Load management on a municipal water treatment plant

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It all starts here ™

Abstract

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Keywords: Water treatment plant, load management, load shift, pump scheduling, Demand-Side Management (DSM).

Water Treatment Plants (WTPs) supply potable water which is transferred by pumps to various end users. WTPs and other sub-systems are energy intensive with pump installed capacities varying between 75 kW – 6 000 kW. It has therefore become important to optimise the utilisation of WTPs. Cost savings can be achieved and the load on the national grid can be reduced. The aim of this study is to develop and implement load management strategies on a municipal WTP.

In this investigation the high lift pumps are deemed to be the largest consumers of electricity. Strategies to safely implement load management on a WTP were researched. By optimising the operations of the pumps, significant cost savings can be achieved. Comparisons between different electricity tariff structures were done. It was found plausible to save R 990 000 annually, on a pumping station with four 1 000 kW pumps installed, when switching to a time-of-use dependent tariff structure.

Strategies to optimise plant utilisation while attempting a load management study include the optimisation of filter washing methods and raw water operations. An increase of 34% in efficiency for a filter backwash cycle was achieved. To accommodate the effects of the load management on the WTP, the operation of valves that allow water to distribute within the plant was also optimised.

The implemented control strategies aimed to accomplish the full utilisation of the WTP and sub-systems to achieve savings. An average evening peak period load shift impact of 2.21 MW was achieved. Due to filter modifications the plant is able to supply 5% more water daily. A conclusion is drawn regarding the success of the strategies implemented. Recommendations are made for further research.

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Abbreviations

COCODAFF	Counter-current Dissolved Air Floatation Filtration
CPI	Consumer Price Index
CT	Current Transformers
CWR	Clear Water Reservoir
DAF	Dissolved Air Floatation
DCS	Distributed Control Systems
DSM	Demand-Side Management
EMS	Energy Management System
ESCo	Energy Services Company
GAC	Granular Activated Carbon
HLPS	High Lift Pump Station
HMI	Human Machine Interface
ICS	Industrial Control System
IDM	Integrated Demand Management
IT	Information Technology
kW	Kilo-Watt
LLPS	Low Lift Pump Station
M&V	Measurement and Verification
Mℓ	Mega-litre
MW	Mega-Watt
OLE	Object Linking and Embedding
OPC	Object Linking and Embedding (OLE) for Process Control
PAC	Powdered Activated Carbon
PID Control	Proportional-Integral-Derivative Control
PLC	Programmable Logic Controller
PS	Pump Station
SCADA	Supervisory Control And Data Acquisition
ToU	Time of Use
UV	Ultraviolet
VSD	Variable Speed Drive
VT	Voltage Transformers
WTP	Water Treatment Plant

1

BACKGROUND

Chapter 1

Chapter 1 provides a brief description of the water distribution systems and electricity situation in South Africa. The need for Demand-Side Management (DSM) initiatives on bulk water distribution systems is identified.

1 Background

1.1 Preamble

Water Treatment Plants (WTPs) supply potable water that is transferred by pumps to various end users. These WTPs and other sub-systems are energy intensive. It is important to optimise the utilisation of the WTP and its sub-systems to realise cost savings.

In Chapter 1 the water distribution industry is identified as energy intensive systems. Water is an essential resource to an economy and its people. Pumps transfer water over vast distances and are the most energy intensive equipment installed at distribution systems.

Water distribution systems have been identified as ideal candidates to aid in reducing the peak electrical demand on the national grid. Eskom, the main supplier of electricity in South Africa, has implemented Demand-Side Management (DSM) initiatives to encourage large electricity consumers to reduce their peak demand.

1.2 Water distribution utilities

Many economic sectors are dependent on water and would not be able to function without water. In Europe 44% of total water abstraction is used for agriculture, 40% for energy production and industry and 15% for public water supply [1]. In the United States the picture looks a bit different. In 2000 thermo-electric power supply used 48%, industrial 5%, agriculture 34% and public supply used 11% of water supply [2].

According to the Department of Water Affairs, water usage in South Africa is dominated by irrigation, which accounts for 67% of all water used in the country. Urban sectors account for 18%, rural sectors account for 4%, mining and power generation account for 7% and commercial forestry plantations account for 3% [3]. Figure 1 presents the water usage of the different major economic sectors.

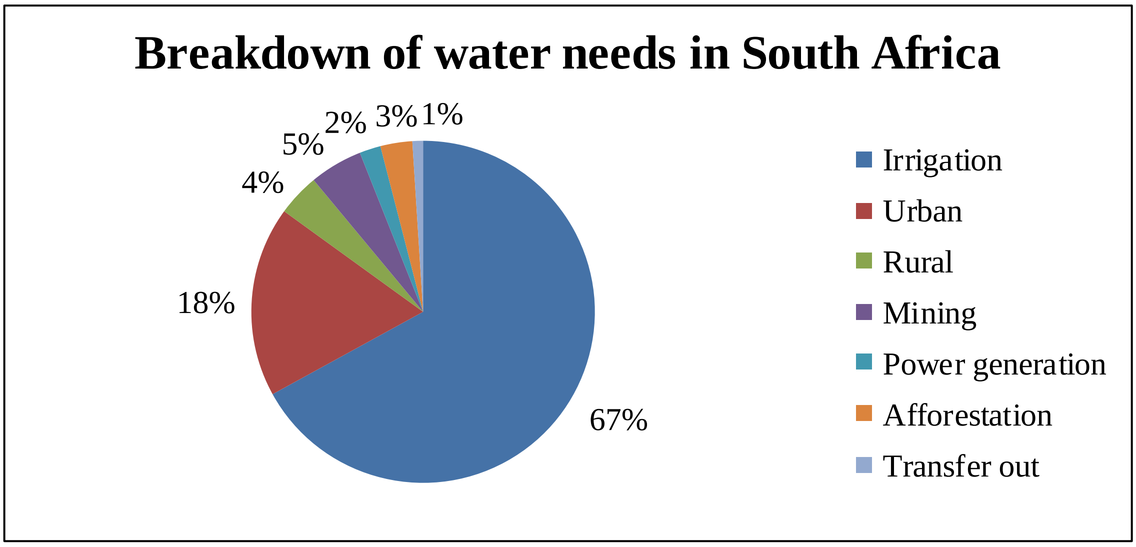

Figure 1: Water needs in the major economic sectors (Adapted from [3])

South Africa's water boards are the major bulk potable water providers in the country. These water boards, of which there are fourteen, supply a total of approximately 2.39 billion cubic metre of potable water per annum at an annual operating cost of approximately R 4.3 billion [4].

The design capacity of the potable WTPs in South Africa is approximately 3.1 billion cubic metre, while their collective demand is approximately 2.4 billion cubic metre, resulting in an collective utilisation of 77% [4]. However, some of these WTPs operate at the designed capacity and are fully utilised. These WTPs need to operate in the most effective manner to maximise the productivity of the plant.

1.2.1 The water environment in South Africa

In South Africa, it is a basic human right to have access to sufficient water according to the constitution of the Republic of South Africa no. 108 of 1996. Only 89.5% of South Africans had access to piped water in 2011 [5]. It is of vital importance that people have access to safe drinking water, as many deaths occur due to waterborne diseases in Africa.

In developing countries waterborne diseases cause the majority of illnesses, with diarrhoea being the leading cause of childhood deaths [6]. It is very important to supply clean, safe and drinkable water to people. Water is not only consumed, but is used for cooking, cleaning, and various domestic and industrial uses [7].

Seven percent of worldwide electricity is consumed by drinking water and wastewater treatment [8], [9]. Figure 2 presents the water life cycle through the municipal sectors. In many of these stages pumping is required. Potential cost savings can be achieved by utilising these facilities in an effective manner.

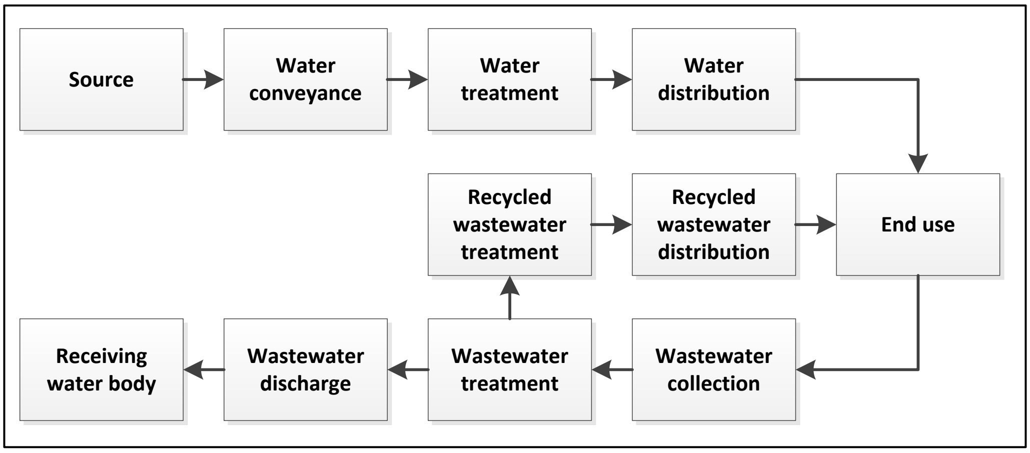

Figure 2: Stages of the water life cycle (Adapted from [7], [10])

Figure 3 presents the cost of sales of a typical WTP. The purchase of raw water is the most expensive cost at 29% [11]. Electricity is second by a small margin at 27% [11]. Saving on electricity costs at a WTP will have positive financial consequences. Electrical cost savings will enable the WTP to be more profitable.

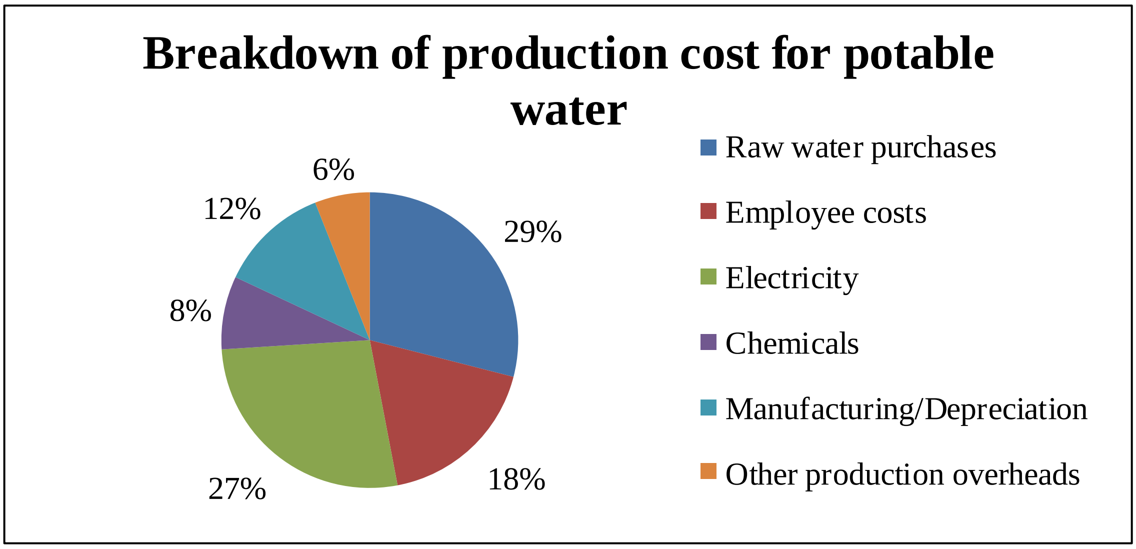

Figure 3: Cost breakdown of operations (Adapted from [11])

Energy is consumed at every stage of the water cycle, including water supply, treatment, use and disposal [7]. The water treatment facilities are energy intensive. The intensity of the energy consumed by such a facility depends largely on the technologies used [7]. Pumping water into a pressurised distribution system consumes about 85% of the total energy in a conventional treatment plant [12], [13]. Figure 4 presents the energy consumers in a typical WTP.

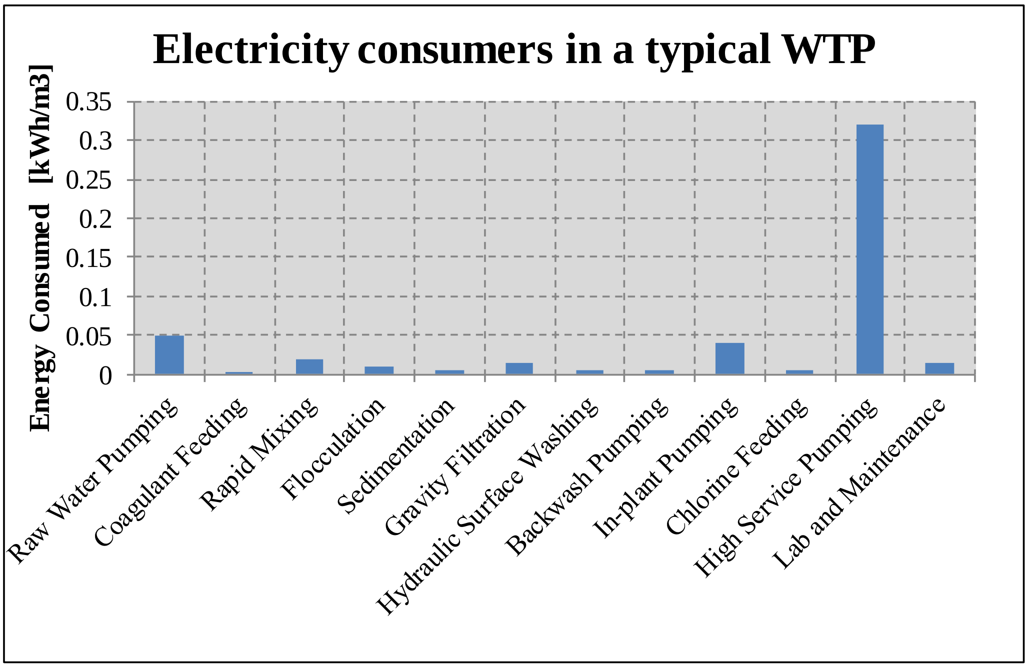

Figure 4: Electricity consumers in a typical WTP (Adapted from [7])

The purification facilities are not always located in close proximity to where water is used. Piped water is often pumped from the main water source to where it is needed. It can be seen from Figure 4 that pumping consumes the most energy, especially high service or high lift pumping.

By optimally operating the high service or high lift pump stations, cost savings can be realised. This study does not focus on decreasing the demand for water, however, leak reduction is plausible. DSM strategies will be implemented to manage the electrical load of a WTP. The electrical load of the high lift pump stations will be shifted out of the peak periods and into the less expensive off-peak periods.

1.2.2 DSM on pumping systems

DSM projects have been widely implemented in various sectors. Figure 5 presents the energy usage by economic sectors. The major electricity consumers can be divided into mining, industrial and municipalities.

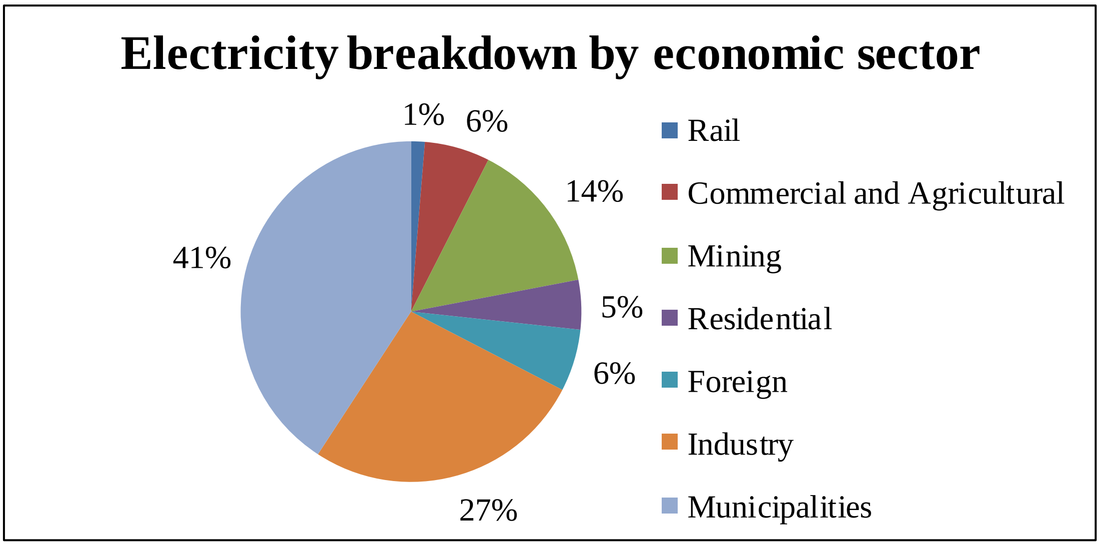

Figure 5: Electricity sales by economic sector (Adapted from [14])

i. DSM on pumping systems within the mining sector

Many DSM projects have successfully been implemented in the mining sector on pumping, compressed air and cooling projects [15]. Mines use water mostly for dust suppression, cleaning, drilling and cooling [16]. The dewatering system of a mine accounts for approximately 15% of the total electricity consumption [16].

The water is sent to the settling tanks where the mud in the water and clear water are separated. The water is then sent to the hot storage dams and is pumped back up the levels for reuse. Many deep mines' dewatering system consists of multiple cascade pump stations. Due to the depth of many of South African mines, dewatering pumps often have to overcome a pressure head of more than a 1 000 m [17].

Successful load management, especially load shifting, can be achieved on a mine dewatering system. However, sufficient storage capacity of the hot dams must be available to allow the dewatering pumps to be switched off during peak times [18]. By effectively scheduling operating times, electricity and cost savings can be achieved.

ii. DSM on raw water pumping systems

South Africa is ranked the 30th driest country in the world [19]. The global average annual rainfall is approximately 860 mm, while South Africa's average annual rainfall is only about 450 mm [20].

In South Africa water is unevenly distributed. Water is not always available where it is needed. It is necessary to transfer water from water abundant areas to water scarce areas to overcome this problem. There are 28 inter-basin transfer schemes with a total transfer capacity of more than 7 billion cubic metre per annum [19].

Water transfer schemes provide water to various sectors including agriculture, power generation, mining and industry [21]. Many of the reservoirs and dams are located at elevated levels above the pump stations [21]. High flow rates are required to ensure that the reservoirs and dams remain adequately full. Due to the high flow rate and high pressure head that is required, these pumps have large installed capacities [21].

Successful load shift projects have been done on these water transfer schemes; provided sufficiently large reservoir and dam capacities are available. This is necessary to accommodate the lack of inflow, without compromising water supply to the client. This lack of inflow is attributed to the pumps being switched off during the peak periods for load shifting purposes.

Both pumping systems, dewatering in mines and water transfer schemes have successfully implemented load management projects. Due to the high electricity consumption of municipalities, similar load management projects might be possible. More specifically these include municipal WTPs which pump large volumes of potable water to consumers.

iii. DSM on municipal WTPs

Implementing a load shift project on a municipal WTP requires more attention. This is due to the processes that precede the pump station. For example, the WTPs have raw water entering the plant, which has to be treated and stored before it is pumped to the consumers. All of these processes are inter-dependent upon each other.

Many of the control strategies for stopping/starting pumps during the peak periods for load shifting purposes, have previously been implemented. These control strategies need to be adapted to suit a municipal WTP. Municipal WTPs have more components that need to be considered before decisions can be made to start/stop a pump.

Municipalities have different water treatment facilities. Wastewater treatment and potable water treatment are the two treatment facilities mostly operated by municipalities. Wastewater treatment removes contaminants, such as sewage, from wastewater. It is done by the separation of suspended solids and liquids. It produces a liquid suitable to dispose of to the environment and sludge for disposal or reuse [22].

This study focuses purely on the potable water treatment intended for human consumption. Potable water treatment facilities use fresh water sources such as lakes and rivers to supply safe drinking water. The quality of the end product is tested multiple times a day to ensure the water is within the quality constraints.

1.3 Electricity situation in South Africa and demand reduction initiatives

1.3.1 South African energy situation

South Africa has a large coal mining industry, but has limited reserves of oil and natural gas. South Africa uses its coal-fired power stations to meet most of its energy needs [23]. Eskom is the primary electricity supplier in South Africa and produces 95% of its electricity. Approximately 40% of Africa's demand for electricity is supplied by Eskom [24]. Approximately 85% of Eskom's electricity is produced by coal-fired power stations with an installed capacity of 42.0 GW [25].

Approximately 5.7% is produced by gas-fired stations [25]. Approximately 4.4% is produced by Koeberg, South Africa's only nuclear generation plant with an installed capacity of 1 910 MW [23]–[25]. Approximately 5% is produced by hydroelectric generation plants with a combined installed capacity of 2 000 MW [23]–[25]. Figure 6 presents the generation capacity of Eskom's power stations.

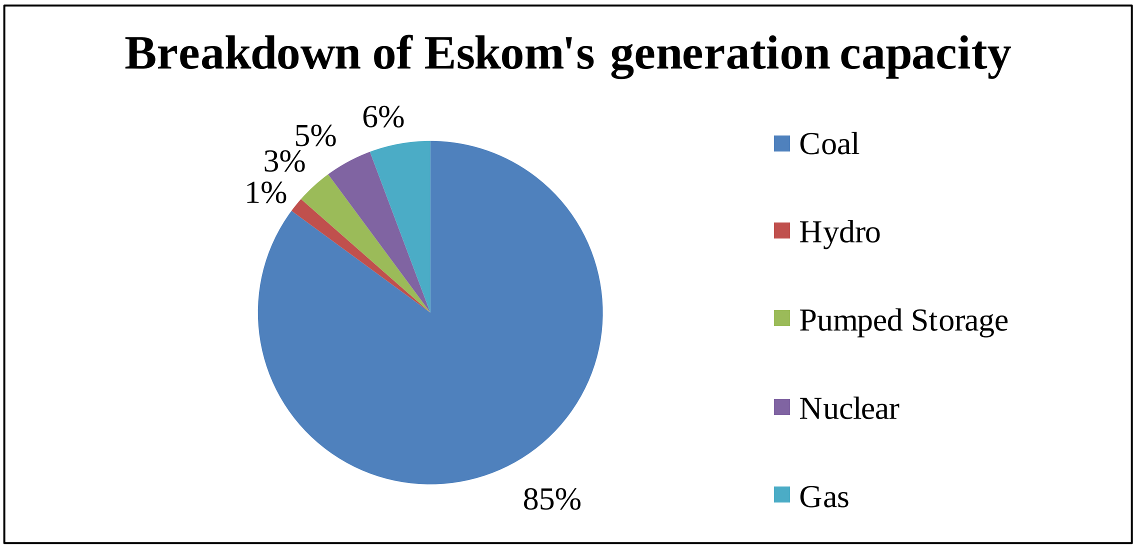

Figure 6: Eskom's generation capacity (Adapted from [25])

The average life span of a coal-fired power station is between 30 and 40 years [26]. Presented in Figure 7 is the age of Eskom's power stations. Some of these power stations have reached the 40-year mark, such as Komati and Camden. Many other power stations are nearing the retirement age of 40 years. The average of all the Eskom power stations is 30 years.

During November of 2013, Eskom urged some of its biggest clients to cut back on their electricity consumption by 10% to avoid blackouts [28]. In the early months of 2014 (6 March 2014) Eskom declared a state of electricity emergency [29], [30]. Eskom has lost about 5 500 MW due to reduced imports and unplanned outages in March 2014. Eskom implemented load shedding in parts of South Africa as a last resort. Note that this happened during a South African summer month which is the low demand season.

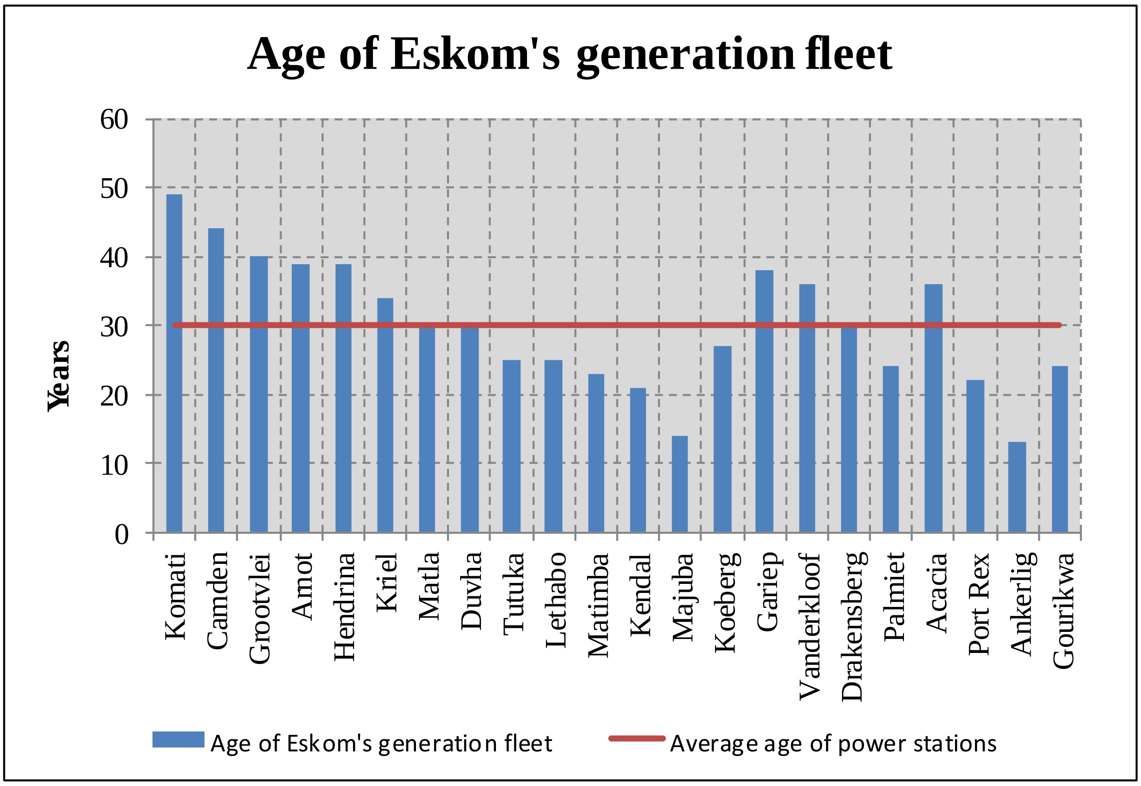

Figure 7: Age of Eskom's generation fleet (Adapted from [27])

Maintenance is needed on these aging power stations. Due to the high electricity demand, maintenance could not be done as planned on these stations. This created a maintenance backlog [27]. For example, during the winter months of 2014 approximately 2 000 MW was not available due to planned maintenance [31]. This does not include the unplanned outages.

South Africa's power grid is constrained by a very small margin between the peak demand and the available electricity supply [23]. The load profile during the winter is much higher when compared to the summer profile. During a typical weekday the demand increases between 07:00 and 10:00 and again in the evening between 18:00 and 20:00. Figure 8 presents the average load profile of a typical summer and winter day.

It can be seen from Figure 8 that the demand during the evening peaks is much higher than in the morning peak periods although the morning peak last longer. Eskom introduced a Time of Use (ToU) tariff structure. ToU tariff structures are a common practice in developed countries [32]. ToU encourages consumers to use less electricity during the peak periods which subsequently reduces the demand of electricity on the national grid [33].

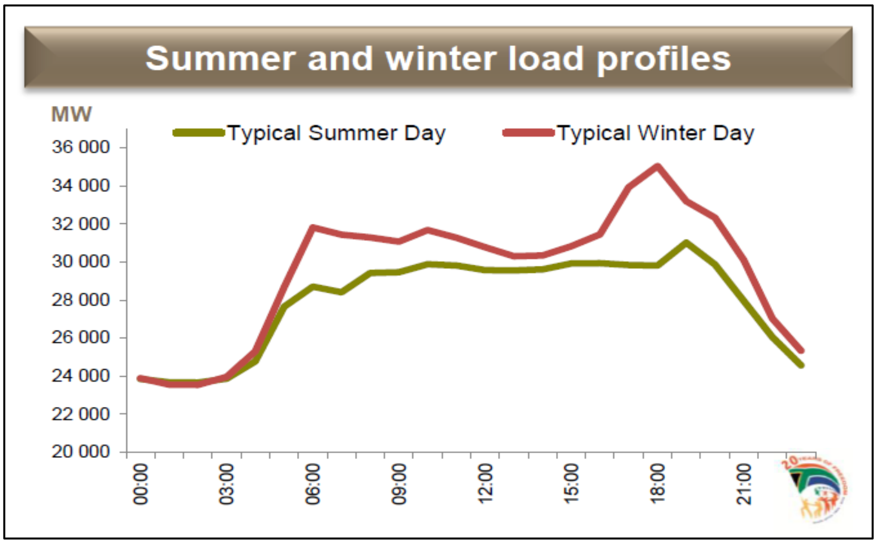

Figure 8: Typical summer and winter load profile [27]

Presented in Figure 9 is the average margin or operating reserves from 2009 – 2014. During the peak periods minimal reserves were available, although adequate reserves were available throughout the rest of the day [25]. It can also be seen from the figure that the small margin available during peak periods decreased in recent years.

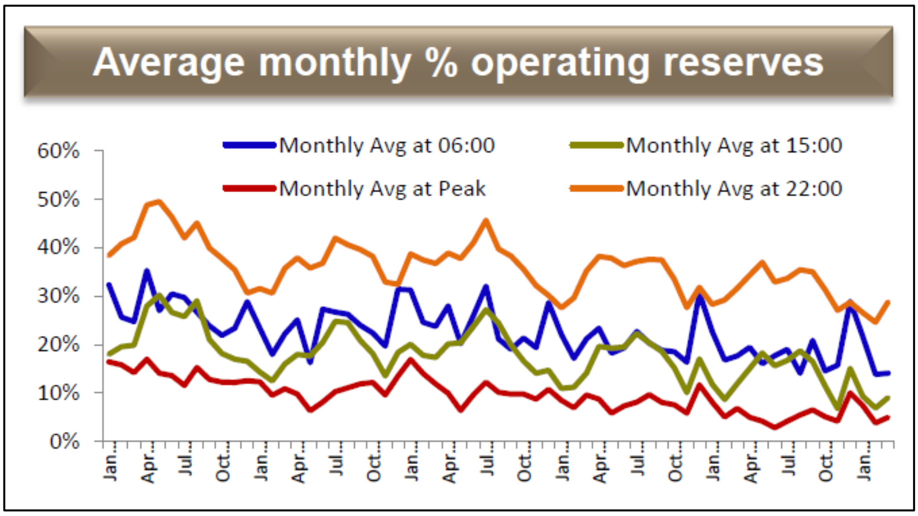

Figure 9: Average operating reserves [25]

The supply of electricity is not always able to meet the demand. To increase the supply of electricity Eskom started building new power stations, such as Medupi and Kusile. Eskom plans to add 17.1 GW of new generation capacity by the end of 2018 [27]. The building of these power stations will still take some time and in the meantime Eskom has implemented DSM projects to decrease the demand.

1.3.2 ToU tariff structures

The ever increasing electricity tariffs are a major concern and financial risk for energy intensive users. The electricity tariff adjustment for the past 20 years is presented in Figure 10. The Consumer Price Index (CPI) is also presented in Figure 10 to put the price increases into perspective. The CPI is a measure of the changes in price of consumer goods purchased by households.

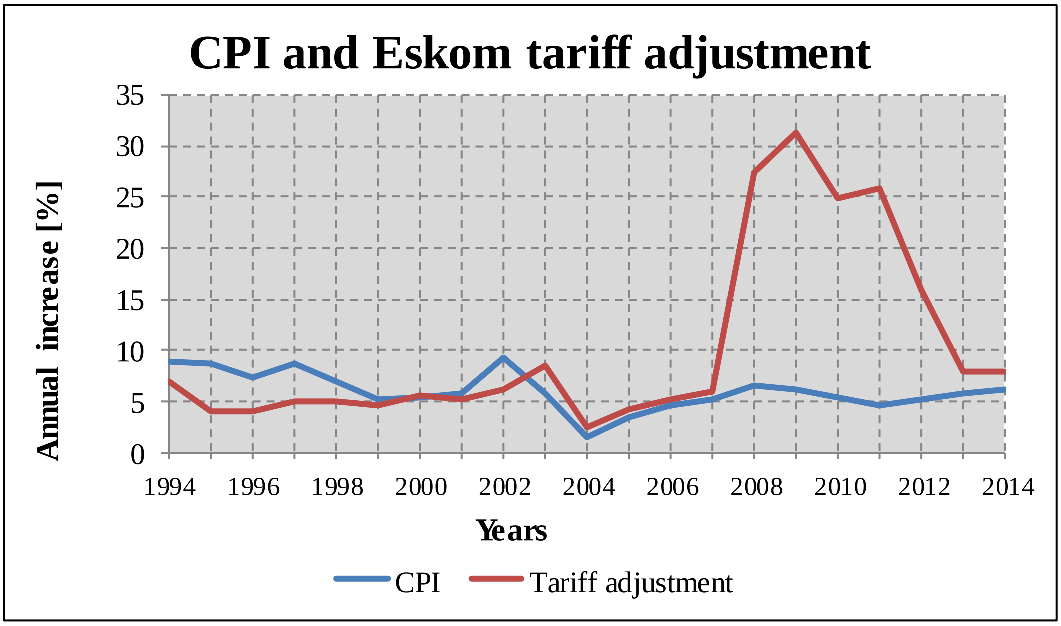

Figure 10: CPI and Eskom tariff adjustment (Adapted from [34])

ToU tariffs reflect the supply-and-demand of a power utility. When the electricity demand is high, the electricity tariff is also high. Mainly two of these ToU tariff structures will be investigated and discussed briefly due to their relevancy to the cost implications of a particular pumping system. There are, however, many other tariff structures but these are not relevant to the scope of this study.

