each of these scenarios and the objective functions to be minimized are:

- Freshwater intake into the station
- The sum of freshwater intake and wastewater produced
- Cost associated with water intake and waste handling

All the scenarios and objective functions were evaluated both with a model utilising a desalination plant and one without a desalination plant.

Savings of between 4% and 13% may be possible by changing the way water is currently utilised and re-used at the station. These figures translate to L/kWh sent out values of 2.23 to 2.04 respectively. These savings still do not achieve the design water consumption target of 1.8 L/kWh sent out. The same objective function values are achieved by minimizing freshwater consumption or the sum of freshwater consumption and wastewater produced.

Reuse of the wastewater treatment plant effluent has a direct impact on water consumption and investment in infrastructure to enable the introduction of good quality sewage effluent into the cooling towers shows savings in the order of R 2.2 million per year.

Optimisation of the stations water network still brings 3% savings without implementation of any of the three preliminary findings mentioned.

Keywords: Functional objective, Process integration, Optimisation, Recycle, Reuse, Sink, Sources

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GLOSSARY OF TERMS AND ABBREVIATIONS

DWS	Department of Water and Sanitation
WSA	Water Services Authorities
WSP	Water Service Providers
DOE	Department of Energy
L/KWh	Litres per kilowatt hour energy sent out
GAMS	General Algebraic Modelling System

CHAPTER 1

1.1 Background

Water is a rare commodity and South Africa is among the water scarce countries in the world. The population growth, implication of climate change on rainfall patterns, growing industrialisation, depleted environment and deterioration of key catchments are major concerns for future water supply, resulting in the quantity and quality of water slowly declining. Access to water and water availability remains a key factor in ensuring the sustainability of development in the South Africa (Media's, 2015).

Water is a critical element to sustain socio-economic development and the eradication of poverty and should be at the core of the green economy in the context of sustainable development and poverty.

1.1.1 Water governance & management

The Department of Water and Sanitation (DWS) leads and regulates the water sector in South Africa, develops policy and strategy, and provides support to the sector. The DWS is governed by two Acts, the National Water Act, 1998 (Act No. 36 of 1998) read with the National Water Amendment Act, 2014 (Act 27 of 2014) and the Water Services Act (1997). This, together with national strategic objectives, governance and regulatory frameworks, provides an enabling environment for effective water use and management

The department is further mandated to operate at national, provincial and local levels across all elements of the water cycle (i.e. from water resource management, water abstraction, water processing and distribution of potable water, wastewater collection, to treatment and discharge). The DWS does not execute all these

functions but some are constitutionally assigned to appropriate sector partners. The DWS owns most of the large dams and related water resource infrastructure and undertakes the necessary planning and implementation of future water resource development projects. On the other hand, regional bulk water distribution is managed by Water Boards, municipalities and the DWS. Water Boards and some of the larger metropolitan municipalities (Metros) purify water to potable standards (South African Water Guideline: volume 1 second edition 1996). Provisioning of water services (water supply and sanitation) is the constitutional responsibility of local government (Metro, Local or District Municipalities) who act as the Water Services Authorities (WSAs) and often also Water Service Providers (WSPs) for all communities in their areas of jurisdiction.

The objective of water governance and management is to research ways to reduce freshwater consumption from the water sources. The regulation is used as a guide to monitor the water users regarding the amount of water that can be withdrawn from the sources and the effluent quality that can be discharged to the environment and the purchase price of water. The correct application of water and process treatment strategies, combination of chemistry, monitoring and control programs can contribute to sustainable development of water users.

A variety of human activities e.g. agricultural activities, municipalities, industries, mining, power generation and recreation all compete for the water supply and usage.

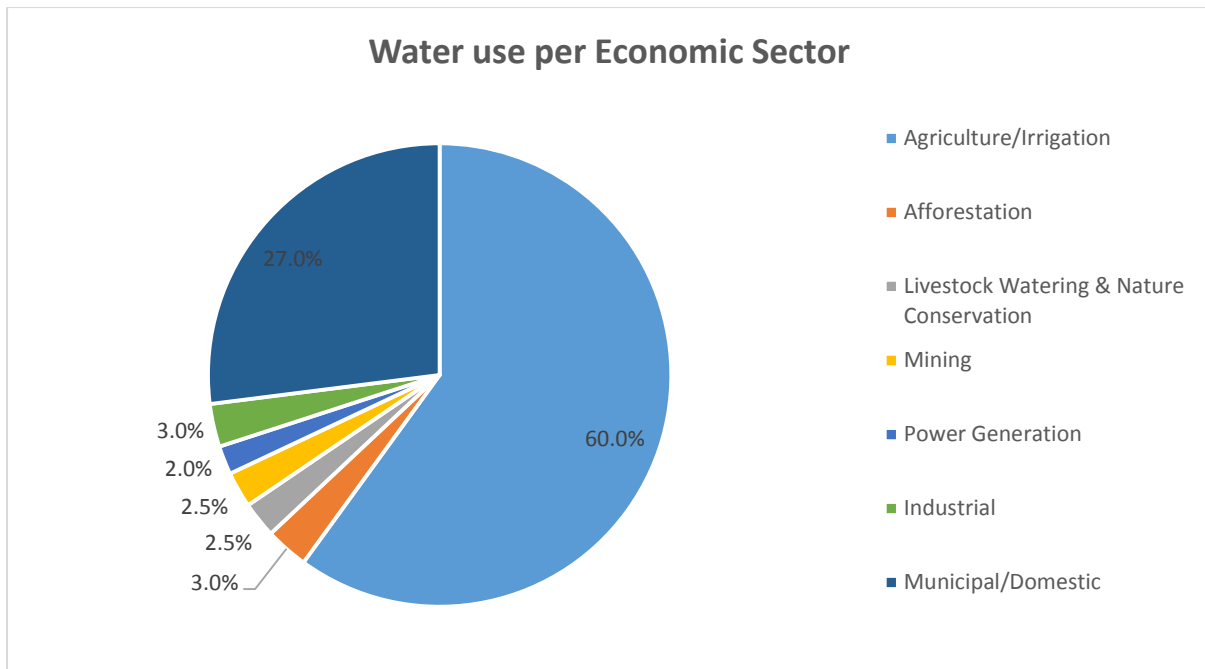


Figure 1.1: Water use per economic sector (Presidency, 2016)

The largest user of water is the agricultural sector which consumes 60% of the total water supply. This sector has a socio-economic impact in rural communities and water is one of the limiting factors to the growth of this sector. Energy generation is only allocated 2% of the available water resources, but it generates about 95% of the electricity in South Africa. Mining uses about 2.5% and its contribution to the economy is also significant.

Manufacturing, Tourism, Food and Beverage sectors are highly dependent on water for sustainability and growth.

1.2 Introduction

Water and energy are among the most basic needs for human existence and due to the population and industrial growth, the need for both will continue to increase. As energy costs increase, the intersection between energy consumption and water usage becomes important.

During his State of the Nation Address on 11 February 2016 (The South African Presidency, 2016), President Jacob G Zuma, former President of the Republic of South Africa, on the occasion of the Joint Sitting of Parliament in Cape Town, has reflected on the Nine-Point Plan to respond to sluggish growth. He highlighted the critical need for building a water infrastructure so that the government can expand access to the growing population of South Africa and industry (Water, 2015). He further mentioned the successful completion of the first phase of the Mokolo and Crocodile Water Augmentation project in the Lephalale area in Limpopo as fully operational. It will provide 30 million cubic meters of water per annum in addition to the existing projects and water schemes to minimise the country's water problems (Water, 2015).

In addition, the South African Government has ventured into bilateral agreements with the Lesotho Government on the Lesotho Highlands water project. The project comprises of several large dams and tunnels throughout Lesotho and South Africa. The purpose of the project is to provide Lesotho with a source of income in exchange for the provision of water to the Central Gauteng Province via the Orange River and the Vaal River where most of industrial and mining activities take place.

The three Eskom pumped storage schemes (Palmiet, Drakensberg and Ingula power stations) are also a joint venture between Eskom and the Government (Department of Water and Sanitation) (Media's, 2015). They serve a dual purpose of generating electricity while on the other hand are used to supplement the water supply to the nearby areas. The Drakensberg and Ingula pumped storage are of a significant value to the surrounding Highveld areas of Kwazulu Natal and the Free

State province. The Palmiet pumped storage scheme is catering for the areas surrounding the Grabouw and the Cape Town areas, in the Western Cape (Media's, 2015).

South Africa's power base is made of coal fired generation plants and one nuclear generation plant. The Energy plan (Integrated Resource Plan 2010-2030) for South Africa, initiated by the Department of Energy (DoE) laid out the proposed generation of the new build fleet of power generation for South Africa for the period 2010 to 2030 and beyond (Eskom Hld Soc Ltd, 2014). The coal and nuclear generation stations are forecasted to be built during that period and or beyond the year 2030. The extensive use of coal to generate electricity is projected to continue for many years.

Within the power generation process, water is used in the steam/water cycle, cooling systems and auxiliary plant processes and most of the power stations in Eskom are using a thermoelectric generation technology. This type of power plant uses a heat source (usually in the form of coal) to produce steam to turn a turbine, which in turn is used to generate the electrical power. Coal-fired power plants consume huge quantities of water, and in a water-stressed country like South Africa, power plants compete with other water users for the limited water supply available. Access to water and its availability remains a key factor in ensuring the sustainability of any further development in Africa. Extensive use of coal to generate electricity is projected to continue for many years, and there is an increasing demand for electricity, hence an increasing water supply will be needed (Africa, 2015).

1.3 Eskom situation

Eskom uses approximately 2% of the country's total water consumption annually and supplies about 95% of South Africa's electricity and more than half of the electricity used on the African continent (Water, 2015).

Eskom uses raw water, which must be pumped from the dams, treated and purified before entering the boiler for steam production. The salinity of the raw water determines the volume of effluents produced during the treatment process, and it has been shown that the salinity of the raw water is gradually increasing, whilst the company has endorsed the zero-liquid discharge policy (Report, 2012). Eskom aims to reduce freshwater usage and thus reduce the liquid effluent discharge, which will also reduce the high cost of chemicals that are used to treat the water.

During the 2014/2015 financial year, Eskom used approximately 313 billion litres of water for electricity generation, mainly at its coal-fired power stations (Ltd, 2013-2018). Water use targets in terms of litres per unit of electricity sent out are set for each power station every year, which are linked to the Eskom Sustainability Index (SI) contained in performance compacts, which are in turn linked to a business unit and individual performance bonuses. The targets are benchmarked against historical data as well as theoretical water consumptions for each particular type of plant.

The specific water use indicator is dependent upon the type of power station, whether open or closed loop cycles, the type of cooling and ashing processes and the quality of raw water.

There are six different types of power generation plants in Eskom, each with its unique water consumption, as illustrated by Table 1.

Table 1.1: Eskom power generation (Eskom Hld Soc Ltd, 2014)

Type of Power Generation	Water Consumption (L/kWh)
Recycle wet-cooled coal fired plant	1.95 L/kWh
Once-through wet cooled coal fired plant	6.5 L/kWh
Dry cooled coal fired plant	0.09 L/kWh
Nuclear plant	0.073 L/kWh
Hydro-electric	Not applicable
Gas turbine	0.78 L/kWh

Eskom aims to reduce its water consumption from 1.39L/kWh in 2016 to 1.34L/Kwh by 2020 (Eskom Hld Soc Ltd, 2014). This amount is the average for both wet and dry cooling, i.e. for wet cooling like Kriel power station it will be more and less for dry cooling power stations. The following technologies have been considered to lower the water consumption: dry cooling, dry ashing, the treatment of mine water which can be used to supplement supply from raw water sources, alternative energy which does not use water (e.g. solar energy and storage) (Africa, 2015), as well as improved management and operation process such as to practice the Zero Liquid Effluent Discharge philosophy (Report, 2012) (Eskom Hld Soc Ltd, 2014)Figure 1.2: shows the water consumption as L/Kwh over five years.

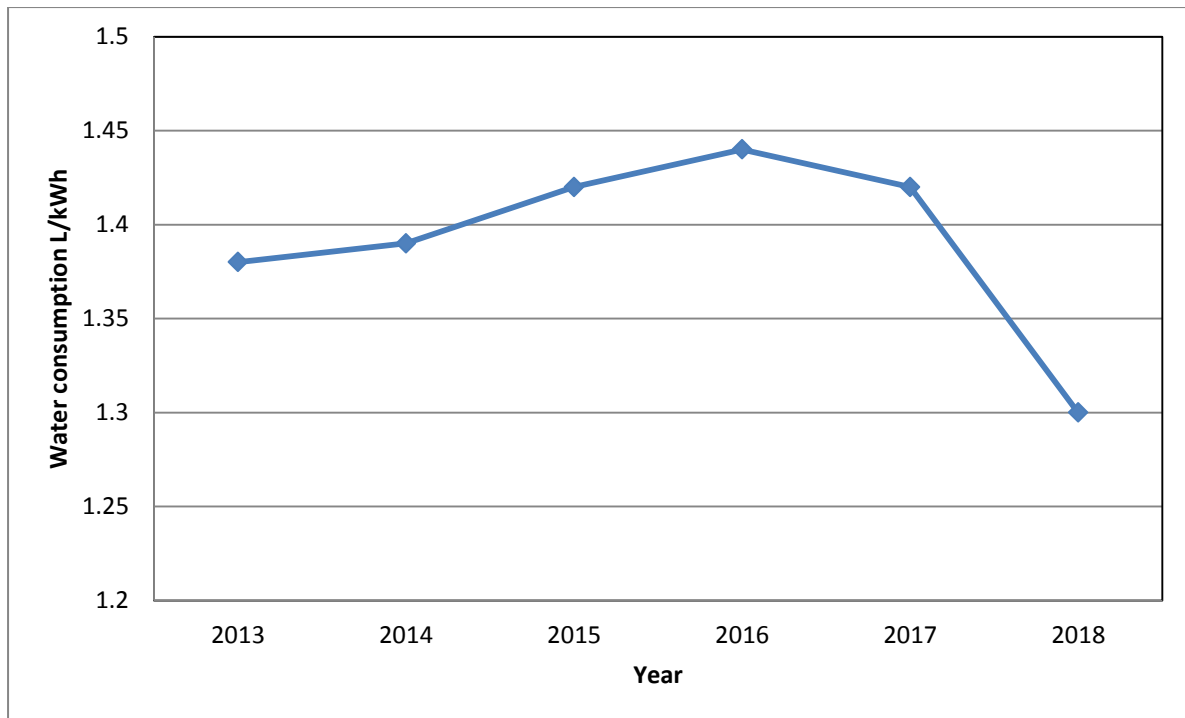


Figure 1. 2: Litres per kilowatt hour energy sent out (Ltd, 2013-2018).

The objective is to bring Eskom's water consumption relative to power produced to 0.99 litres a kilowatt-hour by 2030 (Report, 2012). The new power stations like Kusile and Medupi that are built are dry cooling only, the wet power stations are approaching their life span limits.

1.4 Objective of the study

The primary objective of this study is to determine the possible reduction of the raw water intake of an existing power station by applying process integration techniques to optimise the use of water available in the system. The secondary objective is to reduce the waste water produced within the process, hence reducing the cost of water, reducing the amount of chemicals and reducing the energy needed to treat the water. This will be achieved by considering a system as a whole (i.e. integrated or holistic approach) to improve its design and/or operation which exploits the

interactions between different units to employ resources effectively and to minimise costs.

Process integration is one of many techniques that can be implemented such as desalination of polluted mine water for reuse at the power stations, technical improvements on treatment processes to maximize the beneficial use of water and water conservation and water-demand practices.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, a review of the literature that was used as the basis for the research conducted, is given, which includes amongst others water minimisation approaches and techniques. A broad and comprehensive review of water network synthesis and optimisation modelling is presented which includes the different modelling techniques. This is based on graphical and mathematical methods used in water network optimisation. Finally, a detailed discussion on water regeneration is given, paying particular attention to water recovery by reverse osmosis regeneration which is the technology of choice in the current study.

2.2 Industrial water management

Industrial water uses include processing, cooling/heating, cleaning, transporting and flushing of waste, and are the operations within a plant that determine quality, volume, the water demand and wastewater generated. Industrial freshwater supplies include rivers, dams, groundwater and municipal water, whereas disposal sites include rivers and sewers. While the water sector is growing globally, there is an increased demand on freshwater supplies and as environmental regulations on wastewater disposal become more stringent, the rise in freshwater costs as well as effluent treatment costs have become more noticeable. As such, the process industry has been incentivised to reduce the freshwater intake and wastewater generation to maintain plant profitability (Kuo & Smith, 1998). This is achieved by the

development of water networks (WN), which can either be designed for new plants or retrofitted of existing plants. A water network is a collection of *water* using processes, which either requires or produces water, and within the operations some can be able to purify wastewater and regenerate other water sources. Other elements of a WN may include freshwater sources, wastewater disposal sites, mixers, splitters and sometimes storage tanks (Jeżowski, 2010)

2.2.1 Characteristics of water networks

Water utilisation processes can be defined as mass transfer or non-mass transfer processes. Mass transfer operations, also known as quality controlled or fixed load operations, are characterised by the mass load of contaminants that should be carried by the water, which include solvent extraction, absorption and equipment washing. Non-mass transfer processes are also known as quantity controlled or fixed flow rate operations (Jeżowski, 2010) and can be further divided into water sources and water sinks. A *water sink* is a process that consumes water and is normally a mixture of freshwater, reuse/recycle water from the sources and regenerator products. A *water source* produces water that may be used by the water sinks, the regenerator or discharged as waste (Tan et al., 2009).

Water networks consisting only of sources and sinks are known as water-using networks (WUN). The class of water network synthesis problems that allows for partial treatment of effluent is known as water regeneration network synthesis (WRNS). When the system is extended to include a centralised end-of-use effluent treatment system (ETS) it is known as a total water network synthesis (TWNS). The

combination of TWNS and pre-treatment networks results in a complete water system synthesis (CWSS) (Khor et al., 2014).

2.2.2 Water minimisation approaches

Water consumption in process plants can be altered by affecting the process conditions, such as temperatures, pressures and feed conditions. However, excluding the possibility of affecting the actual process under consideration, there are four water recovery schemes adopted in process integration (Y. P. Wang & Smith, 1994) and are illustrated in **Figure 2.1**.

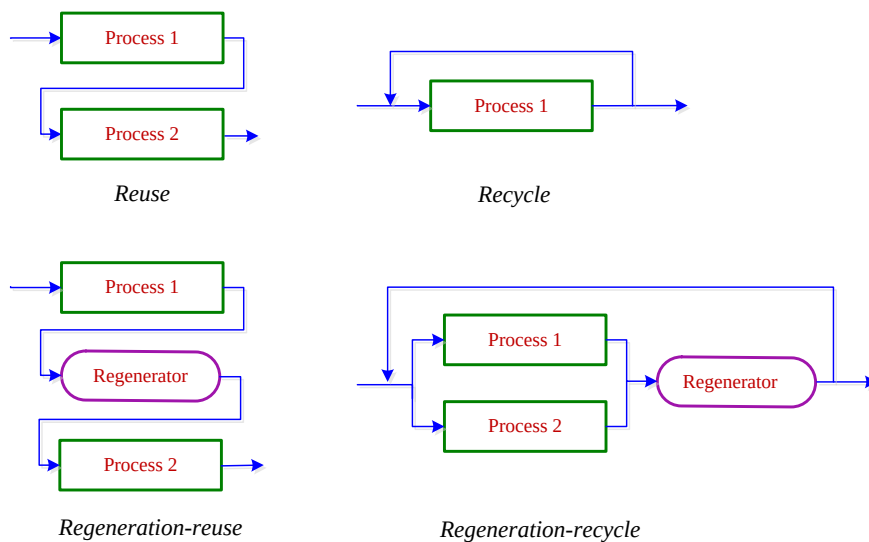


Figure 2.1: Water minimisation schemes (Y. P. Wang & Smith, 1994)

- Direct reuse. Effluent produced by one source is then reused in other operations, provided that the level of contamination does not interfere with the process. This case is shown in **Figure 2.1**.

- Direct recycle. A subset of water reuse, effluent is channelled back into the process in which it was produced, as depicted in **Figure 2.1**. In both reuse and recycle, effluent can be blended with water from other operations or freshwater before it is reused or recycled.
- Regeneration reuse. As shown in **Figure 2.1**, water from a source can be partially treated to remove contaminants, i.e. water is regenerated, to make it amenable for reuse in other sinks.
- Regeneration recycle water. Effluent is partially treated to remove contaminants that may have built up, and then recycled into the same operation. This is depicted in **Figure 2.1**.

The combination of the above four cases gives rise to the formation of the water regeneration network synthesis (WRNS) plan. Partial purification can be performed using membranes, chemical additives and steam stripping, among other processes (Cheremisinoff, 2002). When synthesizing water networks, for optimal operation, a combination of all schemes must be allowed. While regeneration reduces water consumption, this may come at the expense of energy and a high capital investment.