The simplest tariff comprises only two tariff periods. The electricity consumer is charged a peak rate between 06:00 and 22:00 on weekdays, and off-peak for the rest of the time. This tariff structure is called the Nightsave urban tariff. The tariff periods of Nightsave urban is presented in Figure 11. Eskom also differentiates between a high demand season, which is from June to August, and a low demand season, which is from September to May.

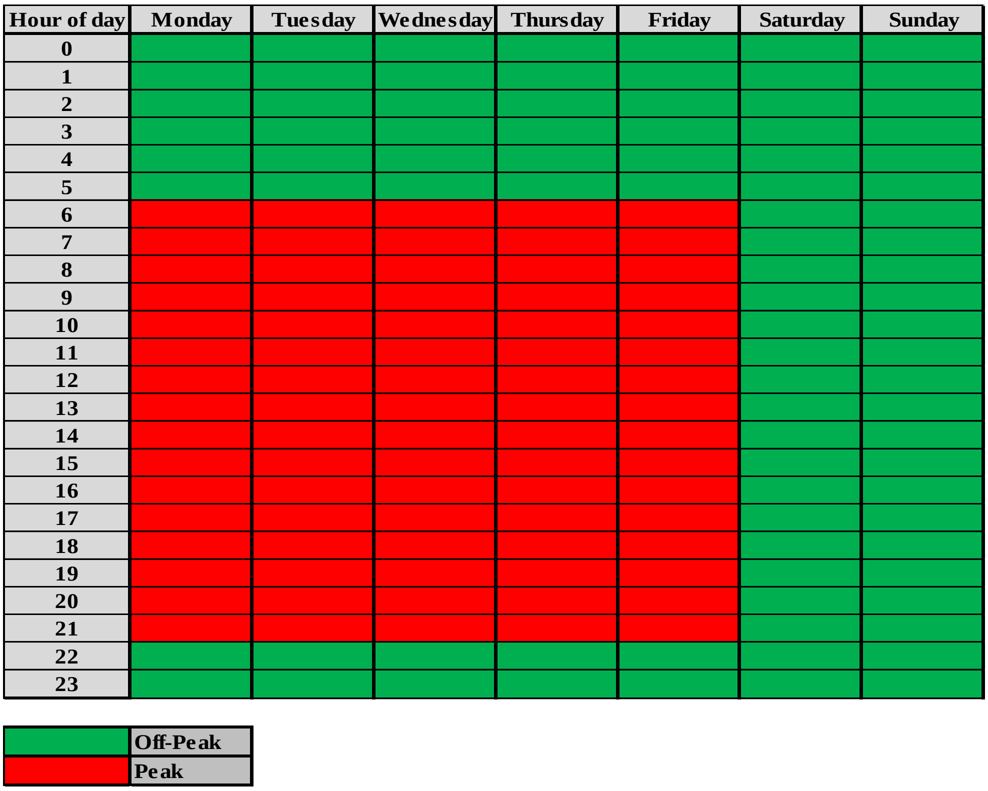

Figure 11: Nightsave urban tariff periods (Adapted from [35])

The cost of electricity on the Nightsave urban tariff is calculated as follows [35]:

- An active energy charge based on the supply voltage and transmission, which is seasonally differentiated.
- A seasonally differentiated energy demand charge based on the supply voltage and transmission. The energy demand charge is calculated from the chargeable demand, which is the highest average measured kVA in a month during peak periods.

Presented in Table 1 is the Nightsave urban tariff pricing structure for 2014/2015. It is important to note that the Nightsave urban tariff does not allow for peak and off-peak periods on active energy. This is due to the fact that the peak and off-peak comes into play with the energy demand charge. The energy demand charge is calculated from a chargeable demand, which is only applicable during peak periods.

Table 1: Nightsave urban tariff pricing [35]

Nightsave Urban		**Active energy charge [c/kWh]**		**Energy demand charge [R/kVA/month]**	
Transmission zone	**Supply voltage**	**High demand season [Jun – Aug]**	**Low demand season [Sept – May]**	**High demand season [Jun – Aug]**	**Low demand season [Sept – May]**
≤ 300 km	**≥ 500 V & ≤ 66 kV**	52.93	41.31	161.52	22.58

The second, more complex ToU, is called the Megaflex tariff structure. The Megaflex tariff comprises three tariff periods, namely peak, standard and off-peak. Presented in Figure 12, is the time periods of the Megaflex tariff. The peak periods, coloured in red, are more expensive when compared with the standard, in yellow, and off-peak periods, in green.

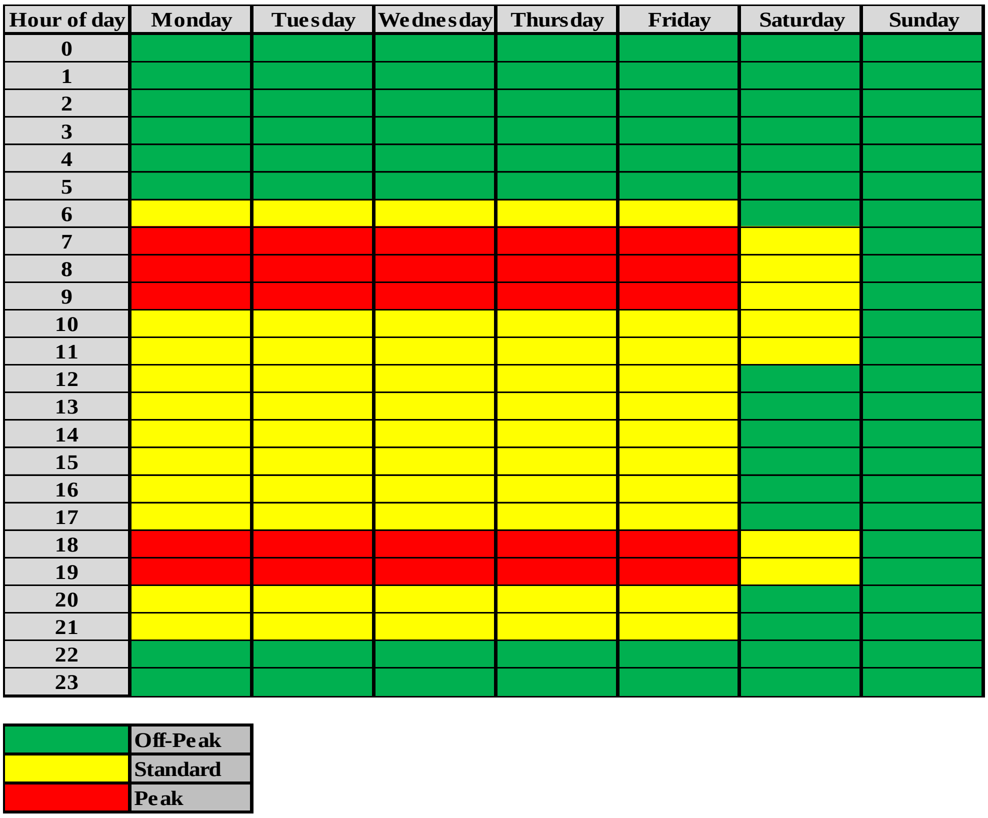

Figure 12: Megaflex tariff periods (Adapted from [35])

The cost of electricity on the Megaflex tariff is calculated as follows [35]:

- A seasonally and ToU differentiated active energy charge based on the supply voltage and transmission.
- A reactive energy charge of the kWh recorded during the standard and peak periods, only applicable during high-demand season.

Presented in Table 2 is the Megaflex tariff pricing structure for 2014/2015. Note the difference in the price for the different tariff periods. The high demand season peak period is more than three times higher than that of the low demand season peak, as presented in Figure 13. By effectively utilising the electricity usage of a consumer, large cost savings can be achieved on electricity bills.

Table 2: Megaflex tariff pricing [35]

Megaflex		**Active energy charge [c/kWh]**					
Transmission zone	**Supply voltage**	**High demand season [Jun – Aug]**			**Low demand season [Sept – May]**		
		Peak	**Standard**	**Off-peak**	**Peak**	**Standard**	**Off-peak**
≤ 300 km	**≥ 500 V & ≤ 66 kV**	222.73	67.48	36.64	72.66	50.01	31.73

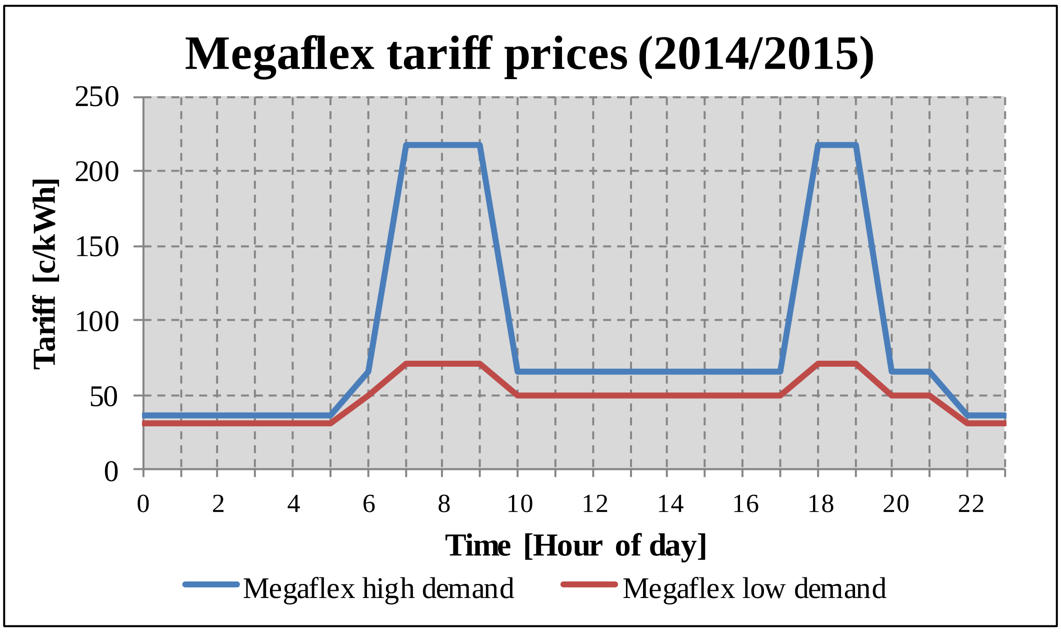

Figure 13: Megaflex tariff prices (Adapted from [35])

The Eskom bill received by the electricity consumer will include additional costs such as distribution network charges; reliability service charge; administration charge; service charge; electrification and rural network subsidy charge; and affordability subsidy charge [35].

1.3.3 Demand-Side Management (DSM)

Integrated Demand Management (IDM), or previously known as DSM, has been implemented by Eskom. DSM can be defined as: "The process by which electricity utilities achieve predictable changes in customer demand and load profile, which can be considered as alternatives to the provision of additional generation plants" [36]. Presented in Figure 14 is the cumulative savings achieved by various DSM initiatives.

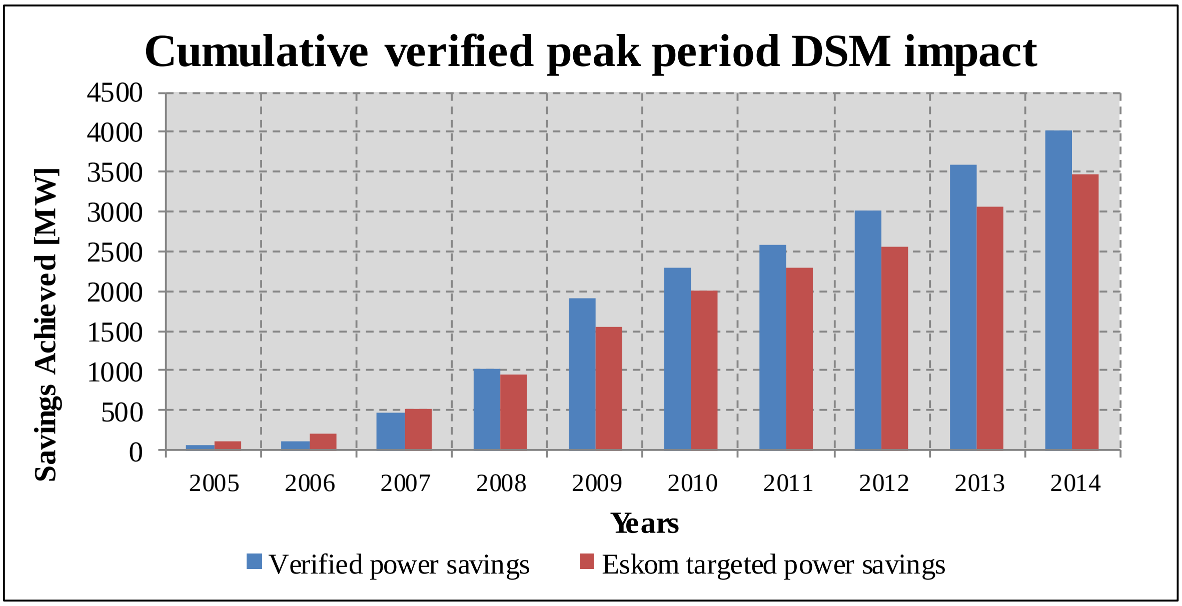

Figure 14: Cumulative DSM impact achieved (Adapted from [25])

This peak period load reduction, which is also known as the DSM impact, has been achieved by Energy Services Companies (ESCos). An ESCo is a company that provides energy solutions to clients [37]. An ESCo enters into an agreement with Eskom to achieve an agreed upon load reduction impact. The ESCo is compensated by Eskom for the resulting impact achieved [38].

Effective management of electricity is to optimise the operation of equipment on a specific plant [36]. Replacing old technology with higher specification equipment can also aid in more effective electricity usage [36]. These DSM initiatives include peak clipping, energy efficiency and load shifting.

Between 1985 and 1995 a peak period load reduction impact of more than 29 GW was achieved in the United States by more than 500 utilities. The cost of achieving these electrical savings was one and a half times less than the cost of building power stations to supply the equivalent demand. Other developed countries also successfully implemented DSM strategies [39].

Presented in Figure 15 is a typical load shift profile, the peak periods as per Megaflex tariff are included in orange. Load shifting is when the electricity consumption is strategically reduced at certain times of the day, such as peak periods. The electricity that was reduced to allow for the peak periods needs to be recovered [33].

The electricity consumption needs to be energy neutral to a normal operation day provided that load has been shifted correctly. By reducing the electrical load at strategic periods, such as peak periods, large cost savings on electricity bills can be achieved [16].

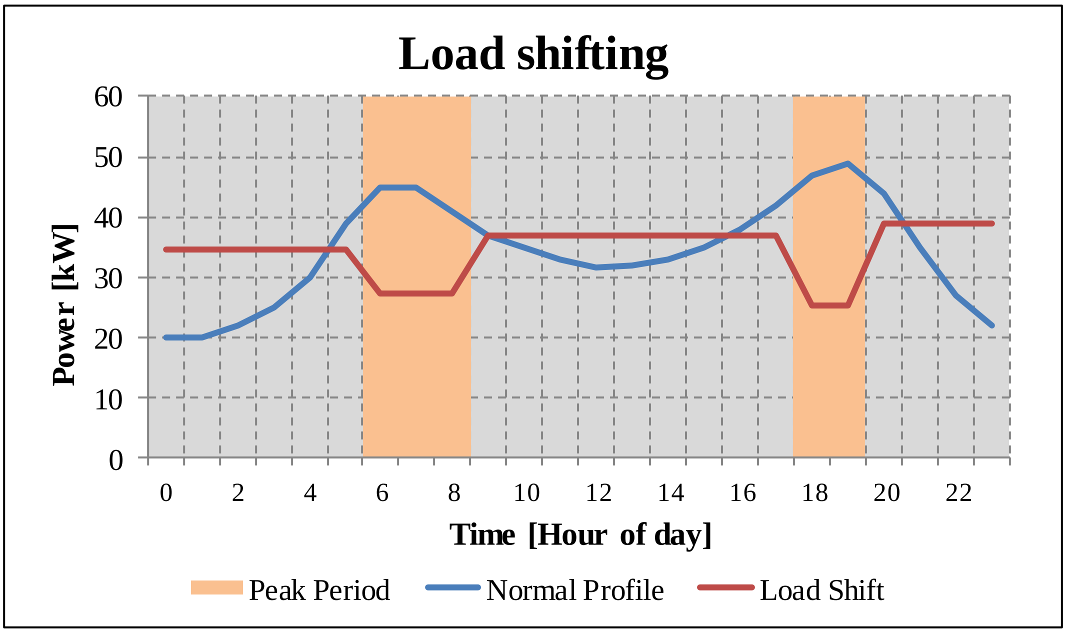

Figure 15: Typical load shift profile

A typical peak clipping profile is presented in Figure 16. Peak clipping is when the electrical consumption during the peak periods is reduced, but not recovered in other periods. Peak clipping will allow the electricity consumer to cut down on the electricity bill, not only by managing the consumption during peak periods, but also by consuming less electricity throughout the day.

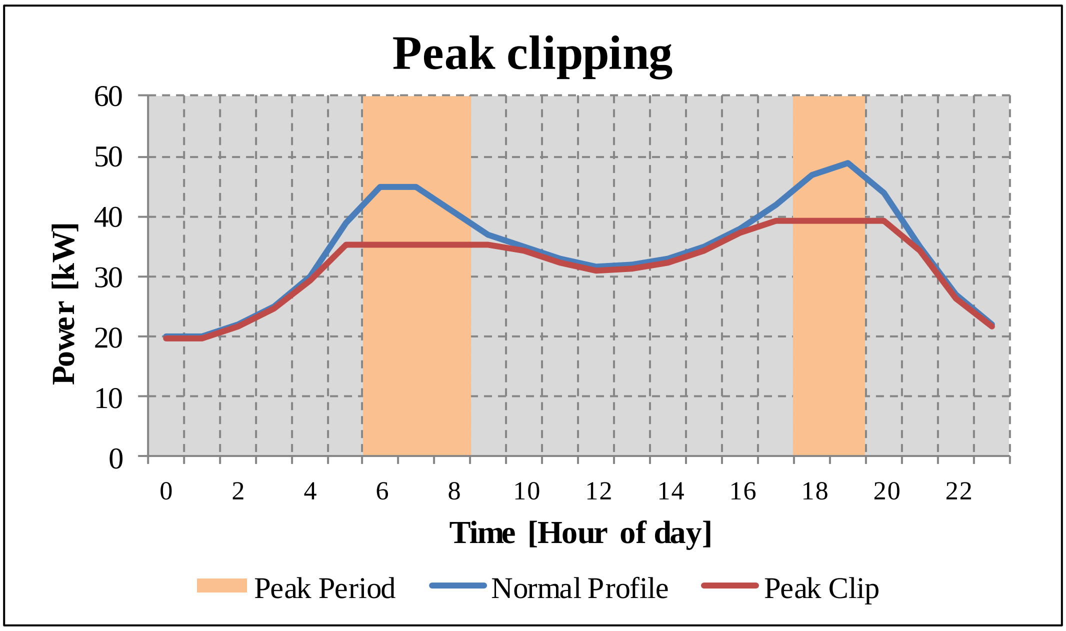

Figure 16: Typical peak clipping profile

Presented in Figure 17 is a typical energy efficiency profile. An energy efficiency initiative involves the conservation of energy throughout the day. This is done by installing more efficient technology and also by optimally operating installed equipment.

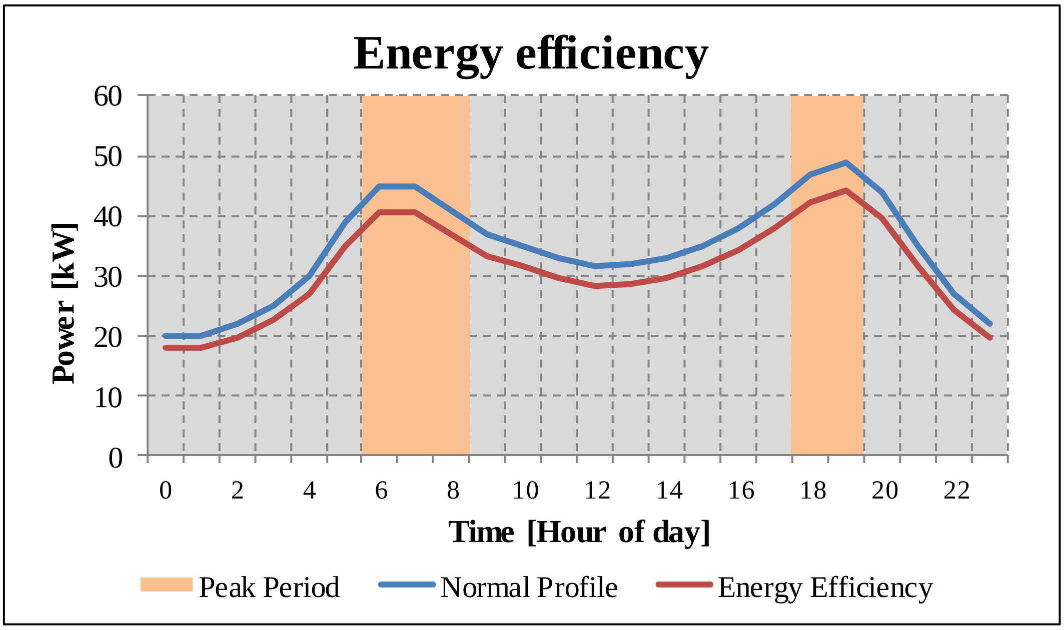

Figure 17: Typical energy efficiency profile

1.4 Overview of industrial control systems

Water distribution utilities and especially WTPs rely on control systems. These control systems monitor, log and control many processes on the plant. These systems provide an overview of the important processes. Information such as flows, pressures, temperatures and many more can be monitored. These systems can be utilised to achieve sustainable load management.

An Industrial Control System (ICS) is a broad term used for a system implemented for control and monitoring purposes in the industry [40]. These systems include Distributed Control Systems (DCS), Supervisory Control And Data Acquisition (SCADA), Programmable Logic Controller (PLC) and many other similar products [41].

ICSs are used in a wide range of industries such as water and wastewater, electrical, oil and natural gas, transportation, chemical, pulp and paper, pharmaceutical, food and beverage and manufacturing [41]. ICSs are vital to the operation and data acquisition of such facilities.

A SCADA is a software interface that focuses on data acquisition and presentation of the Human Machine Interface (HMI) [42]. A SCADA system is a centralised monitoring and control system for field instrumentation, using communication networks. The monitoring and control can be done over long distances if the communication network allows. The SCADA system receives information from the field instrumentation [41].

Commands can be sent back to the field instrumentation by an automated set of commands via the SCADA or HMI [42]. Field instrumentation control operations include starting and stopping equipment, opening and closing valves, collecting data and monitoring alarms [41].

The SCADA system communicates with field instrumentation which is, in most cases, a specialised PLC. Most SCADA systems are able to forward data to other applications using Object Linking and Embedding (OLE) for Process Control (OPC). SCADA is purely a software-based system and is easily affected by Information Technology (IT) problems, such as computer hardware and operating systems [42].

A DCS system is similar to a SCADA in functionality. It is a software-based program that communicates with control infrastructure and presents the controlled equipment at a centralised

HMI [42]. The difference between SCADA and DCS is presented in Table 3. DCS is used mostly in process-based industries such as automotive production, power generation and oil refineries [41].

Table 3: Difference between DCS and SCADA (Adapted from [42])

DCS	SCADA
Process driven	Event driven
Small geographic areas	Large geographic areas
Suited to large, integrated systems such as chemical processing and electricity generation	Suited to multiple independent systems such as discrete manufacturing and utility distribution
Good data quality and media reliability	Poor data quality and media reliability
Powerful, closed-loop control hardware	Power efficient hardware, often focused on binary signal detection

PLCs are used in nearly all industrial processes. PLCs are specialised computer-based electronic devices that stand at the heart of ICS. PLCs are industrial control systems that continuously monitor inputs from devices. It makes decisions based upon the installed program to control the output of specified devices [41]–[43].

PLCs were initially used to replace the old hard-wired relay logic controllers and aided in the transformation of automating many industrial plants. Modern PLCs are smaller in size, cheaper, able to operate within a plant and are capable of communicating with a centralised data acquisition system. PLCs simplified the wiring of the system by replacing the relay logic setup. Modifications to a system can now be done much easier [21], [41], [42].

PLCs can be easily programmed and reprogrammed, even if different brands of PLC are used in conjunction with one another. Modern PLCs have the ability to perform Proportional-Integral-Derivative Control (PID Control) and can perform analogue and binary inputs and outputs. A typical industrial control system, as presented in Figure 18, consists of maintenance tools, HMIs and other remote diagnostics and control loops [41], [42].

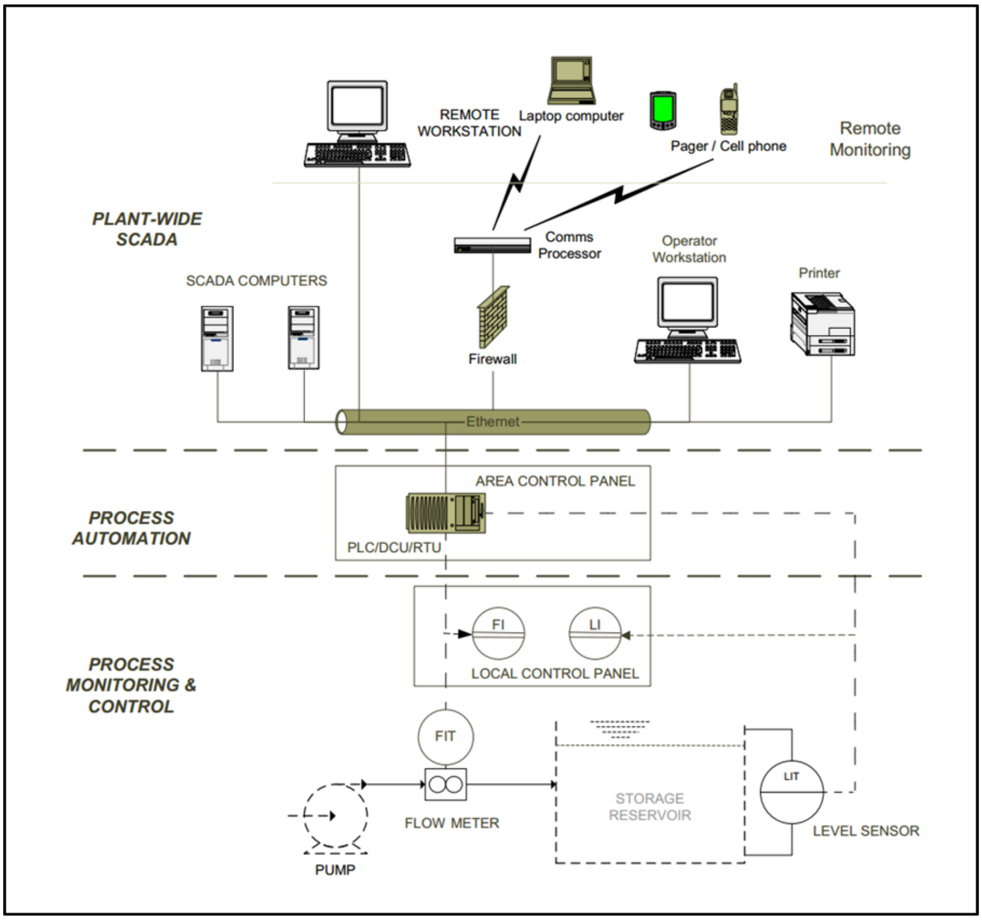

Figure 18: A typical industrial control system configuration [44]

All these components form a complex and integrated control system. ICSs are responsible for the control and protection used to operate an industrial plant [42]. These systems aid in automating industrial plants, causing them to be safer and more effective work environments for plant personnel.

1.5 Need for load management on water distribution systems

The study has thus far provided an overview of the electricity and water situation in South Africa. The demand for electricity is at a point where it nears the maximum supply, especially during peak periods. DSM initiatives have been implemented on various sectors to decrease the demand during peak periods.

DSM initiatives, especially load shifting, have been successfully implemented in water distribution systems. These systems include mine dewatering systems and raw water distribution systems. Water distribution systems have energy intensive equipment, especially the high lift pumps.

WTPs have similar pumping stations, since they supply water over vast distances and at high pressures. This causes the pumps to have significant power consumption. WTPs with large storage capacity in the form of reservoirs make them ideal candidates for DSM initiatives.

Optimising the operation of pumps can reduce the peak period consumption. Successful implementation of load management on municipal WTPs will reduce the load on the national electricity grid. Cost savings can also be achieved if a ToU tariff structure is utilised. A WTP has been identified as an ideal DSM candidate and will be discussed in more detail in this study.

1.6 Objectives of this study

The objectives of this study are as follows:

1. Investigate and understand WTP control philosophies and systems constraints.
2. Identify the scope for load management on a WTP.
3. Conclude load management viability by quantifying potential peak period power saving.
4. Develop a unique control system for WTPs.
5. Configure and implement an Energy Management System as a control system on a WTP.
6. Achieve load management impact and sustain impact on WTP, as a case study.
7. Optimise utilisation of plant by optimising operations.

1.7 Layout of this study

The water situation and water distribution systems in South Africa are introductory to this dissertation in Chapter 1. Chapter 1 also summarises the energy generation and the electricity demand situation in South Africa. A brief introduction to industrial control systems is also provided in Chapter 1.

Chapter 2 commences with background on water treatment processes and typical equipment installed on WTPs. Load management previously done on water pumping systems such as mine dewatering systems, national water distribution systems and potable water distribution systems is presented. Implications and risks involved in these types of initiatives are discussed in Chapter 2.

Chapter 3 offers the development of a unique control system for a WTP. The methodology to implement the control system is discussed. The methodology includes the investigation phase, simulations and tests. The optimised operation is also presented in Chapter 3.

Chapter 4 presents the performance of the implemented DSM strategies on a WTP as a case study. The results of the optimisation strategies are also presented. The results of a comparison between different tariff structures are presented. The study is concluded by recommendations for further research.

2

LITERATURE REVIEW

Chapter 2:

Chapter 2 provides more detail of the treatment process and the equipment involved in these processes. Existing DSM strategies which were implemented on related studies are discussed. The implications and risks associated with these DSM initiatives are briefly discussed.

2 Literature review

2.1 Preamble

In Chapter 1 the electricity shortage in South Africa was identified, especially during peak periods. Large water distribution utilities that supply water to various customers were identified for DSM initiatives. Water distribution utilities pump water at high volumes and pressures with energy intensive pumps.

These systems can reduce production costs by implementing load management to reduce peak period electricity costs. These water distribution utilities were identified as ideal candidates for DSM initiatives, mainly load shift, due to sufficient storage capacity of these systems.

In Chapter 2 the water treatment process which precedes the high lift pumping, as well as the functionality of equipment in a WTP, is discussed. Chapter 2 provides information of similar studies that has previously been done. These studies include pumping in the mining sector, national water distribution systems and potable WTPs.

Ideal DSM candidates are identified as facilities with sufficient storage capacity in the form of reservoirs and pumps sufficiently large to accommodate the comeback load. Risks and implications involved as a result of DSM initiatives are briefly discussed.

2.2 Functionality of equipment on typical WTPs

Most WTPs utilise the same general guidelines to purify the water. These strategies will be discussed in more detail in this section. Selecting the best combination of processes to treat water depends on a number of factors, which include [45]:

- Concentration of suspended particles;
- Nature of suspended particles;
- Turbidity of the water;
- Chemical properties of the water;
- Volume of water to be treated; and

- Availability of space and facilities.

The conventional water treatment process can be summarised by the following processes:

- Intake and pre-treatment;
- Coagulation;
- Rapid mixing;
- Flocculation;
- Sedimentation;
- Filtration;
- Disinfection; and
- Distribution.

2.2.1 Intake

Most municipal WTPs are situated close to a fresh water source such as a river, lake or reservoir. The incoming untreated fresh water is called raw water. From the water source the water is pumped or gravity-fed to the treatment facility. Large debris such as sticks, rubbish, rocks, fish and other plant material is removed by a mesh. This step is called screening [46].