2.3 Process integration

There are quite a number of studies where resource management problems are collapsed into subproblems such that the interactions between the different parts are not simultaneously explored (Alva-Argaez, (1998); Karuppiah & Grossmann, (2006)). The motive for this notion being the need to avoid handling complex interactions between subsystems (Chang & Li, 2005). The same idea was inherent in the early works on water minimisation studies as described by Huang et al., (1999). Examples

include work by El-Halwagi & Manousiouthakis (1989), Gupta and Manousiouthakis (1994) and El-Halwagi et al., (1996), all of which used sequential design strategies.

Process integration is a holistic approach to process design, retrofitting and operation that emphasises the unity of a process by virtue of the strong interactions that exist between the different unit operations (Tan R, (2009)). As far as sustainability is concerned, process integration is a powerful and effective framework for sustainable design due to the minimisation of resource consumption through designing and planning utility networks within industrial manufacturing plants under a unified framework (Tan R, (2009)). As shown in **Figure 2.1** water minimisation can be achieved through a water recycle, reuse as well as regeneration-recycle and regeneration-reuse process integration.

Increased economic and environmental awareness in relation to sustainable engineering has driven designers towards more efficient water systems through process integration. In this regard, the optimisation of water networks has become a vital instrument of sustainability as it allows extensive exploration of the synergies that exist between water-using operations and water treatment systems to ensure their efficient integration. Water management through these techniques has grown to be a mature field where complex conditions are analysed and solved. There are two main approaches commonly employed when addressing water network problems and are known as insights-based techniques and mathematical model-based optimisation techniques.

2.4 Insight-based techniques

In water network optimisation, the most common insight-based method is *water pinch analysis* (WPA), which is a graphical technique. The method of pinch

technology was initially developed for heat integration in heat exchanger networks (HENs) by Linnhoff & Hindmarsh (1983). They developed a method for the minimisation of energy and utilities in a heat exchanger network, while simultaneously reducing the number of required heat exchange units. This was achieved by identifying and exploiting thermodynamic bottlenecks, known as pinch points in the systems. The optimal HEN was then developed based on the location of the pinch points, rather than a mere comparison of the available and required energy in the hot and cold streams in the network. As a result, it was possible to achieve the highest degree of energy recovery at a minimum capital expense. The same concept was later applied to the synthesis of mass exchange networks (MENs) (El-Halwagi & Manousiouthakis, 1989). In this case, the technique was used to improve the configuration of MENs to maximise the amount of a species that can be transferred between rich and lean process streams of the network.

Wang & Smith (1994a), proposed the first water pinch approach for the minimisation of water in process plants. Using concepts from heat exchange networks and mass-exchange networks, the methodology starts by developing limiting water profiles for each of the unit operations considered in the plant. Each profile indicates the limiting case when the minimum water flowrate is used by a unit; that is, when the maximum inlet and outlet water concentrations are specified. **Figure 2.2** graphically illustrates a limiting water profile for a typical process.

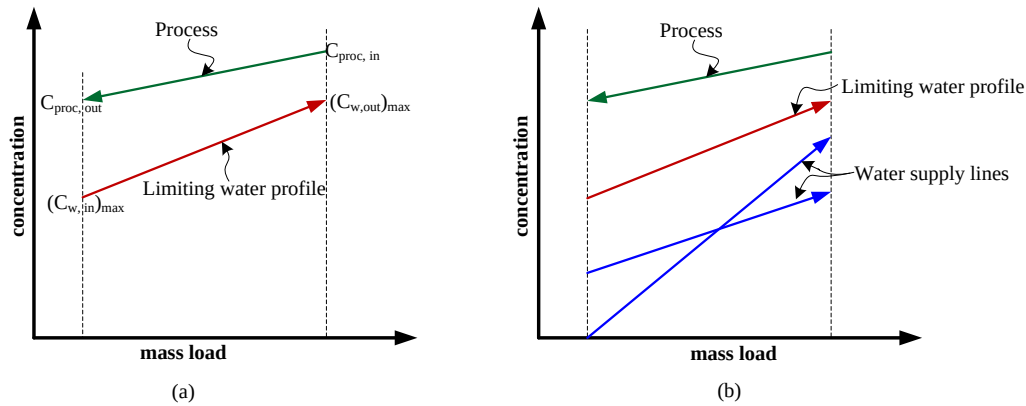


Figure 2.2: Graphical representation of a typical water limiting profile (Y. P. Wang & Smith, 1994)

Any water supply line below the limiting profile line satisfies the requirements for the given process. The limiting data for each unit is determined based on:

- i. mass transfer behaviour
- ii. solubility limits
- iii. need to avoid precipitation
- iv. fouling and corrosion limitations
- v. flowrate limit to avoid solid material settling

To incorporate the holistic nature of process integration, individual profiles are combined to form a limiting composite curve which represents the overall water sources (flow rate and concentration) available on the plant, as well as the water sinks. The minimum fresh water flow rate through the overall process is determined by matching the overall freshwater supply line against the limiting composite curve as shown in **Figure 2.3**. According to the water supply line the graph touches the limiting composite line at an intermediate point called the '**pinch point**'.

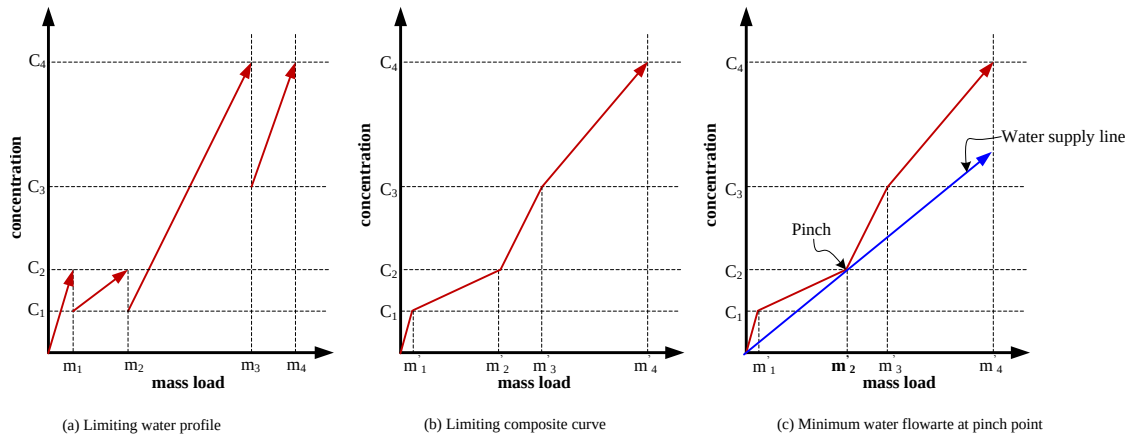


Figure 2.3: Graphical representation of the limiting composite curve ((Y. P. Wang & Smith, 1994)

The water pinch point indicates the bottleneck for further water minimisation. Operations below the pinch require freshwater and those above the pinch can reuse water from other operations. To decrease the usage of water further, only processes under the pinch point need to be considered (Wang & Smith, 1994a). After the targeting step, some rules are used to derive a set of alternative network design structures. In practice, each of the networks obtained is evaluated for its applicability and the best one is then chosen.

Using this basic approach, Wang & Smith (1994a) tackled cases for single and multiple contaminants, with options for wastewater regeneration also explored. The authors observed that the approach led to designs with unnecessary complexity and as such they modified it to produce alternative water network designs that exploit bypassing and mixing to minimise the number of recycle/reuse matches (Wang & Smith, 1994a). Noteworthy is that in their approach, freshwater targets are set before the water network is designed.

In later work, Wang & Smith (1994b) presented a method for the design of distributed effluent treatment systems using pinch technology. The approach was very similar to their earlier work (Wang & Smith, 1994a). The aim was to minimise the flow rate of effluent to be treated, under the assumption that cost is minimised when the quantity of wastewater to be treated is minimised. As such, the treatment flow rate was the target flow rate and instead of having a composite limiting curve, a composite effluent curve was derived. Based on the analysis of the work, they managed to set design rules, specifically for targets to be achieved in practice based on the location of the pinch point. Streams starting below the pinch completely bypass treatment and those above, are fully treated, while those starting at the pinch are partially treated.

Despite being able to provide useful insights into the design of distributed effluent systems, for some instances, the method by Wang & Smith (1994b) fails to give minimum targets for treatment flow rates because it is the network structures that are optimised not the targets. Additionally, it failed to address important design features when using multiple regenerators as all the design structures that emerged from the method were always connected in series.

In light of these limitations, Kuo & Smith (1997) improved the technique by considering optimisation costs that are based on the targets instead of the individual designs. This was achieved by subjecting the initial design to detailed simulation and costing after which the design is either approved or iterated back to the targeting and network design. They also further extended the approach to handle retrofitting cases.

It was the pioneering work of Wang & Smith (1994a) that stimulated a series of enthusiastic research activities in the field of water pinch. Since their work, heuristics

and somewhat similar graphical and tabular schemes have been amalgamated into water pinch theory to refine and modify the technique and extend its applicability to various systems found in the real world. This includes the water mains method by Kuo & Smith (1998) which involved pinch identification, operation grouping and operation migration. In this method sharply reduced freshwater consumption resulted, however, it does not guarantee optimal solutions (Teles, 2008).

Noteworthy is that all the water pinch techniques discussed thus far are based on a mass transfer model. As such, units such as reactors, boilers and cooling towers that handle only flow rates and not the amount of contaminant transferred cannot be modelled adequately in a similar way. Moreover, the early method could not handle cases of several aqueous streams entering a unit as well as water gains and losses which are very common in practical operations.

In response to these limitations, Dhole et al., (1996) developed a new technique to overcome these difficulties; however, the technique was not purely displayed in a graphical way. In this approach, network designs are first developed using mathematical programming and then graphical representation of the designs are developed afterwards (Hallale, 2002). Details of the technique are shown in

Figure 2.4.

Later, Hallale (2002) adapted ideas from Dhole et al., (1996) to develop a new graphical targeting approach. Unlike the method proposed by Dhole et al., (1996), this technique is purely graphical and therefore gives water targets *a priori* and not the design (Hallale, 2002). In this approach, demand composite and source composite are plotted based on the fractional water purity (vertical) versus the flow

rate (horizontal) axes, hence the plots are made up of horizontal and vertical lines as illustrated in **Figure 2.4**.

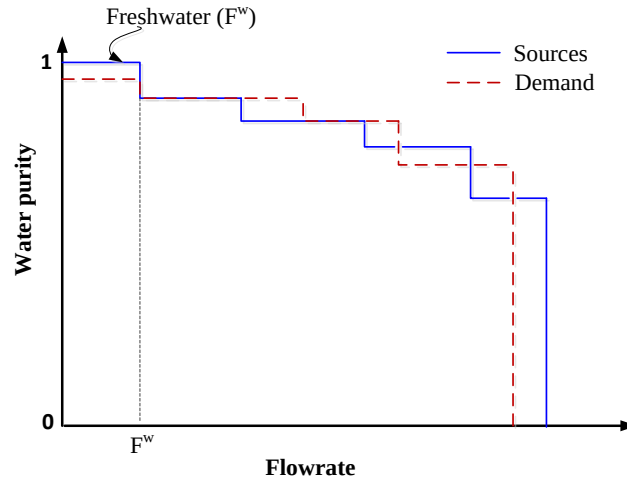


Figure 2.4: Simplified graphical representation of construction diagram of demand and source composites (Hallale, 2002)

A freshwater flow rate is arbitrarily assumed and included in the source composite in the technique the feasibility for the assumed freshwater flow rate by means of water surplus diagrams is examined. These are constructed, noticing that at some regions the source composite is above the demand composite implying a surplus of pure water and vice-versa. The pure water surplus and deficit at each region is determined by calculating the area of the enclosed rectangles. The cumulative surplus is plotted against the water purity to form the water surplus diagram as shown in **Figure 2.5**.

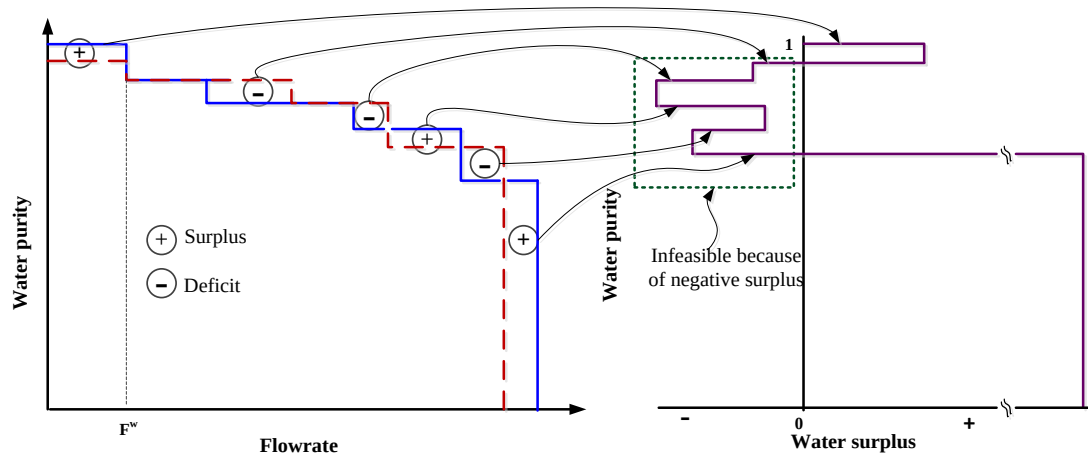


Figure 2.5: A graphical illustration of the construction of a Water Surplus Diagram (Hallale, 2002)

Because the cumulative surplus is enclosed between the two composites in an integral function, the approach automatically incorporates the possibility of mixing sources. If part of the plot lies on the negative side, it implies that there is insufficient purity and more freshwater must be added until no part of the surplus diagram is negative. The procedure is repeated until the minimum freshwater and wastewater targets are achieved; that is when the plot just touches the vertical axis, as shown in

Figure 2.6

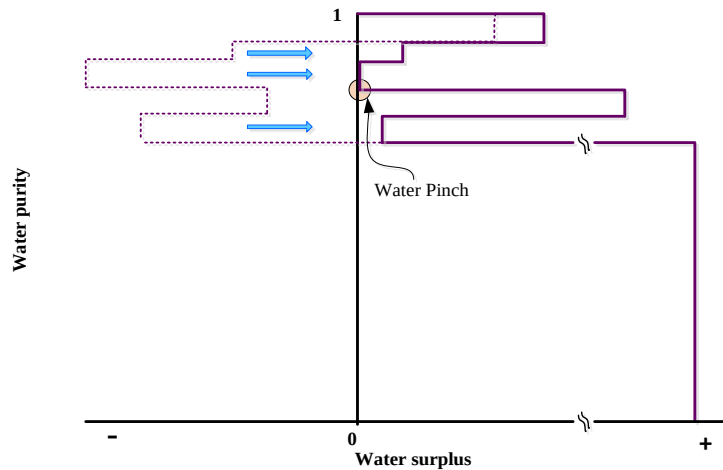


Figure 2.6: Graphical representation of the determination of minimum water targets (Hallale, 2002)

The targeting problem is thus a linear representation and can be obtained using mathematical programming to attain an overall optimum; however, the graphical technique offers increased insights on beneficial process modifications and regeneration (Hallale, 2002). Once the target has been set, a set of network designs is developed and the best one chosen based on economic, geographical and safety constraints.

The major drawback in the method proposed by Hallale (2002), is the extensive calculations required to produce surplus diagrams. In view of this, El-Halwagi et al., (2003) developed a new single-stage, systematic and graphical targeting technique for recycle/reuse networks building on from the work of Dhole et al., (1996) and the ideas presented by Hallale (2002). In their method, optimality conditions were first established using dynamic a programming formulation and parametric optimisation. The results of applying the conditions are then used in developing a pinch-based graphical representation of composite load versus flow rate (El-Halwagi, et al., 2003).

Manan et al., (2004) developed a new systematic numerical alternative to water surplus diagrams referred to as the water cascade analysis (WCA). This tabular technique eliminates the tedious iterative procedure of the water surplus diagrams and allows for quick and accurate determination of water targets as well as assessments for regeneration opportunities and process changes. According to Manan et al., (2004), a good targeting technique to determine true minimum targets should include the following:

- i. handle both mass-transfer based and non-mass-transfer based water operations
- ii. consider both flow rate and concentration driving force (water purity) for water reuse
- iii. be non-iterative and yield exact targets

In the method an interval water balance table, to determine net water source/demand at each level, is used. The cumulative net water source/demand is obtained from water cascading which is then used to determine the minimum water targets. Manan et al., (2004) showed that water cascade analysis is a numerical equivalent of the water surplus method as was described by Hallale (2002). The method can generate exact utility targets and pinch location more quickly. To date, this technique has been applied successfully in industry and continues to be used (Ng, et al., 2007).

2.4.1 Limitations of the Insight-based techniques

Despite the success in achieving minimum water targets, water pinch has the limitation of failing to obtain high accurate targets, because of its graphical nature.

Additionally, the technique fails to consider multiple contaminants simultaneously (Hallale, 2002) and as the problem becomes bigger, that is; multiple contaminants, multiple sources and sinks and multiple treatment processes, are introduced, it becomes tedious and less accurate (Kuo & Smith, 1997). It was also observed that many of the early water pinch methods struggled to deal with multiple pinches and retrofitting cases although the later methods managed such situation relatively well (Hallale, 2002; Manan, Tan, & Foo, 2004).

Another major limitation of water pinch is its inability to incorporate all constraints of the problem. As highlighted by Doyle & Smith (1997), water minimisation problems are not confined to concentration and flow rate constraints only. Other constraints such as economic, geographical and safety constraints also exist and these affect the optimal designs to be considered. Additionally, cost constraints determine the economic feasibility of a design. However, most water pinch methods do not guarantee cost optimal solutions (Doyle & Smith, 1997). A true robust method needs to consider all these constraints however complex they may be.

2.5 Mathematical based techniques

Mathematical programming to solve the problem was inspired by the many limitations of using insight-based approaches, primarily the need to eliminate the tedious steps of graphical targeting and to incorporate all constraints into the problem. The mathematical programming approach of water networks is based on the optimisation of a network superstructure. The superstructure of a water network is a description of all possible feasible connections between water using processes and water treating processes. The optimal solution is a subset of the superstructure

and is identified using optimisation methods. Based on this superstructure, a mathematical model, describing the problem with all economic, geographical, control and safety constraints included, is built. This enables the technique to deal with more detailed design considerations such as data uncertainties, life-cycle impacts, network topology and capital costs (Tan R, (2009)). The optimisation problem represented as a mathematical model is then solved using rigorous algorithms to obtain global or near-global solutions. Minimum water targets are determined simultaneously with the network design.

Within mathematical programming, problems can be modelled by using either a fixed contaminant mass-load framework or a fixed flow rate framework. Fixed mass load operations are quality controlled and the data is usually expressed by limiting the flow rate and maximum inlet and outlet concentrations (Bandyopadhyay & Cormos, 2008). Outlet concentrations on units are dependent on the inlet concentrations and flow rate; however, inlet and outlet flow rates are assumed to be the same (Teles, 2008).

On the other hand, fixed flow rate operations are quantity controlled. They can be used to model both mass transfer-based operations and non-mass transfer operations (Bandyopadhyay & Cormos, 2008). A unit is treated either as a water source or as a wastewater sink with fixed output or input flow rates, respectively. A fixed contaminant concentration for the sources is specified as well as the concentration upper limits to the sinks' inlets. Inlet and outlet flow rates need not be equal therefore the outlet concentrations are independent of the inlet concentrations (Teles, 2008).

(Bandyopadhyay & Cormos, 2008; Poplewski, 2010) show that operations under a fixed flow rate framework are more prominent than those under a mass load framework and as such, have become more attractive compared to fixed-load models. They can be applied to various situations, in miscible phase networks, water allocation in industrial parks, in urban water networks as well as in some mass-transfer based operations that require a fixed flow rate framework.

Trends, similar to those observed in the development of water pinch, in terms of which framework to adopt, have been observed in the development of mathematical programming techniques. Early approaches were mostly mass-load based while the later methods shifted towards a fixed-flow rate framework (Khor et al., (2014). The decision of which framework to adopt depends on the author's opinion and the availability of data.