Large treatment facilities use a tower-like structure that can house intake gates, screens, control valves and pumps [45]. Raw water pumping stations are generally located close to the intake structure. The purpose of the raw water pumping station is to lift the water to an adequate height from where it can be gravity-fed to the treatment plant. The water can be transported from the raw water pump station by an open canal, pressured pipeline or a combination of the two [45].

2.2.2 Pre-treatment

The incoming raw water is chlorinated to decrease the growth of contaminating organisms such as algae, this is called pre-chlorination. The chlorine is used as a primary disinfectant and oxidant. Chlorine kills micro-organisms and oxidises iron and manganese in the raw water [47]. During this time lime or soda ash is added to raise the pH level of the water. The alkaline water improves the coagulation and flocculation processes [46].

Ozonation is used as an oxidising agent in raw water and aids in removing iron, sulphur, manganese, taste, odour and colour [48]. Ozonation aids in the flocculation potential of the raw water [47]. Ozone has advantages such as [48]:

- Effective over a wide pH range;
- Reacts rapidly with bacteria, viruses, and protozoa and has stronger disinfectant properties than chlorination; and
- Does not add chemicals to the water.

2.2.3 Coagulation and Flocculation

Coagulation and flocculation are the next steps in a conventional treatment process. This is the addition of chemicals, called coagulants, to aid in the removal of suspended particles [45]. Coagulation and flocculation is used when the natural settling rate of the suspended particles is too slow to provide adequate clarification [49].

The coagulant which is added to the raw water pipeline enters a rapid mixing process to ensure homogenous mixing of the coagulant with the raw water. The following chemical coagulants are typically used [49]:

- Aluminium-based coagulants include aluminium sulphate, sodium aluminate and aluminium chloride.
- Iron-based coagulants include ferrous sulphate, ferric sulphate, ferric chloride and ferric chloride sulphate.
- Other chemicals used as coagulants include magnesium carbonate and hydrated lime.

During the rapid mixing process it promotes the particles to collide into each other [50]. Coagulants neutralise the charge of the suspended particles. This binds the particles together to form larger particles called microfloc or precipitate [45]. Figure 19 depicts the coagulation and flocculation process.

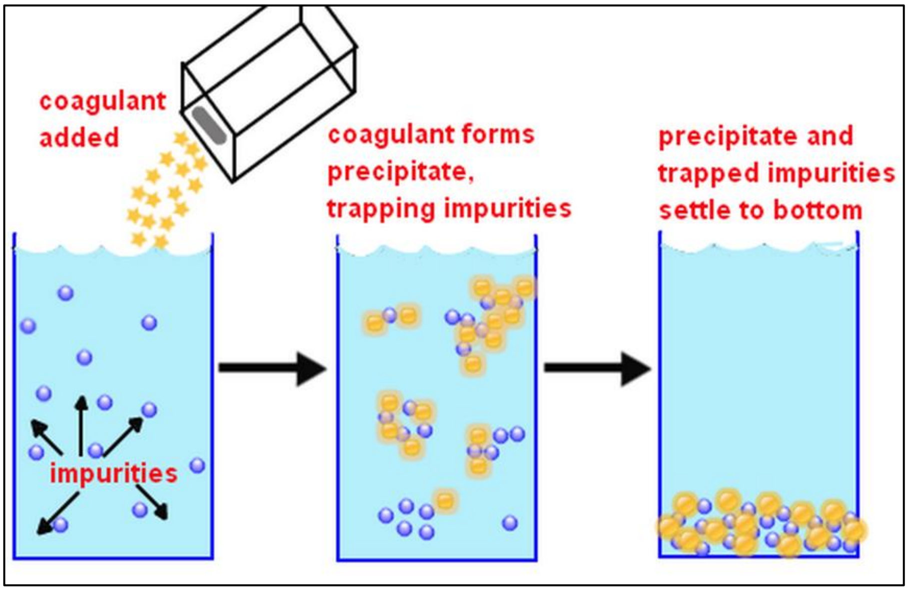

Figure 19: Coagulation and flocculation [51]

For effective flocculation to take place, the coagulants and the raw water need to be mixed homogenously. A rapid mixing process is followed by a slower, gentler mixing process. The slow mixing process encourages the microfloc to grow into larger suspended particles, called floc [50]. These particles continue to strengthen and grow in size and weight. The larger and heavier flocs ensure a faster settling rate [49].

2.2.4 Clarification

Once the optimum size and strength of the floc is reached, it is ready for the sedimentation process. Sedimentation tanks, also called clarifiers, are used in conventional treatment plants. Sedimentation is skipped by direct-filtration treatment plants, as the water is filtered directly after coagulation-flocculation [50].

Sedimentation tanks, depicted in Figure 20, allow the floc to settle before the water is filtered. The sedimentation tanks have low water flow velocities and allow the floc to settle to the bottom of the tank. A sludge collection device should be used to remove the settled floc at the bottom of the tank. A sedimentation tank typically overflows and the overflowing water is sent to the next steps in the treatment process [46].

In Figure 20 the water enters the tank on the right-hand side after the rapid mixing process (a), which is also depicted. The water flows through the tank and the floc settles at the bottom of the settling tank (b). The water is extracted to the filters from the overflow basins (c) on the left hand side. Figure 21 presents the process from coagulation to sedimentation.

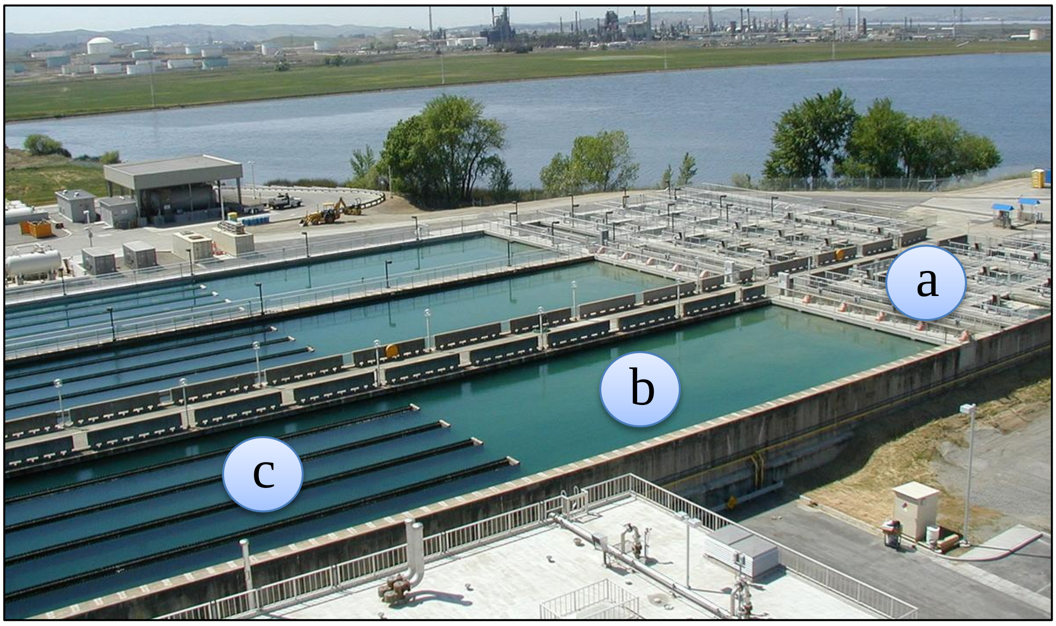

Figure 20: Sedimentation tank on a typical WTP [52].

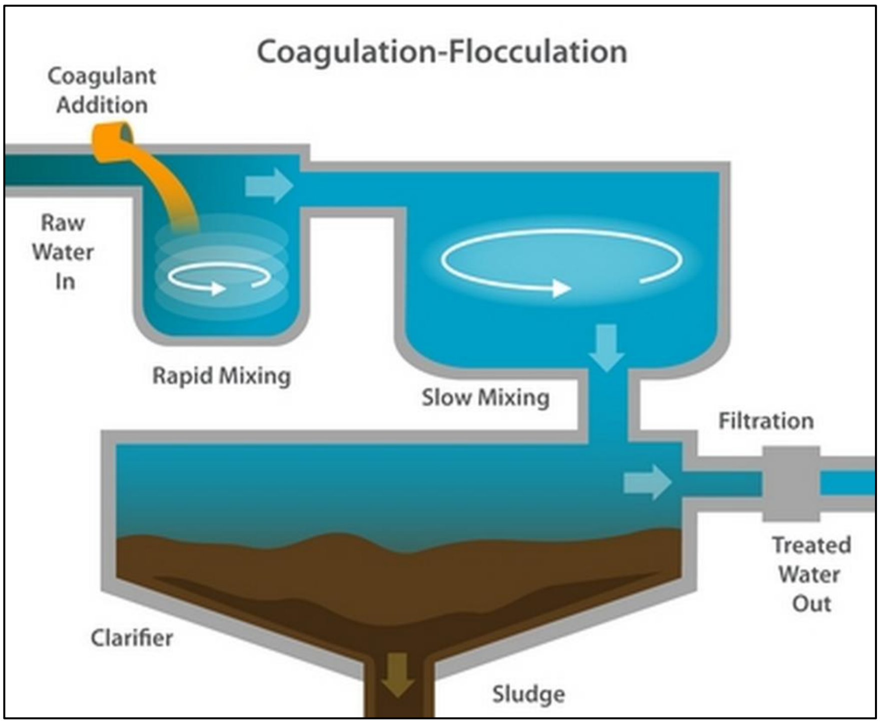

Figure 21: Coagulation-flocculation and sedimentation [53].

There is another method which is widely used called Dissolved Air Floatation (DAF), presented in Figure 22. The separation of water and suspended particles is achieved by dissolving air into the water. The dissolved air bubbles are released into the floatation tank at atmospheric pressure [54]. The dissolved air bubbles attach to the suspended particles. This causes the suspended particles to float to the surface of the tank.

A floating floc blanket is formed which can be removed from the top by a scraping or skimming mechanism [54], [55]. The clarified water is withdrawn from the bottom of the DAF tank [56]. The DAF process is better suited to areas which are dependent on the seasonal change in raw water quality [57].

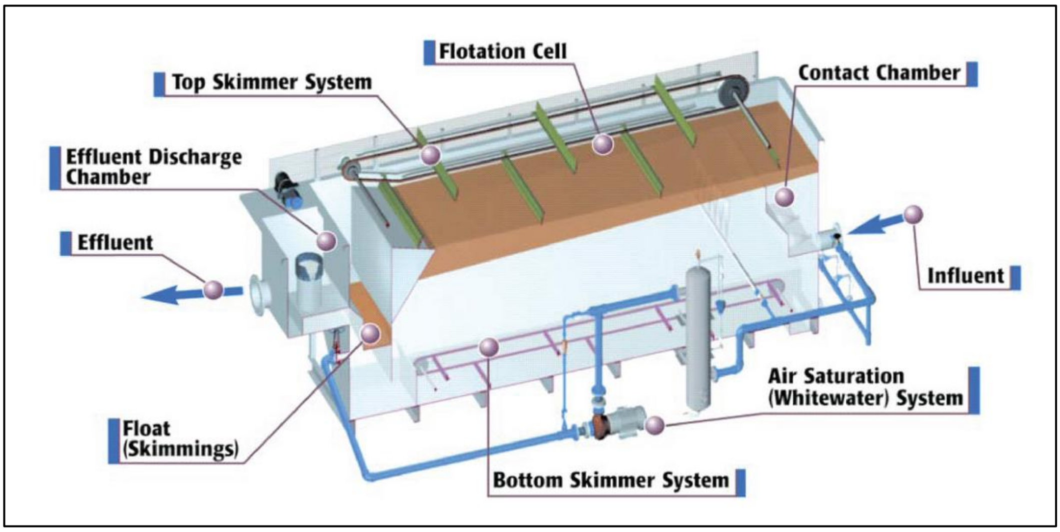

Figure 22: Dissolved Air Floatation treatment [58]

2.2.5 Filtration

The next step in the treatment process is filtering the water. Filtration follows floatation or sedimentation as the final "cleaning" process in the conventional water treatment [45]. Filters remove all the finer particles that were not removed by flocculation and settling or floatation.

There are mainly two type of sand filtration processes:

- Rapid gravity sand filtration; and
- Slow sand filtration.

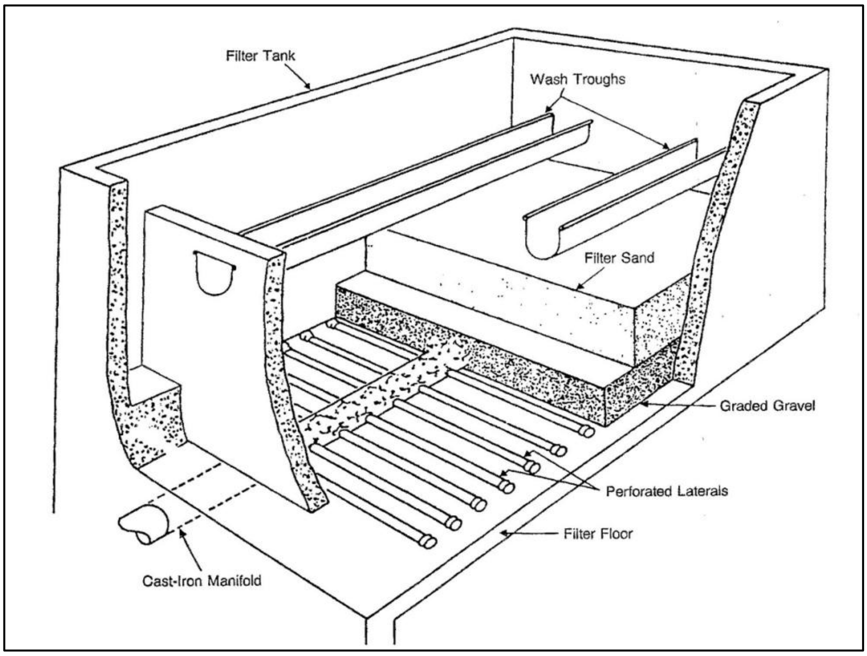

Figure 23: Cutaway section of a typical sand filter installed on WTPs [59]

Rapid gravity sand filtration is the most widely used filtration system in conventional WTPs. Pre-treatment, such as coagulation, flocculation and sedimentation, is usually required for rapid sand filtration [60]. Water moves vertically downward through the bed of sand. The sand bed often has a rougher top layer of carbon or coal, which aids in taste and odour removal [61].

Most of the suspended particles pass through the top layers of carbon and sand. These particles are trapped in the smaller spaces deeper in the sand bed and adhere to the sand particles. The water flows through the entire depth of the filter bed [46]. These pores in the sand bed become clogged. This causes an excessive head loss and deterioration of the filter quality [62]. At this stage backwashing needs to be initiated, or when the predetermined filter run time has elapsed, to clean the filter [62].

Filter cleaning is done by a process called backwashing or backflushing. Water is quickly passed in the upward direction (in the opposite direction the water flows when it is being filtered). Air scrub is introduced together with the water to remove the deposit from the filter sand by means of vigorous agitation [62]. This removes all of the deposit from the sand and loosens the sand in the sand bed. The backwash water is dirty and is removed along with the sludge. Figure 24 presents the filtering and backwash stages.

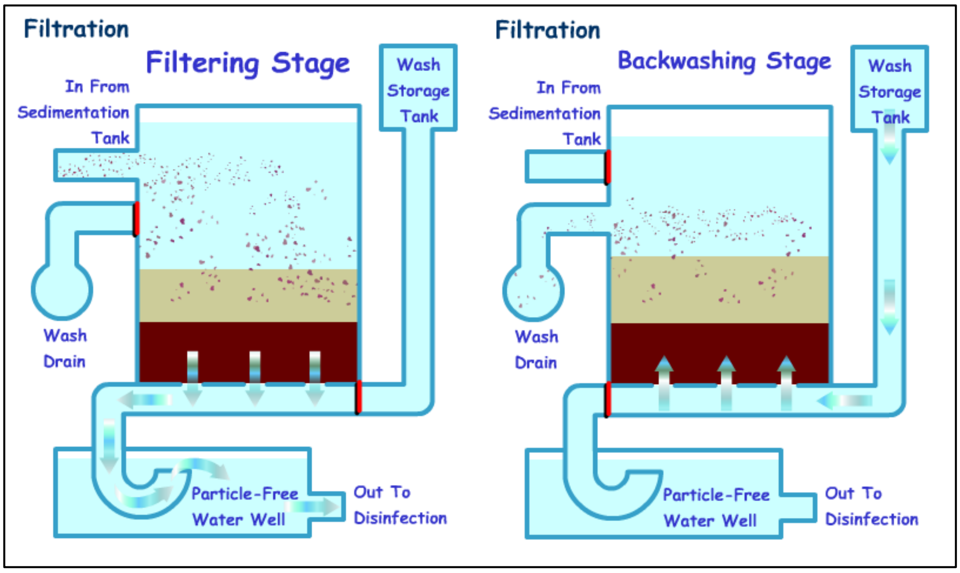

Figure 24: Filtering and backwash stages of a rapid sand filter [63]

New development in filter technologies has combined floatation/filtration units [64]. One of these units, called a Counter-current Dissolved Air Floatation Filter (COCODAF Filter) which is presented in Figure 25. Flocculated water enters the filter via inlet channels, which distributes the water flow evenly. The water flows downward through the rising air bubbles to the filter bed below.

The air bubbles form a continuous bubble blanket to float suspended particles to the surface. At the same time the water is being filtered to the bottom. The filtration is similar to a rapid gravity sand filter [64]. The filter must be backwashed to clean as with a normal rapid sand filter. The sludge blanket formed at the top of the tank can be removed by hydraulic means [65].

Pressure filters are not commonly used in large treatment plants. Water is forced through the filter media which is enclosed in a pressure vessel. These filters can withstand pressure differences of approximately 2–5 atmospheres across them [46]. These filters can also be cleaned by backwashing and the filter media can be reused.

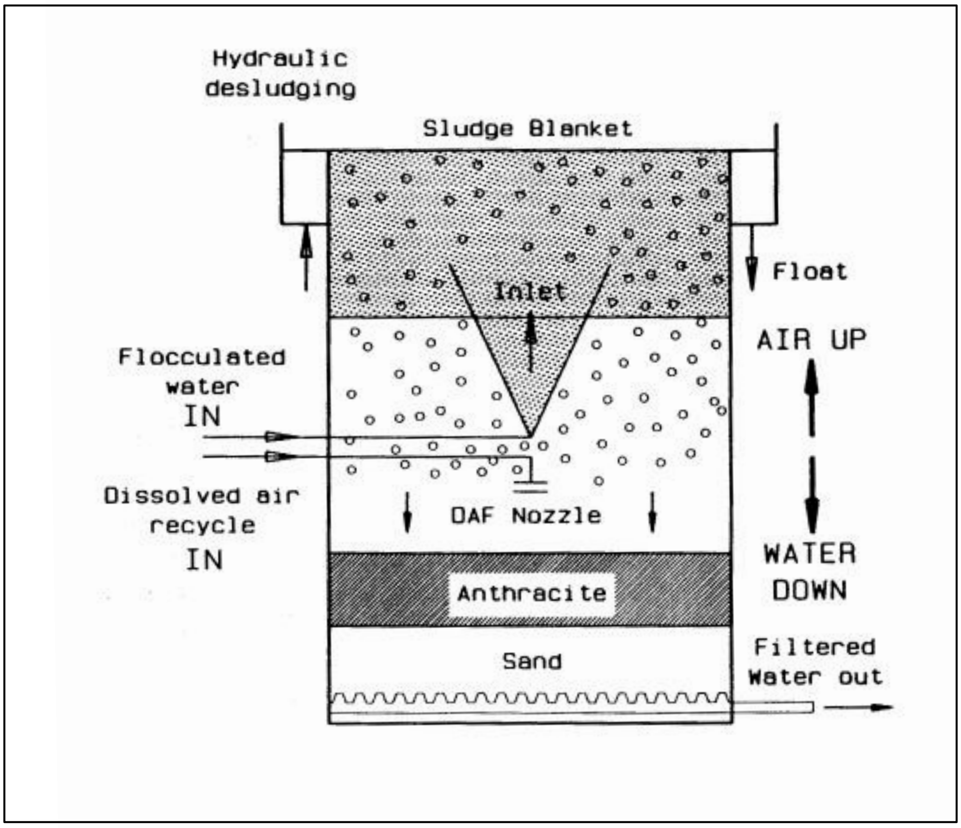

Figure 25: COCODAF filter unit [66]

Slow sand filters are widely used for their simplicity, reliability and economy [67]. No pre-treatment is required for slow sand filters, but the water is passed through very slowly [60]. These filters are carefully constructed with different layers of filter media. The coarsest layer of sand along with gravel is located at the bottom and fine sand is located in the top layer.

Water that lies above the filter sand provides a sufficient pressure head for the water to slowly pass through the sand layers. A layer of biological active micro-organisms form on the top layer of sand, called the Schmutzedecke, the water must pass through this before reaching the filter media itself [67]. These micro-organisms break down, digest and entrap organic matter contained in the raw water passing through [68]. The water enters the sand and is filtered similar to the rapid sand filter. Figure 26 presents a diagrammatic slow sand filter.

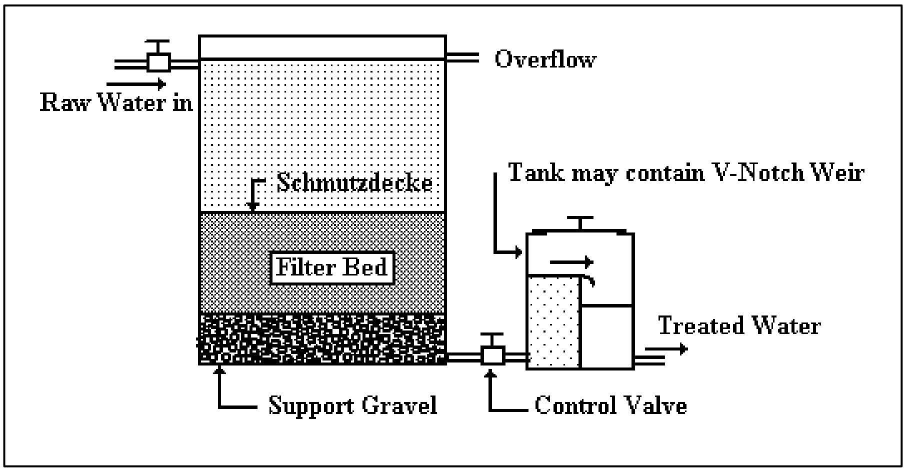

Figure 26: Conventional slow sand filter [69]

Rapid sand filters and slow sand filters differ by the biologically active sand medium and slow filter times. Rapid sand filters utilise physical removal of the suspended particles. Rapid sand filters also need to be backwashed regularly. Slow sand filters are cleaned by periodically scraping the existing Schmutzedecke layer and allowing time to develop again [67]. Slow sand filters can be in operation for weeks, even months, whereas a rapid sand filter has to be backwashed on a daily basis.

Membrane filtration might be a suitable alternative for flocculation, clarification, sand filtration and extraction [70]. Membrane filters use the membranes inside the filter as a physical barrier that removes solids and other unwanted particles [71]. Different types of membrane can be used in conjunction with one another for different purposes[71]. Recent technologies have reduced the cost of membranes. These new membranes produce more water and cost less to replace.

2.2.6 Disinfection

It is important to disinfect water as it may still contain disease-causing pathogens, such as E.coli, tuberculosis, cholera, Hepatitis A and giardiasis [72]. Disinfection can be achieved by chemical or physical processes. The disinfecting agents kill micro-organisms and pathogens, but also remove organic contaminants which serve as nutrients for micro-organisms [73].

Disinfection must continue to be active after the process is introduced. It should prevent micro-organisms from growing throughout the distribution system [73]. Clear water reservoirs usually allow adequate contact time for disinfection, but the distribution systems provide additional contact time [47].

Chemicals used for chemical disinfection include:

- chlorine,
- chlorine dioxide,
- ammonia,
- ozone,
- bromine chloride,
- alcohols,
- soaps, and
- detergents.

Disinfectants used for physical disinfection include:

- ultraviolet light (UV),
- electronic radiation, and
- heat.

2.2.7 Distribution

As mentioned in Section 1.2.1, high service or high lift pumping is the most energy intensive stage of a WTP. For this reason, emphasis will be placed on the pumping system to achieve peak period load reduction. The purpose of a distribution system is to deliver the treated water to the users, for drinking, cooking, sanitation and other uses. Water is also supplied to businesses and industries which use it for processes [74].

Energy is needed in the form of a pressure difference to distribute water from one area to the next. This pressure difference can be achieved with a pump. Pumping stations are used to distribute and boost potable water through the distribution system. The distribution system consists of a network of storage reservoirs/tanks, valves, pumps, motors and pipes [75].

i. Pumps

The most widely used method to pump water is by means of a centrifugal pump [76]. Centrifugal pumps can be divided into three classifications based on their configurations; end-suction centrifugal pump, split case centrifugal pump and a vertical turbine centrifugal pump. A centrifugal pump increases the pressure of the fluid from the inlet to the outlet by transferring mechanical energy to the fluid through the rotating impeller [77].

The fluid enters the eye of the impeller and moves into the vanes of the impeller. The fluid is accelerated by the centrifugal force exercised on the fluid by the fast rotating impeller. The fluid reaches a maximum velocity as it exits the impeller vanes [78]. The kinetic energy added by the impeller is transformed into pressure energy as the fluid flows through the ever increasing geometry of the volute, where it reaches a maximum pressure [79]. Presented in Figure 27 is the principle of operation of a centrifugal pump.

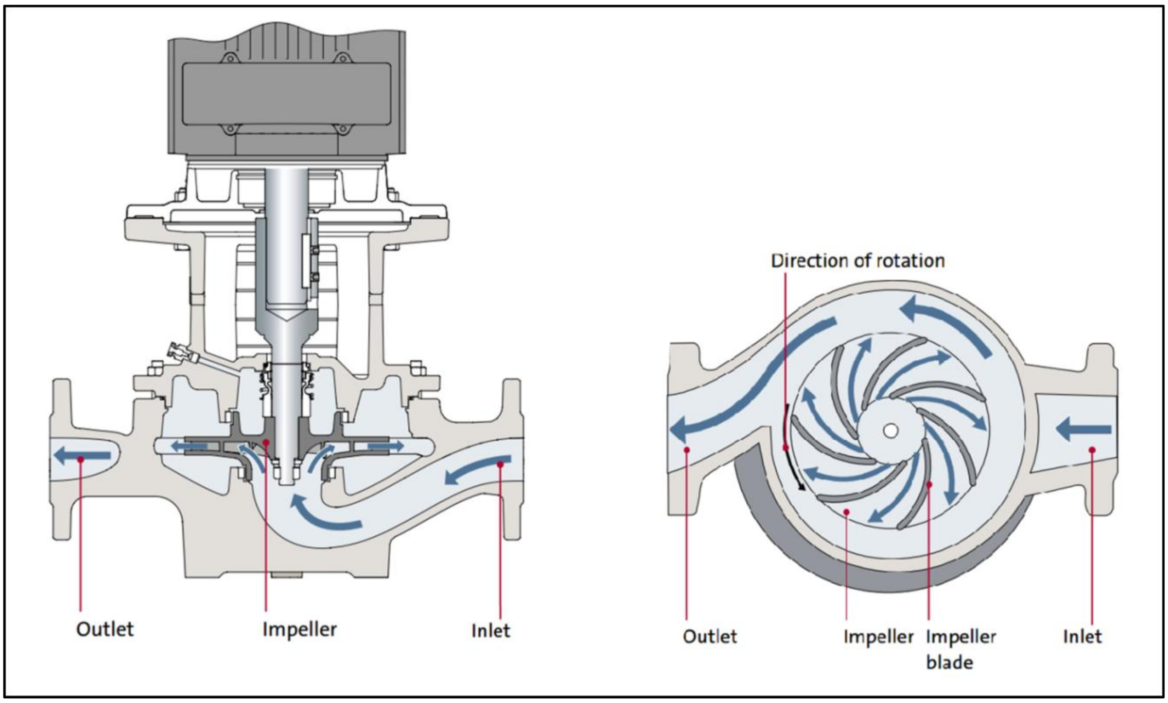

Figure 27: Principle of a centrifugal pump [77]

Multistage centrifugal pumps have more than one impeller on a common shaft. With this configuration the delivery of one stage is the suction side of the next stage [80]. With each passing stage the pressure is increased. Presented in Figure 28 is a cross section of a typical multistage centrifugal pump.

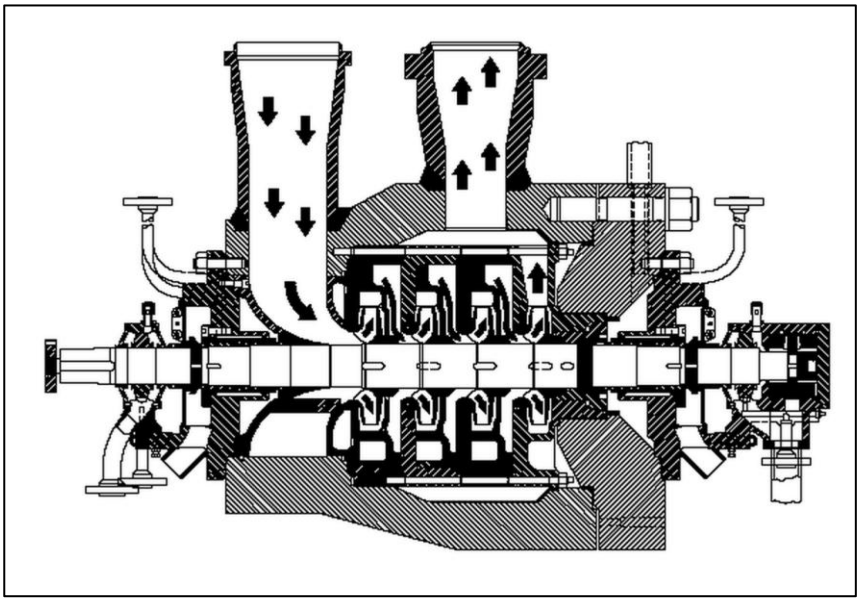

Figure 28: Multistage centrifugal pump [80]

Vertical turbine pumps were originally designed to replace centrifugal pumps for when the suction head of the water was lower than the suction capability of the pump [76]. Vertical turbine pumps are also called line shaft turbine pumps. These pumps have capacities of up to 4 550 m^3/h at a head of 460 m. Presented in Figure 29 is a cross section of a typical vertical turbine pump [81].

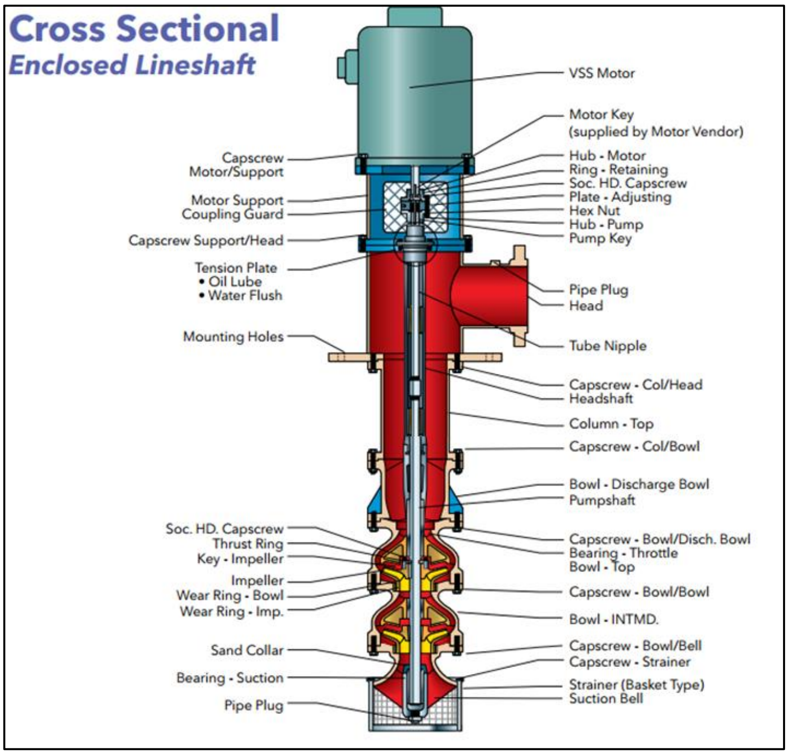

Figure 29: Vertical turbine pump [82]

The potable water needs to be pumped long distances and in most cases over hills and mountains. The pressure head that needs to be overcome is high. A high flow is also required to supply ample water to end users. The power needed to pump water is also high according to the hydraulic power equation (1).

$$P_h = \frac{\rho * g * Q * h}{\eta} \quad (1)$$

Where:

P_h = *Hydraulic power (Watt)*

ρ = *Density of liquid (kg/m3)*

g = *Gravity constant (m/s²)*

Q = *Flow rate (m3/s)*

h = *Hydraulic head/load to overcome (m)*

η = *Efficiency (dimensionless)*

Pumps are often used in different configurations. Pumps are used in series to increase the pressure head of the system [83]. This is often done when a primary booster pump provides a sufficient inlet pressure to a larger secondary pump. Presented in Figure 30 is a graphic illustration of the influence a series configuration has on the flow and head of a system. This is called a characteristic curve. Please note these are for identical pumps.

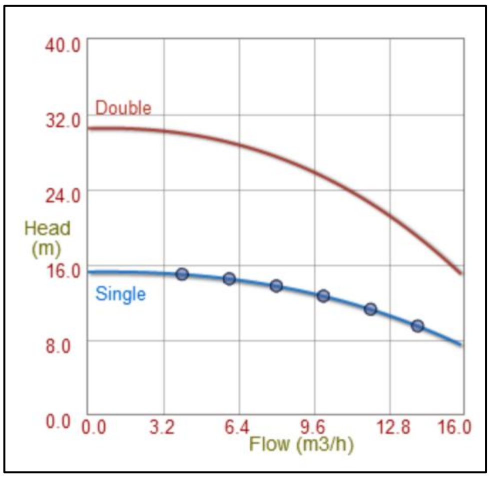

Figure 30: Pumps operated in series [84]

Pumps are more often used in parallel. When pumps are used in a parallel configuration the flow in the system is increased. Presented in Figure 31 is the pump characteristic chart for pumps used in a parallel configuration.

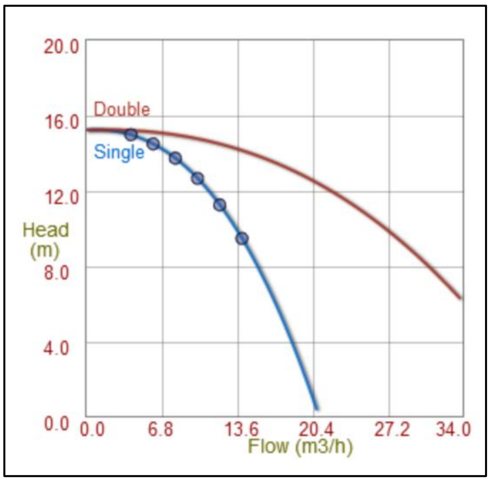

Figure 31: Pumps used in parallel [84]

Pumps are often used in a combination of series and parallel configurations. Presented in Figure 32 is a pump station utilising pumps in series and in parallel configurations.

Figure 32: High lift pumps operated in series and parallel

ii. Motors

Electrical motors are needed to supply the necessary energy to the pumps. The most widely used electrical motor is the squirrel-cage induction motor. Electrical induction motors convert electrical energy into mechanical energy from the magnetic flux in their magnetic circuits. One magnetic circuit is the stator and the other is a rotor [85].

This magnetic flux linkage between the rotor and stator produces a moment of force which results in torque on the motor shaft. This torque coupled with the speed of rotation equals the power output of the motor [85]. This power is used to drive a pump. Presented in Figure 33 is a section view of an electrical induction motor.

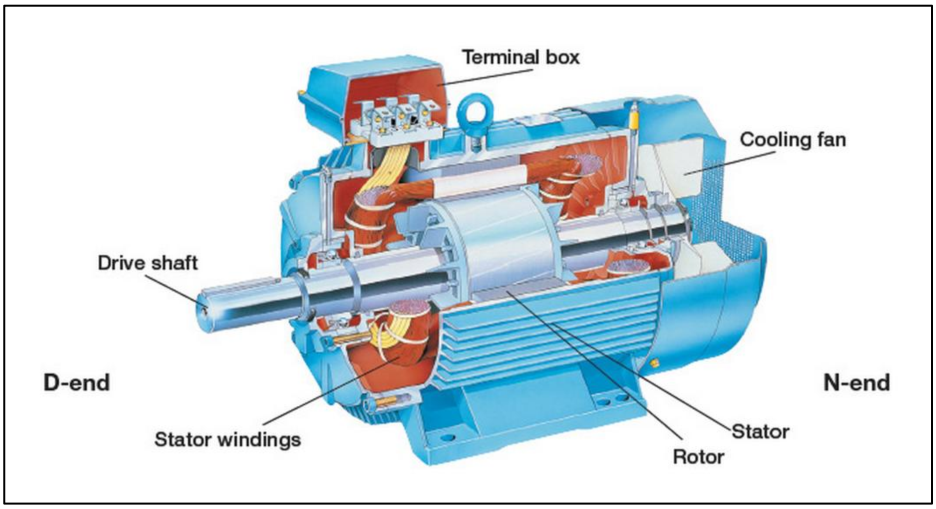

Figure 33: Electrical induction motor [86]

The squirrel-cage induction motor is widely used due to its excellent reliability, availability, ease of replacement and continuous performance. It is also easily adapted to operate in conjunction with a Variable Speed Drive (VSD). The squirrel-cage motor consists of a conventional wound stator with a specific number of poles and phases, and a rotor with cast or brazed bars imbedded [85].

Most of these induction motors use three-phase power supply. With three-phase power supply the electrical power can be calculated using equation (2).

$$P_{elec} = \sqrt{3} * V * I * pf \tag{2}$$

Where:

P_{elec} = *Electrical power (Watt)*

V = *Supply voltage (V)*

I = *Supply current (A)*

pf = *power factor of power supply (dimensionless)*

The efficiency of a motor and pump combination can be calculated by using equation (1) and (2). The efficiency of the motor and pump combination is given by equation (3).

$$\eta = \frac{P_h}{P_{elec}} \tag{3}$$

Electric induction motors are the most widely used method to supply mechanical energy to pumps. Other methods exist, but do not fall within the scope to this study.

iii. Problems encountered with distribution systems

Cavitation is a phenomenon that occurs when the suction pressure of the liquid falls below the vapour pressure of the liquid. This causes vapour bubbles to form in the liquid. The liquid becomes a gas at the vapour pressure. These bubbles form at the inlet to the impeller when the pressure is reduced and velocity increased [87].

When these bubbles move to a higher pressure region along the impeller vanes, they collapse and implode with tremendous force [87]. Pitting of the impeller can result due to these implosions occurring close to a metallic surface. Figure 34 presents an impeller eroded by cavitation.

Figure 34: Impeller eroded by cavitation [88]

Chocked flow in a pipe is a phenomenon which can occur in pumping stations. The Venturi effect is the reduction in pressure when a fluid flows through a constricted section in a pipe line [89]. The Venturi effect occurs when the velocity of a fluid inside a pipe increases as the cross sectional area decreases and the corresponding pressure decreases [89].

Chocked flow occurs when the pressure drop across a pipe section is increased, the flow reaches a point where it no longer increases [90]. Once this happens a larger pressure drop across a pipe section will result in no additional flow [90]. This can result when pumps provide more flow than what the pipe line was designed to handle.

Water hammering is another problem water pumping stations face. Water hammering is a phenomenon which occurs when there is a sudden decrease in fluid flow velocity. This can be caused by closing a valve too quickly. When this happens pressure waves are generated that travel along the pipe section. These pressure waves are powerful and can damage equipment. Presented in Figure 35 is a pipe section that was damaged by water hammering [16], [91].

Figure 35: Cast iron pipe damaged by water hammering [92]

All of the abovementioned problems need to be taken into consideration when attempting to perform safe load management on a water distribution system.

2.3 Existing load management strategies on large pumping systems

Most existing pump stations are oversized and many of them are oversized by more than 20%. Inefficient pumps and pump combinations and inefficient operation schedules are the main concerns in optimising pump systems. It is crucial that these operations are optimised to achieve a cost effective operation. Load management, more specifically load shifting, is a widely discussed topic due to the ever increasing electricity tariffs and introduction of ToU tariffs [93].

Load shifting does not require costly equipment to be installed to achieve significant cost savings. Changing the operation schedule is a very effective way to achieve load shifting. Effectively making use of ToU integrated tariffs, cost savings can be achieved. In this section load management that has previously been done on water related projects will be reviewed.

The load shift impact refers to the reduction in peak period power consumption as a result of the DSM initiative. The load shift impact is shifted from the peak periods to the off-peak and standard periods.

2.3.1 Mining water reticulation systems

Mine pumping alone accounts for 2 300 MW of the 36 937 MW peak electricity demand in South Africa [39]. Without influencing the production schedule of a mine water pumping system, load shifting can be achieved. Sufficiently large reservoirs and pumps below the surface are cleverly utilised to accomplish load shifting during peak periods [39].

In order to implement a load shift strategy on a mine, the mine's operation schedule needs to be changed. This will not be done unless it can be proved with certainty that the load shift will not affect production and/or safety. An Energy Management System (EMS) was developed to simulate pump operations and subsequently verify the simulated results with actual achieved results. These results are obtained by installing the EMS on a mine to realise a real-time actual load shift impact [94].

As mentioned in Section 1.2.2.(i) load shifting has been implemented very successfully within the mining sector. Load shift on the water reticulation systems of mines have yielded significant cost savings and a load reduction during peak periods. De Kock [95] summarised the load shift impact on the water reticulation system of six mines. An average cost saving of 16% during high demand season and 5% during low demand season was achieved [15], [95].

An EMS was implemented on six deep gold mines in South Africa. A few advantages of the EMS are mentioned in the study. These advantages include electricity cost savings and labour cost savings. Reducing the human element in the pumping systems showed a sustainable load shift impact. Table 4 presents the results De Kock obtained. A combined evening peak period load shift impact of 33.8 MW was achieved on average due to this intervention. This showed a combined financial saving of approximately R 4.32-million annually (2005/2006 tariffs) [95].

Table 4: Load shift impact achieved by De Kock (Adapted from [95])

Mine	Installed Capacity [MW]	Flow Delivered [Mℓ/day]	Load Shift Impact Achieved [MW]
Mine 1	26.0	23.0	4.5
Mine 2	27.2	22.0	3.5
Mine 3	23.8	65.0	7.0
Mine 4	18.8	11.0	4.0
Mine 5	11.0	19.0	3.8
Mine 6	47.2	45.0	11.0

Le Roux [96] implemented an EMS on the clear water pumping system on four South African gold mines. In the study the system was implemented on three types of mines. It was implemented on mines with intricate pumping systems, mines with three pipe water pumping systems and mines with minimal control infrastructure [96].

Table 5 presents the results of the study done by Le Roux on four South African gold mines. A combined evening peak period load shift impact of 17.6 MW was achieved by implementing an EMS and controlling the clear water pump. The load reduction impact relates to a combined annual cost saving of almost R 1.78-million (2004/2005 tariffs) [39], [96].

Table 5: Load shift impact achieved by Le Roux (Adapted from [96])

Mine	Installed Capacity [MW]	Flow Delivered [Mℓ/day]	Load Shift Impact Achieved [MW]
Mine 1	24.0	65.0	6.1
Mine 2	18.0	30.4	3.3
Mine 3	11.0	11.0	4.2
Mine 4	11.0	19.0	4.0

Similarly the EMS was implemented on eight pumping systems of South African gold mines in a study done by. Kleingeld et al. [94]. A combined evening peak load shift impact of 41.81 MW was achieved, with an average over performance of 34%. This equates to a annual electrical cost saving of approximately R 5.4-million [94].

Whilst these mines mentioned above share similarities, all are different in detail. These mines also have different equipment, capacities and operating parameters. Load management has successfully been implemented on mines with simple and intricate pumping systems as well as mines with minimal instrumentation and control infrastructure.

The load shift strategies implemented in the clear water pumping systems, for many different mines, can be used for surface pumping systems.

2.3.2 Water pumping systems

A study on the benefits of pump scheduling for potable water suppliers was done by Bunn and Reynolds [97]. A SCADA or similar systems are installed in most developed utilities and pump stations. These systems continuously log data of important operations. Substantial historical data of operations has been gathered [97].

The focus is on pumping systems that supply potable water from the treatment plants. These systems are dependent on systems such as SCADAs. These systems read, store and provide detailed time-stamped historical data for parameters such as flow, pressure, and reservoir levels. Valuable information can be extracted from the data to support decision making and the performance improvement for these processes [97].

A number of methods have been developed to optimise scheduling of pump run times. Most of the scheduling has been done to minimise energy consumption during peak periods of ToU tariffs.

According to Bunn and Reynolds [97] it is considered impractical to explicitly solve the scheduling of pumps mathematically, due to the complexity of most water distribution systems and production constraints. Evolutionary algorithms have been developed to search for a solution of these complex mathematical problems [97].

Evolutionary algorithms use the theory of evolution to apply random solutions to simulations to find a better solution. The genetic algorithm, a derivative of the evolutionary algorithm, has been widely used on pump scheduling problems. The genetic algorithm is well suited for binary problems, where the pumps are either on or off [97].

Previously pump efficiency improvements focused on the static process of calibrating a pump curve, assuming an operation point and then modifying the pump characteristics. However, many of these solutions are not focused on the real-time optimisation of a distribution system. A real-time solution to optimising pump scheduling is required as a pumping system is a very dynamic system [97].

A program has been developed to avoid using complicated genetic algorithms. It makes use of linear programming and mixed integer programming due to the faster operating speed. The software is able to explicitly calculate the efficiency of a pump based on the performance data, such as flow, pressure and power. This approach reduces electricity costs by exploiting ToU tariffs and additionally optimising the peak period operation, by operating only the most efficient equipment [97], [98].

The program can schedule pumps based on flow and pressure constraints, storage capacity and level constraints, operating run times of pumps and cool down time. It can schedule the operation of pumps with on/off control as well as for pumps with continuous control such as VSD-driven pumps [97].

The program collects, automatically corrects and stores the data. The data is obtained from instrumentation, telemetry and recreates missing data by using a hydraulic model of the system.

These specific data sets are then compiled into larger data sets which are used in an optimisation algorithm [97].

The program identifies equipment which is not operating effectively. The program can therefore also be used for equipment replacement assessments. To reduce electricity costs, a program is required to automatically schedule pumps, taking into account predicted values to select the most efficient pump combinations to be operated [97].

The program was implemented in a case study in California in 2006. The implementation yielded an electricity cost saving of 12% and an improved efficiency of 9%. The improved efficiency was achieved by optimising the operation schedules of cheaper but less efficient gas engine driven pumps and more expensive but more efficient electrical driven pumps using a ToU tariff structure [97], [99].

Tang et al.[100] investigated the issue of load shifting and energy efficiency. The study has been treated as an efficiency improvement of the operation, since the cost of operation will decrease when electricity costs decrease due to load shifting.

Previously the number of pump switches and total operation time were not considered in pump station optimisation. In this study the general optimal control of pump stations were considered to form an optimal control with consideration to pump switches and operating time. Mathematical optimisation algorithms were implemented to solve these problems [100].

The formulation of the optimisation algorithms takes the ToU tariffs into account and the load is consequently shifted out of the peak periods. Theoretically these control approaches can save nearly 30% on energy costs. The saving is achieved by shifting the operation of pumps into off-peak periods. The control approach, however, was not implemented on a case study to verify the achievable impact [100].

Similar studies have also been done by Lansey and Awumah [101] and McCormick and Powell [102]. Lansey and Awumah explored the multi-objective optimisation to evaluate an optimisation strategy taking into account the number of pump stops and starts [101]. McCormick and Powell evaluated the optimisation strategy by minimising the electrical demand charges during peak periods. Both achieved significant electrical cost savings and peak period load reduction [102].

Moreira and Ramos [103] identified that the majority of the life cycle cost of a pump is spent on electricity, approximately 90% in a 30-year lifetime [97]. Maintenance and purchase cost attributing to the rest of the costs. A genetic algorithm was used to determine the best daily pumping schedule [103].

By analysing and modelling different pump characteristics the most efficient operating point could be achieved. The main goal is to analyse a system and simulate several pumping schedules in order to reduce the electricity costs. Different tariff structures and different demands throughout the day need to be considered. The simulation took into account the number of starts allowed per pump [103].

A case study in Portugal was used as a base for the study. The system was fully analysed with parameters such as [103]:

- Types of pump installed;
- Flows supplied by pumps;
- Overall efficiency of pumping system;
- Discharge head needed;
- Pipeline length;
- Reservoir capacities and elevations;
- Profile of water demand;
- Average water demand; and
- Time reservoir can supply water.

The simulation model consisted of two scenarios. Two pumps with three starts and one pump with six starts. A different pump and motor required for each scenario was selected based on the system curves, operating curves and best efficiency point of the combination. The effect of fixed speed drives and VSDs on the pumps was investigated. Small variations in the speed of the pumps can translate to significant power consumption variations. This can increase the cost efficiency of the system.

After implementing the energy efficiency component and the pump scheduling it was possible to reduce the electricity costs by almost 44%. Significant savings could be achieved with a manual override. During the manual override the primary criteria of operation was to avoid operating the pumps in the peak periods and to prevent large variations in the reservoir level.

It is recommended that an optimisation model be done for more complex systems. Systems with interaction between pumping stations would benefit from a detailed optimisation model using a genetic algorithm. From the simulation it was also determined that a system with one pump allowing for six starts was more efficient and versatile compared with a system with two pumps allowing for three stops. It is recommended to implement a system which will allow real-time optimisation and scheduling of a pump system.

Nortjé [21] implemented a load shift study on a water transfer scheme, which provides water to power stations and Sasol entities in the Mpumalanga Highveld, South Africa. These Pump Stations (PS) supply water to power stations such as Tutuka, Matla and Duvha. These facilities have large storage capacities ranging from 885 Mℓ – 900 Mℓ. The pumping system supplies water to various other users connected along the line [21].

Infrastructure and communication systems were installed at the pumping stations. These infrastructure upgrades are paid for by Eskom DSM. The infrastructure upgrades included replacing relay logic controls with PLCs, installation of HMIs and the introduction of a SCADA system.

Additional to the infrastructure installations, an EMS, similar to the system used in the mines, was installed. The installations were necessary to allow for control via the EMS. Previously, plant operators received information about reservoir levels and demand. The operator then had to make a decision based on the information received, taking various other factors into account, whether a pump needs to start or stop [21].

The EMS eliminates the operator as the SCADA communicates the necessary information directly to the EMS. Based on a programmed algorithm the EMS can decide whether to start or stop a pump. The peak periods are programmed into the EMS and subsequently the minimum necessary pumps can be scheduled to operate during the peak periods [21].

Table 6 presents the load shift impact achieved by Nortjé. PS 1 and PS 2 achieved a combined impact due to the fact that these stations are interconnected. A combined evening peak period impact of 12.6 MW was achieved on average at all the stations. This relates to a financial saving of approximately R 4.765-million annually [21].

Table 6: Load shift impact achieved by Nortjé (Adapted from [21])

Pump Station (PS)	Number of Pumps	Installed Capacity [kW/pump]	Flow Delivered [ℓ/s/pump]	Maximum Delivered Flow [Mℓ/day]	Load Shift Impact Achieved [MW]
PS 1 + 2	4 + 4	1650 + 1725	1900 + 1400	355 + 280	3.7
PS 3	5	2150	2100	420	3.1
PS 4	4	3050	1055	310	5.9

Slade [104] identified the success rate of DSM initiatives on the clear water pump stations in the mining sector. A water distribution system has been identified as an ideal candidate for DSM. This is due to the similarities shared between mine pumping systems and potable water distribution systems. The specific water distribution system referred to is situated in the Northern Cape, South Africa [104].

Slade identified that mine pumping systems and water distribution systems have similarities including abstracting water from a source, high flow rates, high pressure heads, storage capacities and large installed capacity of pumps. The pumps are used to transfer water to a higher elevation, such that the water can gravitate to lower elevations. Large capacity pumps are required to overcome the pressure head and supply high volume flow [104], [105].

The distribution system extracts water from a river, purifies the water and pumps the potable water to a reservoir from where it is gravity-fed throughout the system. The distribution system consists of one high lift pump station and two booster pump stations. Three high lift pumps and six booster pumps are installed, each with an installed capacity of 780 kW.

Apart from the electricity consumption of a system, many other factors also need to be investigated. These factors include [105]:

- The capacities of the reservoirs;

- The minimum and maximum percentage levels of the reservoirs;
- The number of columns available;
- The minimum and maximum number of simultaneously operated pumps;
- The flow rates of the pumps; and
- The installed capacities of the pumps.

In many DSM initiatives it is preferred and often required to automate a system. It has been observed in the DSM initiatives implemented in the mining sector that control room operators do not adhere to intervention strategies. The human element prevents DSM initiatives to be sustainable. An EMS can be implemented to ensure that the contractual DSM initiative is achieved [104], [105].

If the information is available on the SCADA, the control room operator is able to see the reservoir levels, pump status, and water flow. Based on this information the operator makes a decision to start or stop a pump to control the level of the upstream or downstream reservoir. With the EMS it is possible to replace the control room operator [105].

The EMS is able to directly communicate with the SCADA system via a common network. All the factors that were investigated, as mentioned above, can be programmed as input parameters. The EMS communicates with the SCADA and gathers information such as reservoir levels, pump statuses and flow rates [104], [105].

Using mathematical models programmed into the EMS, the program can schedule the operation of pumps. The schedule can be optimised in real-time to continuously insure that the best combination is operated. The EMS communicates the schedule to the SCADA. The SCADA communicates the command to the PLCs which will then start or stop a pump, depending on the command given by the EMS [104], [105].

The EMS was implemented on a potable water distribution system. The distribution system is obligated to supply a specified volume of water on a daily basis. This volume of water that needed to be transferred, together with the reservoir levels, played a critical role in the simulation model to determine the optimal operating schedule [104], [105].

The EMS proposed a schedule for the operation of the pump station. The proposed schedule realised a morning peak period load shift impact of 3.6 MW and an evening peak period impact of 3 MW. It was also discovered that the pump station was billed on an Eskom Nightsave tariff structure [104], [105].

The feasibility of switching to a ToU tariff structure was investigated to fully benefit from the DSM initiative. The ToU tariff offers a greater flexibility and saving potential for energy intensive users. By switching to a ToU tariff structure a possible electricity cost saving of R 1.5-million could be achieved based on the 2006/2007 tariffs [104], [105]. All the abovementioned case studies are proof that load shift initiatives are plausible within the water distribution sector.

2.3.3 Ideal DSM candidates

The load management strategies developed in this study can be used with other pumping systems. The power profiles of four water distribution systems are presented in Figure 36. Two of these systems have a treatment facility preceding the pumping station. The other two facilities extract raw water directly from a large dam/river and distribute the water to another large dam/river.

It can be seen from Figure 36 that no load management has been employed by these distribution systems. All of the distribution systems in the figure are billed on the Megaflex tariff. If the pumps can accommodate the comeback load during the off-peak and standard periods and if the storage capacity is sufficient, these facilities are ideal candidates for load shift initiatives.

The maximum operating capacities of these water distribution systems are:

- WTP 1 – 6 500 kW
- WTP 2 – 8 500 kW
- Raw 1 – 10 000 kW
- Raw 2 – 9 800 kW

All of the abovementioned distribution systems have sufficient spare capacity available to accommodate the comeback load.

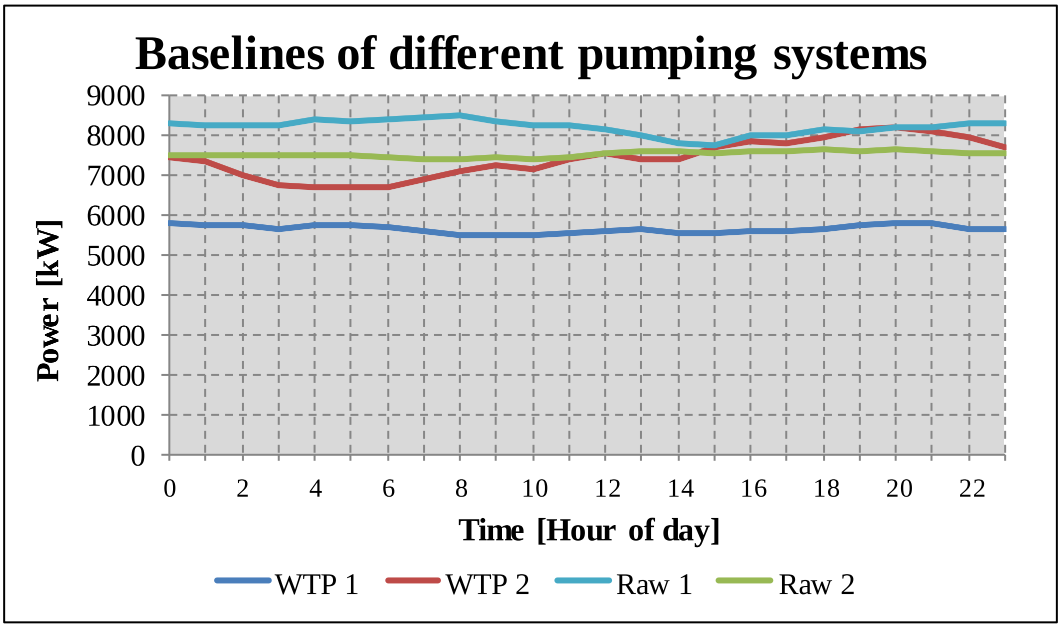

Figure 36: Power profiles of different pump stations

In most cases the scheduling of pumps is determined by the level of the reservoirs. When the downstream reservoir nears the minimum level, pumps are started. When the reservoir fills up, or nears maximum level, the pumps are stopped. If the pumps are operated according to a ToU dependent tariff, cost savings can be achieved [93].

These facilities have sufficient storage capacities in the form of large reservoirs. For example WTP 1 has a combined reservoir capacity of approximately 165 Mℓ. The average peak demand is approximately 1 400 – 1 600 ℓ/s. This peak demand will result in an average reservoir level drop of between 6 – 7 %. The level can be recovered within a few hours if the plant operated at full capacity during off-peak periods.

A water distribution system must have sufficient storage capacity. The reservoirs must be able to supply water for approximately 24 – 48 hours, without any inflow [106]. This is needed when outages occur for maintenance of equipment, which can in some cases last longer than 48 hours.

The distribution systems mentioned above are ideally suited for load shift interventions. These distribution stations will be able to adhere to the production, safety and electricity structure ToU period constraints.

2.3.4 Energy efficiency

An estimated 30% of water is lost worldwide. A similar proportion of energy is also lost as a result. Energy in water distribution systems are lost due to factors such as inefficient pumps, poor design of pump stations, maintenance not done on equipment, old pipes with high head loss, excessive supply pressures and inefficient operations [107].

Energy efficiency optimisation of water distribution systems can be as simple as reducing water leakage, and as complex as demand prediction, pump system optimisation and reservoir storage optimisation [93].

According to Feldman [107] energy efficiency improvements can be done by improvement of pump station design, improvement of system design, installation of VSDs, efficient operation strategies and leakage reduction.

Reducing leakage of a system will reduce the waste of energy. Reducing leakage will also decrease the loss in pressure head of a system and increase the volume of water supplied to users. The most effective method to reduce water leakage is by pressure modulation. Operating more pumps in the off-peak period leads to an efficient operation. The pressure is increased by doing this during the off-peak periods [93], [107].

This is in conflict with another optimisation strategy to dynamically modulate the pressure in a system. The aim of pressure modulation is to reduce leakages by minimising the pressure in off-peak periods. The solution for these conflicting strategies is to isolate distribution areas [93], [107].

Inefficient control and oversized systems cause inefficient pump stations. An opportunity for energy efficiency exists as a result of the oversized systems. Many pump stations are oversized by more than 20%. To control the flow of the pump station, throttling valves, pump speed adjustments and bypass lines can be used. A large dissipation of energy, causing an increased pressure head, occurs when flow is controlled by a throttling valve [93].

Pump speed control is achieved by VSDs. VSDs for pumps allow for operation with fixed flow and variable pressure operation or with fixed pressure and variable flow operation. This reduces the number of pump switches and reduces the likelihood of water hammer. According to Gellings [108] VSDs can potentially save 10 – 20% of pump energy. Kiselychnyk [109] indicates that a 10% speed reduction can realise a reduction of 27% in energy usage [93].

Where flow rate variation is not necessary, pump resizing is a more efficient intervention. Pump resizing includes reduction of impeller diametres or even replacement of a pump. Other methods to enhance the overall efficiency of a water distribution system include [93]:

- Replacing inefficient equipment;
- Managing leaks by regular monitoring;
- Selecting a suitable electricity tariff; and
- Incorporating renewable energy sources.

Some of these methods require high capital expenditure, such as replacement of equipment. Other methods, however, require little to no additional costs, such as selecting suitable electricity tariffs. It is possible to reduce the electricity costs by 50% by utilising a suitable tariff structure [93].

Vilanova and Balestieri [13] summarise state-of-the-art methods to energy and hydraulic efficiency and conservational approaches in water supply systems. An overview of energy efficiency and conservation alternatives is provided. The results of these selected methods are presented in Table 7.

Table 7: Estimated energy cost savings achievable (Adapted from [13])

Energy efficiency and conservation intervention	Estimated energy cost saving
Pressure and water losses management	20-25%
Real-time energy monitoring	5-20%
Operational optimisation of pumping systems	15-30%
Correct pump sizing	15-25%
Replacing inefficient equipment	1-10%
Increasing pipe diameters	5-20%
Reducing oversized equipment	5-10%

2.4 Implications and risks associated with DSM projects

2.4.1 Eskom paid infrastructure

Eskom requires DSM initiatives to be sustainable while achieving consistent evening peak period load reduction. When a DSM initiative is awarded to an ESCo, Eskom provides funds for the installation of infrastructure to achieve a sustainable load shift impact. In most cases, the infrastructure is 100% paid for by Eskom [95].

The infrastructure installation is aimed to realise peak period load reduction. Eskom funds the infrastructure, as well as the installation and commissioning of the infrastructure. The client takes ownership of the infrastructure once it is installed. The client is responsible to maintain and ensure the equipment remains in working order.

Additionally power monitoring equipment is upgraded, repaired or replaced if necessary. The power monitoring equipment is essential to report on the performance of the DSM intervention. By reporting on the power consumption, the personnel become more aware of energy management. The personnel develop an energy awareness, which in turn changes the manner in which decisions are made regarding the operation of equipment.

The required infrastructure installations vary greatly from site to site. It depends on the condition of equipment already installed on a site. The automation of a system is a high priority. Automated systems have the advantage of improved operational efficiency. This is due to the reduced likelihood of human error occurring [95].

An EMS is also funded by Eskom. The EMS is responsible for scheduling the operation of energy intensive equipment, such as pumps, out of peak periods. The advantage of the EMS is that scheduling is done in real-time. By monitoring and measuring the system’s parameters, decisions to start or stop can be done in real-time.

2.4.2 Maintenance

The upgrading of condition monitoring and communication networks also form part of the scope of Eskom’s paid infrastructure. The EMS enables logging of operational data. The system provides time-stamped data for statuses, flows, pressures, temperatures, vibrations and many other parameters. Valuable information can be extracted from the data to support the scheduling of pumps.

The operational condition of equipment is monitored by the condition monitoring equipment. This helps with the management of maintenance operations. It provides a method to reduce or even eliminate unnecessary maintenance and prevent complete equipment failure [110].

Predictive maintenance is the continuous monitoring of the mechanical condition of equipment, and is a condition-driven preventative maintenance effort. This will maximise the interval between repairs, minimise the number and the cost of unplanned maintenance as a result of failures and it will improve the availability of a plant system [110].

Substantial improvements in availability, reliability and operational costs have been achieved due to predictive maintenance efforts. These improvements can be achieved by reducing unplanned maintenance costs, equipment failure and downtime. Based on a survey of 500 plants, the costs associated with maintenance can be reduced by as much as 50%. The number of complete unexpected equipment failures have been reduced by 55% [110].

The EMS aids in these maintenance efforts as it can log the condition of equipment. The efficiency of a pump and pump combination can be logged to allow the most efficient pumps to be operated, especially during peak periods. Additionally a better awareness of plant equipment is achieved, which in return allows for better plant availability.

2.4.3 Frequent start/stop operations

Load shifting on a pumping system requires the pumps to be stopped and started more frequently. Pumps start and stop more frequently if the upstream or downstream reservoirs have small storage capacity.

Frequent starting and stopping of pumps cause overloading of the motor, starter and contactor [111]. When an induction motor is started the inrush current can reach 4–7 times the rated value, as presented in Figure 37 [112]. A motor starter contains a device known as a motor overload, which protects the motor from continued overloads due to starting [113]. Excessive machine loads occur due to the locked rotor torque that needs to be overcome at start-up.