The technique was initially developed in the late seventies, where Takama et al., (1980a) proposed the combination of all possible water allocation and treatments options in a petroleum case study into one integrated system. The preferred option was selected by identifying the variables that resulted in the minimum cost, subject to material balances and interrelations among water-using and wastewater-treating units. The mathematical model presented was a nonlinear programming (NLP) and was solved using an algorithm known as the Complex Method. The authors stated that this method was inefficient for application to complicated problems. In subsequent studies, a modified solution procedure was proposed. This method involved the iterative application of linear programming to linearize the problem. To reduce the complexity of the problem, heuristics, based on practical and economic reasoning were applied to remove unnecessary features of the water network. For example, recycling within a water treatment unit was not allowed; and freshwater

streams were prohibited from directly entering treatment units (Takama et al., 1980b, 1981).

After several years, Doyle & Smith (1997) conducted a study that combined the works of Wang & Smith (1994a, 1994b) and Takama et al., (1981, 1980a, 1980b). The authors used graphical methods to attain physical insights into the parts of the system that require most attention, i.e. pinch points. The mathematical approach involved iterative solutions of both linear and nonlinear models, considering the insights provided by the graphical techniques. This work also enabled the simultaneous modelling of multi-contaminant systems. Similarly, Hallale (2002) presented a method that combined both WPA and mathematical methods. A graphical technique was used to identify the pinch point and by using the insights gained from the composite curves, mathematical models were used to design the network.

Mathematical optimisation provides the benefit of being able to handle complex systems, e.g. multiple contaminants and water regeneration network synthesis. However, since WNS problems are often nonlinear, the computational expense is often very high. Several advancements have since been made in the field, and these have been discussed at length in reviews by Bagajewicz, (2000), Jeżowski (2010) and Khor et al., (2014).

2.5.1 Convexification

Generally, superstructure optimisation models are nonlinear in nature, owing to the large number of economical, topological, component and mass balance constraints associated with them (Bagajewicz & Savelski, 2000). As such, most optimisation

problems result in complex NLP problems or mixed integer nonlinear programming (MINLP) problems that are usually nonconvex and difficult to solve to global optimality. The complexity arises due to bilinear terms (which create nonconvex functions) in the mass balance equations and the concave cost terms in the objective (Ahmetović & Grossmann, 2010), which result in nonconvexities within the model. The complexities are also due to the existence of integer variables, nonlinearities and nonconvexities within the model (Ahmetović & Grossmann, 2010). Standard NLP and MINLP solvers do not guarantee global optimality for nonconvex problems.

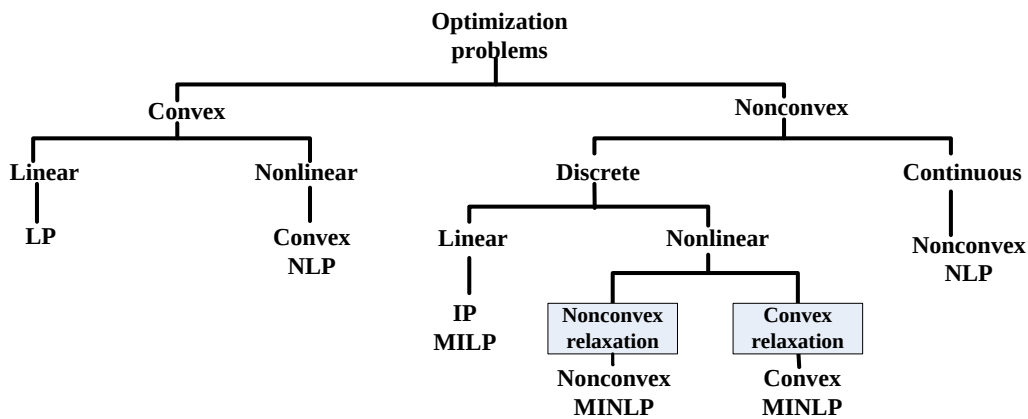


Figure 2.7: Tree diagram showing the problem types related to optimisation problems (Lin et al., 2012)

Algorithms and procedures aimed at solving nonconvex problems target developing convex underestimators (approximations of the nonlinear formulations) to formulate lower bounding convex NLP/MINLP problems that can be solved to global optimality using standard solvers (Grossmann & Biegler, 2004). These convexification methods achieve this, either by directly replacing each nonconvex function with a convex underestimating function, or by introducing new variables (transformations)

and convex constraints that accurately approximate the nonconvex function (reformulation-convexification). These relaxation techniques form the main ingredients of most of the existing exact algorithms for non-convex NLP and MINLP problems.

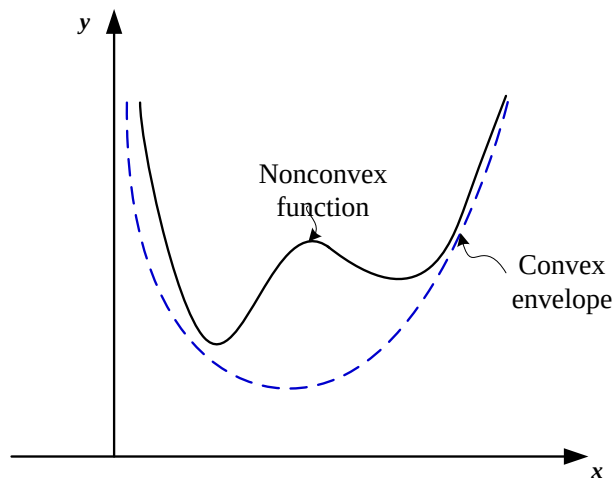


Figure 2.8: Convex envelope for non-convex function (**Grossmann & Biegler , 2004**)

Non-convex models give rise to many suboptimal solutions and lead to certain complications that cause the failure of most local optimisation models (Zamora & Grossmann, 1998). In the absence of convexity, NLP methods fail to locate the global optimum solution (Ryoo & Sahinidis, 1996). This difficulty can, however, be handled in several ways (Jeżowski, 2010) through direct linearization, generating a “good” starting point, using sequential solution procedures and by means of global (deterministic) optimisation methods.

2.5.2 Direct Linearisation

This method involves the linearization of the nonlinear terms in the mathematical model. This is achieved by the selection of linear conditions for optimality. In the context of WN, linearity constraints exist for non-mass transfer processes as well as processes with or without regeneration, which are defined by fixed outlet concentrations (Jeżowski, 2010). Relaxation methods proposed by McCormick (1976) and Glover (1975) can be used to linearize an MINLP problem. Different methods for linearizing NLP and MINLP models have been proposed over the years.

Bagajewicz & Savelski (2001) showed that a WN with mass transfer processes and single contaminants can easily be linearized when freshwater minimisation is the only objective of the optimisation. They proposed an iterative method, which involved LP formulation for the optimal solution of the single contaminant problem and an MILP for the design of the different possible network alternatives. The method was based on the previously developed necessary conditions of optimality. Partial regeneration of wastewater was also considered in the formulation. In the case where no regeneration was considered, a sequential two-step procedure was proposed in which the LP (freshwater minimisation) solution was made the starting point of the MILP, which minimises the number of interconnections. The bi-linearities were eliminated in this case by setting the outlet concentrations to their maximum values. In the case where regeneration was considered, an additional step which involved the MILP solution being the starting point of another LP with the objective of determining the minimum amount of water through the regenerator. The optimality conditions for water regeneration without recycle were also determined. This method, however, uses the fixed load method and was limited to single contaminants.

Savelski & Bagajewicz (2003) then extended the work by Bagajewicz & Savelski (2001) for multiple contaminants through the selection of a key component. This work was the first to provide proof for optimality conditions for multiple contaminants and proved that at least one contaminant reaches its maximum allowable concentration at the outlet of the freshwater-using process and that concentration monotonicity only holds certain key contaminants. The first condition was that, at every outlet of a partial water provider, the outlet concentration of a key component should not be lower than the concentration of the same component from the precursors. The second condition states that the outlet concentration of a key component of a partial provider head process must be equal to its maximum concentration and the third condition was that the outlet concentration of at least one component of an intermediate process reaches its maximum value. Regeneration of streams was, however, not considered in their work and the model was based on a fixed load model. Freshwater minimisation was the only objective of the work.

The methods provided by Bagajewicz & Savelski (2001) and Savelski & Bagajewicz (2003) provide an exact linearization method as the method is applied to LP and MILP problems. Exact linearization is, however, not possible for non-convex MINLP models.

2.5.3 Generating a “good” starting point

In this method a global optimum or “good” optimal solution is determined. This is achieved by using problem linearization to provide a good starting point for the non-convex MINLP problem. The initial point can be obtained by stochastic optimisation or through problem linearization. The most common practice for mass transfer water

using operations is to remove the bilinear term by fixing outlet concentrations in all operations to their maximum values (Jeżowski, 2010). The initial guesses adopted for solving NLP and MINLP models have a significant impact on the convergence process and must therefore be chosen with reliable methods (Zamora & Grossmann, 1998).

Li & Chang (2007) proposed an efficient initialisation strategy to solve NLP and MINLP models for WN synthesis problems with multiple contaminants by generating near feasible guesses. The model is based on a superstructure and the initialisation strategy is based on knowing the mass load of contaminants in every water-using unit, the rate of water loss in each unit and the upper bounds of the corresponding inlet and outlet concentrations (Li & Chang, 2007). The computational time for solving the NLP and MINLP models was reduced as a result. The NLP model was, however suited for small-scale problems while the MINLP model could be used to optimise larger water using systems by including structural constraints for the simplification of the network configuration. The method, however, did not guarantee global optimality.

Teles et al., (2008) proposed an initialisation procedure that replaces the NLP with a succession of LP models that are then solved for all operation sequences. The LP model was first relaxed and used as a starting point for the NLP model. Teles et al., (2008) therefore looked at four initialisation methods for the NLP model which were proposed and tested. The first method looks at a single starting point by linearizing the NLP by looking at the maximal concentrations or by removing connections among the fixed load operations. The other method looks at using multiple starting points. Each point is, however, related to a predefined sequence of fixed load operations and the LP model is also generated by the two methods used in the

single starting point scenario. The best solutions were obtained in the case where multiple starting points were used with the maximal concentration linearization method. This method, however, was computationally expensive. The procedure proposed does not guarantee global optimality but provides a large probability of finding the globally optimal solution. The model does not also consider regeneration.

Galan & Grossmann (1998) looked at the optimum design of a distributed wastewater network where multiple contaminants were considered where a NLP and MINLP model for the superstructure was proposed and it was presented by Wang & Smith (1994b). This paper was the first to address the synthesis regeneration networks within the WN. Three formulations were presented with the first formulation looks at a NLP model for the distributed wastewater treatment network synthesis with nonlinear bi-linearities in a mixer unit. The second formulation looks at an MINLP model that employs 0-1 variables for the selection of different treatment technologies. The treatment units in this case were described by a constant removal ratio. The final formulation looks at an NLP model for membrane-based treatment technologies by using short-cut design equations instead of a fixed removal ratio. A search procedure, that is based on a relaxed linear model was thus proposed with the LP relaxation based on the method proposed by Quesada & Grossmann (1995). The solution from the LP model was then used as a lower bound as well as a starting point for the NLP model. Different objective functions were used in the LP model to provide different starting points for the NLP model (the best objective function was then selected), which led to different locally optimal solutions. The best solution was then chosen as the upper bound for the globally optimal solution. The non-convex exponential terms in the objective function was linearized by using linear under estimators, as proposed by Zamora & Grossmann (1998). Near global or global

optimum solutions were found, however, computationally demanding even though it was very effective.

NLP and MINLP models can therefore be solved with less computational time once a “good initial starting point” is provided, which therefore aids in the convergence process of the model. This method does not guarantee an overall optimal solution and minimises the chance of a nonlinear solution becoming a local solution, which is far from the globally optimal solution (Doyle & Smith, 1997).

2.5.4 Sequential solution procedures

This section describes the iterative methods used in the sequential solution procedure. With regards to WNs, the concentration intervals are divided into smaller intervals until convergence is achieved. The work by Takama et al., (1980) was the first to use this sequential optimisation procedures for solving WN problems.

Doyle & Smith (1997) then presented the first model for a sequential superstructure optimisation approach for WN synthesis, which was based on an iterative procedure. The superstructure used considered direct reuse and recycle streams. The solution procedure they proposed, involves a sequential procedure that uses a linear programming (LP) approximation as an initial guess to solve an NLP. The model considered multiple contaminants and water regeneration was not considered. The linearization was based on the assumption of a fixed maximum outlet concentration and the water using processes were then modelled by assuming a fixed mass load for the NLP. The LP problem is solved first and used as a starting point for the NLP problem. Convergence was, however, achieved by the introduction of additional constraints on the maximum wastewater flows and forbidden stream matches.

Feasibility was also achieved by relaxing the concentration balance as an inequality. The method they proposed, however, does not guarantee a globally optimal solution, but does reduce the difficulties that are associated with NLP problems.

Gunaratnam et al., (2005) used the sequential superstructure optimisation approach to generate a WN which considers both water-using operations and water-treating systems in three steps. In the first step, the material balance equations are relaxed by setting the outlet concentration at a maximum and introducing slack variables to create an MILP. In the second step, the flow rate solutions are then used as the starting point for solving the LP relaxation. This generates new concentration values that can be used in the MILP in the next step. The objective of the LP problem is to minimise the summation of the slack variables. In the last step, convergence is achieved when the sum of the slack variables becomes small and this then becomes the solution for the MINLP. The LP and MILP models are therefore solved iteratively until convergence and then used as a starting point for the MINLP model. The network complexity was also reduced through the specification of the minimum permissible flow rate, maximum number of streams allowed at a mixing point and piping costs. Binary variables are also used to enforce/eliminate certain substructures from consideration.

This method is computationally demanding and does not necessarily guarantee an overall optimum solution. Regeneration recycling was also eliminated to avoid concentration build-up. The number of water-treating operations was fixed and was modelled using the removal ratio. This therefore means that a detailed design was not used to describe the treatment systems. The cost of effluent treatment was also assumed to be proportional to the effluent flow rate.

2.6 Membrane regeneration systems

Membrane technology has gained a growing level of application in the process industry (Galan & Grossmann, 1998). This is because membrane technology is less energy intensive than the traditional separating processes such as distillation. Membrane systems also have a low capital and utility cost. They are based on thin film-like structures that separate two fluids and act as selective barriers to retain pollutants in a contaminated stream in order to allow water (solvent) to permeate into a purified stream. Membrane systems are therefore impermeable to certain particles when exposed to a specific driving force such as pressure. The feed stream is split into two product streams namely the permeate and retentate products. The permeate stream has a low contaminant concentration and the retentate has a high contaminant concentration level. A schematic representation of a simple membrane separation process is shown in **Figure 2.9**

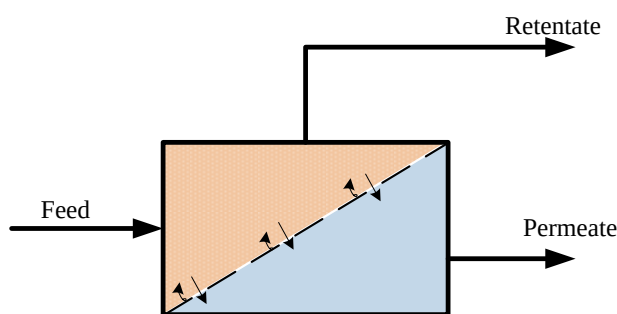


Figure 2.9 Schematic representation of a reverse osmosis membrane

There are many different types of membranes used in the process industry for the treatment of wastewater and seawater. Membranes are selected based on the types of material that passes through their pores, the type of wastewater that needs to be

treated and the driving force for the separation process. The focus of this research will, however, be on membranes due to their distinct characteristics. The different types that will be discussed briefly in this review are:

- (i) Microfiltration membranes
- (ii) Ultrafiltration membranes
- (iii) Nano filtration membranes
- (iv) Reverse osmosis membranes
- (v) Forward osmosis
- (vi) Membrane distillation
- (vii) Electro dialysis

(i) *Microfiltration (MF)*

MF is a separation process that allows a solution to flow perpendicular to a porous membrane. The pore sizes of MF range from 0.1 μ m to 10 μ m (Baker, 2012). It is a low-pressure separation process with pressures of 0.2 bar to 5 bar. It therefore means that any particle that exceeds the pore size is retained on the membrane and as such the solution then filters out of the membrane. MF is used to remove sediments, algae and protozoa within the wastewater. They are therefore used in the pharmaceutical industry, clarification of juices/wine/beer, oil/water separation, water treatment, dairy processing etc. (Baker, 2012). MF membranes are often used as pre-treatment for UF, RO and NF membranes.

(ii) Ultrafiltration (UF)

UF is a membrane separation process that involves the use of a pressure gradient to separate solvents from solutes through a semipermeable membrane. UF is similar to MF with a smaller pore size of 1nm to 100nm. The membranes are characterised by the molecular weight cut-off (MWCO) of the membrane, which refers to the lowest molecular weight solute in which 90 percent of the solute is retained by the membrane. UF membranes are used to remove particulates, macromolecules, bacteria, colloids, dispersed fluids and suspended solids from the contaminated solution (Koch, 2013).

(iii) Nano filtration (NF)

NF is a high-pressure process which is similar to RO, but is however used to remove only divalent and large ions. NF membranes have a low rejection to monovalent ions and are therefore used mainly for de-salting of a process stream. In water treatment, NF membranes are used to remove pesticides and also for colour reduction (Koch, 2013). It uses nanometer sized cylindrical through-pores which penetrate the membrane at an angle of 90 degree Celsius. NF membranes have a pore size that ranges from 1nm to 10nm. NF is, however, the least used method in industry as the pore size has to be in nanometers and incurs high maintenance costs (Baker & Martin, 2007).

(iv) Reverse Osmosis (RO)

RO membranes have the smallest pore size, which ranges from 0.0001 μm to 0.001 μm . RO membranes separate a water stream into a lean stream of low

contaminant concentration known as the permeate and a highly contaminated stream known as the retentate stream. The process is achieved by applying an external pressure to the feed solution to reverse the osmotic phenomenon. As a result of this process, retentate streams exit the membrane at a high pressure. RO membranes are used to remove different types of molecules and ions. RO membrane systems are often used for seawater and brackish water desalination (Maskan et al., 2000).

(v) *Forward Osmosis (FO)*

FO membranes are similar to RO membranes, but the driving force for the separation is an osmotic pressure gradient. More energy is, however, required for RO than FO. FO is used in desalination and wastewater treatment. FO membranes are often used as pre-treatment for RO membranes.

(vi) *Membrane distillation (MD)*

MD is a thermally driven separation system and separation is brought about by a phase change. The driving force is due to a partial vapour pressure, which is driven by a temperature difference. The membrane is hydrophobic and displays a barrier for the liquid phase, which in turn allows the vapour phase to pass through the pores of the membrane. This technology is applied in seawater desalination, water treatment and water purification (Winter et al., 2011).

(vii) *Electro dialysis (ED)*

ED is a process, which is based on the electro migration of ions across cation and anion exchange perm selective membranes by means of a direct electric current (Tsiakis & Papageorgiou, 2005). The ED membrane allows the movement of positive and negative ions through its pores. ED is used for the desalination of high salinity water, wastewater minimisation etc.

It can be concluded that the focus of this review will, however, be on reverse osmosis membranes due to their low energy consumption (compared to multistage flash distillation), high quality and product recovery. RO units are also easy to operate and have a modular plant design. They are also attractive as they can meet varying feed water concentrations and varying production water qualities (Lu et al., 2012). The RO system is also moderate in energy consumption when compared to thermal separation systems (Marcovecchio et al., 2005) and other separation systems. Cost of maintenance is also significantly lower (compared to thermal separation processes) for RO units (Voros et al., 1997). These advantages therefore make the RO system more attractive than other conventional separation processes (Saif et al., 2012).

2.7 Reverse osmosis membrane system

RO is a pressure driven process, where the solute is retained on the pressurised side known as the retentate side and the solvent is allowed to pass through to the less pressurised side known as the permeate. RO membranes are able to retain molecules and ions due to their small pore size, which are less than 0.5 nm in size (Saif et al., 2012).

Solutions with different solute concentrations create a chemical potential difference when separated by a semi-permeable membrane. The chemical potential difference in a mixture is defined as the slope of free energy of the system with respect to a change in the number of moles of just that species. The chemical potential difference allows the carrier solvent to be transported from a low concentration side to a high concentration side, known as osmotic flow and causes an increase in pressure on the retentate side. The system will then reach equilibrium when the pressure difference across the membrane balances the chemical potential across the membrane. An external pressure, which is larger than the osmotic pressure is applied to the solution in order to reverse the osmotic phenomenon. The external pressure allows the solvent to pass through the membrane while the solute remains in the retentate stream (El-Halwagi, 1992). The presence of the osmotic pressures of the solutions limits the expansion of the RO membrane, as the value must not exceed the applied pressure (Evangelista , 1986).