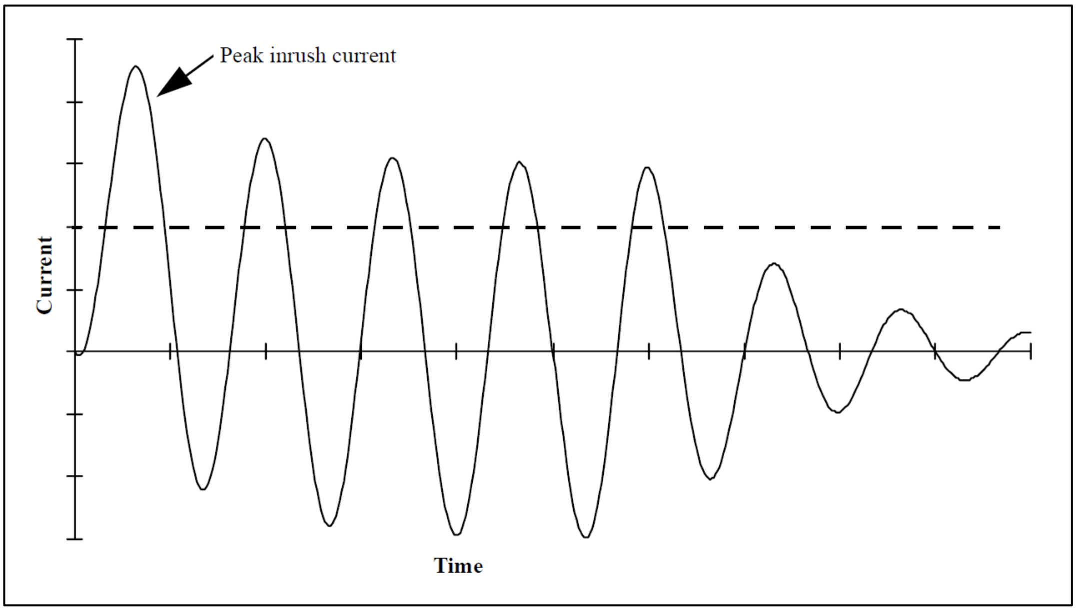

Figure 37: Inrush current when starting a motor [114]

Soft start motor controllers can control the starting process by controlling the acceleration time, starting current, overload current and motor torque [113]. The starter can limit the inrush current that a motor draws when it is started. Secondly, it reduces the stress on mechanical systems. Soft starters are widely used in the industry to limit the effects of frequent motor starting [113].

Although the overload only happens briefly it does reduce the life time of the equipment. Pumps should not be started and stopped frequently without reason. Operators should be trained to schedule the starting and stopping of pumps more effectively. Operators should still adhere to the production constraints and Eskom's peak periods to allow sufficient load management.

The EMS can optimise the scheduling of pump switches, which ultimately increases the pump lifetime.

2.4.4 Algal blooms

Algal blooms occur when the nutrients in the water source cause rapid growth of the algae. Algal growth is influenced by water composition, temperature and light intensity. It can cause major concerns for WTPs, especially where water treatment is done by direct filtration [115].

These algal blooms cause a number of issues such as clogging of intake screens, choking of weirs, ineffective floc settling, increased coagulant and chlorine demand, pH fluctuations and most of all filter clogging [116]. Figure 38 presents the typical algal blooms observed in the raw water source.

Figure 38: Typical algal bloom in raw water source [117]

COCODAF filtration is now a more established process for treatment of raw water with high algae content. Raw water with high algal content causes a rapid increase in filter head loss and consequently in filter run time due to clogging. Apart from the increased filter clogging, algae also causes taste and odour problems [65].

A treatment analysis was done by the City of Bellingham [118] because the filters clogged much earlier than the filter run times. During the summer months of 2009 the filter run times became substantially shorter, requiring more frequent backwashing. The capacity of the WTP was greatly reduced due to the clogged filters operating less efficiently, shorter runtimes and more frequent washing [118].

The capacity of the WTP was reduced to the point where water restrictions were implemented to reduce the customer's demand. During the summer months WTPs experience significant demand increases. The filter clogging was attributed to high algae content in the raw water supply. Historical and ongoing monitoring of algae showed that algal blooms are typical for that time of year [118].

To mitigate the adverse effects of algal blooms on the WTP the city evaluated the treatment, intake and lake management improvements. After the study recommendations were made to implement DAF. DAF was found to be a technically superior treatment alternative and the most cost effective to implement. Other alternatives were identified such as withdrawing water from different locations and depths [118], [119].

The algal blooms present a risk to the load management on a WTP. The algal blooms cause the filters to clog which results in less filter run time. More water is wasted due to increased number of filter washes that need to be done. The combined effect is that the capacity of the WTP is essentially reduced. This causes downstream reservoir levels to decrease and load management potential reduces.

2.5 Conclusion

In Chapter 2 various elements that need to be considered when attempting load management on a WTP were identified. The functionality of various equipment and processes on a WTP was discussed, as well as a number of studies previously done on water pumping systems. These studies include load management on mine pumping and national water distribution systems.

Sufficient proof was found that load management on municipal WTPs is plausible and a viable method to reduce production costs. By effectively shifting operation of energy intensive equipment out of the peak periods, substantial cost savings can be achieved. The need for an EMS was identified to control the operating schedule of the pumping system. Energy efficiency measures to reduce the overall production costs were briefly discussed.

3

DEVELOPMENT OF A UNIQUE WATER TREATMENT PLANT CONTROL SYSTEM

Chapter 3

Chapter 3 provides a detailed investigation on WTP AA, during which the main production constraints and process variables are identified. A control system is developed for a WTP, which verifies if the proposed load shift impact is attainable. The proposed load shift impact is verified by means of a simulation and validated by a seven-day load shift test. The control system is then implemented on WTP AA.

3 Development of a unique WTP control system

3.1 Preamble

In Chapter 3, the development of a control system specifically for a WTP will be discussed. An existing system, namely the EMS, will be reconfigured to control a WTP. The necessary parameters that need to be examined are identified and explained for a specific site. The case study is based on a WTP situated near Brits in the North West province. More detail is provided for the operation strategies and constraints of the particular WTP.

The evening peak period load shift potential of the WTP is determined by taking various factors into account, such as the power consumption baseline. Portable power loggers log the power consumption and this is then used to determine the load shift potential. A simulation is done on the pumping system to determine if the load shift potential is achievable.

The simulation is tested by doing an actual load shift test on the pumping station. The duration of the test is seven days, to observe the impact of the load shift over a full operation cycle. During the seven days the simulation is validated by obtaining load shift results which correlate with the proposed impact. Finally the control philosophy is discussed.

3.2 Investigation

During the investigation period the plant layout and operating schedules need to be confirmed. The constraints and other variables that play an important role in the operations of the WTP will be discussed. All this information is needed to determine if load management will be viable on a WTP. The findings of the investigation are discussed below.

3.2.1 Plant layout and description

This case study is based on a WTP which is situated near a fresh water dam. This dam is supplied with water from various sources including rivers and rainfall. For client confidentiality the names have been removed. Throughout this study the WTP in question will be referred to as WTP AA.

WTP AA has an interconnected layout. It can be separated into three main treatment plants. A simplified layout of WTP AA is presented in Figure 39. The water is transferred between these plants by pumps and by gravity. The different treatment plants can therefore augment each other. When one treatment plant has to stop due to unforeseen circumstances the other plants can fill the reservoirs.

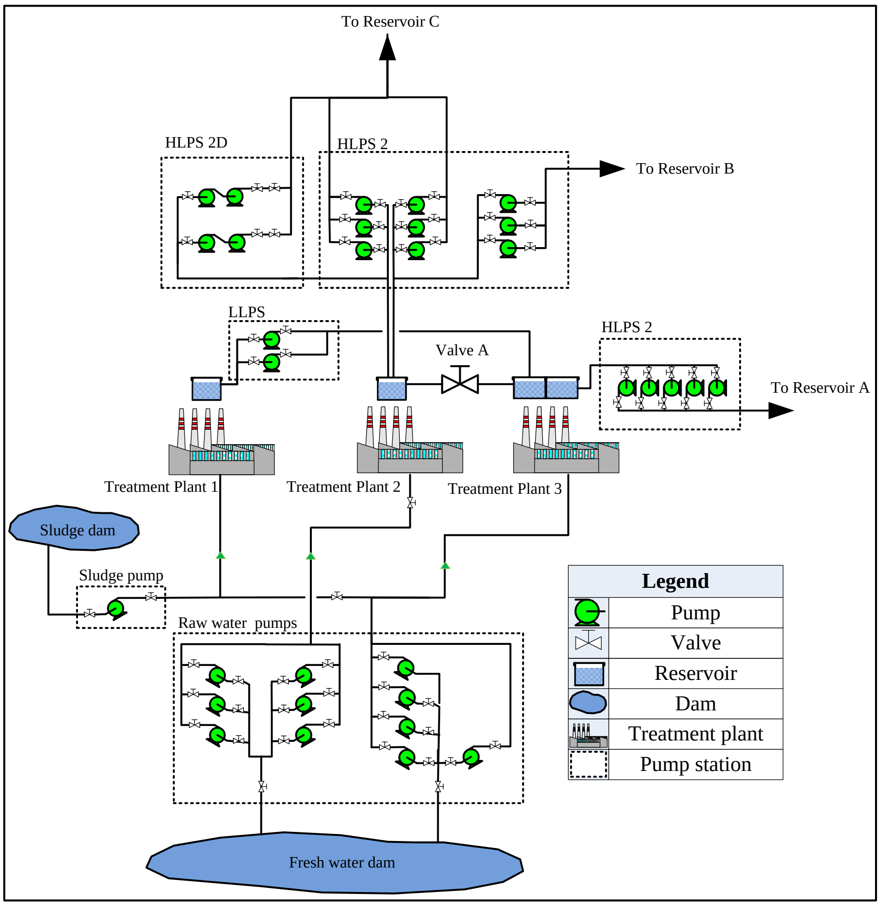

Figure 39: Plant layout

Raw water is supplied to the treatment plant by 11 raw water pumps. The raw water pumps have an installed capacity of eight 132 kW and three 275 kW pumps. The raw water pumps have a common intake from the fresh water dam. These are relatively small pumps when compared to the High Lift Pump Station (HLPS) pumps.

The pressure head that needs to be overcome by the raw water pumps is only about 20 m. The WTP is situated approximately 1 km from where the raw water pumps are situated and is presented in Figure 40. All the raw water pumps can be started or stopped from the control room.

Figure 40: Satellite view of WTP case study is based on [120]

The sludge dams are used to catch wasted water in other areas of the plant. After the suspended particles in the wasted water have settled, the water is sent back to the plant as supernatant. Treatment Plant 1 is supplied by supernatant water from the sludge dams.

Treatment Plant 1 also receives a portion of the raw water supplied to Treatment Plant 3. A valve in the pipeline controls the volume of water that passes to Treatment Plant 1. The pump supplying this pipeline is raw water pump 11. Treatment Plant 1 utilises the most recent water treatment technology, i.e. ozone. It is a smaller treatment plant (25 Mℓ) when compared to Treatment Plant 2 and 3.

Treatment Plant 2 is the largest treatment plant and is supplied by raw water pumps 1–6 (6 x 132 kW pumps). Treatment Plant 2 treats the most water (90 Mℓ), but utilises older purification technologies. Treatment Plant 3 is supplied by raw water pumps 7–11 (2 x 132 kW and 3 x 275 kW). Note that Treatment Plant 1 receives a portion of the water from this pipeline. Table 8 presents the average volume of water sent through the plant, which was logged for a two month period. The exact designed capacities are not known.

Table 8: Plant capacities

Plant	Volume [Mℓ/day]
Raw water Plant 1	28
Supernatant	5
Raw water Plant 2	78
Raw water Plant 3	73
Treatment Plant 1	25
Treatment Plant 2	90
Treatment Plant 2 (Reservoir C)	13
Treatment Plant 2 (Reservoir B)	5
Treatment Plant 2 (2D)	72
Treatment Plant 3 (Reservoir A)	78

The maximum number of pumps which can be operated on the HLPS 3 pipeline are three. These pumps are driven by VSDs. The speed of the VSDs can be changed from the control room. The flow rate can be controlled via the VSD until the required flow is reached. All the raw water pumps can be started and stopped from the control room.

Most WTPs utilise the same strategies to purify the water. The strategies and processes mentioned below are utilised by WTP AA to purify water.

- Pre-chlorination takes place in the raw water pipeline downstream of the raw water pumps. At this stage Powdered Activated Carbon (PAC) is also added to allow sufficient contact time. Lime is added to adjust the pH level.
- Polymer is added during a rapid mixing process to aid in the floc formation. Flocculation takes place in a series of baffled channels.
- DAF uses dissolved air bubbles in the water to attach to algae that float to the surface to be skimmed off.
- Treatment Plant 1 uses ozone which is a powerful oxidant. Treatment Plant 1 and 2 use rapid gravity sand filters to remove remaining particles. Treatment Plant 1 also uses a carbon filter system. Granular Activated Carbon (GAC) is used as filtration media. Treatment Plant 3 uses a COCODAF system.
- To ensure that all micro-organisms are removed, post-chlorination is done. If a pump is stopped or tripped, the dosing will automatically be reduced or stopped. This is valid for all three the treatment plants.

3.2.2 Distribution network

The plant supplies water to a large number of users as presented in Figure 41. Focus is placed on three high demand reservoirs. Various other reservoirs are connected to the pipelines supplying these reservoirs. Other reservoirs extract water from these three reservoirs. A large number of users can be supplied with potable water in this way. The average demand of the reservoirs are listed below.

- Reservoir B (10 Mℓ) – 65 ℓ/s
- Reservoir C (75 Mℓ) – 1 100 ℓ/s
- Reservoir A (70 Mℓ) – 860 ℓ/s

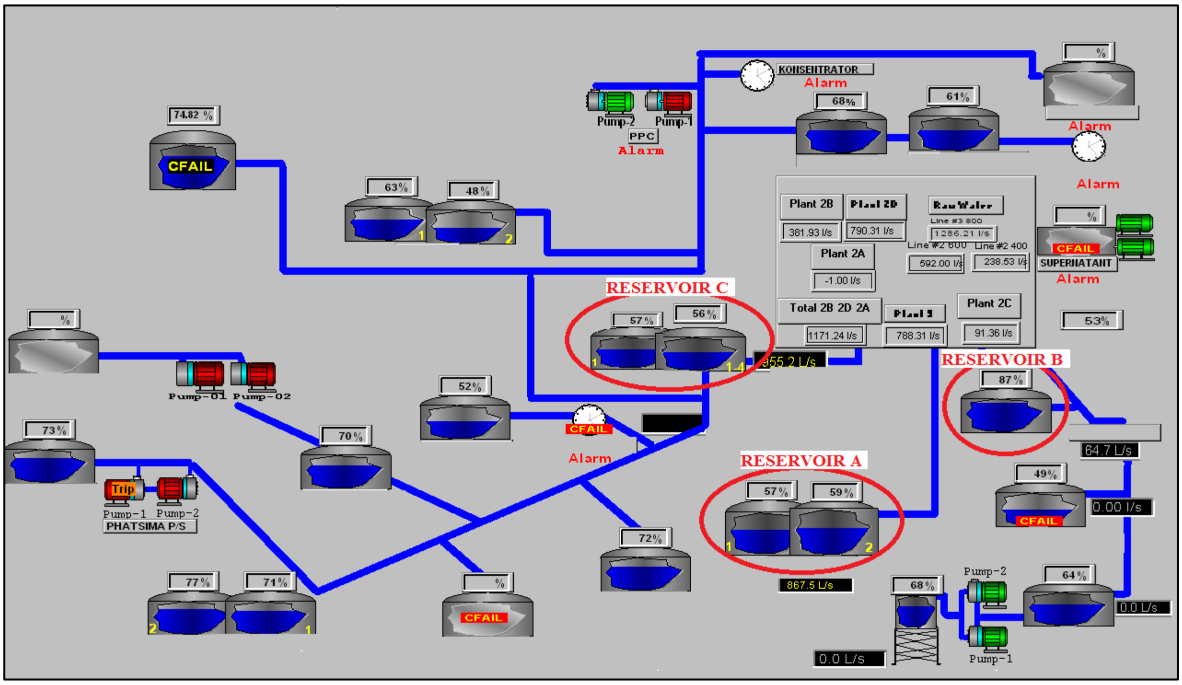

Figure 41: Distribution network presented on the SCADA

When the level of Reservoir A drops below 40%, problems in distribution can be encountered. The demand of Reservoir A can reach up to 1 200 ℓ/s. Note that 860 ℓ/s is the average demand of the entire line and not just the volume of water extracted from the reservoir itself. Other users on the line extract a portion of the water before it reaches the reservoir.

The bulk of the users supplied by WTP AA are fed via the Reservoir C line. When the Reservoir C levels are low, more water from Treatment Plant 3 is transferred to Treatment

Plant 2. This is done by manually opening valve A (presented in Figure 39 and in Figure 43) between Treatment Plant 2 and 3 to add water to the pumping system.

Presented in Figure 42 is the average weekday water demand over a 24-hour period. The figure clearly shows an increase in demand in the morning period and also in the evening. The morning peak starts at approximately 06:00 and the evening peak starts at approximately 17:00. These peaks correlate with the peak demands experienced by Eskom presented in Figure 8. The average demand of the reservoir during the evening peak is 880 ℓ/s. The volume of water pumped daily by HLPS 3 is logged by the SCADA.

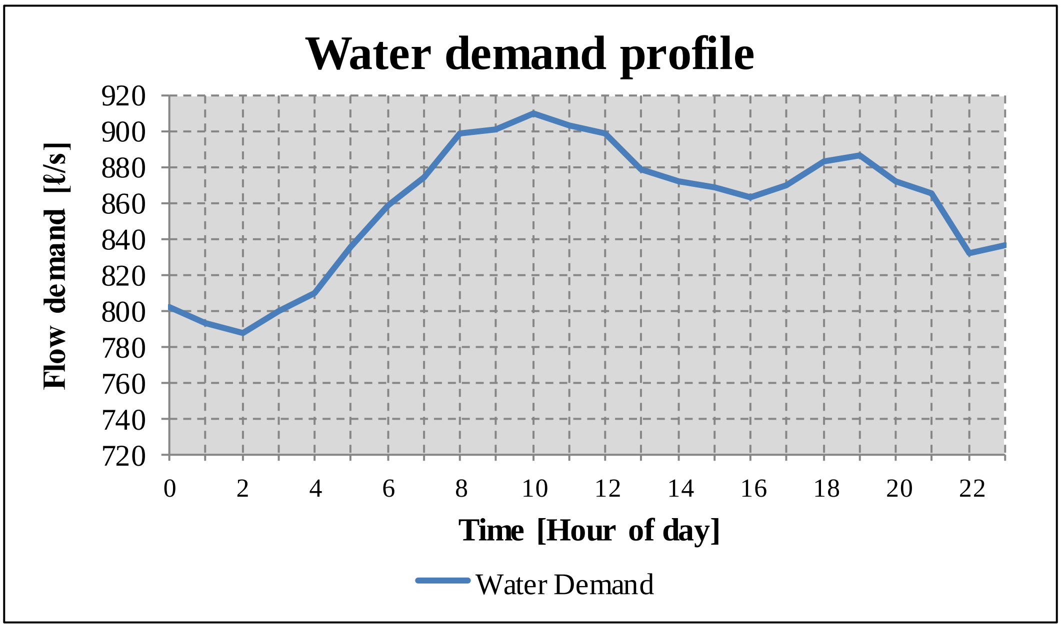

Figure 42: Flow demand of HLPS 3

3.2.3 Operation strategies of high lift pump stations

Low Lift Pump Station (LLPS) receives its water from Treatment Plant 1. Two small pumps (37 – 45 kW) are used to send water to the Plant 3 CWR. These two pumps are not operated simultaneously. CWR 1 is relatively small (10 Mℓ). The water level rises to 90% before a pump is started in order to pump the water to Treatment Plant 3. The pump stops when CWR 1 level reaches 60%. This is done automatically by the PLC.

HLPS 2 consists of nine pumps. An additional pump station (HLPS 2D) was added during upgrades, adding two pump sets, consisting of two pumps each. High lift pumps 1–6 supply water to Reservoir C. HLPS 2D also supplies water to Reservoir C. The secondary pumps in the HLPS 2D have installed capacities of 2 450 kW each. High lift pumps 7–9 supply Reservoir B with water. Presented in Table 9 is a presentation of the installed capacity of the HLPSs.

Table 9: Installed capacities of HLPSs

Plant	Pump no.	Installed capacity per pump	Reservoir supplied
HLPS 2A	1, 2, 3	750 kW	Reservoir C
HLPS 2B	4, 5, 6	1090 kW	Reservoir C
HLPS 2C	7, 8, 9	400 kW	Reservoir B
HLPS 2D	1, 2	3200 kW	Reservoir C
HLPS 3	1, 2, 3, 4, 5	1250 kW	Reservoir A

HLPS 3 consists of five pumps (1250 kW installed and 320 ℓ/s). The maximum number of pumps that are operated is four. The remaining pump is for standby. HLPS 3 supplies water to Reservoir A.

For this study, load management was only done on HLPS 3. This is due to the high demand of Reservoir C which HLPS 2 and 2D supply. HLPS 3 is not usually operated at full capacity, and thus the spare capacity can be used to implement a load shift. If load management were to be implemented on HLPS 2 and 2D a reduction in supply will be evident. The Reservoir B demand will allow for load management, but this will compromise the supply to Reservoir C.

There are two reasons for this; firstly, the comeback load is restricted by the choking of the pipeline and secondly, due to the fact that Treatment Plant 2 is already fully utilised. LLPS is only operational when the reservoir is drained to Treatment Plant 3. LLPS also has small pumps compared to the HLPSs. The raw water pumps were also excluded from the study. This study only focuses on HLPS 3, but all the other plants and pump stations have an effect.

3.2.4 HLPS 3 operation

A SCADA system is installed at WTP AA. The SCADA displays most of the operations at the plant. This includes all the pump stations, all the reservoirs and many other operations of the plant. The SCADA is also used to control certain operations of the plants, for example scheduling filter washes. The SCADA screenshot of the HLPS 3 is presented in Figure 43.

The raw water pumps can be started and stopped from the SCADA. The speed of pumps 7–11, which are connected to the VSD, can also be changed from the control room. All the high lift pumps have to be started from the pump station itself using theHMI. The main reason for this is safety. These pumps can, however, be stopped from the control room. A flow meter is installed at the end of the mainline to determine the water supplied to Reservoir A.

In Figure 43 the reservoir levels of CWR 2, CWR 3.1 and CWR 3.2 are shown. The figure also shows the control valve between Treatment Plant 2 and Treatment Plant 3 (Valve A in Figure 39). The valve controls the volume of water supplied to CWR 2. The valve will continue to supply Treatment Plant 2 with clear water until the level of CWR 2 is above 95%. The figure also shows that the level of CWR 3.1 is 100%. This is due to the weir inside the reservoir.

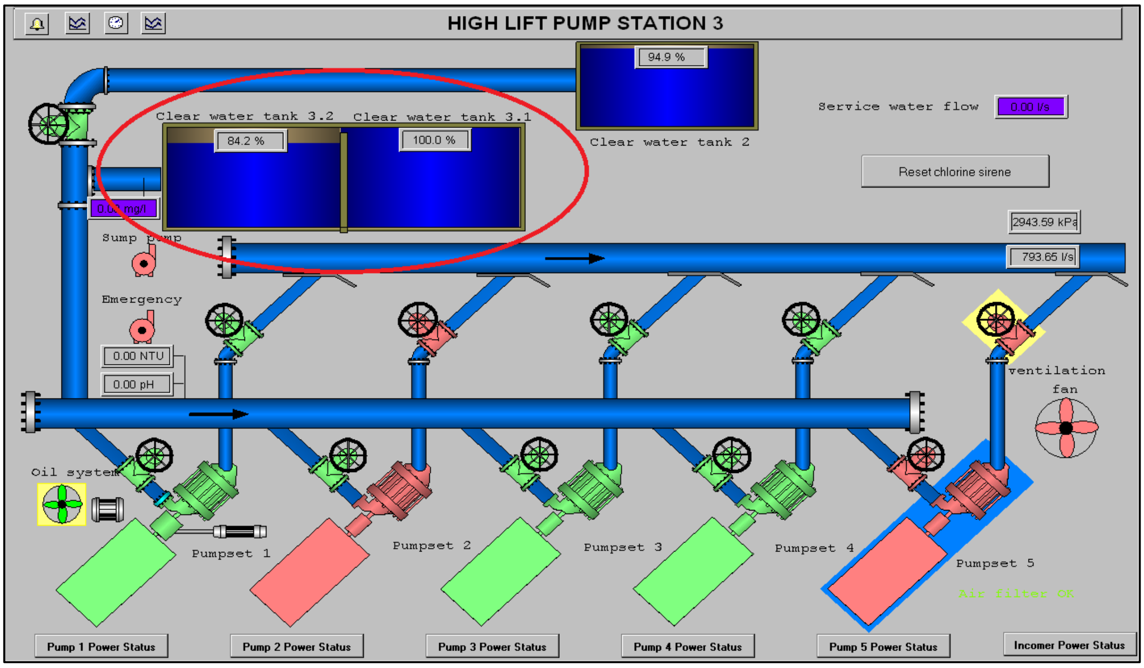

Figure 43: SCADA Screen shot of HLPS 3

Clear water from the treatment plant is supplied to CWR 3.1; refer to the encircled section presented in Figure 43. The reservoir fills up until the water level reaches 95%. The water then overflows the weir inside the reservoir into CWR 3.2. Water from CWR 3.1 is used to backwash the COCODAF filters.

From CWR 3.2 the water is distributed to the end users via the high lift pumps. The water that is gravity-fed to CWR 2 is also extracted from CWR 3.2. It is important to note that when the filters are backwashed, the level of CWR 3.1 will drop. Consequently less water is supplied to CWR 3.2 and ultimately to CWR 2.

The high lift pumps installed in HLPS 3 have an installed capacity of 1 250 kW each, but a running capacity of approximately 1 000 kW. Five pumps are installed in HLPS 3, but during the time of the study Pump 5 was removed due to unplanned maintenance. The pumps have an average head of approximately 300 m (2 950 kPa) to overcome. The delivery flow, when different pumps are operated, is presented in Table 10.

Table 10: Flow delivered by HLPS 3 Pumps

No. of pumps operated	Flow delivered [ℓ/s]	Efficiency	Loss
1	314.16	100%	0%
2	593.99	95%	5%
3	841.16	89%	11%
4	994.61	79%	21%

Figure 44 presents the flow of the HLPS 3 pumps and is a graphical presentation of Table 10. From Figure 44 it can be seen that the pipeline starts to choke when the forth pump is started. Operating the fifth pump will choke the pipeline even further and the additional pump will add little flow.

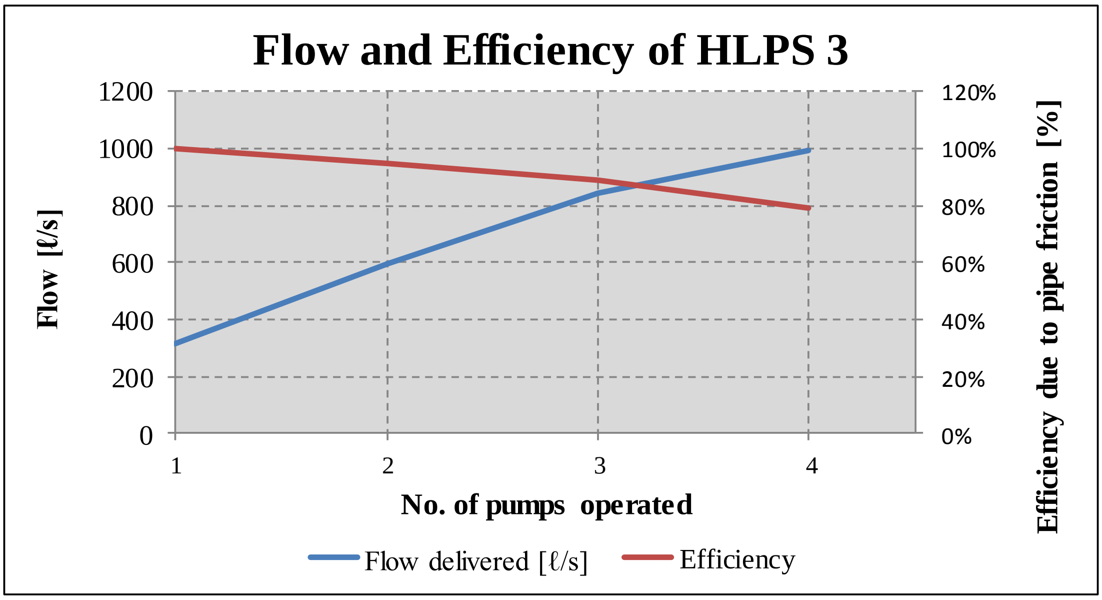

Figure 44: Flow delivered by HLPS 3

Data was extracted from the SCADA to determine the average level of Reservoir A. The data for a period of one month was used. The average daily level is presented in Figure 45. It can be seen that the level fluctuates significantly within a few days. This shows how much the demand and supply can fluctuate. Various reasons exist for these fluctuations.

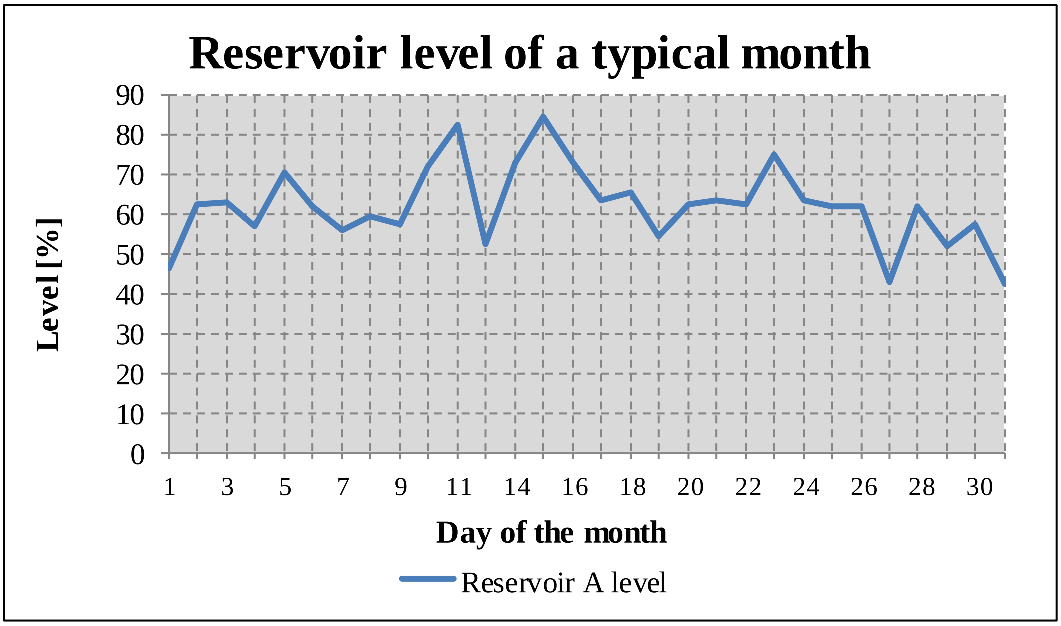

Figure 45: Average level of Reservoir A for one month

3.3 Estimation of load shift potential on a WTP

WTP AA makes use of the Eskom urban Nightsave (Large) tariff structure. The ToU of the urban Nightsave tariff is presented in Figure 11. This structure has two flat rates, namely, the active energy used for winter and summer periods. This means that the active energy is not ToU dependent.

The only items that are ToU dependent are the energy demand charge and the distribution network charge in R/kVA. This means that the WTP is not concerned about the peak periods as stipulated by the Megaflex tariff structure. No electrical cost savings could be achieved by load shifting between the peak hours as stipulated by the Megaflex tariff.

The baseline of the plant needs to be determined before the potential load shift impact can be calculated. The baseline represents the electricity consumption prior to load management implementation. The baseline is constructed by measuring the electrical demand of the plant and is summarised over a 24-hour period.

There are some requirements that the baseline has to adhere to:

- Data needs to be collected for a complete cycle of operations. Usually this is at least three consecutive months.
- The data needs to be summarised in 30-minute intervals to compile a 24-hour daily profile.
- The baseline needs to include all the equipment that will be affected by the load shift, in this case HLPS 3 pumps.

Portable Dent power loggers, presented in Figure 46, were used to log the electricity consumption of HLPS 3. These loggers were installed on the main incomers for HLPS 3. If the SCADA system was able to log flow data for longer periods, this could also have been used to convert flow data to power consumption.

Figure 46: Dent power logger

The loggers need to be set up correctly for each site. The loggers are connected to the power displays of the main incomer with clamps called Voltage Transformers (VTs) and Current Transformers (CTs). They convert the energy displayed on the main incomer to the actual power that is entering the plant. This is a much safer way to work with high voltages.

The baseline for HLPS 3 is presented in Figure 47. The average weekday consumption is approximately 3 050 kW, which implies that an average of three pumps are operated continuously. The average Saturday and average Sunday consumption are approximately 3 190 kW and 3 150 kW respectively.