The performance of RO membranes (membranes in general) is, however, affected by fouling and scaling (Sassi & Mujtaba, 2011). The mass transfer on the high-pressure side of the RO membrane (retentate), causes fouling (Evangelista, 1985). Fouling affects membrane performance as it deteriorates membrane permeability. Fouling also results in a decreased product quality and increased feed pressure to maintain the freshwater demand (Sassi & Mujtaba, 2011). It also increases the energy consumption and because chemicals are needed to remove the foulants, this results in an increase in the total treatment cost. This therefore means that the membranes must undergo regular maintenance (Zhu et al., 1997). The performance

of the RO membranes is, however, recovered by being chemically or mechanically regenerated (Zhu et al., 1997).

The performance of RO units is also affected by concentration polarisation, which is the accumulation of the solute on the membrane surface. This therefore means that the solute concentration at the membrane wall becomes greater than that of the bulk feed solution, which affects the solvent and solute recovery as they are dependent on the wall concentration, which in turn is a function of the solvent and solute fluxes (Evangelista, 1986).

In order to minimise capital cost, the membrane module must provide a large area per unit volume to create a more efficient separation system. RO units consist of four module configurations: hollow fibre, plate and frame, spiral and tubular wound (Evangelista, 1986). The choice of a module configuration therefore depends on ease and cost of module manufacture, energy efficiency, fouling tendency, required recovery and the capital cost of auxiliary equipment (Maskan et al., 2000). Hollow-fibre reverse osmosis and spiral wound modules are commonly used in industrial processes as they offer a large surface area to volume ratio, self-supporting strength of fibres and negligible concentration polarisation (El-Halwagi, 1992).

2.8 Water network regeneration

Recent efforts around process integration for wastewater minimization in the process industry have been focusing on the use of mathematical optimization models. These approaches usually involve a water network synthesis-based superstructure representation of design alternatives using membrane regenerators.

2.8.1 Black-box regeneration

Water regeneration within water networks has been considered in a number of published papers [Cheremisinoff, N. P., 2002,, El-Halwagi, et.al, 2003, Tan, et.al, 2009]. In most instances either the regenerator technology and performance, number of regeneration units and arrangement of the regeneration train or regeneration design parameters are not set as decision variables. Rather they are assumed to be known and fixed or represented in oversimplified ways (Rangaiah & Wei, 2010). referred to this ideology as the 'black-box' concept. According to Galan & Grossmann (1998), although some conventional treatment technologies (biological, chemical and physical) can be approximated in this way, others like membrane technologies do not follow a similar approximation.

Few studies have considered the development of stand-alone detailed regenerator models for water networks. The more recent research has increasingly involved rigorous optimisation-based models, particularly for membrane-based technologies (Khor et al., (2014). Reverse osmosis models have been developed by El-Halwagi (1992) and Saif et al., (2013). Work on electro dialysis has been presented by Lee et al., (2002), Tsiakis & Papageorgiou (1995) and. Zeman & Zydney (1996) and Brunah et al., (2006) addressed work on ultrafiltration and microfiltration.

Different treatment technologies have different advantages and disadvantages over others and as such the treatment technologies of choice that match the system under consideration must be identified. Numerous researchers have failed to identify the type used, while others give umbrella terms, such as 'membrane based', 'non-membrane-based' or 'biological', to identify the type without specifying the actual technology adopted.

For regenerator performance, the norm has been to represent it by means of fixed removal ratios or fixed exit concentrations with energy consumption terms embedded implicitly within simplified linear cost functions. For instance, in the study by Galan & Grossmann (1998), in one example they considered regenerator technology selection and the options they had for treatment were physical, biological and chemical treatment. The performances of these units were described in a black-box fashion.

In another example, Galan & Grossmann (1998) considered non-dispersive solvent extraction as the treatment technology and they used shortcut models in a 'grey-box' fashion to represent the unit performance. Grey-box in this context describes an intermediary model between a black-box and a detailed model (white-box). Similarly, Alva-Argaez et al., ((1998)) addressed the water network problem and considered the use of steam strippers, API separators, dissolved air floatation units and biological treatment units to meet the environmental requirements, all of which had their performance described by fixed removal ratios.

More recently, Yang et al., (2014), made use of short-cut models of the regenerators having identified the technology types available. They considered using reverse osmosis, ion exchange, ultrafiltration, activated sludge and trickle filters for wastewater regeneration.

Closely related to the performance of the treatment units are the design parameters for the units. These include the length of the unit, number of membrane modules/cell pairs, pressure drop and membrane area. It is these design parameters that determine the units' performances as well as the capital and operating costs associated with the units. The design variables can be determined by the use of

detailed or shortcut models as shown by El-Halwagi (1992), Tsiakis & Papageorgiou (1995), Galan & Grossmann (1999) and Yang et al., (2014). The black-box concept ignores the design of the regeneration network.

The arrangement of the regeneration train concerns the topology and synthesis of the regeneration network. It includes the way in which the different regeneration units are connected to achieve the target concentrations and water recoveries. Synthesis of the network is related to the design depending on the system and the limitations of the treatment technology at hand. For instance, it may be possible for a single regenerator, operating at its maximum capacity, to be incapable of achieving contaminant removal targets that two/three regenerators would be able to achieve. In this instance, the assumption of using one treatment unit may lead to unrealistic and erroneous results, hence simultaneous design and topological considerations within the regeneration network must be made.

Chang & Li (2005) confirm the merits in the philosophy of using multiple regenerators. However, the authors also highlight the need for the system to choose only the necessary treatment units even if it means by-passing other available units. Most researchers that have considered the use of multiple regenerators have also taken this into account for the synthesis of optimal regeneration networks. This includes El-Halwagi (1992), Alva-Argaez et al., ((1998)), Galan & Grossmann (1998) and Yang et al., (2014).

2.8.2 Detailed regeneration models

The black-box and short cut or grey-box models do not give accurate representation of the regeneration units, hence there is a need to consider a detailed formulation of the regeneration units to incorporate the water network superstructure. This will give an accurate cost function of the regeneration units and optimal design parameters. Khor et al., (2014) addressed the gap on the work of Tan et al., (2009) by developing a detailed model representation for water network regeneration synthesis using MINLP optimization framework to obtain a rigorous cost-based relation between membrane regenerator and the overall superstructure. In their effort, Khor et al., (2014) incorporated the concepts of regeneration reuse/recycle and considered fixed flow rate water using processes, as opposed to the more traditional mass transfer-based fixed contaminant load models. The overall optimization of the proposed work leads to cost of water regeneration network that is a true representation of minimum cost as compared to other efforts that used a simplified black-box. The overall superstructure is optimized to get the optimal water network superstructure and optimal design parameters of the ED sub network.

CHAPTER 3

METHODOLOGY

Kriel power station is located between the towns of Kriel and Ogies in Mpumalanga province in South Africa. The planning and design of Kriel Power Station began in the early seventies. Construction also started in the early seventies and the station began operating at full capacity early 1979. When Kriel was completed in 1979, it was the largest coal-fired station in the Southern Hemisphere. Kriel Power Station, generating 3000 MW, was the forerunner of the new generation of giant coal-fired power stations developed to generate the increasing supply of electricity demanded by South Africa's constant growth.

In this chapter, the process integration approach will be applied to the Kriel Power Station with the objective of finding ways of reducing fresh water intake and waste water produced. The mathematical model that will be used to model the whole process will be based on the source-sinks framework.

The Department of Water Affairs supplies raw water to the station terminal reservoirs through the pipeline from the Jericho Dam. **Figure 3.1** shows the layout of the Kriel/Camden power station raw water Usutu scheme. Kriel Power Station receives raw water from the Vaal and Usutu water schemes, where water from the Usutu water scheme is used for potable and demineralised water production and the water from the Vaal system is used for cooling purposes.

The Jericho Dam is gravity fed from the Westoe Dam and a pumped supply is also available from the Morgenstond Dam. From the Jericho Dam the water is pumped to the Camden reservoir complex via the Onverwacht reservoir

The power station consists of six once through boilers and steam turbines each generating a maximum of 600MW of electricity. The freshwater intake averages 110 ML/d, which is defined as the water metered from the raw water source and used in the plant processes for all operations requiring fresh water such as (Operating, 1992)

- Demineralisation (demin)
- Potable water
- Cooling Water (CW) system (including dry dust compressor head tank)
- Fire hydrant system

3.1 Demin water

The purpose of the demin water is to supply water to:

- The station for boiler feed water.
- Demin plant regeneration.
- Condenser polishing plant (CPP) regeneration.
- Motive water (the water used to transport the lime from the lime silo to the cooling towers) for resin transfer.

During the demin process, the raw water is treated to remove solids and impurities to produce pure water with low conductivity 0.065 $\mu\text{S}/\text{cm}$, which is then used in the condensate system.

The purpose of the demin plant is to produce sufficient, high quality demin water for the use in six boilers rated at 600 MW each. The demin water is converted into

steam at high pressure and temperature and submitted to the turbine as a driving medium, which in turn drives the alternator to generate electricity.

Water used for boilers must be free of impurities, solid and hardness, as the impurities can stick to the boiler tubes at lower pressures, come adrift at a maximum boiler pressure and cause damage to the turbine blades when coming into contact at the turbine operating speed, which necessitates the reason why the raw water must be treated before use.

In large power stations a demineralisation plant is required and the plant is operated according to the water requirements. The raw water is treated by passing it through resin beds where the impurities in the water are absorbed by the resins. The duty of the plant operator is to attend to the plant and to arrange for the pumping of the treated water to the storage facility.

The treated water is stored in the three demin storage tanks which are large enough to hold a supply for two days in case the provision of raw water to the site is interrupted by a burst main pipe or failure of pumps.

There is furthermore a loss of steam and water from the station during the operation of the plant and this has to be replaced. This requirement is a reasonable overall average amount, which is 2% of the total water which is changed into steam in the boiler (Operating, 1992) .

3.2 Potable water

On the raw water line from the dam, the water is treated in clarifiers with flocculants and coagulants. Suspended solids in the water are removed in this process and flows through the clarifiers. Water is pumped to the sand filters after which there is a chlorination dosing point and soda ash is dosed on the suction manifold of the potable supply for pH correction. Potable water is supplied to the power station, mines and Kriel Town.

3.3 Cooling water

The cooling water (CW) circulating system is probably the most important auxiliary system in a power station, where water used for cooling, is river water. The cooling water flows through the condenser tubes, with the steam on the outside. Because of the temperature difference between the water and steam, condensation is achieved. The warmed cooling water flows to a cooling tower where an upward draft of air removes the heat from the water. After cooling, this water returns to the condenser. In the wet cooling system, with this upward movement of air, approximately 1.576 mega litres per gigawatt hour of water is lost (Hanekom, 2007). This is due to evaporation, as the water to be cooled is in direct contact with the air. The white plume seen on top of cooling towers at most thermal stations is pure water vapour.

The north and south CW plants consist of two cooling towers and a CW pump house each. The cooling water is circulated between the station and the cooling towers via the pump house. Note that the north and south CW ducts are not interconnected, i.e. they are two completely independent cooling water systems.

The north CW system supplies units 1, 2 and 3 and the south CW system supplies units 4, 5 and 6 with cooling water.

The piping that carries the supply of cooling water to the station is referred to as the cold duct. Those that carry the return water from the station to the cooling towers are referred to as the hot duct. The typical layout of a power plant is shown in

Figure 3.1.

3.4 Fire hydrant system

There are three pumps that supply the fire hydrant system with raw water:

- A jockey fire pump to maintain pressure in the hydrant system
- An electric fire pump that supplies water to the hydrant system
- A diesel fire pumps that supplies water to the hydrant system in case of a power failure to the electric pumps.

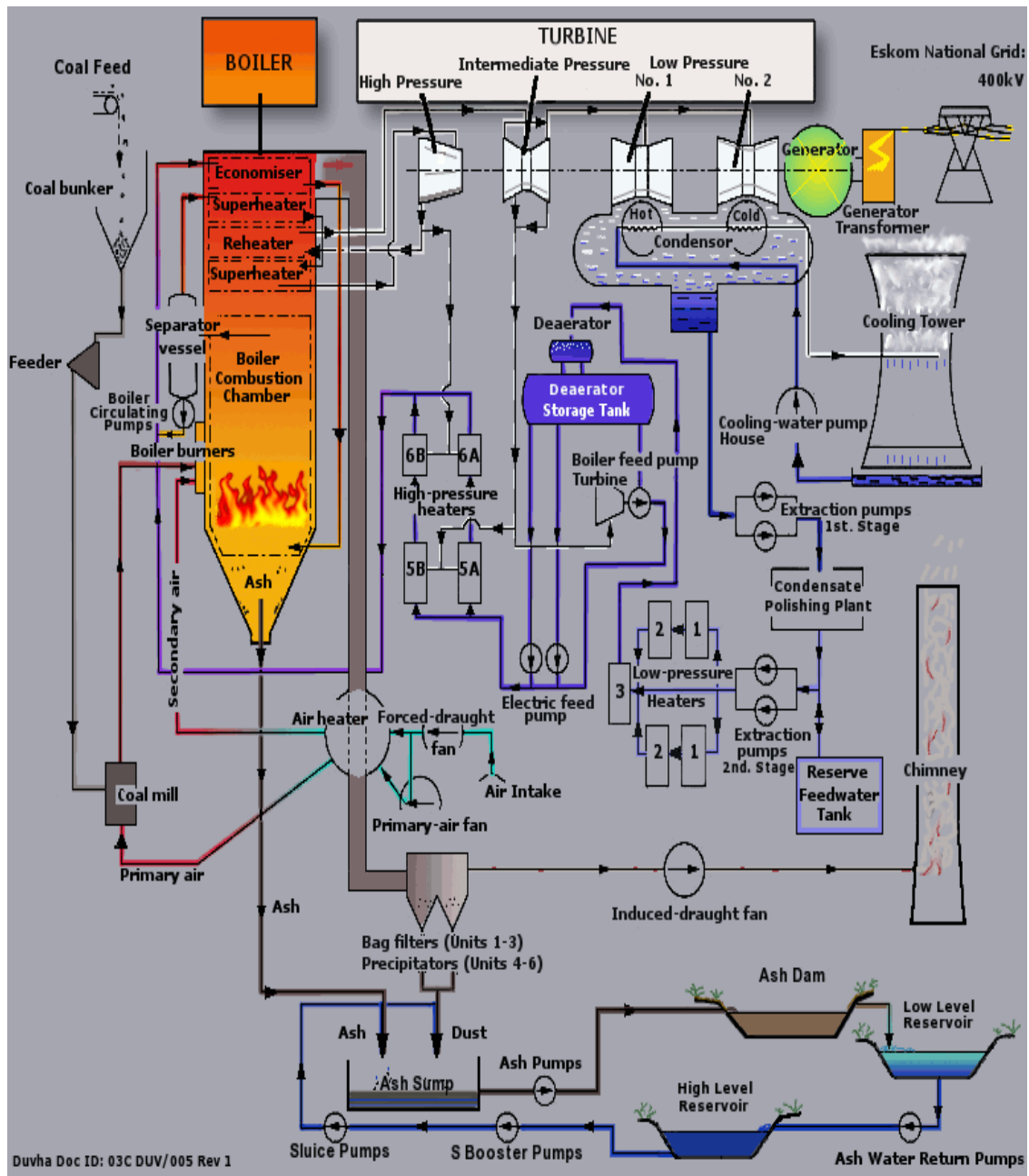


Figure 3.1: Block diagram of a typical power station layout (Station, 2005)

3.5 Data gathering and analysis

The first step in data gathering was a crucial step in the entire process and must be detailed and carefully done, because any neglected information will lead to misleading results for further interpretation. The overall water network of the plant was obtained from process flow diagrams (PFD) and process and instrumentation

diagrams (P&ID). In the case of Kriel Power Station, the water network starts from the raw water source, which is the dam to demin production, portable water, CW system and ends in the effluent plant where all the water that is used in the power station is accumulated.

Flow data used in the model was taken from the Saltman model, which was developed by Dirk Hanekom (Hanekom, 2007) who was a Water Specialist in Eskom. The objective of the Saltman model used, is to conduct a water and salt balance within the production process. In the Saltman model excel spread sheet the following procedure is done, the water systems are separated into plant sections, and for each system the inflow and outflow are quantified and the water analysis of the system was done. Internal circulation needed to be accounted for on a continuous basis for the purpose of process control. The systems within the water network were the raw water intake, demin plant, potable water, boiler, cooling water, ash plant, emergency pan and sewage works. The whole network was then linked together for a complete water balance for the power station. The water balance is a computerised process where inputs are regularly updated automatically or manually. The inputs were electronically processed and cross-correlated to produce outcome, which will assist with water management of the power station.

The water using operations were grouped into two categories which are mass transfer based and non-mass transfer-based operations (Liu, 1999). The mass transfer-based operation was classified by the transfer of contaminants from a stream which is high in concentration (conductivity) named a rich stream (relatively higher than the lean stream) to water which is low in conductivity and is named a lean stream e.g. cleaning. The water with low concentration after the process of cleaning it, ends with a high concentration, there are species that are transferred.

In the cleaning process water that is used is called a sink (in a water network a water sink is a connection requiring water of certain purity) and the waste water generated is a source (in a water network a water source is a connection supplying water of certain purity) to another process.

A non-mass transfer operation covers functions of water other than as mass transfer. In this study, a non-mass transfer-based operation is used, where there are water sinks and water sources. An example of a non-mass transfer is where there is no mass transfer involved, water is being utilised as a heating or cooling medium. This will happen in a case of a cooling tower or boiler, where water is used as a raw material and being withdrawn as product, water goes into the system but is lost as it evaporates as shown in Figures 3.2 (a) and 3.2 (b).

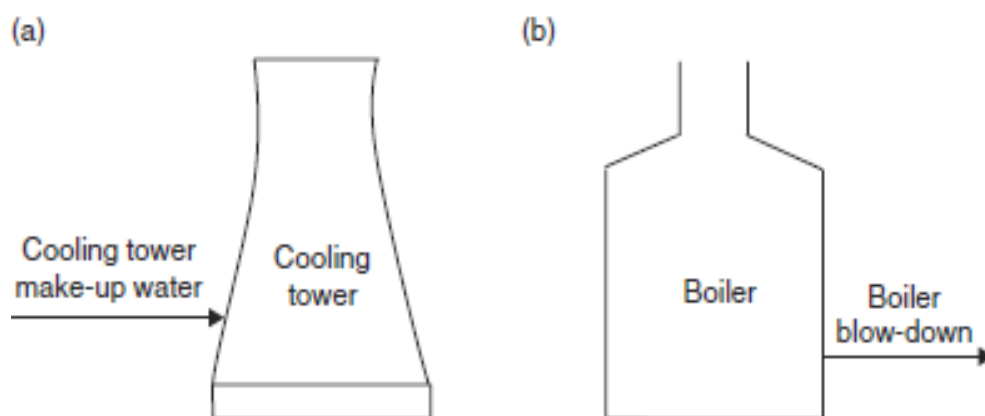


Figure 3.2: Types of the non-mass transfer water using operations (a) cooling tower make-up and (b) boiler blow-down (Liu, 1999)

Water as a cooling medium, or raw material feed is not intended to transfer parameters between the streams, therefore it represents non-mass transfer operation. The water flow rate is more important than the number of accumulated parameters. Normally the parameters are chemical oxygen demand, total organic

content, total suspended solid, conductivity and total dissolved solids that prevent direct reuse in the water systems.

The Kriel water flow diagram is shown in **Figure 3.3**.