Figure 47 clearly indicates that no load management was done prior to the implementation of this study. The maximum running capacity of HLPS 3 is approximately 4 000 kW. This baseline will be used throughout the implementation of this study to evaluate the load shift impact that was achieved.

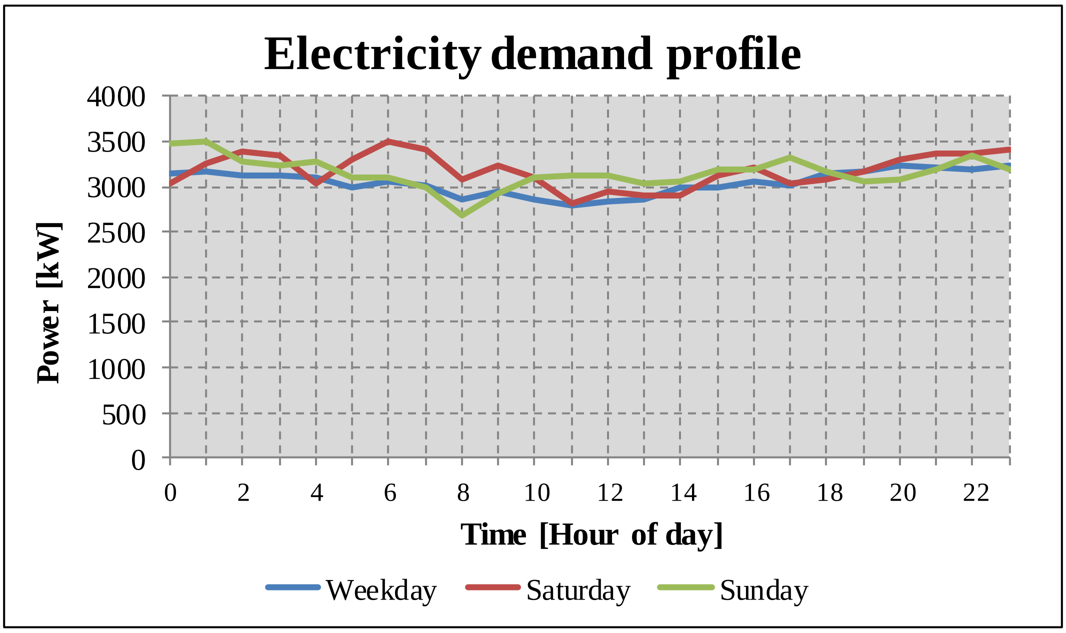

Figure 47: Electricity demand baseline

The next step is to calculate the potential load shift impact of HLPS 3. The potential impact is defined by the average baseline during the peak period, minus the average actual power consumption during the peak period. The load shifted from the peak period to the off-peak periods (comeback load) cannot exceed the maximum running capacity. The potential impact cannot exceed the average of the baseline during the two peak hours.

It is important that the proposed profile and the baseline be scaled energy neutral, to accurately represent the load shift impact. Another scaling method that can be used, which is proportional to the power usage, is to scale according to the volume of water pumped by the pump stations.

The demand of the pipe line can be determined by using the volume of water pumped daily and calculated back to ℓ/s. The maximum and minimum operational levels for Reservoir A are 95% and 55% respectively. The average daily demand of the pipeline is 860 ℓ/s and the average during the peak period is 880 ℓ/s.

The next step is to determine by how much the level of Reservoir A will drop if all the pumps are stopped during the two peak hours. 880 ℓ/s equals 3.168 Mℓ/h. 3.168 Mℓ/h for 2 hours equals 6.336 Mℓ which equates to approximately 9% of Reservoir A’s volume. The Reservoir A level will drop by approximately 9% if all the pumps are stopped and an outflow of 880 ℓ/s is assumed.

The next step is to determine how long it will take to recuperate the reservoir level to a safe load shift level (above 65%). This is done by calculating the maximum flow the plant can supply for an extended period. For HLPS 3 this flow is approximately 995 ℓ/s. With an average outflow of 860 ℓ/s it will take approximately 11 hours to raise the level 10%.

Plant personnel mentioned that switching off all the pumps is not viable when the level is less than 80%. Since Reservoir A’s level is rarely above 80%, it is proposed that at least one pump is operated during the peak periods. If one pump is operated during the peak period Reservoir A’s level will only drop by 6%. This will also decrease the time it takes to recuperate the level to 7 hours.

The proposed profile with a potential impact of 2.17 MW is presented in Figure 48. The proposed profile shows that one pump is to be operated during the peak period (18:00 – 20:00). The comeback load is distributed into the eight off-peak hours. This is to ensure that the comeback load is in the least expensive periods.

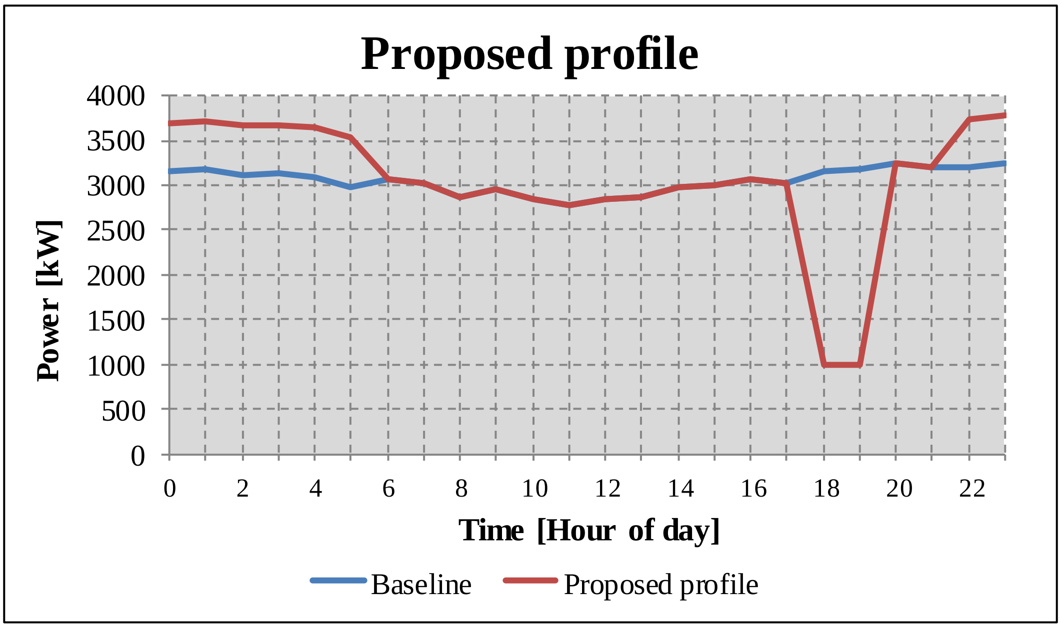

Figure 48: Proposed profile

The demand for water is not the same from day to day, it is therefore important to capitalise on the load shift impact when possible. For example if the reservoir levels are high (above 85%) it might be possible to switch off all the pumps and achieve a significant impact. On other days it might not be possible to switch off any of the pumps, therefore achieving a good average impact.

3.4 Control system for a WTP

3.4.1 Design of control system

Before a control system can be designed, it is important to know the parameters that have to be adhered to. This includes, but is not limited to:

- The capacities of the reservoirs;
- The number of columns available;
- The minimum and maximum number of simultaneously operated pumps;
- The flow rates of the pumps;
- The installed capacities of the pumps; and
- The minimum and maximum percentage levels of the reservoirs.

The maximum and minimum CWR levels are presented in Table 11.

Table 11: Maximum and minimum clear water reservoir levels

Reservoir	Min Level	Max Level
CWR 1	60%	95%
CWR 2	85%	98%
CWR 3.1	95%	100%
CWR 3.2	65%	95%

The functional operating levels of these reservoirs are presented. The operators ensure that the reservoirs are kept within these limits. When the reservoir level nears the minimum operational level, cavitation is prone to happen. Cavitation can occur due to the low delivery pressure caused by low reservoir levels [87]. Therefore the PLC trips the pumps as a safety precaution before cavitation can occur.

There are various other reasons a pump may be tripped by the PLC. These reasons include:

- Maximum number of pumps operated;
- Pump health from panel;
- Suction side valve health;
- Delivery side valve health;
- Delivery line pressure health;
- Bearing temperatures health;
- Casing temperature health;
- Winding temperatures health; and
- CWR level below minimum.

Additional protection is provided by the motor’s protection system. It protects the motor against incidents such as over current/overloading and line voltage imbalance.

The level of Reservoirs A, B and C play an important role in the operation of the plant. If the level of any of these reservoirs is low, the plant will operate at full capacity to raise the levels. It will operate at full capacity, even if that means it has to operate with the maximum number of pumps during the peak periods. The distribution of potable water will remain the most important parameter for the WTP. The upper and lower reservoir limits are presented in Table 12.

Table 12: Maximum and minimum reservoir levels

Reservoir	Min Level	Max Level
Reservoir A	55%	98%
Reservoir B	55%	95%
Reservoir C	65%	95%

Adhering to maximum and minimum reservoir levels is a rule the operators should follow. It is not always possible to keep the reservoirs above the minimum level due to many reasons. The demand during summer months is sometimes so high that the plant cannot keep the reservoir levels high. It can also happen that unplanned maintenance needs to be done, consequently stopping pumps.

3.4.2 Simulate control system

The EMS was used to simulate the proposed load shift as mentioned in section 3.3. EMS has the capabilities to simulate a system in real-time. The simulation can be sped up by using a second/second ratio. This function was used to determine if the proposed control philosophy could be followed.

The simplified layout of HLPS 3 is presented in Figure 49. This layout was used for the simulation. This layout represents the essential parameters that are needed to perform an accurate simulation. To start the simulation all the reservoir capacities need to be known and programmed into the EMS.

The simulation is important to check if the proposed profile is a viable one. The simulation will test if the reservoirs will be kept within the allowed margins. For the simulation to be as accurate as possible the flow demand at Reservoir A, as suggested in Figure 42, was used.

For the control purposes of the simulation the CWR 3.2 level was not included. This is due to the fact that the volume of water entering the CWR 3.2 from the COCODAF filters is unknown. The volume of water which Treatment Plant 3 is designed to supply was used to ensure that the simulation is correct.

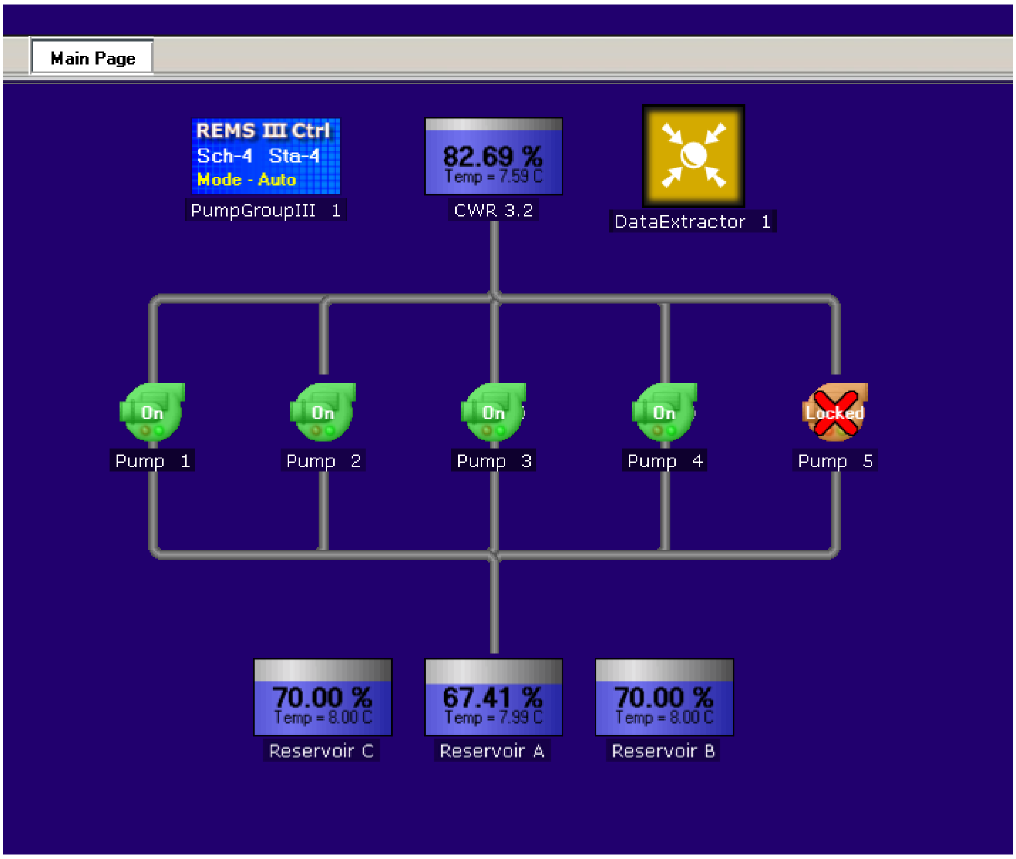

Figure 49: EMS Layout for simulation

Water is supplied to end users in the simulation without exhausting the CWR 3.2. The volume of water exiting CWR 3.2 to Treatment Plant 2 is also unknown but a fraction of the water was assumed for the simulation. It was therefore assumed that Treatment Plant 3 is able to supply sufficient water to the CWR 3.2. To thoroughly test if the proposed profile is viable, an actual test on site should be done.

The effect of Reservoir B and Reservoir C on the WTP was also not included in the simulation model. When the levels of these two reservoirs are low, more water from Treatment Plant 3 is sent to Treatment Plant 2. More pumps are operated to fill the reservoirs; and HLPS 3 operate fewer pumps. The volume of water from Treatment Plant 3 to Treatment Plant 2 is unknown.

The results of the EMS simulation are presented in Figure 50. According to the simulation, an average evening peak impact of 2.35 MW is achievable. The proposed impact, calculated in section 3.3, correlates closely with the impact that was simulated by EMS. There is still spare capacity available, from approximately 12:00 only three pumps were operated in the simulation.

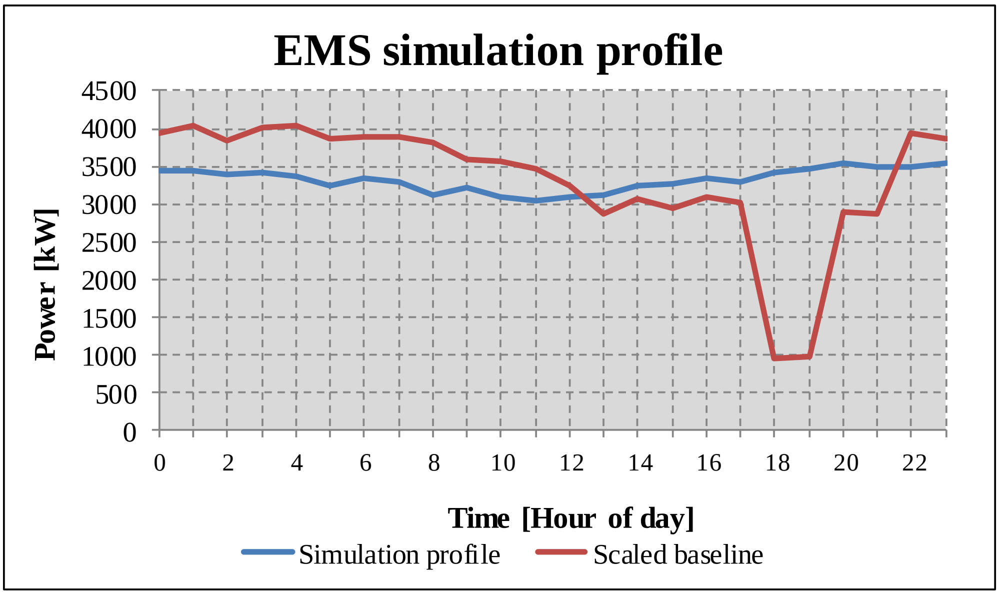

Figure 50: Results of EMS simulation

The reservoir levels were kept within the acceptable limits during the simulation period as presented in Figure 51. The maximum and minimum reservoir levels for Reservoir A are 98% and 55% respectively. During the weekends when the electricity tariffs are lower, more pumps can be operated to raise the level if needed.

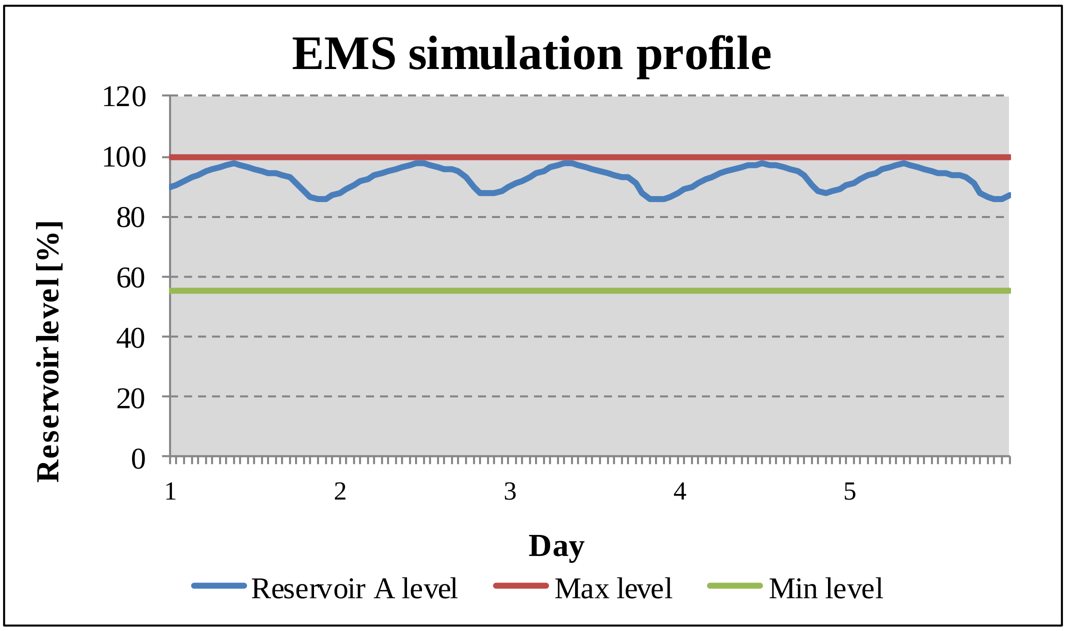

Figure 51: Simulated Reservoir A level

3.4.3 Test control system

The next step is to do a test on WTP AA. This will validate the accuracy of the proposed impact and the simulation model. During these tests, any unforeseen parameters that are important to the load shift will arise. It is important to monitor the important parameters when the pumps are switched off during the tests. The important parameters include reservoir levels, filter levels, raw water inflow and raw water motor speed. On WTP AA most of these parameters are logged by the SCADA system.

When attempting a load shift test, it is important to communicate what is planned during the test. It might be necessary to communicate weeks prior to the test. This ensures adequate time for plant personnel to prepare for the load shift. If the reservoir levels are too low, load shift tests will not commence. With sufficient time, the reservoir levels can be prepared.

The results of the load shift test which were performed on WTP AA are presented in Figure 52. The load shift test was done over a five day period. During the five weekdays, an average evening peak load shift impact of 2.13 MW could be achieved. The average profile of the five days is presented in Figure 53. This correlates with the proposed impact of 2.17 MW (within a 2% margin).

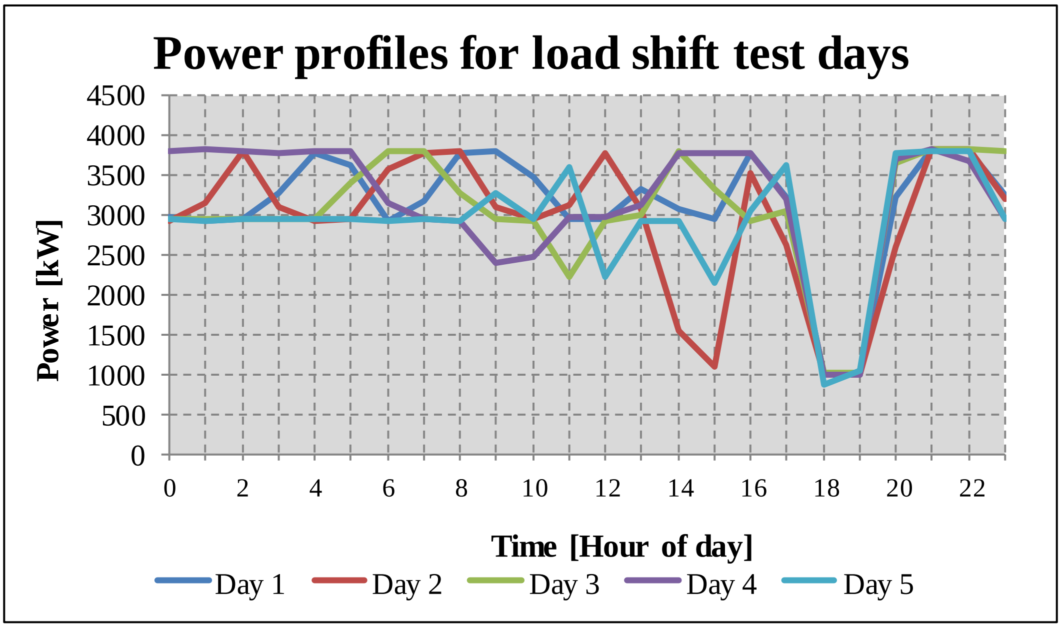

Figure 52: Power profile of load shift test days

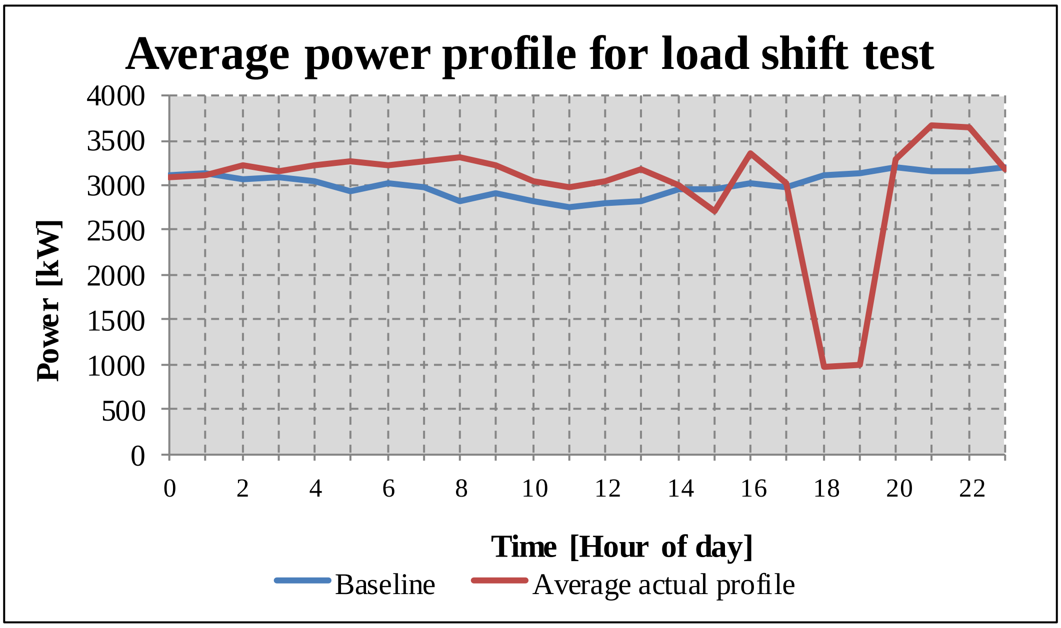

Figure 53: Average power profile of load shift test

Figure 54 presents the Reservoir A level during the test. It can be seen that the reservoir level was easily recovered. The reservoir levels on Monday morning and Sunday night are 60% and 65% respectively. This means that during the seven-day load shift test period, the reservoir was kept at an acceptable level. The comeback load was not more than what the plant could handle.

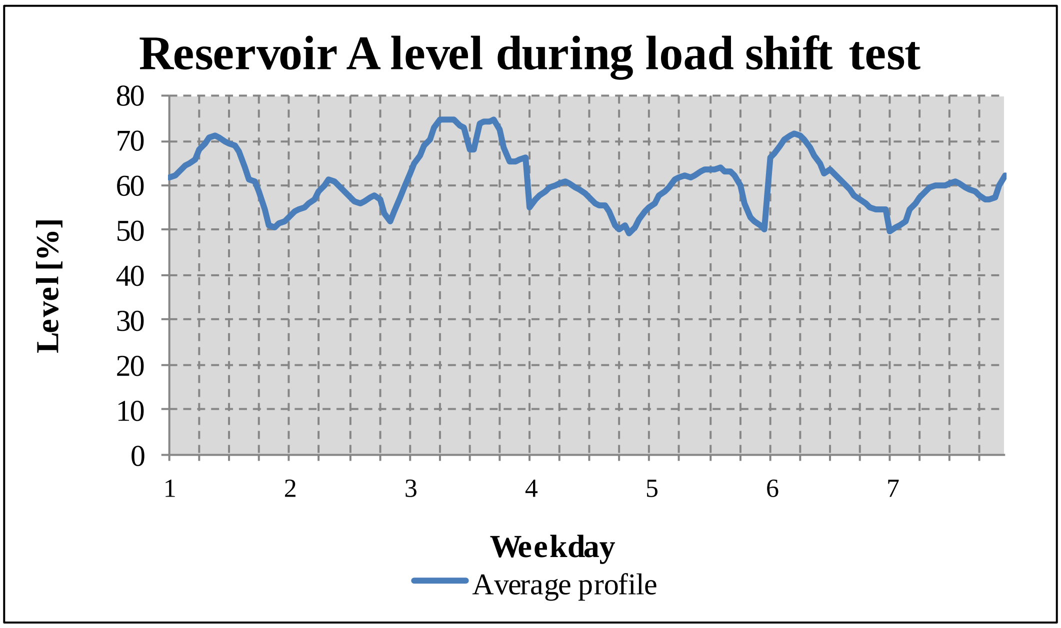

Figure 54: Reservoir level during load shift test

During the load shift test, it became clear that the proposed operation, as depicted by Figure 48 in Section 3.3, could not be followed exactly. When four pumps are operated during the off-peak periods (comeback load), the CWR 3.2 is emptied. The plant cannot supply sufficient water to continuously operate four pumps, as assumed for the simulation. According to plant personnel this is due to the filters not operating efficiently. The loss in effectiveness can mainly be attributed to high algal content in the raw water.

3.5 Implementation of control philosophy

In this section, the control philosophy will be discussed in more detail. This control philosophy will be used by WTP AA to implement the load shift initiative. The load will be shifted out of the evening peak periods by scheduling the operation of the pumps to off-peak periods.

Firstly, it is important to remember that the pumps are not stopped or started by the EMS. Only suggestions are made to the plant operators as to which pumps to operate. The operators switch off the pumps manually on the SCADA system.

The following are priorities for load shifting with consideration to the need for water:

- Load shifting will take place between 18:00 and 20:00 on weekdays;
- The comeback load will take place between 22:00 and 05:00, if this is not possible the comeback load will be during the rest of the day.

The main aim can be summarised: To operate the least amount of equipment during peak period. More equipment should then be operated during off-peak periods to catch up what was lost during peak periods.

During the implementation of this study, the control philosophy was continuously updated and changed. This happened when more information became available. The further the load shifting progressed, the clearer certain parameters became. Some of these parameters were unknown before the implementation started. These iterations of the control philosophy and important parameters will be discussed in more detail in this section.

The main focus of the control philosophy is the operation of the HLPS 3, as this is from where the load shift impact will arise. The control philosophy for the HLPS 3 involves mostly the starting and stopping of the pumps. For a pump to completely stop from the SCADA takes approximately 5 minutes. The high lift pumps need to be switched off between 17:40 and 17:45 on weekdays to ensure all pumps are off at 18:00.

3.5.1 Raw water pumps

The raw water pumps 7–11 are operated with VSDs. To determine how many raw water pumps must be operated and at what speeds to be operated at, the following was done:

- The flow rate the pump supply is known.
- The small pumps were stopped and only the larger pump were operated (275 kW).
- The speed of the raw water pump was then controlled with the VSDs to produce the required flow rate.

During the first phases of the control philosophy the speed of the raw water pumps were reduced at approximately the same time as the high lift pumps were stopped. The treatment plant can be seen as a buffering reservoir. This means that when the speed of the raw water pumps is reduced it takes some time before the clear water exiting the filters is reduced. This caused the CWR 3.2 to overflow after the high lift pumps were stopped.

An additional pump then needed to be started during the peak periods to keep the reservoir from over flowing and wasting water. This problem was rectified by slowing the speed of the raw water pumps between 17:20 and 17:30. This was sufficient time for the plant to reduce the production of clear water when the high lift pumps were stopped at 17:45.

The exact opposite happened when the raw water pumps were started around the same time as the high lift pumps were started. The CWR 3.2 would be drained not long after the pumps were started and had to be stopped again. This is due to the retention time within the treatment plant. This was rectified by starting the raw water pumps much earlier than the high lift pumps. The raw water pumps were started at 19:25.

The control philosophy for the raw water pumps kept the CRW 3.2 within the upper and lower control limits. The upper and lower control limits for CWR 3.2 are 95% and 65% respectively. The treatment plant was able to supply more water than what was pumped away by HLPS 3. This is due to the LLPS which is also supplying CWR 3. The raw water pumps for Treatment Plant 1 were also reduced at the same time as the raw water pumps for Treatment Plant 3. The raw water for Treatment Plant 1 was not reduced as much as for Treatment Plant 3.

Before the pumps are stopped for the peak period, the pumps are operated to drop the CWR 3.2 level to its minimum of around 65%. This creates a buffer against the risk of an overflowing reservoir due to the time it takes to fill the reservoir. By the time the peak period has passed, the CWR 3.2 level has recovered and is nearly full. The pumps can be started and operated for an extended period and do not need to be stopped due to the high reservoir level.

Slightly more water is supplied by the treatment plant than what is pumped away by HLPS 3. Treatment Plant 2 is supplemented with water from CWR 3.2. Water from CWR 3.2 is gravity-fed through an actuated valve to CWR 2. This valve continues to pass water to CWR 2 until CWR 2 reaches 95%. This causes the level of CWR 3.2 to rise slower. This can also be seen as a buffer against the risk of overflowing reservoirs.

During the off-peak and standard periods and during the weekends the raw water pumps were operated to supply a flow rate equal to the designed capacity. This means that the raw water pumps were controlled to supply water to the treatment plant at the same rate it can be utilised by the plant. If too little water is transferred to the plant, the plant is underutilised. If too much water is transferred to the plant, plant losses will arise. This is due to, among other things, the overflowing of filters and settling tanks.

3.5.2 Low lift pumps

It can be concluded from the section above that the high lift pumps should be stopped between 17:40 and 17:45 on weekdays. This allows sufficient time for the pumps to completely stop when the peak period starts. The volume of water which enters the CWR 3.2 is not measured by a flow meter. Only predictions can be made regarding this figure. It is therefore more logical to control the high lift pumps according to the CWR 3.2 level and the Reservoir A level. LLPS also plays a role in the control of the HLPS 3 pumps, since it supplies water to CWR 3.

LLPS consists of two relatively small pumps (37 kW – 45 kW), but they deliver approximately 370 ℓ/s. These pumps are controlled with a PLC and are stopped and started automatically. Water from the treatment plant enters the CWR 1 and fills it until it reaches 95%. This is when one of the pumps is started. The two pumps do not operate simultaneously. These pumps transfer water from CWR 1 to CWR 3. It continues to do so until the level of CWR 1 reaches 60% when the pump is stopped. LLPS is not necessarily stopped during the peak periods.

3.5.3 High lift pumps

The control philosophy of the high lift pump stations is limited to HLPS 3. It does, however, take the other pump stations into consideration. The philosophy, by which the pumps are controlled during standard and off-peak periods and during the weekends, will be discussed in this sub-section.

The HLPS 3 pumps are firstly controlled according to the CWR 3.2 level. If the level rises above 95% the maximum number of pumps need to be operated to keep the reservoir from over flowing. If the level of CWR 3.2 drops below 70%, three pumps should be operated. This will allow the CWR 3.2 to fill again, provided sufficient inflow. If the reservoir level drops even further, below 65%, two pumps should be operated to avoid tripping the pumps.

Secondly, the HLPS 3 pumps are also controlled according to Reservoir A, Reservoir B and Reservoir C levels. If Reservoir A's level is below 85%, four pumps should be operated. If Reservoir A's level is above 85%, three pumps should be operated. If the reservoir level is above 95%, only two pumps should be operated.

Water is sent from the CWR 3.2 to CWR 2, therefore HLPS 2 is also affected. When HLPS 2 needs to operate additional pumps, pumps in HLPS 3 are stopped to supply water to HLPS 2 pumps. When either Reservoir B or Reservoir C is below 55%, only three pumps should be operated at HLPS 3.

If both Reservoir B and Reservoir C are below 55%, two pumps should be operated. This allows sufficient water to HLPS 2 to fill the reservoirs. However, if Reservoir A is below 55%, four pumps should be operated regardless of the level of Reservoir B and Reservoir C. Reservoir A is the main control parameter for HLPS 3.

At 17:15 on weekdays the control philosophy considers the Reservoir A level. If the reservoir level is below 55%, no load shifting will take place. The raw water pumps continue to pump as normal. If the reservoir is above 55%, the raw water should be reduced. If load shift is able to take place, the pumps need to be stopped between 17:40 and 17:45 on weekdays to allow sufficient time for all the pumps to stop.

The high demand of Reservoir A, especially during the peak periods, prevented switching off all the pumps in HLPS 3. The load shift impact can be maximised by switching off all the pumps. It was agreed by plant personnel that, if the Reservoir A level is above 80% at 17:15, all the HLPS 3 pumps can be switched off. The necessary provisions should then be made prior to stopping the raw water pumps.

3.5.4 COCODAF filters

Raw water samples are collected periodically throughout the day. These samples are tested and analysed. These samples can provide more information regarding the quality of the water. With experience the plant personnel can accurately estimate how the filters will perform for specific water qualities. Even though the COCODAF filters are not controlled by the EMS it does play a major role on the performance of the plant.

The runtime of the filters is set by experienced plant operators. The filter runtime is the time the filter operates before it is backwashed. If the algae content in the raw water is high, the filters perform less effectively. The run times are decreased significantly, due to clogging of the filters. The filters then need to be switched to a manual backwash cycle. This causes the filters to be backwashed out of sequence.

The filters have an outlet valve which controls the outflow of water. The valve opens and closes automatically according to the level of the filter. The filters are designed to operate most efficiently when the level is 80%. If the level of the filter rises in normal operation it is a sign that the filter is starting to clog. The inlet valve that supplies water to the filter will not allow the level to rise above 85%. A certain way to know when a filter is clogged is when the level of the filter is 83% or more and the outlet valve is fully open.

When the filter is clogged it is very inefficient and supplies only a fraction of the water compared to an unclogged filter. Another important point to remember is that when a filter is in a backwash cycle, it does not supply any water, but actually uses clear water from the CWR3.2. It is a balance between operating an inefficient filter and taking the time to backwash the filter rather than operating an unclogged filter.

Since the filter will have to be backwashed at a later stage, it does not make sense to operate with a clogged filter. Therefore, whenever a filter is clogged it needs to be backwashed as soon as possible. If the filter is nearing the end of its runtime, it would be better to wait for it to complete the backwash cycle automatically. Otherwise it would be beneficial to backwash the filter, even if it means washing it manually or out of sequence.

3.5.5 EMS for control purposes

There are various control systems that are used in the industry. A control system was developed called the EMS. The EMS has the capabilities of communicating with the SCADA via Object Linking and Embedding (OLE) for Process Control (OPC). The system can also communicate directly with the PLCs.

The EMS will be used as a software platform to simplify the layout of the WTP AA. The simplified layout of the distribution network is presented in Figure 55. The tools used in the EMS will be discussed below. EMS has the capability to simulate a system. EMS can display alarms to assist operators. EMS can be used as a data logging server.

EMS can display alarms which can also be programmed into the system. The system can display alarms for pumps that are not running, reservoir levels which are low, filters which are overflowing, etc. This can assist the operators in monitoring the plant more effectively, which will cause better plant availability due to improved awareness.

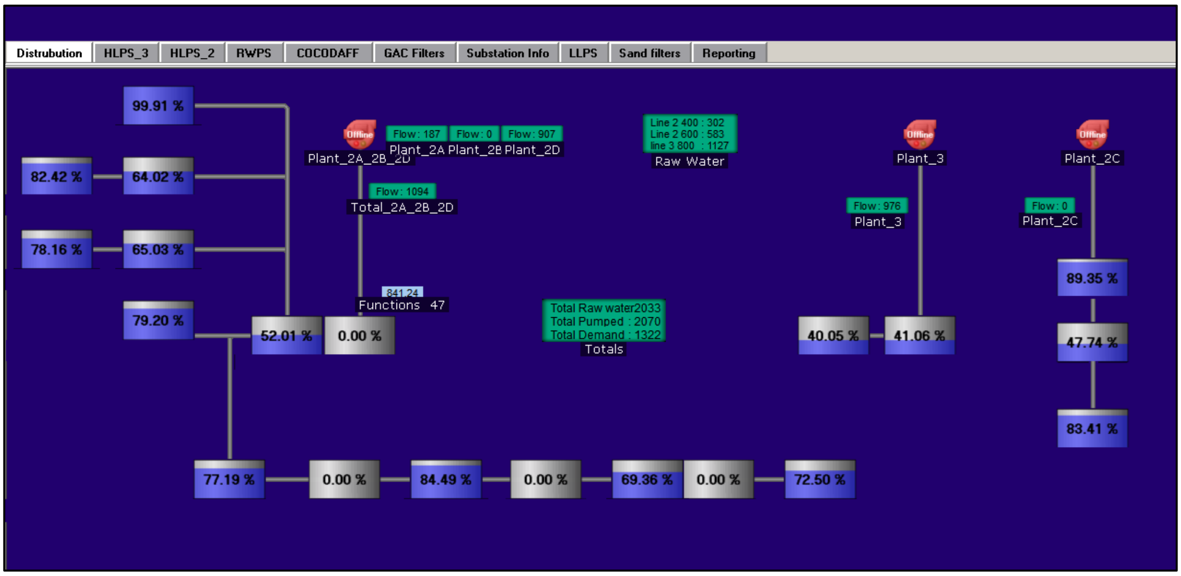

Figure 55: EMS Distribution network

As mentioned above, the high lift pumps cannot be started from the SCADA. This is for safety reasons, but it also motivates the plant operators to check on the plant operations when starting a pump. These checks include checking if no one is working on a pump, if the oil levels are correct, if the valves are in the correct positions, etc. It was therefore also recommended that EMS should not control the start/stop of pumps, but rather give a recommendation to the operators regarding which pumps to start/stop.

The simplified layout of HLPS 3 is presented in Figure 56. The pump's controller in the EMS platform is used to program a control philosophy for a set of pumps. The pump's controller can be programmed using internal tags. These tags are programmed using Java script language. With this programming the EMS can decide which pumps to start/stop.

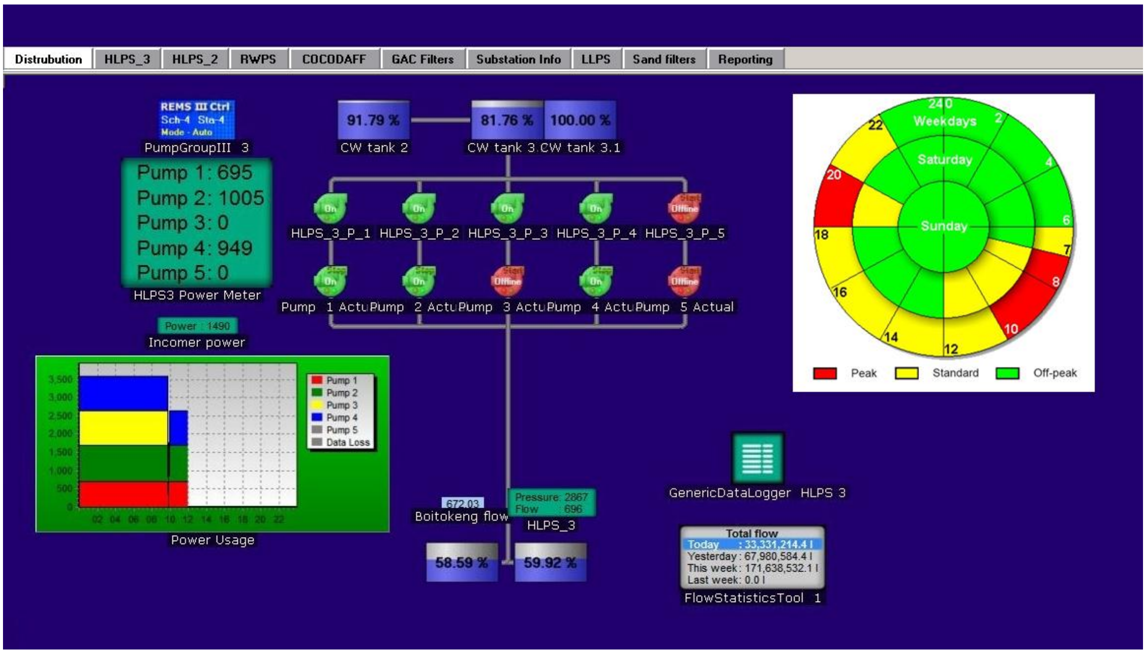

Figure 56: EMS HLPS 3 layout

The fact that EMS is not allowed to control the pumps does limit the sustainability of the load management. As soon as the operators ignore the alarms displayed by EMS, the system is of no operational value. It is therefore important for the EMS to add value.

The EMS controlling the automatic start and stop of pumps has advantages such as:

- Improved control over pumping system operating periods and pump switches;
- Most efficient pump combinations can be determined, as the necessary parameters are logged on the system;
- Sustainable load shift results, as no human error can occur;
- More structured decision making process for the starting and stopping of pumps; and
- Free operators to concentrate on other processes while the EMS controls the pumps.

Disadvantages of the automatic control by the EMS include:

- If maintenance is done on a pump and is not properly locked out, it can be started by the EMS and cause serious damage;
- If a network failure occurs the EMS will not be able to control the system, which could lead to overflowing and pump trips;
- Operators need to learn a new control system, additional to the SCADA; and

- Complex algorithms need to be programmed into the EMS to allow complete control and to enable the EMS to provide alarms to operators.

Risks can be managed and reduced by the following actions:

- Training of the control room operators;
- Thorough system control and interlocking to reduce the risk of system damage;
- Instructions and procedures to be followed during a maintenance procedure;
- Continuous maintenance on the instrumentation hardware and control system; and
- Early warning system to inform the responsible personnel.

The EMS and the SCADA can be password protected to limit unauthorised access. All authorised personnel will receive a password that will grant them the necessary level of access. When performing maintenance on any of the pumps, a lockout procedure must be followed to avoid starting of pumps while the maintenance is performed. Not following the lockout procedure could lead to serious damage.

The power usage of pump sets should be monitored and logged. The most efficient pump speeds (raw water pumps connected to VSDs) and pump combinations need to be determined. Thus only the most efficient pumps can be operated during peak periods. Another method to consider is to run the pumps with the fewest operating hours, thus attempting to equalise the operating hours of the pumps.

It is highly recommended that the pumping system be controlled automatically by the EMS. It was, however, not possible to persuade plant personnel to allow automatic control.

3.6 Conclusion

In Chapter 3 the WTP on which the case study is based was discussed in more detail. The operation and constraints of the WTP were identified and discussed. Various elements which are important when attempting a load shift initiative were discussed in Chapter 3.

Loggers were installed to determine a power consumption baseline for WTP AA. The data was used to calculate a proposed evening peak period load shift impact of 2.17 MW. The pumping system was simulated and an average evening peak period load shift impact of 2.35 MW was found viable. To validate the proposed and simulated load shift impact, an actual load shift test was conducted.

The test was done over a seven-day period to observe the effect of the load shift over a full operation cycle. During the five weekdays an average load shift impact of 2.13 MW was achieved. This correlated with the proposed and simulated impact of 2.17 MW and was proved viable. During the test period, the reservoir level was kept within an acceptable limit, proving that the comeback load was not excessive.

Recommendations are made for a control philosophy. The control philosophy used is to include a load shift during the evening peak periods, while also adhering to the production and demand constraints. It is recommended that an EMS is used to automatically control the pump operations. The client was, however, hesitant to implement the strategy and thus it could not be utilised.

4

RESULTS

Chapter 4:

Chapter 4 presents the results of the load shifting due to the implementation of the control system on WTP AA. The control of a filter outlet valve was optimised and the results quantify the improvement that was achieved. Further potential cost savings are identified by a cost analysis of two different electricity tariff structures.

4 Results

4.1 Preamble

The control system which was developed and reconfigured to function on a WTP in Chapter 3, is implemented on WTP AA. The implementation of an EMS realised actual load shift results as part of a DSM initiative. In Chapter 4 the results of the implementation of the control system, which is known as the performance assessment period, is discussed.

The power consumption profile of the performance assessment period is compared with the proposed power profile. A clear correspondence is found between the two profiles and is within a 2% margin of the impact achieved.

The role of an independent Measurement and Verification (M&V) team is briefly discussed in this chapter. Recommendations are made for a demand based scaling method. The various other impacts the study had on the plant as well as the improvement of a filter backwash cycle are also discussed. The improvement showed a practical increase in the plant capacity.

WTP AA is on the Nightsave tariff structure, which is not ToU dependent for the active energy usage. A cost analysis was carried out to determine the monetary savings that could be achieved on a ToU dependent tariff structure. It would be financially beneficial to migrate to a ToU dependent tariff structure, such as Megaflex.

4.2 Measurement, verification and evaluation method

It was discussed earlier that Eskom provides funding to install equipment on a client's site. This includes power monitoring equipment, which is needed to report on the actual load shift impact achieved. Power monitoring equipment is installed on individual pumps to monitor and log the power usage of each pump.

The power consumption of a pump can be used to determine the pump efficiency, provided the flow and pressure are also available. It is important that the equipment is calibrated to ensure the measurements are correct. A calibration certificate is usually issued by the manufacturer, but the readings need to be verified once installed. The EMS is used to continuously log the power consumption of the pumps.

The EMS sends the power consumption data, as well as other important plant processes logged by the EMS, to a database via GSM networks. The data is sent daily, once a full day has passed, i.e. after midnight each day. The data is interpreted by a preprogrammed algorithm which generates a report for the day's power consumption. The data is summarised into a daily 24-hour power profile. An example of the power consumption report is presented in Figure 57.

Redundancy measures should be in place if the communication network fails. Portable power loggers can be used to measure the power consumption, but data will have to be downloaded manually from the logger. The data will be manually translated into usable data for the algorithm to generate reports. Logbooks of operational status and flow meter readings can also be used as redundancy measures in special cases.

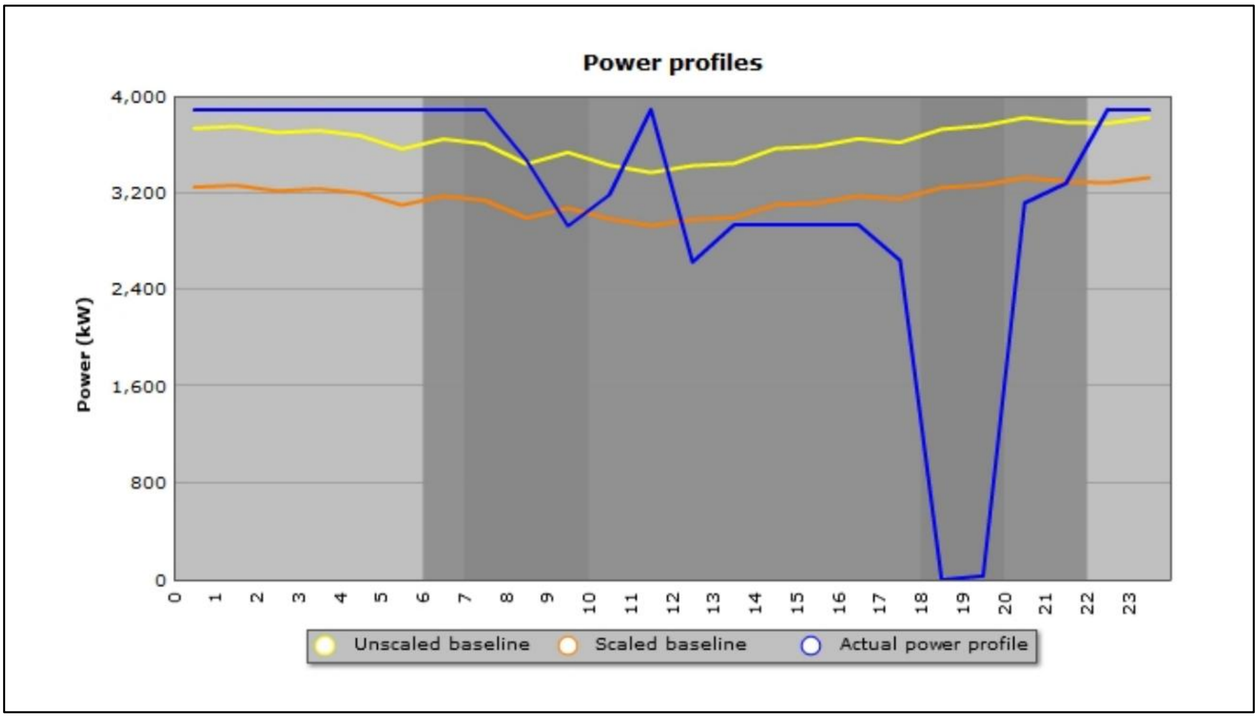

Figure 57: Daily power consumption report

An independent organisation is responsible to verify the load shift impact that an ESCo reports on. These teams are called the independent M&V teams. The M&V teams provide reporting on an impartial, quantified, measured and verified impact achieved to all stakeholders. The primary task of the M&V teams is to compare the electricity consumption after the implementation of a DSM initiative with the electricity consumption prior to implementation.

Additionally the M&V teams are responsible for scoping and development plan reports, baseline and post implementation reports, performance assessment and performance tracking reports and performance certificate approval. The M&V teams determine the scaling method used for a specific site. The scaling of a baseline is done by adjusting the pre-implementation baseline with a scaling factor. Baseline scaling is used to accurately reflect the actual load shift impact achieved.

Most pumping projects are scaled energy neutral on a daily basis. Figure 57 presents a baseline which is scaled energy neutral. The baseline in Figure 57 was scaled down due to the energy consumption of the specific day being less than during the baseline period. Many DSM initiatives, which are dependent on the weather, are scaled according to the ambient conditions. Such as mine cooling systems are scaled according to the ambient temperature and humidity.

When the ambient conditions are, for example warm and humid, consumers of a WTP will use much more water. On other days, when it is cold and rainy, consumers will use much less water. The demand of the consumers has a significant influence on the load shift ability of a WTP. If the demand is very high the WTP cannot allow load shift, as it will result in a major decrease in reservoir level. The comeback load will not be able to recuperate the reservoir level.

An alternative scaling method is necessary to accurately evaluate the effect of a load shift initiative on a WTP. A possible scaling method involves scaling the baseline according to the water demand. Another possible scaling method is to scale the baseline according to the ambient conditions at the point of extraction. To implement another baseline scaling method was not attempted for the scope of this study.

4.3 Performance assessment of implemented load management strategies

The study moved into a new phase once the Eskom paid infrastructure has been installed on site. This phase is called performance assessment. The performance assessment is for a three-month period. During this time the ESCo needs to prove to Eskom and the client that the proposed impact is achievable. As previously mentioned the impact achieved is only applicable for the weekday evening peak period between 18:00 – 20:00.

Table 13 presents the average evening peak period load shift impact that was achieved during the performance assessment period. In the table it can be seen that the performance assessment spanned over four months instead of the usually required three months. This is due to breakdowns and other incidents that prevented load shifting from taking place. A condonable day can be described as a day in which an unexpected incident occurred that prevented the plant from load shifting. It includes:

- Breakdowns;
- High algae content in the raw water;
- Extremely high demand;
- Communication failure;
- SCADA Network failure;
- PLC failure; and
- Maintenance on equipment.

Table 13: Performance assessment summary

Month	Average evening peak period power saving
August	2.29 MW
September	2.18 MW
October	0.96 MW
November	2.16 MW

The reason October was a condonable month is due to multiple breakdowns on the plant. The raw water was also dirty with high algal content. This caused the filters to be backwashed more frequently. The quality of raw water plays an important role in the load shift ability. The outlet valve of a COCODAF filter was faulty and caused ineffective wash cycles and sometimes caused the backwash cycle to be skipped entirely. Faulty chlorine injectors were not operating correctly and had to be replaced.

WTP AA is a supplier of an essential service i.e. potable water. It is therefore of cardinal importance that the supply of potable water to customers is not interrupted. The breakdowns and inefficient filters caused the supply of potable water to be jeopardised. This caused the load shift to be abandoned.

Water analytical services conducted a study on the algal content in the raw water. The results of the study found the Chlorophyll-665 algae content to be above normal specifications. The normal content is 30 μg/ℓ, and the raw water of WTP AA had an algal content of 105 μg/ℓ. The Chlorophyll-665 algae is not toxic, but can cause filter clogging and cause taste and odour problems.

The average impact achieved during the three months (Aug, Sept and Nov) of performance assessment was 2.21 MW. The average weekday profiles for the performance assessment period are presented in the figures below. Figure 58 presents the August performance assessment. Figure 59 presents the September performance assessment. Figure 60 presents the October performance assessment. Figure 61 presents the November performance assessment. In all these figures the scaled baseline has been scaled energy neutral to the actual achieved profile.

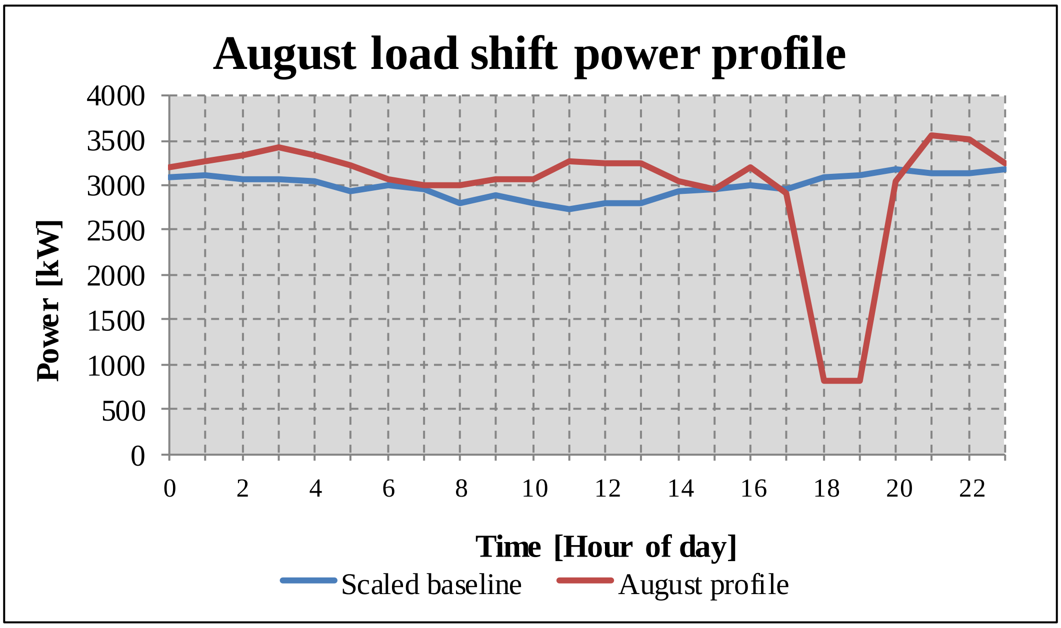

Figure 58: August load shift impact during performance assessment period

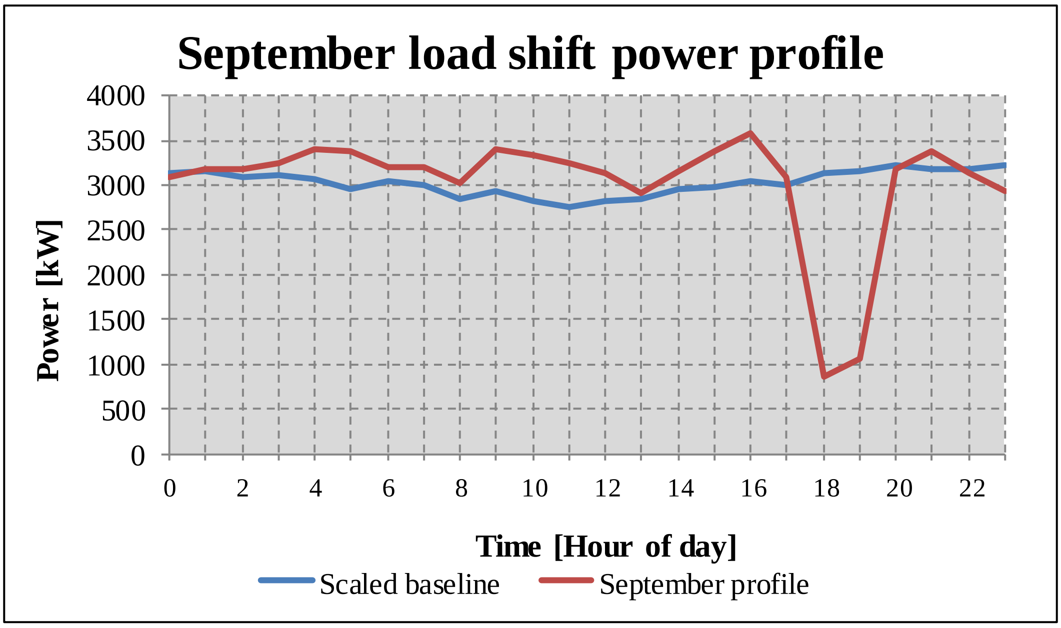

Figure 59: September load shift impact during performance assessment period

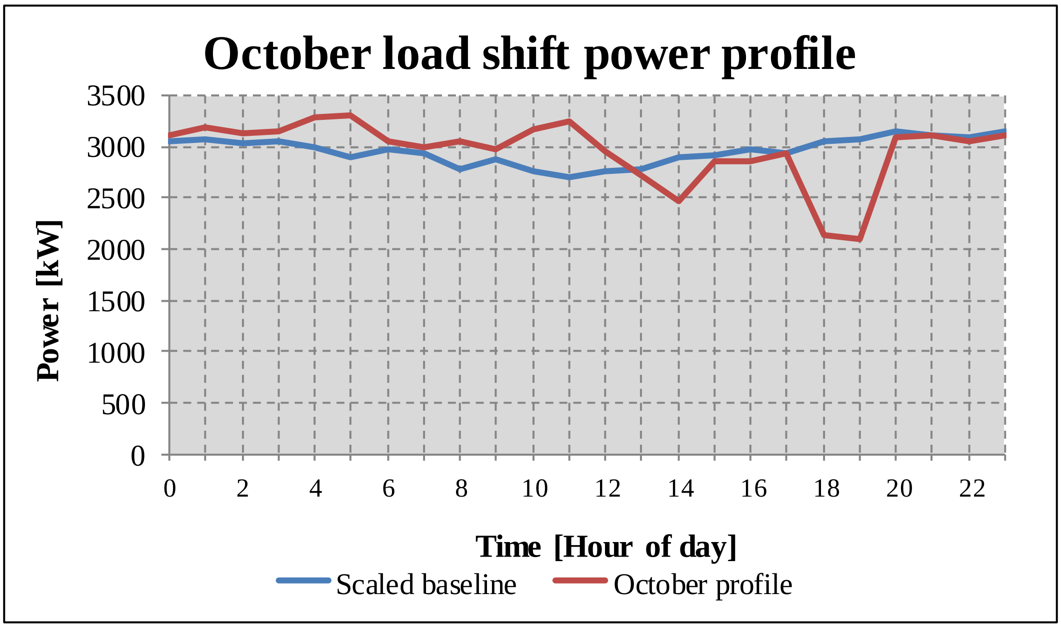

Figure 60: October load shift impact during performance assessment period

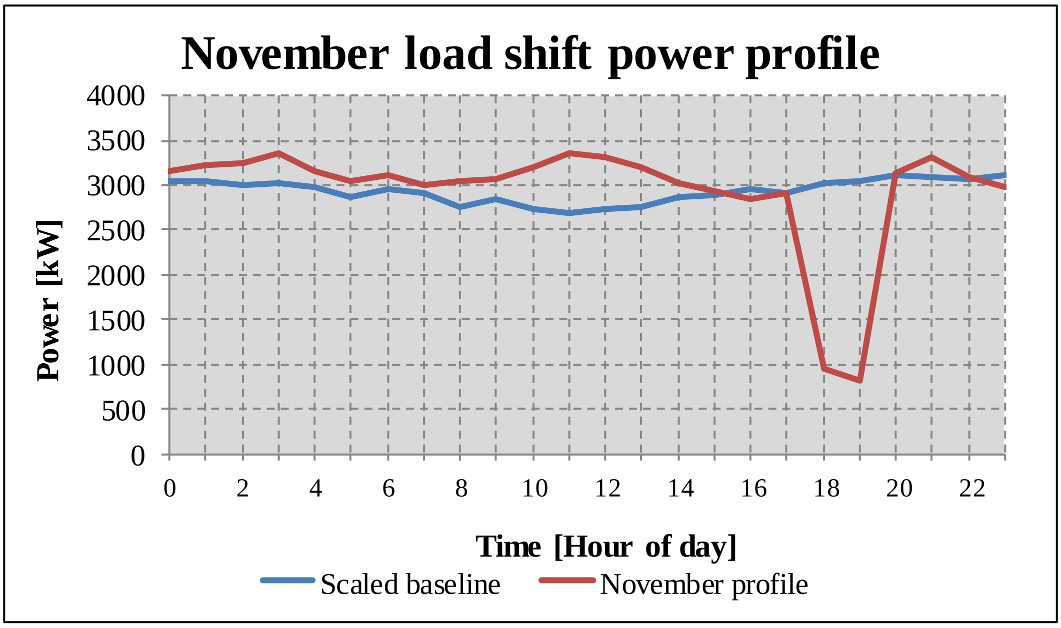

Figure 61: November load shift impact during performance assessment period

It can be seen in Figure 58, Figure 59 and Figure 61 that the power consumption during the peak period was less that the running capacity of one pump. This means that for a few days during the weekday peak period no pumps were operated. As discussed in Section 3.5, this can occur when the Reservoir A level is above 80%. The risk of not being able to supply water to users is much lower when the level is high and therefore all the pumps can be switched off.

The average actual profile achieved during performance assessment (Aug, Sept and Nov) is compared with the proposed profile and is presented in Figure 62. These two profiles have been scaled energy neutral. It can be seen that the two profiles are not the same. The comeback load of the proposed profile is only during the off-peak periods. While the comeback load of the actual profile is during the entire day.

This is mainly due to the availability of clear water. The plant is always operated to the full available capacity, except during the peak periods. When the CWR 3.2 is full the pumps need to be started. When four pumps are operated for an extended period, the level of the CWR 3.2 drops and pumps need to be stopped. This causes three pumps to sometimes be operated in off-peak periods and four pumps in standard periods.

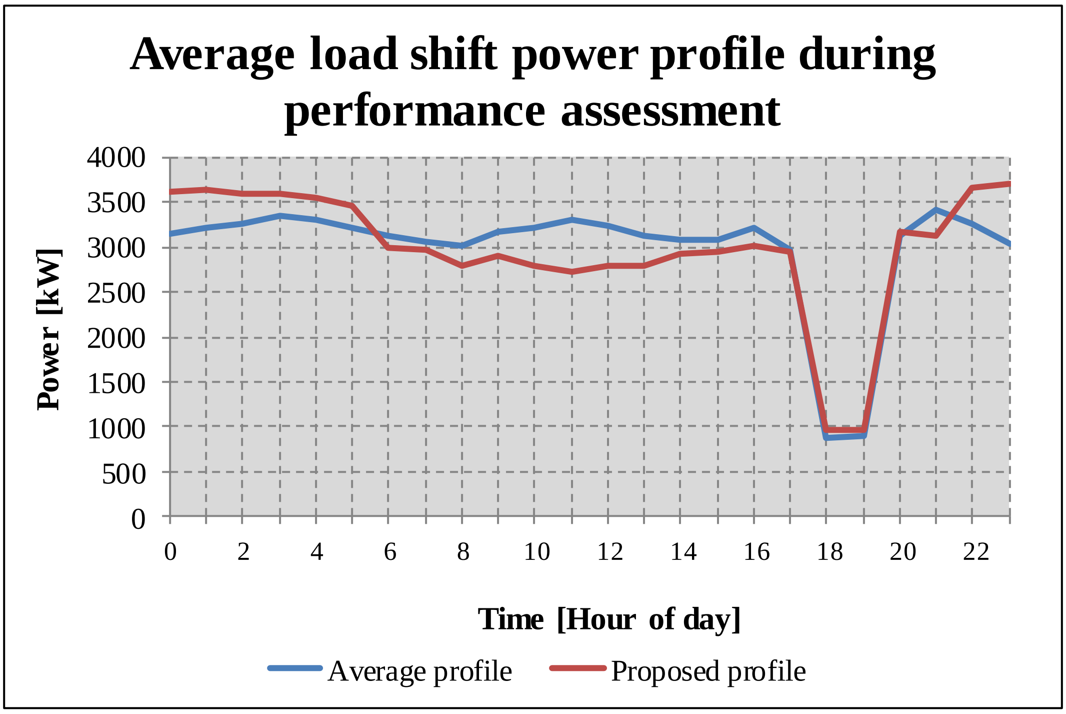

Figure 62: Average load shift power profile and proposed power profile

It should also be noted that during December, after performance assessment, an average impact of 2.75 MW was achieved. During February an average impact of 2.66 MW was achieved. This is mainly due to the high reservoir levels and therefore all of the pumps could be switched off during peak times. The high reservoir levels can be contributed to many factors of which rainfall, clean raw water and lower demand are only a few.