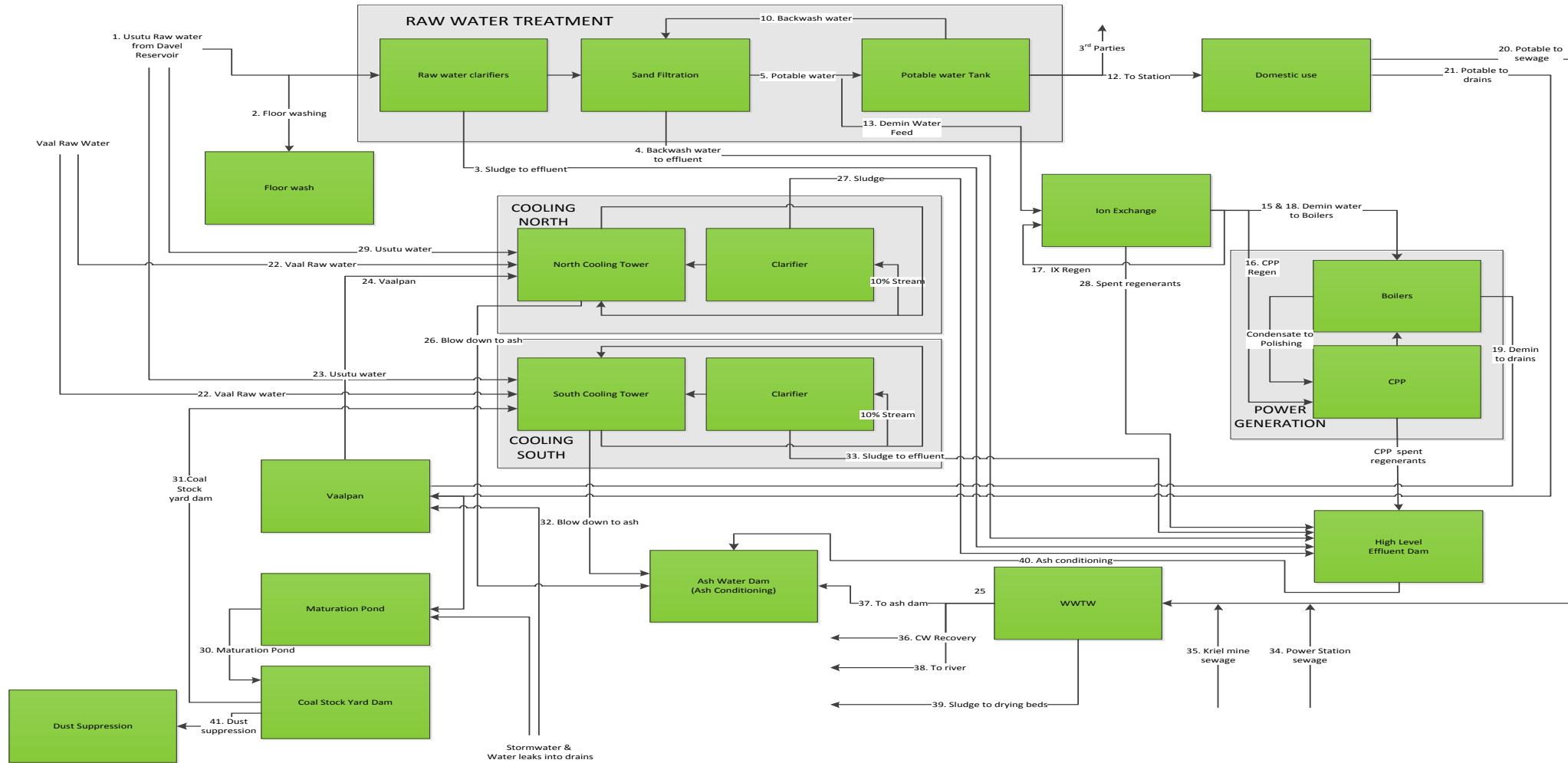


Figure 3.3: Kriel water flow diagram (Operating, 1992)

3.6 Sources and sinks

The second step was to identify water sources and sinks from the process flow diagram with the potential for reuse and recycling. When analysing the water network, the water processes are grouped into plant sections. In most circumstances processes chosen are preferably geographically close, and are also chemically related, to determine data from water using operations that allow for water reuse and thus minimise the quantity of waste water involved.

The limiting water flow rate and limiting parameter of streams within the water network will be the determining factor for reuse and recycling (Klemes, 2013). The outlet of each water-using operation within a network is a potential water source, the inlet to each water-using operation is a water sink that must be satisfied by a suitably water source which will be within the required flowrate and parameter. Conductivity of the water is the parameter that prevents the direct reuse of water sources and water sinks.

The network can be mathematically modelled either as a single or multiple parameter system. The system was modelled as a single contaminant, the modelling of aggregated contaminants as a single contaminant is known as a pseudo-single contaminant system. The proposed network then needed to be reassessed by checking that all other contaminant concentrations not considered were still within allowable limits before implementation.

The water sources, sinks flow rates and quality requirements for each water-using process were determined. The water sources and sinks data were obtained by identifying the maximum concentration limit and the minimum flow rate limit of the wastewater source from each process. **Table 3.1** shows the respective processes

classified as water sources and sinks. Note that a process unit may serve as both a source and a sink - for example a cooling tower has a demand for water and is a source of blow down water. The raw water sources were labelled as variables because that will be the variables that the model will seek to minimise.

Table 3.1: Identified variables, sources and sinks

Unit Operations	Sources	Sinks	Variables
Usutu Raw Water			X
Vaal raw water supply			X
Floor Washing		X	
3rd parties		X	
Sand filter backwash water		X	
Dirty Sand filter backwash water	X		
Power station potable water use (bathrooms, kitchen, etc.)		X	
Power station potable water leaking into drains	X		
Power Generation: Water		X	
Power Generation: Demin Water to drains-mostly tank overflows	X		
Power Generation: CPP spent regenerants	X		
Ion Exchange: Spent regenerants	X		
Effluent Dam	X		
North Cooling Tower	X	X	
South Cooling Tower	X	X	
WWTW	X		
Ash Dam/Ash conditioning		X	
Dust suppression		X	
Vaalpan – mostly from leaks from process units	X		

Table 3.2 shows the flow rates and qualities associated with the respective streams numbered on the flow diagram, depicted in **Figure 3.4**. With the lack of flow measurements on the plant it was decided to use the flow data as calculated by the “Saltman Model” excel data sheets. In the model the water balance for the station based on chosen operational parameters and received water qualities, which corresponded well with the available metered values, was calculated.

Although the General algebraic modelling software (GAMS) model can incorporate multiple components (such as sulphates, conductivity, total dissolved solid (TDS) etc., it was decided to initially use only conductivity as modelling or monitoring parameter. Stream compositions for all process streams will be needed if more components are to be incorporated. It is important to note that the sulphate concentration is of concern as it is in most cases the limiting parameter in cooling towers because the sulphates attack the cement and cooling tower are mainly made of cement.

Table 3.2: Stream values and qualities (Report S. , March 2014)

Stream No	Stream description	Flow rate (m3/d)	Stream quality	
			TDS (mg/l)	Conductivity (uS/cm)
1	Usutu Raw water from Davel Reservoir	14749	43	68.1
2	Floor washing (Fire-hydrants)	2203	43	68.1
3	Raw water clarifier sludge to effluent	444	61	95
4	Dirty backwash water to drains	444	48	75
5	Filtered water	14305	45	70.4
6 - 9, 11	Water 3rd parties		45	70.4
	Water to Kriel town		45	70.4
	Water to Kriel mine and NW Shaft		45	70.4
	Water to contractors		45	70.4
	Water to kwanala centre		45	70.4
	3rd parties	3000	45	70.4
10	Clean filter backwash water	444	45	70.4
12	Potable to Power Station	3000	45	70.4
13	Demin water feed	7862	45	70.4
14	Demineralized water production	7506	0	0.07
15	Demineralized water to Power Station	6824	0	0.07
16	Water to CPP regeneration	682	0	0.07
17	Demineralized water to regeneration	682	0	0.07
18	HP Demineralized to Power Station by pump	0	0	0.07
19	Demin water to station drains	3412	0	0.07
20	Potable water to Sewage plant	300	255	400
21	Potable water to Station drains	1890	58	91
22	Vaal raw water supply	92778	130	204
23	Usutu Raw water to north cooling system	0	45	70.4
24	Recovered water from Vaalpan	800	732	1150
25	Recovered sewage effluent	1216	249	391
26	North cooling tower blow down	3177	2548	4000
27	North cooling tower clarifier sludge	714	2548	4000
28	Spent regenerants to effluent system	1039	127	200
29	Usutu raw water to south cooling system	0	45	70.4
30	Recovered water from the maturation pond	0	567	890
31	Recovered water from coal stock yard	0	510	800
32	South cooling tower blow down	6467	2548	4000
33	South cooling tower clarifier sludge	627	2548	4000
34	Sewage from the Power Station	300	255	400
35	Sewage from the Kriel mine	1350	255	400
36	Sewage effluent for use in cooling	0	249	391
37	Sewage effluent to ash dams	0	249	391
38	Sewage effluent to the environment	0	249	391
39	Sewage sludge to drying beds	50	249	391
40	Ash conditioning	1400	6369	10000
41	Dust suppression	400	2548	4000

3.7 Modelling

The General Algebraic Modelling System (GAMS) mathematical optimisation software was used to develop the process integration model. The diagram, shown in **Figure 4**, served as the basis for further development of the GAMS model.

GAMS is an effective method for analysis, synthesis, and retrofit of water using networks for industrial water reuse and wastewater minimisation and of distributed effluent treatment systems for minimising the waste treatment flow rates and will be discussed in more detail in the next section. The GAMS software is specifically designed for modelling linear programming (LP), nonlinear programming (NLP) and mixed integer optimisation problems. LP is used to determine the minimum freshwater flow rate for water-using operations involving a single key contaminant, and NLP is used for multiple-contaminant.

In this study a NLP was used to optimize a system using conductivity as the single objective function. The inputs to the software were the water balance derive from Saltman model the objective function (the functional property to be optimised in mathematical programming), conductivity, flow rates of streams and constraints to the water network. The software was used for minimisation of water through identification of recycling, re-use and regeneration opportunities, hence minimising the water produced. The program works from knowledge of the constraints on water quality and flow rate required by each operation.

Table 3.2 was used to develop a model that generates a water use network by calculating optimal distribution of available water sources (at specified qualities) with the goal of minimising the intake of freshwater as well as wastewater generated. It is

also worth noting that the regeneration process unit in the superstructure allows for the calculation of optimum placement and capacity of a water treatment facility.

3.7.1 Mathematical model

The mathematical formulation is based on the superstructure shown in Figure 3.5.

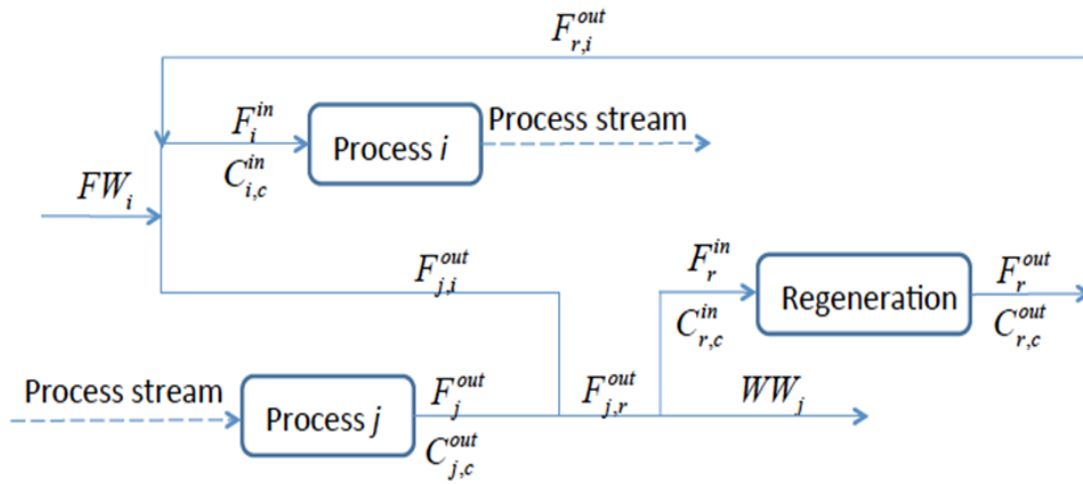


Figure 3.5: Superstructure for the mathematical model (Jir13)

Fresh water is coming into the process i which is a water sink (the inlet of water using operation where water is required) the water has a specified concentration and flow rate. Process j which is a water source (the outlet from a water using operation where waste water is produced). The water from process j is going out at a specified concentration and flowrate. The waste water is the feed to the water regenerator and its concentration is reduced so that it can be recycle or reused in process i

Sets

$$I = \{i \mid i = \text{water using operation (sink)}\}$$

$$J = \{j \mid j = \text{water generating operation (source)}\}$$

$$C = \{c \mid c = \text{contaminant}\}$$

$$R = \{r \mid r = \text{regenerator}\}$$

Continuous variables

$$FW_i = \text{freshwater into sink } i$$

$$WW_j = \text{wastewater stream from source } j$$

$$F_{j,i}^{out} = \text{recycle water stream from source } j \text{ to sink } i$$

$$F_r^{in} = \text{inlet water stream into regenerator } r$$

$$F_r^{out} = \text{outlet water stream from regenerator } r$$

$$F_{r,i}^{out} = \text{recycle water stream from regenerator } r \text{ to sink } i$$

$$C_{r,c}^{out} = \text{outlet concentration of contaminant } c \text{ from regenerator } r$$

Binary Variable

$$y_{i,j} = \begin{cases} 1 \leftarrow \text{if a stream exists between units } i \text{ and } j \\ 0 \leftarrow \text{otherwise} \end{cases}$$

Parameters

$$C_{j,c}^{out} = \text{outlet concentration of contaminant } c \text{ from source } j$$

$$C_{i,c}^{in} = \text{inlet concentration of contaminant } c \text{ into sink } i$$

$RR_{r,c}$ = removal ratio for contaminant c in regenerator r

F_i^{in} = inlet water stream into sink i

F_j^{out} = outlet water stream from source j

$F_j^{out,U}$ = maximum outlet flowrate from source j

d = minimum allowable flowrate in the final design

Constraints

All concentrations and flow rates are positive:

$$F_i \geq 0$$

$$C_i^{out} \geq 0$$

$$W_i \geq 0$$

Regenerator constraints

The constraints are shown Equation 1 to 4. Constraint (1) states that the total flow rate into a regenerator is made up of individual flows from each source to the regenerator. Constraint (2), on the other hand stipulates that the outlet stream from a regenerator is the sum of all the streams to various sinks from the same regenerator. Constraint (3) gives the inlet concentration of contaminant c into the regenerator. Lastly, constraint (4) is the definition of the rejection rate that is specific to contaminant c in regenerator r .

$$F_r^{in} = \sum_{j \in J} F_{j,r}^{out} \quad (1)$$

$$F_r^{out} = \sum_{i \in I} F_{r,i}^{out} \quad (2)$$

$$C_{r,c}^{in} = \frac{\sum_{j \in J} F_{j,r}^{out} C_{j,c}^{out}}{F_r^{in}} \quad (3)$$

$$F_r^{out} C_{r,c}^{out} = (1 - RR_{r,c}) F_r^{in} C_{r,c}^{in} \quad (4)$$

Operation constraints

Constraint (5) states that the total flow rate into sink i , comprises the freshwater flow rate plus the total flow from all the relevant sources and the flow from the regenerator. In its current form, this constraint assumes a single regenerator. Constraint (6) states that the outlet stream from source j is made up of wastewater that is dispensed with as effluent, the overall reuse stream from source j to all the relevant sinks, as well as the water stream into the regenerator. Constraint (7) states that the total load of contaminant c into sink i , cannot exceed the maximum allowed load of the same contaminant in the sink. Lastly, constraint (8) is a feasibility constraint that ensures that all the flow rates in the final design are within allowable limits.

$$F_i^{in} = FW_i + \sum_{j \in J} F_{j,i}^{out} + F_{r,i}^{out}, \quad i \in I = \{i \mid i = \text{sink}\} \quad (5)$$

$$F_j^{out} = WW_j + \sum_{i \in I} F_{j,i}^{out} + F_{j,r}^{out}, \quad j \in J = \{j \mid j = \text{source}\} \quad (6)$$

$$C_{i,c}^{in} \leq \frac{\sum_{j \in J} F_{j,i}^{out} C_{j,c}^{out}}{F_i^{in}}, \quad i \in I = \{i \mid i = \text{sink}\}, c \in C = \{c \mid c = \text{contaminant}\} \quad (7)$$

$$0 \leq F_{j,i}^{out} \leq F_j^{out,U}, \quad i \in I = \{i \mid i = \text{sink}\}, j \in J = \{j \mid j = \text{source}\} \quad (8)$$

Objective function

The objective function is the property to be optimized in mathematical programming, focusing on the minimization of the total freshwater intake into the facility is given in constraint (9a). It may also include the amount of wastewater generated as in (9b) or minimize the costs associated with intake of freshwater and treatment of wastewater as in (9c)

$$\text{Min } FW = \sum_{i \in I} FW_i \quad (9a)$$

$$\text{Min } FW, WW = \sum_{i \in I} FW_i + \sum_{j \in J} WW_j \quad (9b)$$

$$\text{Min } Cost = \sum_{i \in I} FW_i \times CostFW + \sum_{j \in J} WW_j \times TreatmentCostWW \quad (9c)$$

All three objective functions were used to minimize the respective variables. This will enable power station management to make decisions from both a water use target and cost point of view.

CHAPTER 4

RESULTS

In this section, the applicability of the developed GAMS model is demonstrated by applying it to two scenarios. Firstly, the model was developed to optimise the water utilisation network without recovery and regeneration (desalination plant). Secondly, the developed model was applied to a regeneration unit or desalination plant that was able to clean water with a high salt load to produce good quality effluent.

The freshwater intake for Kriel Power Station was about 109,7 ML per day., which translates to more than 2.35 L/kWh sent out . This is significantly more than the reported design specification of 1.8 L/kWh sent out or the current 2.19 L/kWh sent out target for the station (Eskom, 2015).

With each of the two models, three different objective functions were set (given by equations 9 (a), (b) and (c) in Chapter 3) namely:

- to minimize freshwater intake,
- a combination of the freshwater and wastewater i.e. dilution for re-use
- or costs associated with pumping raw water and chemicals used to treat water.

Each of the options provided unique network and different targets, being whether it is to minimise freshwater intake, minimise waste production or to minimise costs associated with water usage and waste management.

After formulating the initial model with sources and sinks, as listed in Table 3.1 in Chapter 3, it was apparent that certain modelling outcomes could contribute to more effective water management, the outcomes were as follows:

1. Re-use of wastewater treatment plant effluent:

Currently the connecting infrastructure between the wastewater treatment plant (WWTP) and the power station are in a state of disrepair. The plant's effluent is also of a poor quality. Capital investment will be required to upgrade or replace the treatment plant and refurbish the connecting infrastructure. The capital expenditure for the modification of the plant was not included in the calculations.

2. Allowing interchange of blowdown water between the two cooling towers

With the two cooling towers operating at different cycles of concentration (CoC), the blowdown water of the South cooling tower (operated at lower CoC) is of acceptable quality to feed into the North cooling tower. If recycling of the cooling tower blowdown is being considered, a careful study of possible accumulation of contaminants at steady state conditions was conducted first, as increased salt concentrations may damage infrastructure in the cooling loop.

3. Use of any water for floor washing operation

Preliminary results indicated that by using certain sources e.g. sewage water and regenerate water, these might be harmful to operators, but this can have a positive influence according to the model on the water network, more water can be saved.

In order to test the impact of each of these possibilities, eight scenarios were created as shown in **Table 4.1**. The scenarios were created by adding or removing constraints (environmental, limit of concentration or flowrates) from the GAMS model.

Table 4.1: Scenarios modelled

Scenarios	Re-use WWTP water	Blowdown Interchange allowed	Floor wash water from any source
Currently	N/A	N/A	N/A
Scenario 1	No	Yes	Yes
Scenario 2	Yes	Yes	Yes
Scenario 3	Yes	No	Yes
Scenario 4	No	No	No
Scenario 5	No	No	Yes
Scenario 6	No	Yes	No
Scenario 7	Yes	No	No
Scenario 8	Yes	Yes	No

The reasoning behind investigating different scenarios was that water saving can thus be quantified for each scenario and associated cost be determined for use in a cost benefit analysis.

Ultimately it is important to keep in mind that all of these findings result from specific inputs to the models and any findings must be evaluated in this light.

The findings for the three discussed objective functions when, with and without a desalination plant, is presented and evaluated.

4.1 Objective function: minimize freshwater intake

The current freshwater intake into the station ranges from 110 – 115 ML/d [according to the Saltman excel spreadsheet (water balance) (Report S. , March 2014)].

4.1.1 Without regenerator/desalination plant

Each of the scenarios were modelled and respective objective function values were obtained as shown in **Table 4.2**.

Table 4.2: Minimum freshwater usage for respective scenarios without a desalination plant

WW-wastewater, FW-freshwater, Z-objective function, Fr-Flow into Regenerator, STP-Sewage Treatment Plant, Flow out of regenerator	Re-use WWTP water	Blowdown interchange allowed	Floor wash from any source	Z as FW usage without regen in ML/d	
Currently	N/A	N/A	N/A	FW 112	WW10
Scenario 1	No	Yes	Yes	FW 96.801	WW 0
Scenario 2	Yes	Yes	Yes	FW 95.591	WW 0
Scenario 3	Yes	No	Yes	FW 103.581	WW 8.008
Scenario 4	No	No	No	FW 104.86	WW 8.008
Scenario 5	No	No	Yes	FW 103.8	WW 6.994
Scenario 6	Yes	No	Yes	FW 96.801	WW 0
Scenario 7	Yes	No	No	FW 104.651	WW 9.06
Scenario 8	Yes	Yes	No	FW 95.591	WW 0

The values reported in **Table 4.2** translate to fresh water savings of about 14% for scenarios 2 and 8. The absolute minimum amount of freshwater intake with the current operational parameters was 95.6 ML/d in both scenario 2 and 8, corresponding to 2.04 L/kWh sent out which is still above the design target of 1.8 L/kWh sent out, but lower than the present station target of 2.19 L/kWh sent out. The station management proposed the minimum target to 2.19 L/kWh sent out as a way forward to start decreasing the water usage in the station (Report S. , March 2014).

The station was generating at 2.35 L/kWh sent out which was above the design value, and this value need to be optimised.

As the current usage figures were used as demands for respective sinks, the above savings were calculated even with prevailing leaks, hence any savings achieved by fixing leaks etc. can be directly subtracted from these values.

The re-use of WWTP effluent contributes close to 3% savings in freshwater intake and a further 2 – 3% savings can be added if the model has the freedom to allocate any source of water to floor washing.

The water networks suggested by the model indicate the minimum objective function for each scenario. According to the model the best options are scenario 2 and 8, they are both reusing waste water. These networks can be used as a starting point to identify the so called low hanging fruit. Practical infeasibilities appearing on these networks can be corrected by collaborating with station personnel during the implementation stage and investigating the effect of altering the model to eliminate the infeasibility.

4.2 With regeneration/desalination plant

Table 4.3 shows the minimum freshwater intake achieved by the model with a regeneration plant for the respective scenarios as defined in **Table 4.1**. Note that scenarios 1, 2, 6 and 8 have approximately the same values as predicted by the model without a desalination plant, while the values for the other scenarios are in the order of 5 - 8% lower than the predictions shown in **Table 4.2**.

Table 4.3: Minimum freshwater usage for respective scenarios with a desalination plant.

WW-wastewater, FW-freshwater, Z-objective function, Fr-Flow into Regenerator, STP-Sewage Treatment Plant, Fret - Flow out of regenerator	Re-use WWTP water	Blowdown interchange allowed	Floor wash from any source	Z as FW usage with regen in ML/d	
Currently	N/A	N/A	N/A	FW 112	WW 10
Scenario 1	No	Yes	Yes	FW 96.81	WW 0
Scenario 2	Yes	Yes	Yes	FW 95.591	WW 0
Scenario 3	Yes	No	Yes	FW 97.62	WW 0
Scenario 4	No	No	No	FW 97.62	WW 0
Scenario 5	No	No	Yes	FW 97.51	WW 0
Scenario 6	No	Yes	No	FW 96.801	WW 0
Scenario 7	Yes	No	No	FW 96.14	WW 0
Scenario 8	Yes	Yes	No	FW 95.591	WW 0

When evaluating the networks suggested by the models it can be concluded that the reason why scenarios 1, 2, 6, and 8 have approximately the same values, is that they have no liquid waste stream even when there is no regeneration unit. These are the scenarios that allowed an interchange of blowdown streams, thereby eliminating the waste. In Scenarios 3, 4, 5 and 7 however, waste streams, were treated by the desalination plant, thus lowering the required freshwater intake.

4.2.1 Without regenerator/desalination plant.

Table 4.4 shows exactly the same freshwater and generated wastewater volumes as the findings obtained from Section 4.1.1, even when the waste was added as part of the objective function to be minimised. Optimum utilisation of water sources

therefore also translated to minimization of waste as previous waste streams were re-used by re-structuring the water use network.

Table 4.4: Minimum combined freshwater usage and waste without a desalination plant.

WW-wastewater, FW-freshwater, Z-objective function, Fr-Flow into Regenerator, STP-Sewage Treatment Plant, Fret - Flow out of regenerator	Re-use WWTP water	Blowdown interchange allowed	Floor wash from any source	Z as FW + WW without regen in ML/d	
Currently	N/A	N/A	N/A	FW112	WW 10
Scenario 1	No	Yes	Yes	FW 96.8	WW 0
Scenario 2	Yes	Yes	Yes	FW 95.6	WW 0
Scenario 3	Yes	No	Yes	FW 103.6	WW 8
Scenario 4	No	No	No	FW 105	WW 8.05
Scenario 5	No	No	Yes	FW 103.8	WW 6.9
Scenario 6	No	Yes	No	FW 96.8	WW 0
Scenario 7	Yes	No	No	FW 104.6	WW9.06
Scenario 8	Yes	Yes	No	FW 95.6	WW 0

In scenarios where there is utilising the blowdown, or a portion of the blowdown water from one cooling tower as feed water in another, show the most better values. This also led to a zero-liquid effluent discharge as the purge of accumulated salts was achieved by using the remaining blowdown water for ash conditioning with regeneration/desalination Plant.

Adding a regenerator to the system the model sends residual waste for treatment and minimizing the waste, the treated water is produced as water that can be used as a raw water source. It can be seen in **Table 4.3** that the scenarios that did not have any

waste streams before, still have the same objective function values when compared to findings from Section 4.2.1, while the scenario's that previously had waste streams, now have significantly lower objective functions.

Table 4. 5: Minimum combined freshwater usage and waste with a desalination plant

	Re-use WWTP water	Blowdown interchange allowed	Floor wash from any source	Z as FW+WW with Regen in ML/d	
Currently	N/A	N/A	N/A	FW112	WW 10
Scenario 1	No	Yes	Yes	FW 96.8	WW 0
Scenario 2	Yes	Yes	Yes	FW 95.6	WW 0
Scenario 3	Yes	No	Yes	FW 95.92	WW 0
Scenario 4	No	No	No	FW 97.62	WW 0
Scenario 5	No	No	Yes	FW 97.51	WW 0
Scenario 6	No	Yes	No	FW 96.8	WW 0
Scenario 7	Yes	No	No	FW 96.1	WW 0
Scenario 8	Yes	Yes	No	FW 95.6	WW 0

From these findings one can conclude that a desalination plant does make a difference in reducing wastewater as well as the freshwater intake when effluent management is considered.

4.3 Objective function: minimizing cost of freshwater intake and waste treatment.

The costs associated with water utilisation and waste management at Kriel Power Station can be calculated in several ways as will be discussed in the following three sub-sections.

4.3.1 Without regenerator/desalination plant and waste disposed on ash dams.

According to internal Eskom information, Kriel power station currently pays

R6 068/ML for freshwater obtained from the Vaal scheme and R8 045/ML for water obtained from the Usuthu Scheme. Cost of treatment of sewage water is estimated to be R4 000/ML (Marlene, 2013). No costs are currently paid for waste disposal as cooling water purge streams are disposed of on the ash dams.

In **Table 4. 6**, there is no regeneration plant, costs were minimised as freshwater intake was minimised. Even if this was the current situation at the power station, attributing no cost to waste management reduces this value for future decision making as waste management threatens to take on significant costs in the future.

Table 4.6: Minimum cost while waste can be disposed of on ash dams.

	Re-use WWTP water	Blowdown interchange allowed	Floor wash from any source	Z as cost of Fw +STP without Regen in ZAR	
Currently	N/A	N/A	N/A	R712 000.00	
				FW 112	WW 10
Scenario 1	No	Yes	Yes	R601 613.64	
				FW 96.807	WW 0
Scenario 2	Yes	Yes	Yes	R598 662.29	
				FW 95.59	WW 0
Scenario 3	Yes	No	Yes	R653 783.55	
				FW 103.62	WW 8.03
Scenario 4	No	No	No	R653 783.55	
				FW 104.86	WW 8.053
Scenario 5	No	No	Yes	R650 522.06	
				FW 103.86	WW 6.994
Scenario 6	No	Yes	No	R606 724.32	
				FW 96.807	WW 0
Scenario 7	Yes	No	No	R659 005.30	
				FW 104.651	WW 9.06
Scenario 8	Yes	Yes	No	R604 237.60	
				FW 95.909	WW 0

4.3.2 With regeneration/desalination plant and disposal of brine to landfill.

The Department of water and sanitation (DWS) intends to prohibit the disposal of saline streams on ash dams in the near future. This means blowdown water will have to be treated via a desalination plant. Costs to do that will be in the order of R5 000 to

R10 000 (with the R10 000 figure being used in the model) per ML treated plus R1 970 000 for the brine disposal landfill. Figure 4.1 Illustrates the cost allocation used in the model for this section.

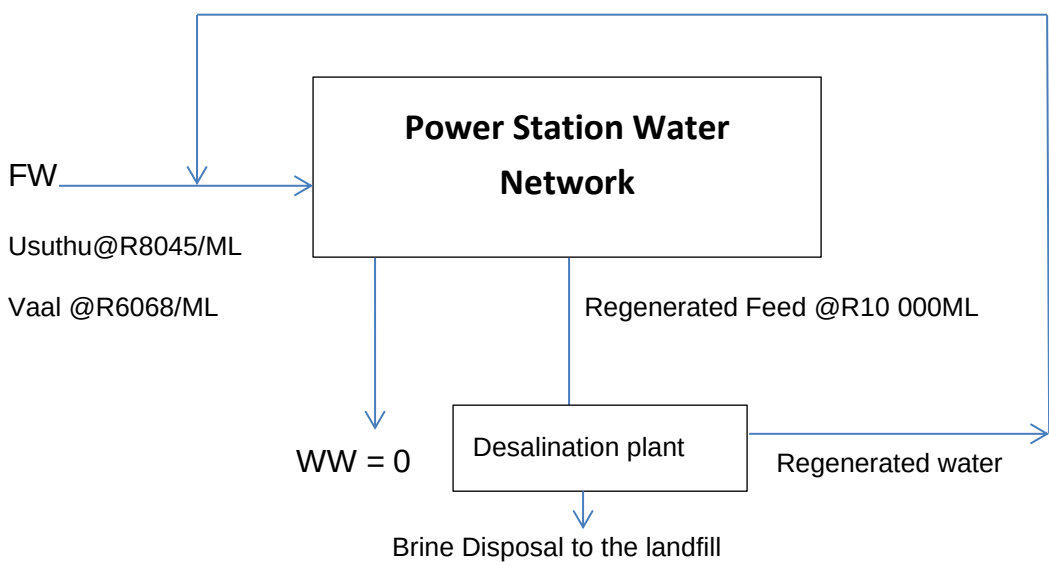


Figure 4.1: Cost allocation when brine is being disposed of in a landfill.

Complimentary to Eskom’s zero liquid effluent discharge (ZLED) policy a desalination plant provides an option for dealing with saline waste streams, however at a cost. While salt rejection from the feed stream may be as high as 99%, the recovery for modern plants is generally around 90% (actual percentage of feed water ending up as product water) with a 10% concentrate stream or waste stream to be managed.

Table 4.7 presents the findings of minimum cost when prohibiting waste water to be released. Note that all wastewater was sent to the regenerator as there was no alternative means of dealing with the waste and complying with ZLED when DWS disallows disposal of salt streams on ash dams.

The cost associated with the current situation in the first row of **Table 4.7** was approximated by assuming the 10 ML of wastewater was sent to the regeneration

plant at 90% recovery to provide 9ML of the required 112ML, while 1ML needs to be disposed of.

Table 4.7: Minimum cost when disallowing any wastewater.

WW-Wastewater; FW-Freshwater; Z-Objective function; Fr-Total flow into Regenerator, STP- Sewage Treatment Plant, Fret- flow out of regenerator	Re-use WWTP water	Blowdown interchange allowed	Floor wash from any source	Z as cost of Fw+Fret+Fr+STP with Regen	
Currently	N/A	N/A	N/A	R2 600 000.00	
				FW 112	WW 10
Scenario 1	No	Yes	Yes	R601 806.30	
				FW 96.81	WW 0
Scenario 2	Yes	Yes	Yes	R596 807.89	
				FW 95.195	WW 0
Scenario 3	Yes	No	Yes	R2 099 949.78	
				FW 95.92	WW 0
Scenario 4	No	No	No	R2 287 548.83	
				FW 97.62	WW 0
Scenario 5	No	No	Yes	R2 071 249 .33	
				FW 97.51	WW 0
Scenario 6	No	Yes	No	R607 707.16	
				FW 96.81	WW 0
Scenario 7	Yes	No	No	R2 560 558.52	
				FW 96.14	WW 0
Scenario 8	Yes	Yes	No	R602 789.35	
				FW 95.7	WW 0

The findings show how the wastewater treatment costs render the cooling tower blowdown management critical, even when it could simply be sent to the treatment plant to re-produce freshwater.

Furthermore, the model's suggested water networks for scenarios that previously produced no wastewater (Scenarios 1, 2, 6 and 8) still prevents any water from being treated by the desalination and this translates to costs that amount to a fraction of that for the other scenarios.

4.3.3 With regeneration/desalination plant and saline water management on site.

An alternative to the cost structure suggested in Section 4.3.2 was to include brine management facilities with the desalination plant at a cost of R40 000/ML of wastewater treated by the plant. These costs include the capital costs attenuated and may be less for a more energy efficient technology such as eutectic freeze or much more if energy costs are high. **Figure4.2** illustrates the cost allocation in the model for this section.

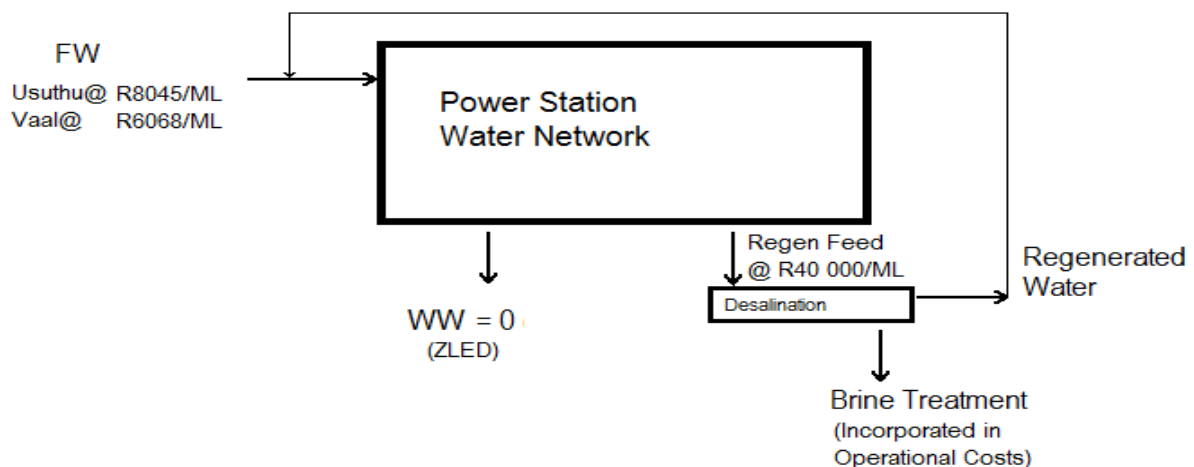


Figure 4.2: Alternative treatment cost allocation for desalination plant.

As before the cost associated with the current situation in the first row was estimated by assuming the 10 ML of wastewater is sent to the regeneration plant at 90% recovery to provide 9ML of the required 112ML of freshwater. **Table 4.7** presents the results the minimum cost with the saline water treatment included.

Table 4.8: Minimum cost with saline water treatment incorporated in treatment costs.

WW-Wastewater; FW-Freshwater; Z-Objective function; Fr-Total flow into Regenerator, STP-Sewage Treatment Plant, Fret-flow out of regenerator	Re-use WWTP water	Blowdown interchange allowed	Floor wash from any source	Z as cost of Fw +Fr+STP with Regen	
Currently	N/A	N/A	N/A	R712 000.00	
				FW 112	WW 10
Scenario 1	No	Yes	Yes	R601 613.64	
				FW 96.807	WW 0
Scenario 2	Yes	Yes	Yes	R598 662.29	
				FW 95.59	WW 0
Scenario 3	Yes	No	Yes	R653 783.55	
				FW 103.62	WW 8.03
Scenario 4	No	No	No	R653 783.55	
				FW 104.86	WW 8.053
Scenario 5	No	No	Yes	R650 522.06	
				FW 103.86	WW 6.994
Scenario 6	No	Yes	No	R606 724.32	
				FW 96.807	WW 0
Scenario 7	Yes	No	No	R659 005.30	
				FW 104.651	WW 9.06
Scenario 8	Yes	Yes	No	R604 237.60	
				FW 95.909	WW 0

The results in **Table 4.8** indicate at least 50% cost reduction with on-site waste management compared to landfilling costs of saline water.

4.4 Selected cost benefit analysis.

The following findings, as was obtained in Section 3, were chosen to do a high-level cost benefit analysis in order to get a provisional estimation of the value that may be contributed by each option.

4.4.1 Sewage treatment plant.

A current heuristic rule for costing of activated sludge sewage treatment plants is a cost of R1 million per ML/d plant capacity. For treatment plants this cost is in the region of 20% lower. A plant with a capacity of 1.6ML/d, translates to cost of +/- R1.3 Million for a new package treatment plant at Kriel.

If it is assumed that treated sewage is at the required quality to replace 1ML of freshwater per day this amount to a saving of $R6064 \times 30 = R182\,000$ /month or R2.2 Million per year.

This figure justifies the upgrade or replacement of the sewage treatment plant and also prioritising the refurbishment/replacement of the current piping infrastructure from the sewage treatment plant to the power station that is in a dilapidated state.

4.4.2 Blowdown management.

With the points discussed in Section 4.1, the cost of an appointed task team to investigate findings from this study and investigate cooling tower operations at Kriel in general must be weighed up against expected savings from the work they perform.

For a scope entailing a desktop investigation and interviews with internal specialists, it is being assumed for the purpose of the evaluation that a team of 2 specialists will

spend 360-man hours at approximately R1000/h on such a study, translating to a cost of R360 000.

If 50% of the 13% freshwater savings from the findings in Section 4.4 of this project associated with blowdown management can be achieved, it translates to at least R50 000 of savings daily or R1.5 Million per month. That is discounting associated wastewater treatment costs.

4.4.3 Regeneration/desalination plant.

With capital costs attenuated into treatment costs, freshwater produced from wastewater sent to a desalination plant will cost an estimated R30 to R50/m³ compared to the R6/m³ currently paid for raw water from the Vaal System.

In terms of the freshwater consumption targets, a desalination plant also only shows an improvement in the scenarios evaluated in Section 4.4 (does not allow blowdown from one cooling tower to be re-used in the other). This is largely due to total elimination of blowdown wastewater when these streams are carefully managed.

As the abovementioned wastewater elimination is only achieved by using a portion of the blowdown water on ash dumps, the one situation where there would be no other option, but some form of wastewater treatment or regeneration is when Department of Water Affairs disallows this practise and therefore forces another form of wastewater treatment.

CHAPTER 5

CONCLUSIONS

The following conclusions can be made from the findings in this study:

- Savings of between 4% and 13% may be possible by changing the way water is currently utilised and re-used at the station, which translate to 2.23 to 2.04 L/kWh sent out respectively (this saving will reduce the actual figure of 2.35 to 2.23 - 2.04). These savings however still do not achieve the design water consumption target of 1.8 L/kWh sent out
- Reuse of the wastewater treatment plant effluent has a direct impact on water consumption and investment in infrastructure to enable the introduction of good quality sewage effluent into the cooling towers shows savings in the order of R 2.2 million per year.
- By adhering to design specification and proper maintenance of the stations water network, 3% savings can be achieved without implementation of any of the three preliminary findings mentioned.
- Observations on site showed a significant amount of water that ends up in station drains. With the bulk of water use at the station going to the cooling towers it is expected that regardless if any other of the findings of this study is implemented, effective maintenance on cooling cycle equipment (such as valves, ejector weirs etc) may reduce water consumption by as much as 5% or R1 million/month. Findings in this report are based on input water demands (for respective unit process) that include prevailing leaks at the station. Any

savings through maintenance is additional to the results already shown in this report.

- Management of the cooling cycle and especially blowdown water with related procedures have a significant impact on the amount of freshwater intake. A thorough understanding of the intricacies of cooling tower operation and performance is critical to optimise this. The appointment of a task team to perform this work approximates savings of R1.5 Million per month after initial investment of an estimated R360 000 and it is highly recommended.
- As the water use target is measured in relation to the amount of power generated, the measurement can be improved by optimising the cooling cycle/boiler relationship. It is recommended that a task team using process optimisation tools is implemented to investigate this.
- If saline waste streams cannot be prevented (where blowdown interchange is not feasible) a desalination plant improves freshwater consumption figures and serves to aid Eskom's ZLED policy. In instances where no waste is produced the desalination plant adds no value in terms of freshwater consumption or otherwise.
- With the incorporation of a desalination plant the daily costs associated with water will rise from around R700 000 per day to R1 million – R2.5 million per day depending on the waste management option chosen.

- It was found that optimisation of the power stations water utilisation has a direct impact on the amount of waste produced which translates to a 50% (or more) reduction in waste management costs (apart from savings in fresh water consumption).
- Implementation of any of the water networks or portions of it should be foregone by a well-executed HAZOP study with risk management. Neglecting to identify instances where the loss of a necessary good quality stream is not introduced to a unit process, may lead to equipment damage.
- Ultimately it is important to keep in mind that all of these findings result from quite specific inputs to the models and any findings must be evaluated in this light.

CHAPTER 6

RECOMMENDATIONS

The following aspects of cooling tower operation must be taken into consideration at Kriel:

- The “Chemistry standard for cooling water” at Kriel sets maximum TDS and sulphate concentrations in cooling water at the same level for both cooling towers. This however contradicts the reported different CoC for the two towers, unless operational staff can manage blowdown on different levels. It would be strongly advised to appoint a task team to revisit the way it is being managed.
- The proactive maintenance of any leaking equipment (such as ejector weirs) within the station may contribute significant water savings and must be managed and executed diligently.

6.1 Freshwater consumption target

The design specification of water consumption target for Kriel Power Station is reported to be 1.8 L/uso. It is important to note that this target was set for better quality coal, thus increasing the efficiency of the generation cycle and possibly also better freshwater quality which would allow higher cycles of concentration and therefore less make-up water needed.

If the findings from the model can be incorporated, a water consumption of 2.04 L/uso may be achieved at the reduced 95ML of freshwater per day and this value may be improved on by eliminating current losses.

It is important to also note that improving the power factor of the plant through optimising the cooling towers (refurbishment, better water quality etc.) or improving boiler performance (better coal quality or optimisation of boiler/cooling cycle interaction) the water consumption rate is also improved as the unit sent out improves.

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APPENDIX 1: GAMS MODEL

Title Kriel Power station Model

\$offupper

\$offlisting

\$ontext

1. First draft of Kriel Model

\$offtext

Sets

K Operations /Effluentdam, SF1, CPP, Boilers,

PSpotwater, Effluent, IX, CoolingTN,

CoolingTS, WWTP,

Ashhandling, CSYdam, MPond, Vaalpan,Dustsup,

3rdparties, Floorwash/

I(K) Sources(Operations) /Effluentdam, SF1, CPP, Boilers, PSpotwater,

IX, CoolingTN, CoolingTS,

WWTP, CSYdam, MPond, Vaalpan/

J(K) Sinks(Operations) /PSpotwater, IX, CoolingTN, CoolingTS, Ashhandling,

MPond, Vaalpan, 3rd parties, Floorwash, Dustsup/
C Contaminant /TDS/

Alias (K, KK);

Table CinMax(J, C) Maximum inlet concentration in ppm
TDS

PSpotwater 54.4

IX 45

CoolingTN 2430

CoolingTS 2430

Ashhandling 10000

MPond 1000

Vaalpan 320 3rd parties 45

Floorwash 1280

Dustsup 800

* 1. The ASH handling TDS is taken as 10000mg/l, liner specifications on ash dumps may add to it. For example max amount of monovalent

* 2. Work on an assumption of cleanwater to Vaalpan and dirtywater to Mpond and CSYdam

* 3. Sulphates is a spec for Coolingwater blowdown...must it be added?

* 4. IX added as sink because together with 3rd parties and station domestic it places a demand for raw water

Table CoutMax(I, C) Maximum outlet concentration in ppm

TDS

Effluentdam 1965

SF1 96

CPP 128

Boilers 3.2

PSpotwater 58

IX 128

CoolingTN 2600

CoolingTS 2600

WWTP 250

CSYdam 1280

MPond 1280

Vaalpan 1150

* Other sources go to effluent - therefore effluent itself not considered one

* SF1 as well as CT clarifiers high in turbidity and TSS (20 -60 g/l) not shown in contaminants

*

* CPP & IX regen conductivity start high but will end very low; rough estimated average reported

* PSpotwater assumed to be grawater to drains

Parameters

Fin(J) Flowrate into a particular sink m3perhour /PSpotwater 3000, 3rd parties 3000, CoolingTN 47583 ,

CoolingTS 50873 , Ashhandling 1400, MPond 500,

Vaalpan 500, Floorwash 2203, Dustsup 400,

IX 7900/

* 1. Figures for Mpond and Vaalpan just placeholders. No actual requirements?

Fout(I) Flowrate out of a particular source

/Effluentdam 1785, SF1 444, CPP 685,
Boilers 685, PSpotwater 1890, IX 1039,
CoolingTN 3177, CoolingTS 6467, WWTP 1650,
CSYdam 0, MPond 0, Vaalpan 4425/

*Clarifiers source of underflow(sludge) - 20 to 60g/l TSS - this is directed to effluent dam

*Pot water to station drains (PSpotwater) seems high (60+% of total feed to station)

*We know around 7000m³/d is recovered from vaalpan, drain water figures given are subtracted for now not to count them double

*CSY, Mpond and Vaalpan has got net anualavaporation of >rainvall. (average)

*During wet season 480m³/d becomes available in Vaalpan and Mpond

Cw(C) Contaminant concentration in FW

/TDS 45/

RR(C) Removal ratio of C

/TDS 0.9/

CoutMax_Up(C) Upper bound of concentration;

CoutMax_Up(C) = smax(I,CoutMax(I,C));

Scalar

FinReg_Up Upper bound on regeneration inlet flowrate;

FinReg_Up = sum(I,Fout(I));

Variables

Cin(J, C) Inlet concentration into a particular sink

Cout(I, C) Outletconcentraion from particular source

Fr(K, KK) Recycle flowrate from a particular source

Fw(J) Fresh water into a particular sink

Ww(I) Wastewater from a particular source

FROUT_reg(J) Water from Regen to J

FRIN_reg(I) Water from Source I to Regen

COUT_reg(C) Outlet Concentration of C from regeneratation

CIN_reg(C) Inlet concentration of C into regenerator

FOUTReg Total flow out of regenerator

FINReg Total flow into regenerator

Lin001(J,C) Liniearization variable

Lin002(C) Linearization variable

Z Objective function

Positive variables Cin, Cout, Fr, Fw, Ww, FROUT_Reg, FRIN_reg, COUT_reg, CIN_reg,

FOUTReg, FINReg, Lin001, Lin002;

Equations

Eq1(J) Sinks mass balance

Eq2(I) Sources mass blance

Eq3(J,C) Maximum load constraint

Eq4 Objective function

Eq5(K, KK) Elimination of recycle

Eq6 C load into regen

*Eq7

Eq8

Eq9

Eq10;

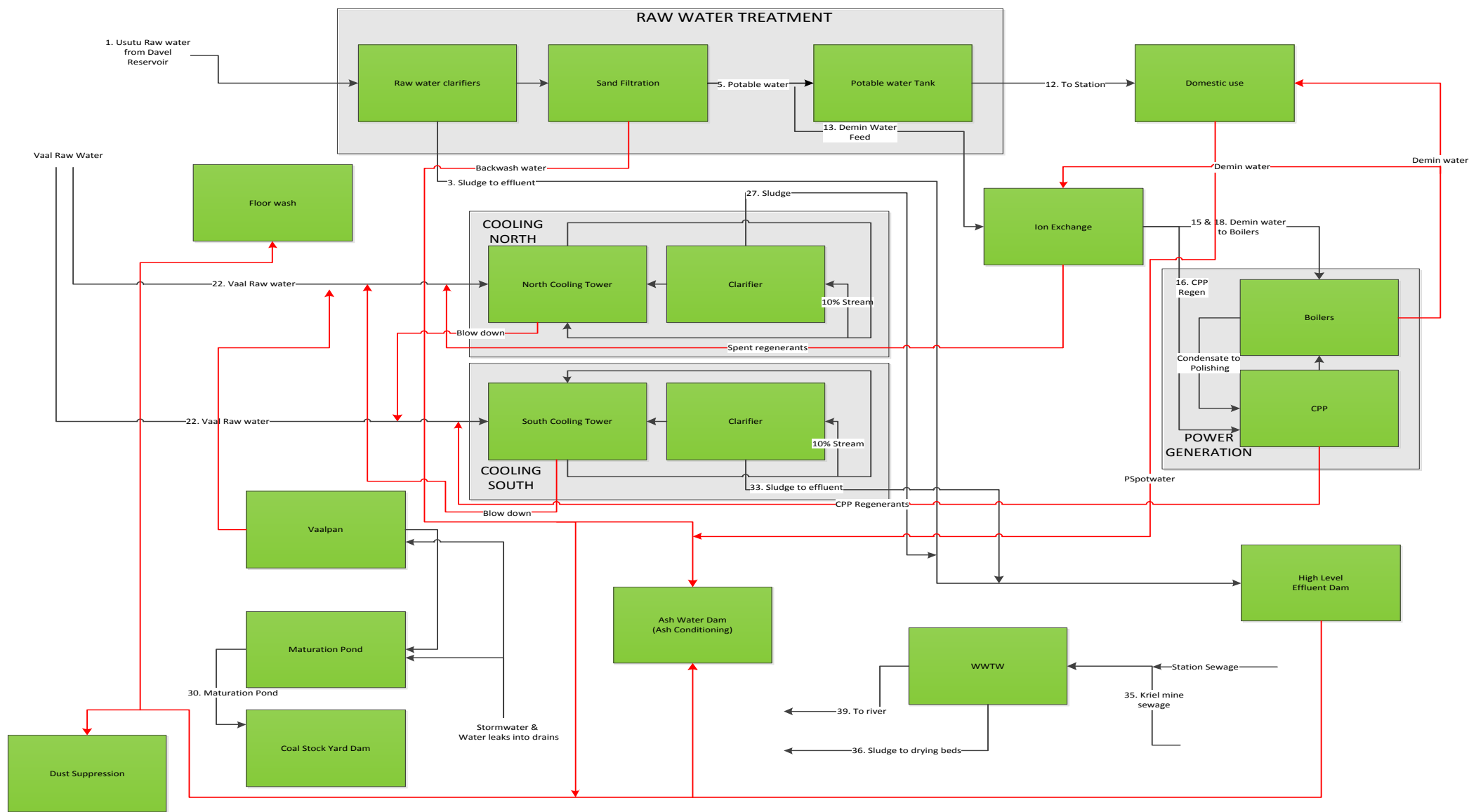
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*Eq11;
Eq1(J).. Fin(J) =e= Fw(J)+sum(I, Fr(I, J));
Eq2(I).. Fout(I) =e= sum(J, Fr(I, J)) + Ww(I);
Eq3(J, C)..
CinMax(J,C)*Fin(J)
=g= Fw(J)*Cw(C)+sum(I, Fr(I,J)*CoutMax(I,C))+Froureg(J)*(1-RR(C))*Cinreg(C);
Eq4.. Z=e=sum(J, Fw(J));
Eq5(K, KK) $(ord(K) = ord(KK)) ..
Fr(K, KK) =e= 0;
Eq6(C)..
Cinreg(C)*FinReg =e= sum(I,Frinreg(I)*CoutMax(I,C));
*Eq7(C)..FoutReg*CoutReg(C) =e= (1-RR(C))*Cinreg(C)*FinReg;
Eq8..sum(J,Froureg(J)) =e= FoutReg;
Eq9..sum (I, Frinreg(I)) =e= FinReg;
Eq10..FoutReg =e= FinReg;
Model Eskom_exact/all/
*linearize non-linear equations (eq3,6,7)
Equations
Lin01
Lin02
Lin03
Lin04 Lin05
Lin06
Lin07
Lin08;
Lin01(J,C).. CinMax(J,C)*Fin(J)
=g= Fw(J)*Cw(C)+sum(I,Fr(I,J)*CoutMax(I,C))+ Lin001(J,C)*(1-RR(C));
Lin02(C).. Lin002(C)
=e= sum(I,Frinreg(I)*CoutMax(I,C));
Lin03(J,C).. Lin001(J,C) =l= Froureg(J)*CoutMax_Up(C);
Lin04(J,C).. Lin001(J,C) =l= Cinreg(C)*Fin(J);
Lin05(J,C).. Lin001(J,C) =g= Froureg(J)*CoutMax_Up(C)+Cinreg(C)*Fin(J)-
CoutMax_Up(C)*Fin(J);
Lin06(C).. Lin002(C) =l= Cinreg(C)*FinReg_Up;
Lin07(C).. Lin002(C) =l= FinReg*CoutMax_Up(C);
Lin08(C).. Lin002(C) =g= Cinreg(C)*FinReg_Up+FinReg*CoutMax_Up(C)-
FinReg_Up*CoutMax_Up(C);
Model Eskom_lin/Eq1,Eq2,Eq4,Eq5,Eq8,Eq9,Eq10/;
Solve Eskom_lin using LP minimizing Z;
Solve Eskom_Exact using NLP minimizing Z;
Display Z,I, Fr,I, Fw,I;

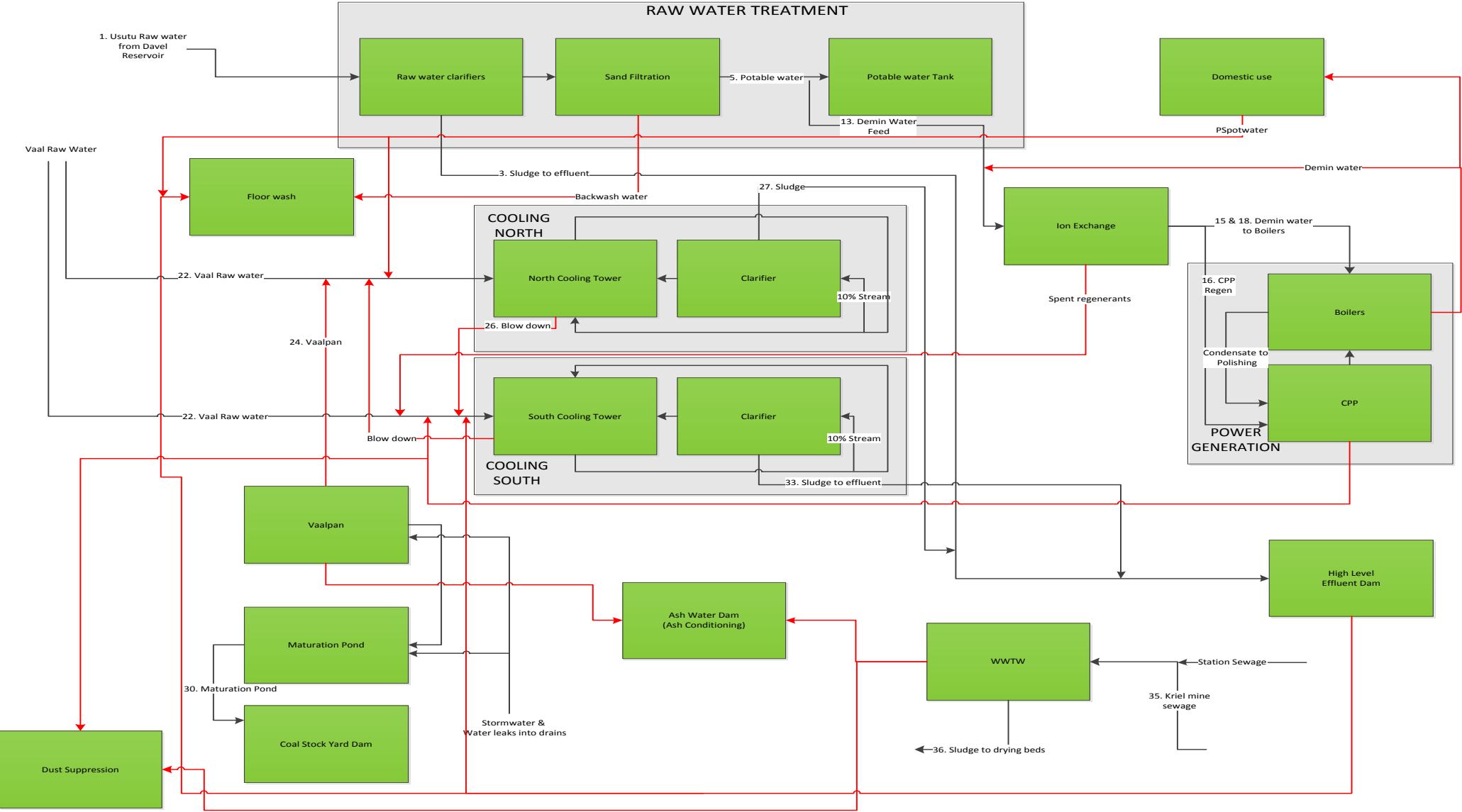
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APPENDIX II: Flow Sheets for Freshwater Minimization Scenarios

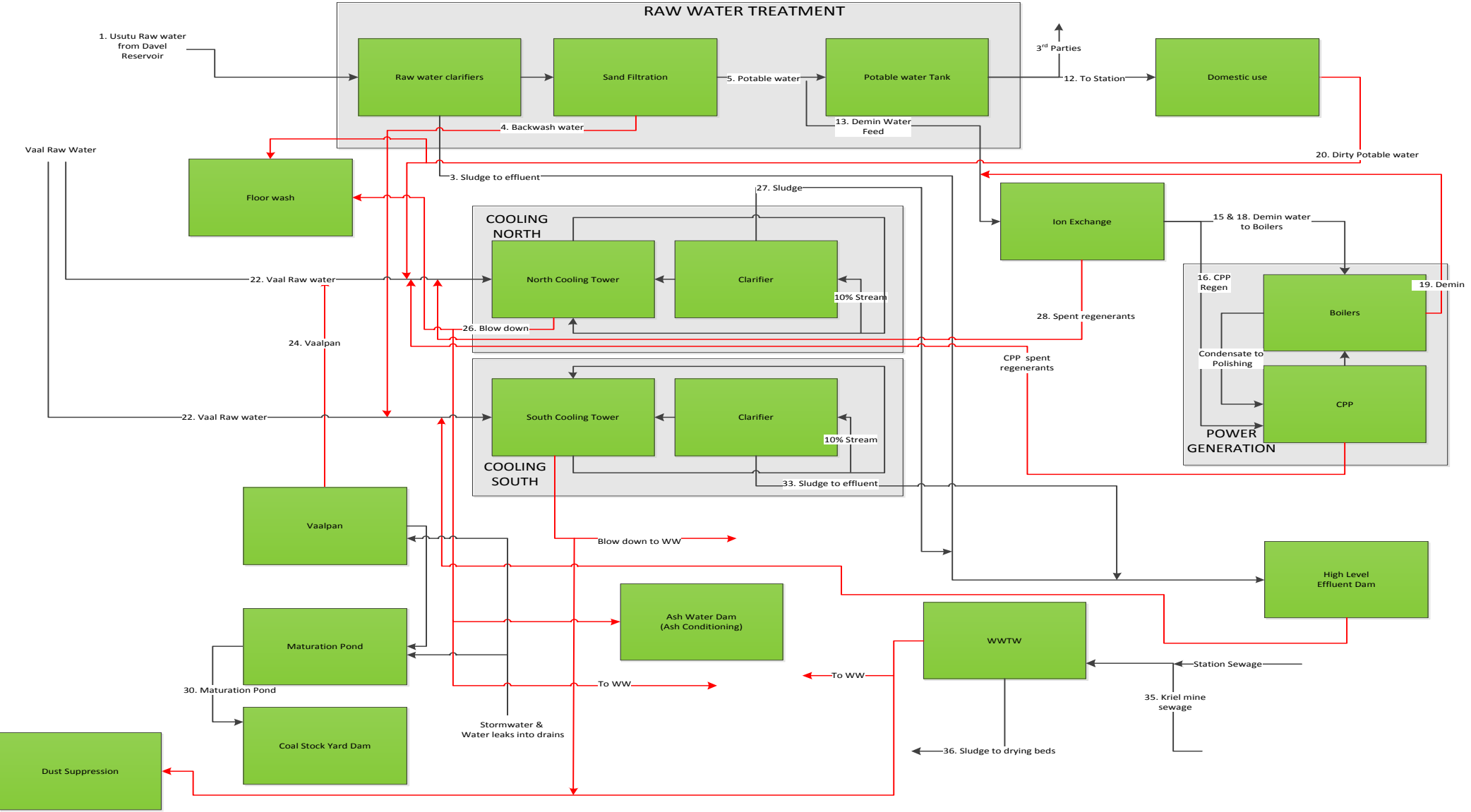
Scenario 1: Freshwater intake (96 801m³/d)



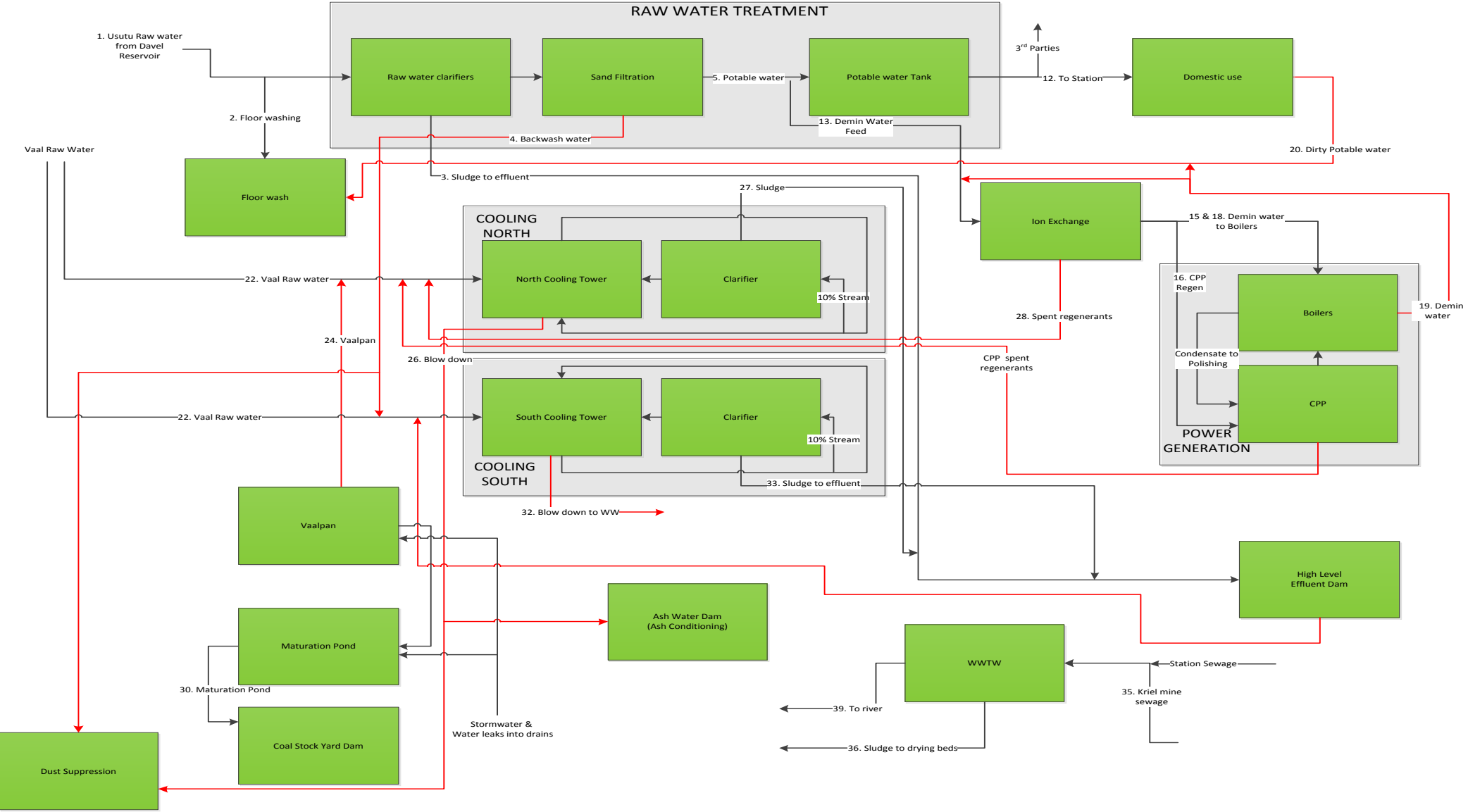
Scenario 2: Freshwater intake (95 591m³/d)



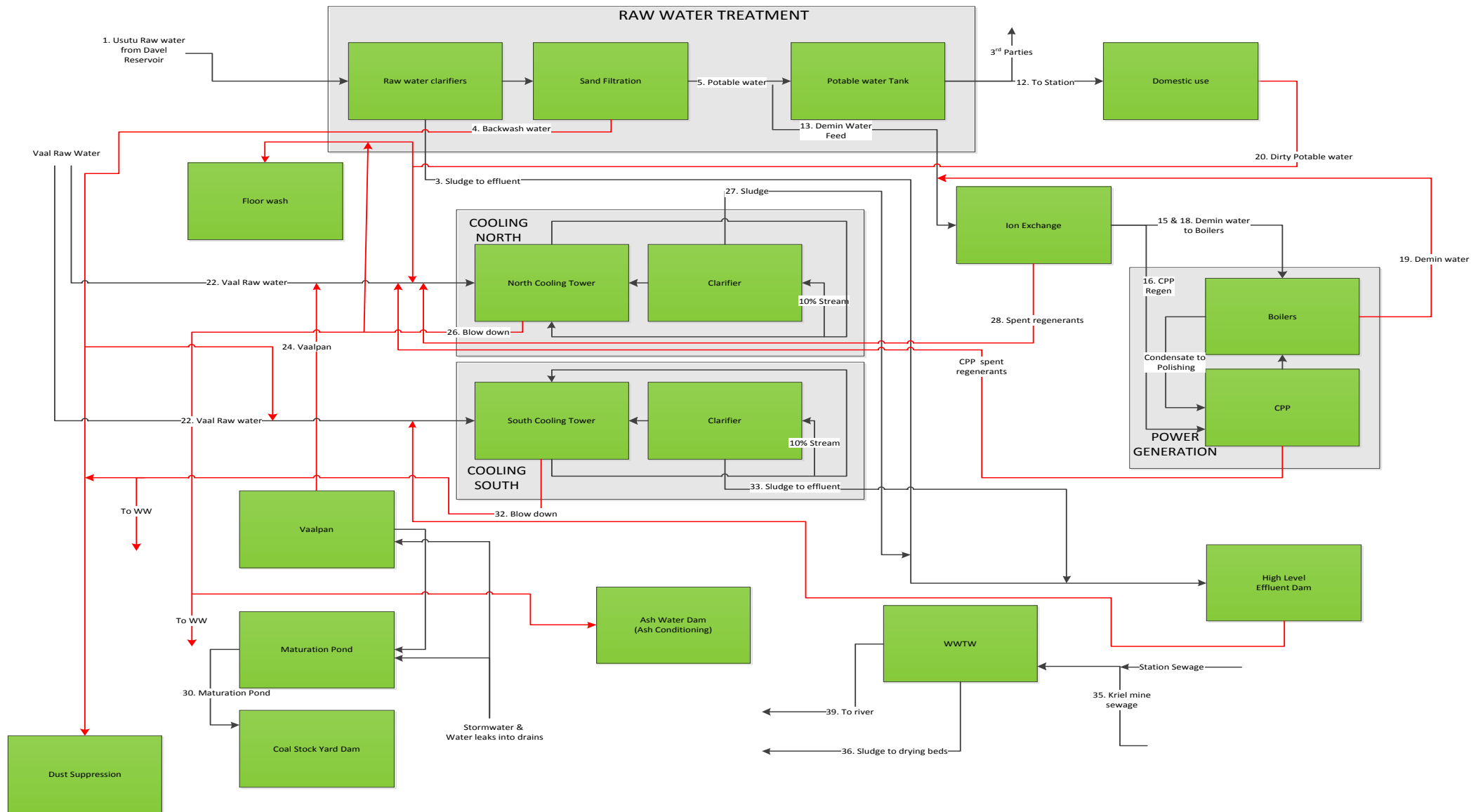
Scenario 3: Freshwater intake (103 581m³/d)



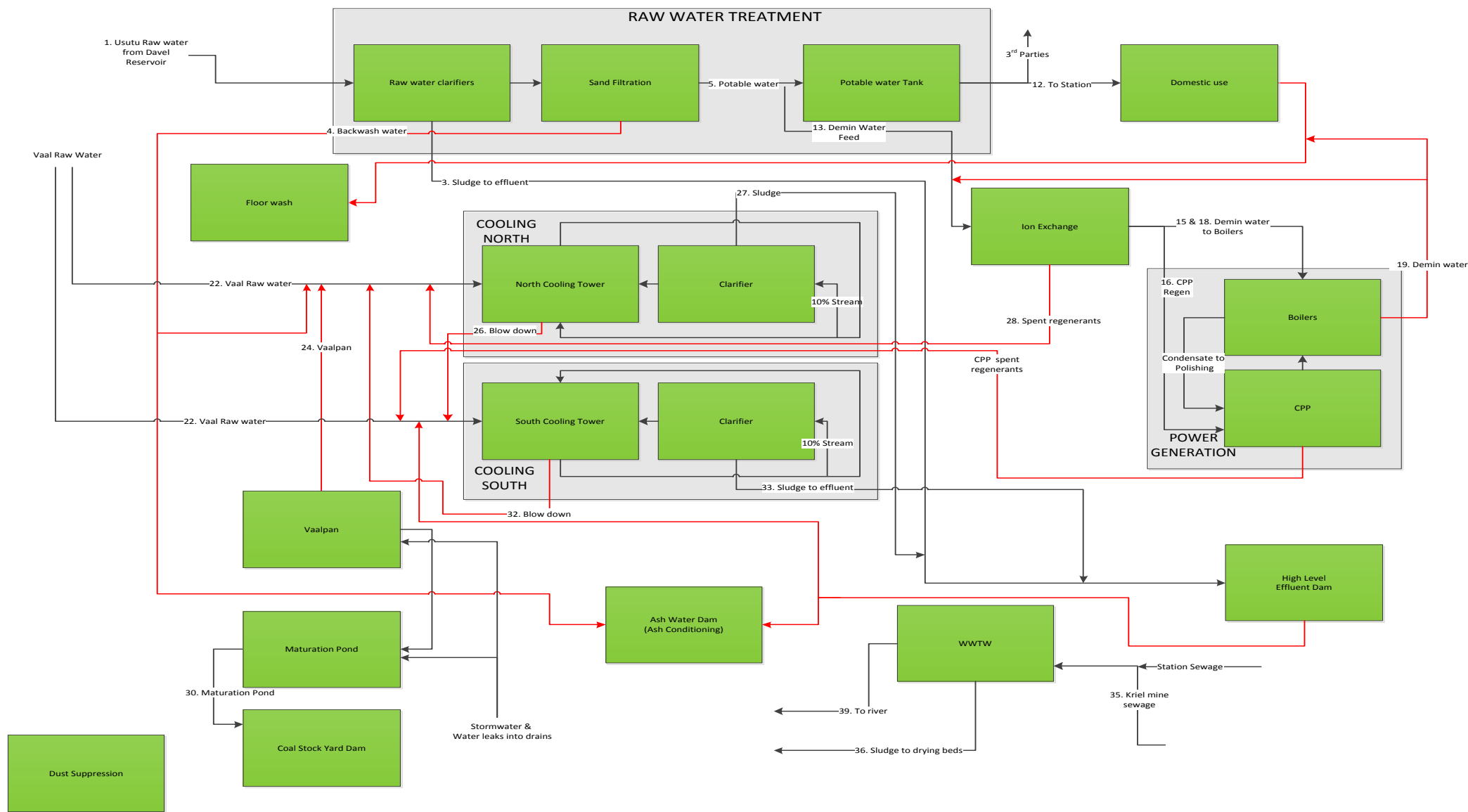
Scenario 4: Freshwater intake (104 860m³/d)



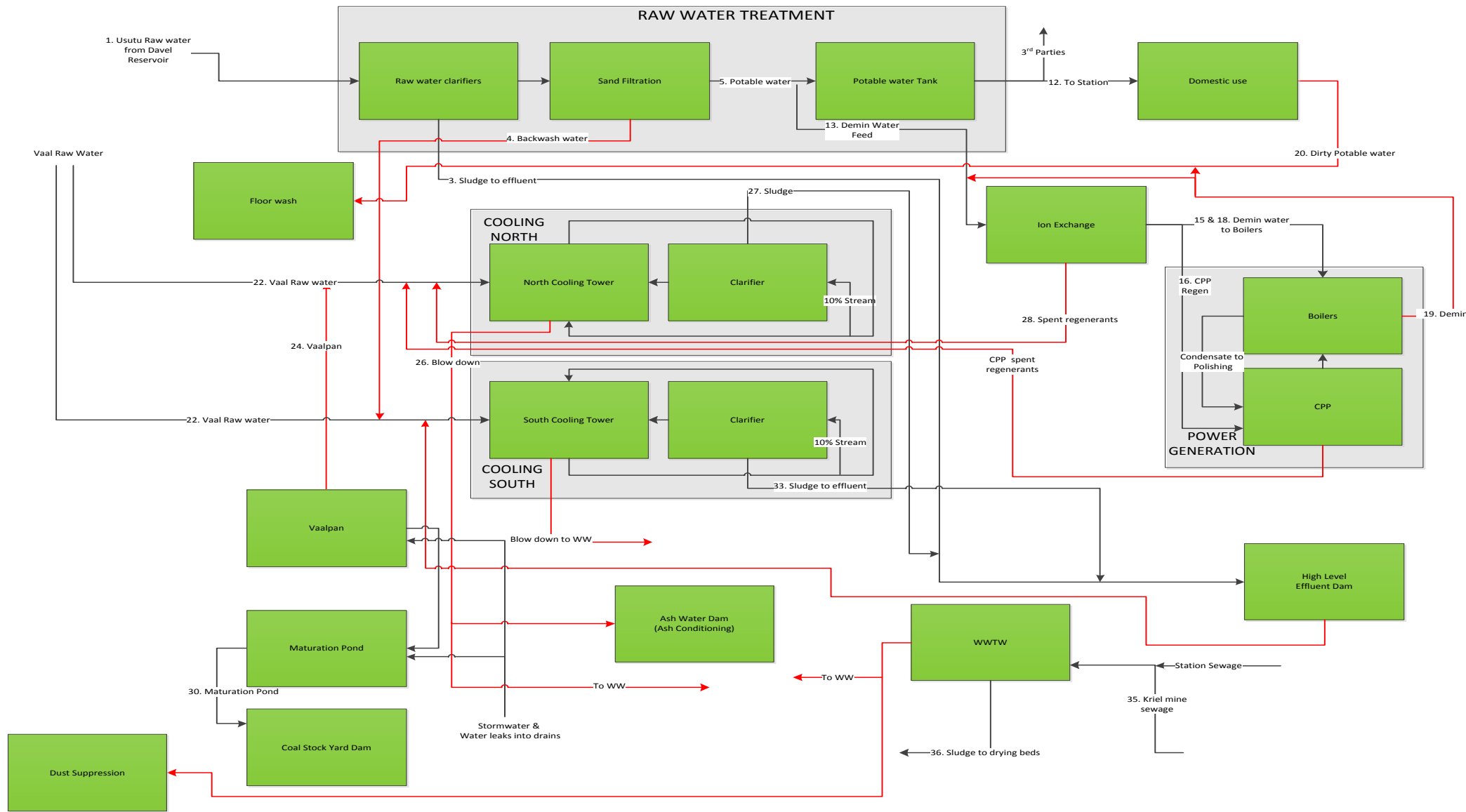
Scenario 5: Freshwater intake (103 800m³/d)



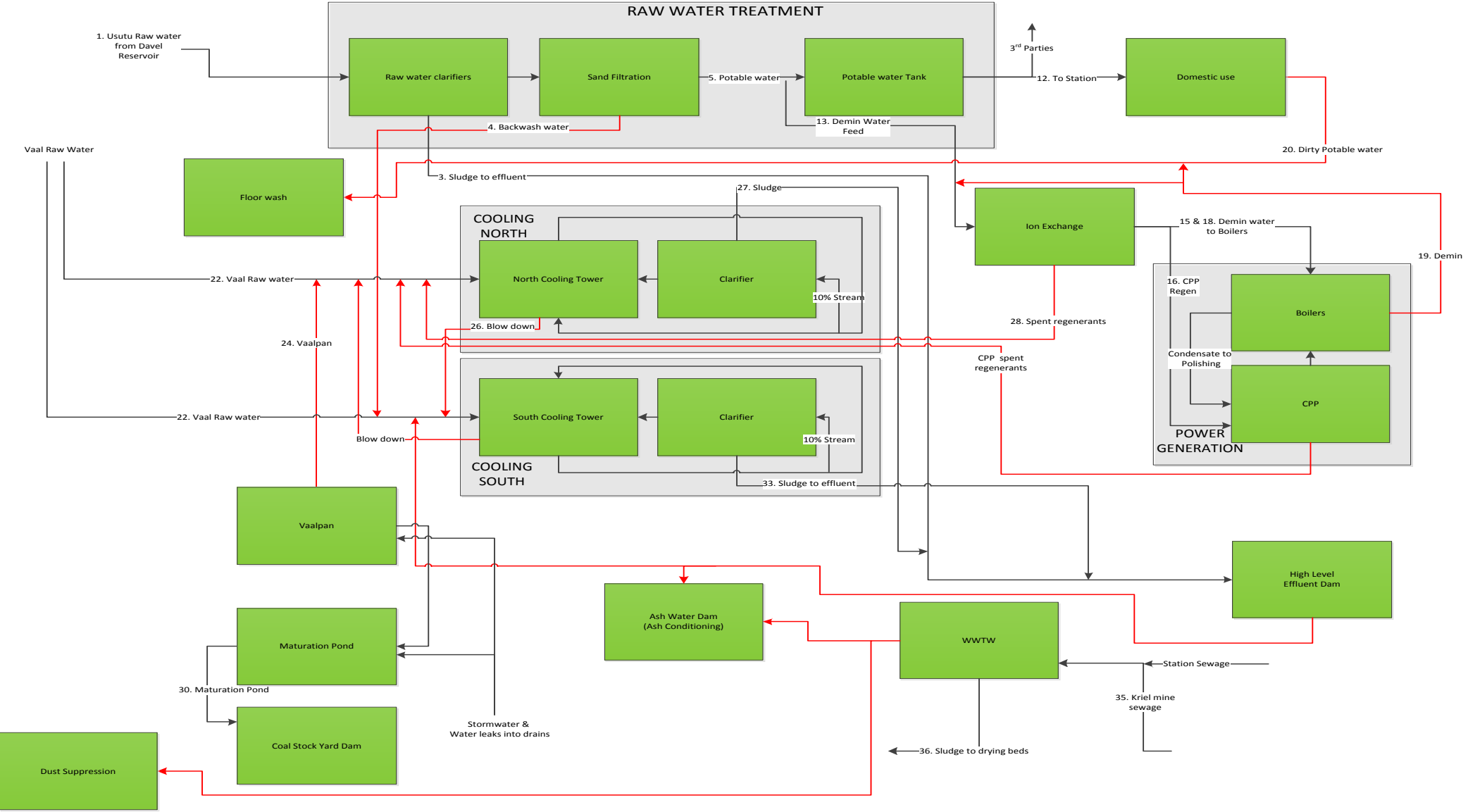
Scenario 6: Freshwater intake (96 801m³/d)



Scenario 7: Freshwater intake (104 651m³/d)



Scenario 8: Freshwater intake (95 591m³/d)



APPENDIX III: Testing a New Water Network With a Cooling Tower Mass Balance.

This example illustrates how the mass balances and operational conditions for the cooling towers have to be evaluated carefully for each suggested water network before implementing changes.

Table 11 contains data from one of the water networks suggested by the model for a scenario incorporating blowdown interchange. The total freshwater intake for this scenario was 95MI/d and no wastewater was produced. The quality data of the streams is taken from the model for TDS and estimated values for sulphates.

Table 3: Example Stream flows and qualities

Streams INTO CTN					
	Flow (m3/d)	SO4 Content(mg/kg)	Fractional TDS		Fractional TDS
Effluentdam	833.3	331	5.78473	1965	34.34137
SF1	181.1	100	0.379815	70	0.265871
CPP	208.22	15	0.065504	128	0.558967
Boilers	0	1	0	3.2	0
Pspotable	588.285	100	1.233791	58	0.715599
IX	518.9	15	0.163241	128	1.392988
Vaal	351.3	435	3.204949	1150	8.472853
CTsblowdn	6000	750	94.37701	2600	327.1736
Fwvaal	39000	15	12.26901	130	106.3314
TOTAL	47681.105				
AVG (mg/kg)		117.4780471		479.3	
Streams INTO CTS					
	Flow (m3/d)	SO4 Content(mg/kg)	Fractional TDS		Fractional TDS
Effluentdam	847.1	331	5.511581	1965	34.91009
SF1	181.3	100	0.356456	70	0.266164
CPP	208.6	15	0.06152	128	0.559987
Boilers	0	1	0	3.2	0
Pspotable	589.6	100	1.159219	58	0.717198
IX	520	15	0.153357	128	1.395941
Vaal	357.3	435	3.055838	1150	8.617565
CTNblowdn	3066.7	750	45.22105	2600	167.2239
Fwvaal	45102.3	15	13.30142	130	122.969
TOTAL	50872.9				
AVG		68.82044393		336.7	

Of interest for our discussion are the average sulphate and TDS contents of the streams going into each cooling tower. Per definition the cycles of concentration is the concentration of the cooling water divided by the concentration of the make-up

water. The station's upper limits for the concentration of TDS in the cooling water are 2600mg/l and 750mg/l for sulphates (if the most conservative standard is used).

When the maximum CoC that can be allowed for the South cooling tower is calculated for instance we find it to be $750/68.8 = 10.9$ for sulphates and $2600/336.7 = 7.7$ for TDS. For the North cooling towers the values are 6.4 and 5.4 respectively. This water network can therefore not be blindly employed and the cooling towers operated at CoC's higher than these values without violating set standards.

This example illustrates how the mass balances