4.4 Impact of this study

During the performance assessment period multiple incidents occurred, which prevented the WTP to perform load shift. The raw water quality and the effect thereof on the filters was a major concern regarding the load shift ability of the plant. The filter clogging algae caused the filter run times to be significantly reduced, less water was filtered and this subsequently caused low reservoir levels. The WTP was unable to shift load due to the low levels.

The WTP AA was prevented from load shifting by many other incidents such as:

- During the performance assessment period multiple breakdowns caused the load shift to be abandoned for a particular day. These breakdowns included:
  - The gearbox of a delivery valve stripped;
  - Motor winding temperature reached excessive temperatures;
  - Malfunctioning chlorine injectors;
  - Compressor supplying air for backwashing COCODAF filter out of order; and
  - COCODAF filter outlet valve gearbox stripped.
- Regular planned and unplanned maintenance caused the plant to be less available for load shifting. During the maintenance operations pumps usually had to be stopped. This caused the level of Reservoir A to decrease drastically. When the maintenance operation finished pumps had to be operated at full capacity to regain the lost production.
- Extremely high demand caused the reservoir levels to be too low to accommodate a safe load shift. As previously mentioned, the plant is not able to perform load shift when the reservoir level is less than 55%.
- Plant losses caused the production of potable water to decrease. These plant losses are caused by incidents such as:
  - Frequent filter washing;
  - Pipe leaks and pipe breaks;
  - Opening filter dump valve when filters are extremely clogged.
- Human error prevented the load shift to be sustainable. Constant observation of the operators was necessary. It is therefore highly recommended that the load management be fully automated. The EMS should be allowed to start/stop to insure the sustainability of load management.

Many other hidden benefits, as a result of the implementation of the load management on WTP AA, were observed. These advantages include:

- Improved plant availability;
- Improved prediction of plant behaviour and demand forecasting;
- Improved maintenance practices;
- Informed personnel enables proactive action and appropriate decision making;
- Improved control infrastructure;
- Reduced production cost;
- Improved plant energy awareness allows energy saving opportunities to be explored; and
- Improved knowledge of power consumption and cost allows for simplified energy audits.

4.4.1 Optimising operation of COCODAF filters

Treatment Plant 3 utilises COCODAF filters to filter the water from the settling tanks. It was found that the COCODAF filters play an important role in the performance of the WTP. The performance of the COCODAF filters depends greatly on the quality of the raw water, which varies seasonally. The seasonal effect of algae and the turbidity of the raw water are the main parameters to consider.

The quality of the raw water depends greatly on the level of the dam. Lower dam levels cause the pipeline tap off point to be near the algae and silt, located closer to the bottom of the dam. The quality of the raw water is completely dependent upon nature. When the water is muddy, it can easily be dealt with by correct dosing of coagulants.

When the water is dirty with a high concentration of algae, the chlorine breaks down the algae, and during the sedimentation stage the algae sinks to the bottom. The sedimentation process does not completely remove the algae. The COCODAF filters are responsible for completely removing algae from the water. The filters capture any suspended particles in the filter bed.

The water, which has higher algae content, is sent to the COCODAF filters. The DAF is very effective at removing algae from the water. However, the filter bed gets clogged due to the overwhelming amount of algae still in the water. These particles block the flow of water through the filter and needs to be washed out.

The normal operation level of a COCODAF filter on WTP AA is at 80%. The level of the COCODAF filter will rise to above 83%, which indicates that the filter is clogging. When the level rises to above 85%, it means that the filter is experiencing excessive head loss and is overflowing. When the filter overflows with a high head loss, its effectiveness is compromised.

When the filter is clogged it needs to be washed also known as backwashed. Treated water from the CWR is used and pumped to the filter. During backwashing, the water flow is in the opposite direction compared to when the filter is in operation. On WTP AA water from CWR 3.1 is used to backwash the COCODAF filers. This uses a great deal of clear water, consequently the level of CWR 3.1 drops.

The backwash process can take between 30 minutes and 1 hour and 30 minutes, depending on how clogged the filter is. In extreme clogging cases the filter cannot effectively drain and the PLC aborts the backwash process completely needs to be washed in manual mode.

The level of a typical COCODAF filter is presented in Figure 63. Figure 63 presents the filter descummed (zigzag peaks on graph) periodically according to a timer. Normally the filter has a set run time, and will automatically wash when the runtime is reached. The runtime of a filter is typically between 1 200 minutes and 1 800 minutes.

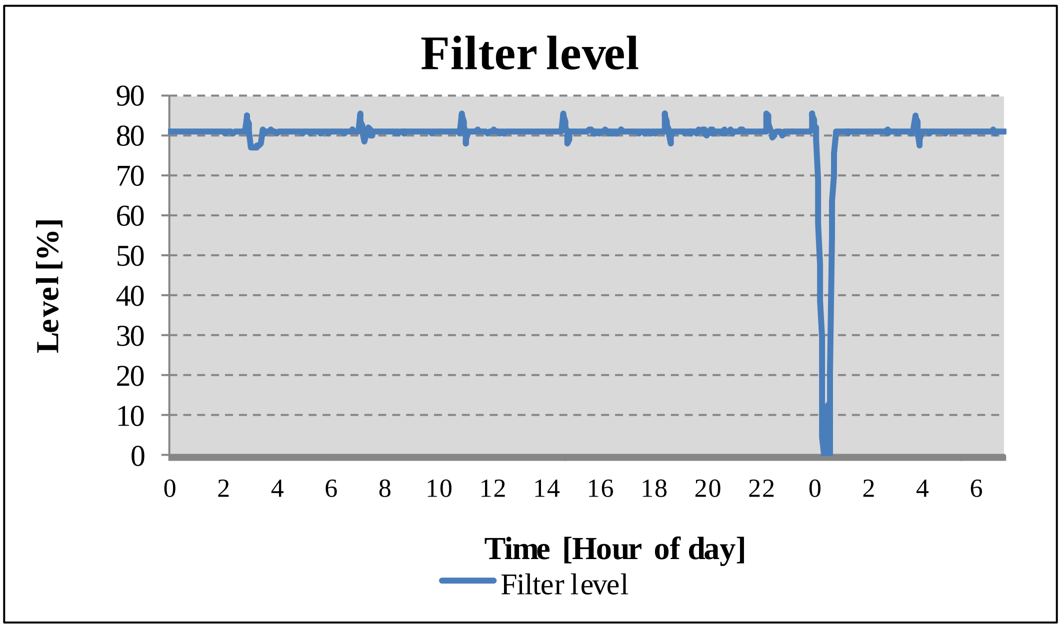

Figure 63: COCODAF filter level

To optimise the operating schedule of the plant, effective use of filter washing and descuming must be accomplished. It was found that the treatment plant cannot supply enough water to constantly operate four pumps. If the filters do not effectively filter the water at a high rate the CWRs can be emptied when four pumps are operated.

The COCODAF filters were found to be the "bottleneck" of the treatment plant. When the raw water quality is low, the filters are backwashed more often. The filters need to be washed to operate effectively when they are clogged. More backwashing means that the total time the filter operates, is much less. This causes much less water to be filtered daily.

The position of the filter outlet valve is important as it indicates if a filter is clogged. If the filter level rises above 83% and the valve is fully open, it is a clear indication of filter clogging. The valve position was made available on the SCADA. The operator could see the level of the filter and the positioning of the outlet valve. This ensures that operators are more aware of the status of the filters.

It also causes the filters to be operated on more effective cycles. Backwashing of filters should occur at more effective time periods due to this improvement. Effective time periods mean that filters will not operate in clogged conditions for long periods, as it will be washed sooner. The filters can also be washed during peak periods to reduce the level of CWR 3.2.

It was found that the backwash cycle of the filter could be improved. A typical backwash cycle of an unclogged filter is presented in Figure 64 and presented in Figure 65 is a typical cycle of a clogged filter. Presented in the two figures that follow are the level of the COCODAF filter and the percentage the outlet valve is open. It is clear from these two figures that a clogged filter takes longer to backwash when compared with an unclogged filter.

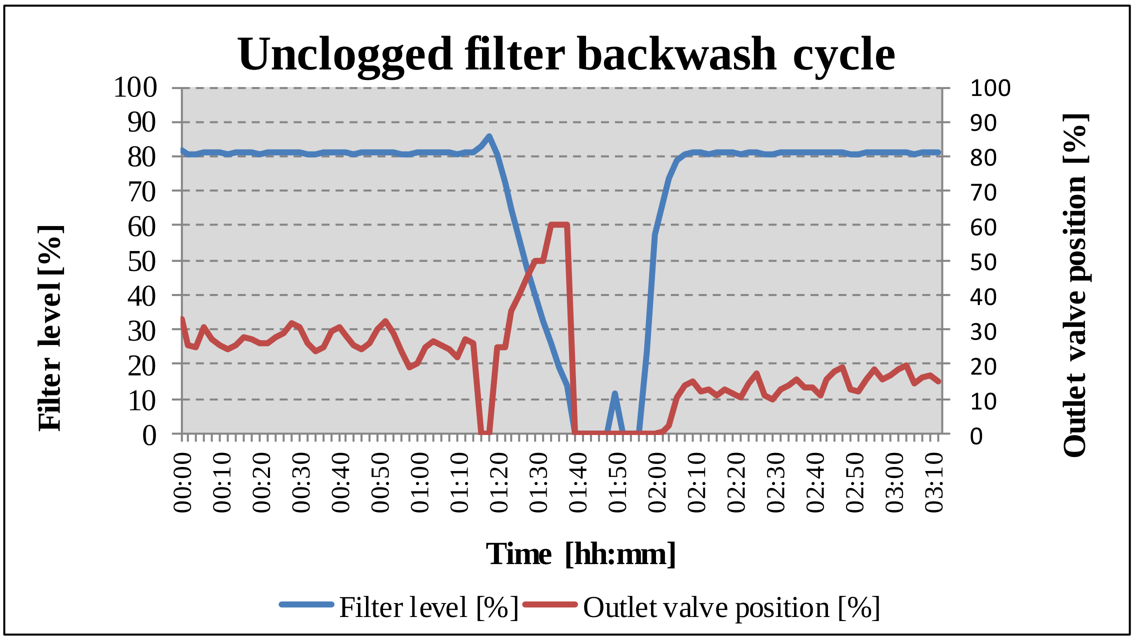

Figure 64: An unclogged filter backwash cycle

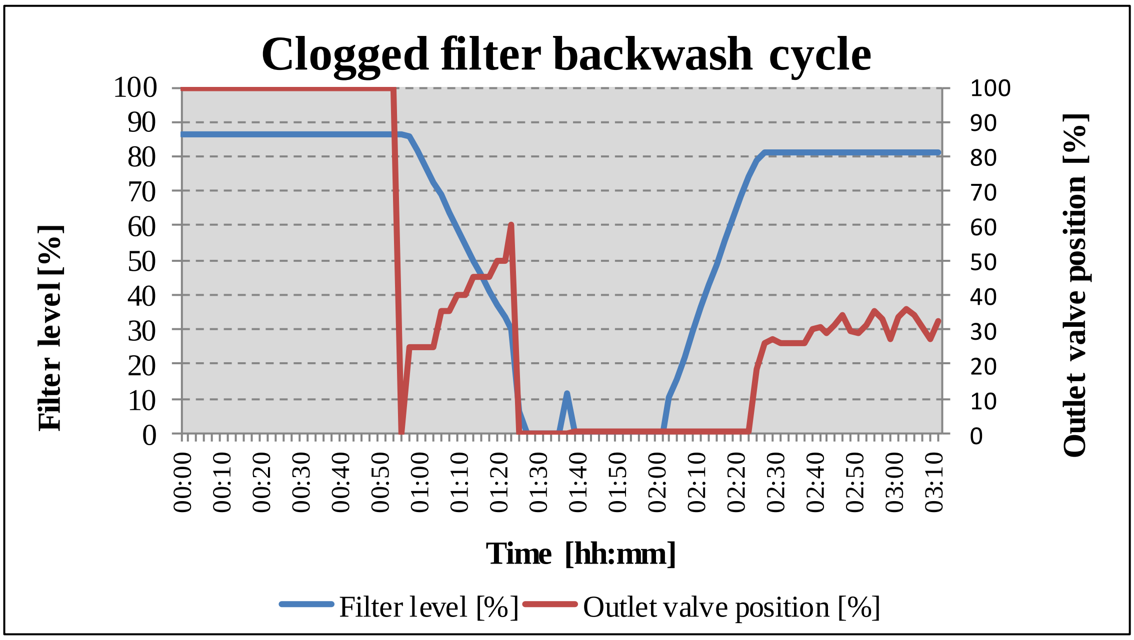

Figure 65: A clogged filter backwash cycle

As mentioned previously, an easy way to see when a COCODAF filter is clogged is to look at the level of the filter. If the level of the filter is above 83% and the valve position is at fully open, the filter is clogged. In Figure 64 (unclogged filter) it can be seen that the level is at 80%. The valve is not fully open and still controlling the flow out of the filter. In Figure 65 the figure presents a clogged filter. The level is 85% and valve is fully open. It is also evident that the clogged filter has a more timeous wash cycle.

The suspended particles, which were floated to the top by the dissolved air blanket, are called the scum. When the filter starts to backwash the outlet valve, which is automatically controlled, closes. The filter firstly descums. The level of the filter is raised until it overflows, see Figure 64. The floating scum overflows the side of the filter along with water. The filter then starts to drain.

To drain the filter, the outlet valve slowly starts to open. The valve opens to 25% initially and then slowly uses a ramp function to open incrementally to a maximum of 60%. The filter drains until the filter is nearly empty (5%). The next steps are the backwash process. This process will not be discussed in more detail. The backwash process is operated by a PLC. The PLC automatically starts all the procedures involved in the backwash process.

The draining of the filter is a time-consuming process. Room for improvement was observed to optimise the draining stage of the backwash cycle. The improvements that were done concentrated on draining the filter faster. If the filter is able to be drained in less time, the filter will be in service for longer. This will ensure that more water is filtered daily. This effectively increases the capacity of the plant.

Figure 66 depicts what was done to improve the control of the filter outlet valve, the control that was used previously and the improved control. The drain cycle was improved by increasing the percentage the valve opens when it starts to drain. The PLC will open the valve to a set value as soon as the draining process starts. In Figure 66 the valve was set to open to 80%. This will allow the filter to drain much faster.

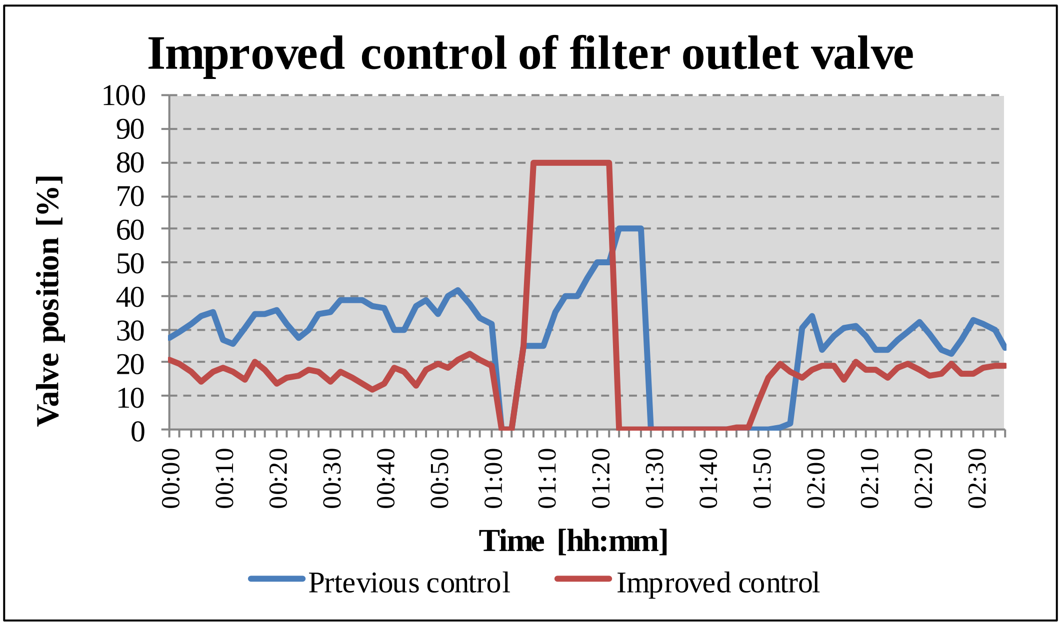

Figure 66: Valve position for filter outlet valve control

There is another method to drain the filter. This is done by opening the dump valve of the filter. All the water inside the filter is discarded and is sent to the sludge dams. This means that plant losses are high and thus it is not a cost effective approach. It is mostly done when a filter is extremely clogged and does not drain during the autodrain cycle.

4.4.2 COCODAF filters improvements

The valve operation was optimised by opening the valve to a value that could be set by the operator on the SCADA. The valve opened immediately to this value, when the filter started to drain. During the implementation the operators only opened the valve to a maximum of 80%. Figure 66 in section 4.4.1 clearly depicts how this was done.

During the implementation of these changes, the necessary parameters were logged. This aided in determining if the efficiency of a backwash cycle was improved. The parameters that were logged were the filter level, the valve position and the time between readings. This was sufficient to determine the time it took for a filter to complete a backwash cycle.

Figure 67 below presents a typical backwash cycle prior to and after the changes had been implemented. It can be seen that the draining time is the only part of the cycle that has been improved. The rest of the backwash cycle uses approximately the same time. It is important to note that in both wash cycles, presented below, the filter was not clogged (level below 85%).

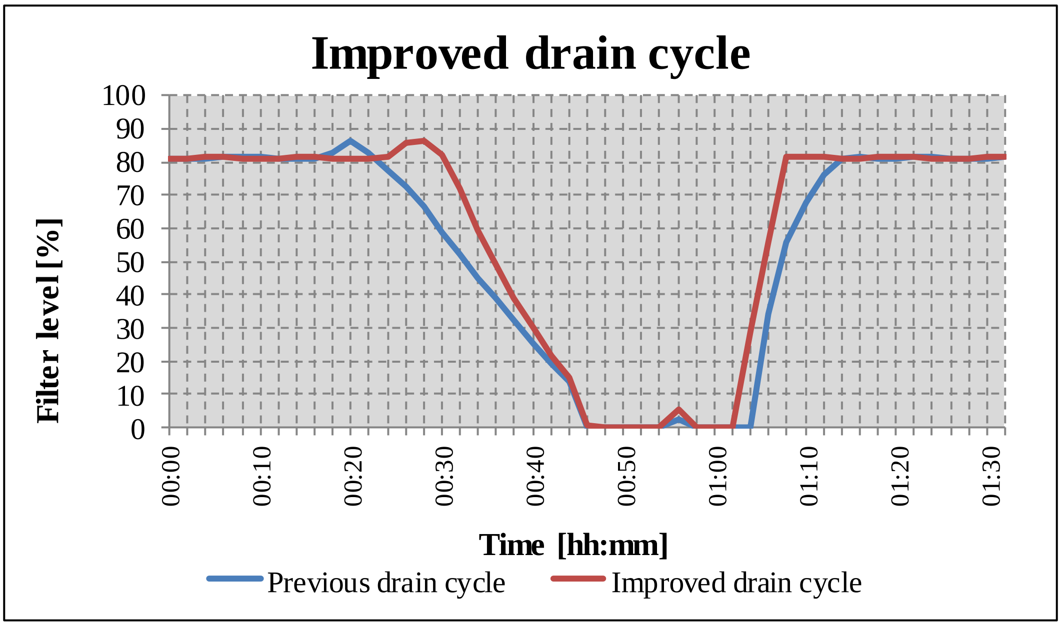

Figure 67: Improved filter drain cycle

The average of approximately 300 backwash cycles was used to calculate the effectiveness of the changes. The drain time is calculated by calculating the time it takes the level of the filter to drop from 80% to 15%. Table 14 presents the results obtained.

Table 14: Filter improvement

	Average draining time [hh:mm:ss]
Previous method	00:38:44
Improved method	00:25:35
Difference	00:13:09

According to the calculations, the filters performed much better in the draining part of the cycle. The draining time of a filter was improved by an average of 13 minutes and 9 seconds. This means that the filter will be operational for 13:09 [mm:ss] longer than previously. The filter backwash cycle efficiency improved by almost 34%.

To put this into perspective: One filter washes 13:09 [mm:ss] faster than usual, implying that it is operational for the same period longer. Assuming the run time of a filter remains the same and is 1440 minutes (24 hours). WTP AA utilise 6 COCODAF filters. This implies that the filters will be operational for 01:15:56 [hh:mm:ss] longer in a 24-hour cycle.

Previously the HLPS 3 pumps were able to supply approximately 72.5 Mℓ/day to the customers. With the filter being operational for 01:15:56 [hh:mm:ss] longer on a daily basis, the filters will in theory be able to supply 76.32 Mℓ/day. This is an improvement of more than 5% on a daily basis.

4.5 Potential for further cost savings

A cost comparison was done to determine whether it would be financially beneficial for WTP AA to migrate to a ToU dependent electricity tariff. WTP AA makes use of the urban Nightsave tariff which was discussed in section 1.3.2. The Megaflex and urban Nightsave tariffs were compared.

The power consumption data for HLPS 3 was used from the 1st of August (start of performance assessment) to 31st of December. The data also included October during which the performance assessment was abandoned, as previously explained. The data also included the condonable days, during which no load was shifted due to various reasons. The average weekday profile is presented in Figure 68. The average evening peak period impact achieved during these five months is 2.14 MW.

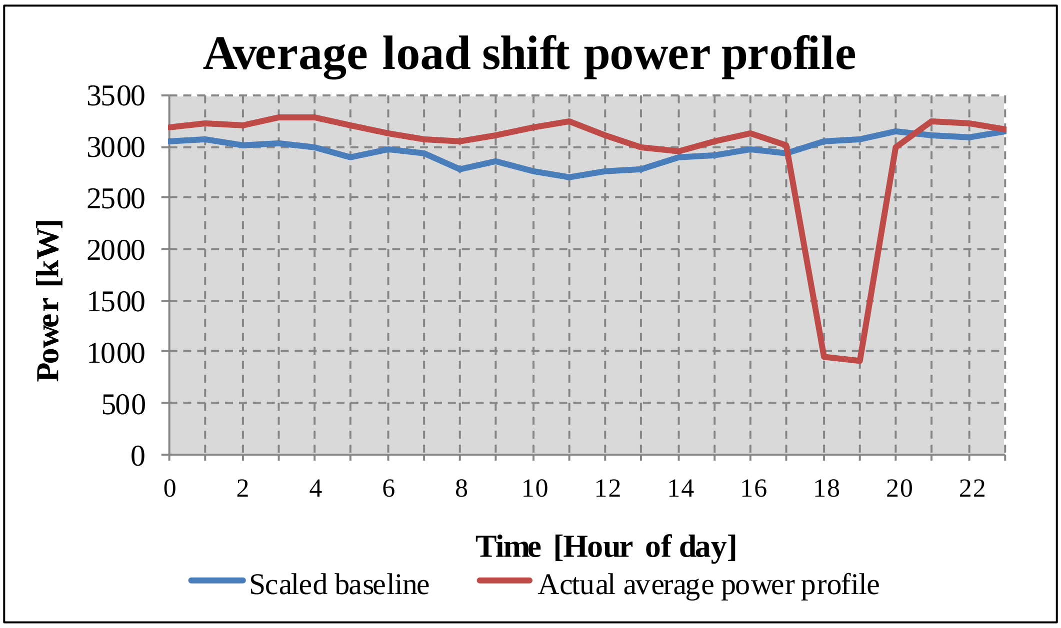

Figure 68: Performance from Aug – Dec

The tariffs for each structure are presented in Table 15. It is important to note the difference in cost between the Megaflex peak periods and off-peak periods, especially during the high demand season. During the high demand season (Jun – Aug) the peak tariff is 210c/kWh, while off-peak is only 34c/kWh. Also note how the low demand season (summer) tariffs differ from the high demand season (winter) tariffs.

Table 15: Electricity tariffs 2014/2015

Winter tariffs	Megaflex Tariff [c/kWh]	Nightsave Tariff [c/kWh]
Off-peak	34.64	47.84
Standard	63.78	47.84
Peak	210.56	47.84

Summer tariffs	Megaflex Tariff [c/kWh]	Nightsave Tariff [c/kWh]
Off-peak	29.99	37.34
Standard	47.27	37.34
Peak	68.69	37.34

To do the calculations some assumptions were made. These assumptions were necessary due to the fact that the power meters could not measure and log all the necessary information for

HLPS 3 separately. A power factor of 0.93 was assumed and used to calculate the kVA from the kW data. The kVAr is not measured for Plant 3 separately; this was calculated from the kW and kVA data.

The cost comparison only took into account the active energy charges. Distribution network charges, administration charges, service charges, electrification and rural network subsidy charges and affordability subsidy charges were excluded. These charges are the same for both tariffs and will not contribute to the comparison.

An average profile was created which summarised all the data of the five months. This profile was used to calculate the average cost of a month (30 days). The annual cost consists of three months of high demand (winter) and nine months of low demand (summer). Table 16 presents the results of the cost comparison.

Table 16: Results of cost comparison

WINTER TARIFF	Megaflex Actual	Night save Actual
TOTAL Daily cost	R 46 740	R 53 107
TOTAL Monthly cost	R 1 402 185	R 1 593 218
Monthly Saving	**R 191 033**	

SUMMER TARIFF	Megaflex Actual	Night save Actual
TOTAL Daily cost	R 29 203	R 30 746
TOTAL Monthly cost	R 876 075	R 922 370
Monthly Saving	**R 46 295**	

TOTAL Annual Saving	**R 989 754**

Average Saving (kW)	**2138**

With an average evening peak impact, the plant is able to save approximately R 990 000 per annum. The effect on the active energy costs if no load shift occurred was also investigated. Switching from one tariff structure to another may imply additional administrative charges which were not investigated.

Finally, it is important to regularly ensure that the tariff structure, which is currently utilised, is the most beneficial for the site. Tariff price increases and changing operational schedules can cause a tariff to not be the most beneficial, and it might be advantageous to migrate to a different tariff.

4.6 Conclusion

In Chapter 4 the results of the performance assessment were discussed. The success of the study is determined by these results. An average evening peak period load shift of 2.21 MW was achieved. Compared to the proposed impact of 2.17 MW, the study achieved an overperformance of 2%. These results prove the study to be successful.

The result of the improved COCODAF filter outlet valve control was discussed. The improved valve control enabled the capacity of the plant to effectively be increased by 5%. The backwash cycle was reduced by more than 13 minutes per filter on average. Impacts of the DSM initiative were discussed. These impacts included incidents that prevented the plant from achieving the full load shift impact. Hidden benefits of DSM initiatives were discussed.

A cost analysis was conducted to determine the feasibility of migrating to a ToU dependent tariff structure. It was found that significant cost savings could be achieved. An annual cost saving of almost R 1-million could be achievable.

5

CONCLUSION AND RECOMMENDATIONS

Chapter 5:

Chapter 5 concludes the study and briefly provides recommendations for further investigation.

5 Conclusion and recommendations

5.1 Conclusion

Water distribution systems are important to the South African economy, supplying both raw and potable water to various sectors. These water distribution systems transfer water over long distances with high flow rates and high pressures. Subsequently the power consumption of these systems is high. South Africa's electricity demand is increasing to the point where it is nearing the maximum supply capacity.

It has become important for large energy consumers to manage their consumption. Load management has been very successfully implemented in mine dewatering systems, as well as raw water pumping systems. The strategies which have been developed for these DSM initiatives can be used for load management in other pumping systems.

Sufficient proof was found that load management on municipal WTPs is plausible and a viable method to reduce production costs. By effectively shifting operation of energy intensive equipment out of the peak periods, substantial cost savings can be achieved. The need for an EMS was identified to control the operating schedule of the pumping system. Energy efficiency measures to reduce the overall production costs were briefly discussed.

A WTP has been identified as an ideal candidate for a DSM initiative; more specifically load shifting. The system has pumps which deliver sufficient flow to accommodate the comeback load and sufficient storage capacity in the reservoirs. The treatment process and functionality of equipment installed on typical WTPs was investigated to better understand the water treatment environment.

A detailed investigation was conducted on WTP AA to determine the operating constraints and system variables. Various elements which are important to consider when attempting a load shift initiative, was discussed. Loggers were installed to determine a power consumption baseline of WTP AA. The data was used to calculate a proposed evening peak period load shift impact of 2.17 MW.

The pumping system was simulated and an average evening peak period load shift impact of 2.35 MW was found viable. To validate the proposed and simulated load shift impact an actual load shift test was carried out. The test was done over a seven day period to observe the effect of the load shift over a full operation cycle. During the five weekdays an average load shift impact of 2.13 MW was achieved.

A control philosophy was developed to achieve the load management on WTP AA. The control philosophy is used to include a load shift during the evening peak periods, while also adhering to the production and demand constraints. It is recommended that an EMS is used to automatically control the pump operations. The client was, however, hesitant to implement the strategy and it could not be utilised.

The success of the study is determined by the results of the performance assessment period. An average evening peak period load shift of 2.21 MW was achieved. Compared to the proposed impact of 2.17 MW, the study achieved an over performance of 2%. These results prove the study to be successful.

During implementation of the study algal bloom and filter clogging caused the load shift impact to be reduced. The operation of the outlet valve of the filters was improved to enable better draining when backwashing commenced. The backwash cycle was reduced by more than 13 minutes on average. The improved valve control enabled the capacity of the plant to effectively be increased by 5%.

Impacts of the DSM initiative, which included incidents that prevented the plant from achieving the full load shift impact and hidden benefits of DSM initiatives, were discussed. A cost analysis was conducted to determine the feasibility of migrating to a ToU dependent tariff structure. It was found that significant cost savings could be achieved. An annual cost saving of almost R 1-million could be achievable.

5.2 Recommendations for further research

The DSM initiative, which was implemented on WTP AA, proved to be very successful. A significant reduction in peak period demand could be achieved. It is therefore recommended that the strategies and controls be implemented on other WTPs. Each system will have its own limitations and constraints, which will need to be investigated in more detail. Significant cost savings can be achieved if these systems are utilising the Megaflex tariff structure.

It was earlier explained that the ambient conditions play a major role in the demand for water. This has an influence on the operation of the pump station, which can cause the load shift to be abandoned. It is recommended that a demand related or ambient condition scaling method be investigated. The EMS system also needs to be set up to allow different scenarios, such as high demand, when controlling a pump station.

It is highly recommended that automatic control be implemented on WTP AA. This will ensure sustainable load shifting. Migrating to a ToU dependent tariff structure will ensure a monetary saving, making the load shifting worthwhile. The EMS must continually determine the most efficient pump set to be operated, especially during peak periods. An energy efficiency component can also be achieved by implementing a leakage reduction campaign. This will ensure that water, and subsequently the energy, is not lost.

The EMS must gather data for more than a year, which can then be used for demand forecasting and further operation optimisations. The raw water quality and filter performance should be logged to gather historic data. This will enable improved dosing strategies and filter operation.

6

BIBLIOGRAPHY

Chapter 6:

Chapter 6 provides more detail regarding the references for the study.

6 Bibliography

[1] European Environment Agency, “Water use by sectors,” European Environment Agency, 2014. [Online]. Available: http://www.eea.europa.eu/themes/water/water-resources/water-use-by-sectors. [Accessed: 21 Jun. 2014].

[2] United States Geological Survey, “Estimated use of water in the United States in 2000,” United States Geological Survey, 2000. [Online]. Available: http://pubs.usgs.gov/circ/2004/circ1268/htdocs/text-in.html. [Accessed: 21 Jun. 2014].

[3] National Water Resource Strategy, “Water for an equitable and sustainable future,” Pretoria, South Africa, 2013.

[4] Department of Water Affairs (DWA), “Strategic overview of the water sector in South Africa 2010,” Pretoria, South Africa, 2010.

[5] Statistics South Africa, “General household survey: 2011,” Pretoria, South Africa, 2011.

[6] United Nations Educational Scientific and Cultural Organization (UNESCO), “Water for people: water for life,” Paris, France, 2003.

[7] A. K. Plappally and J. H. Lienhard V, “Energy requirements for water production, treatment, end use, reclamation, and disposal,” Renewable and Sustainable Energy Reviews, vol. 16, no. 7, pp. 4818–4848, Sep. 2012.

[8] J. S. Young, “Future water/wastewater issues utility perspective,” in Proceedings of the New York City Water Summit, 2010, pp. 1–31.

[9] K. James, S. L. Campbell, and C. E. Godlobe, “Watergy: taking advantage of untapped energy and water efficiency opportunities in municipal water systems,” Washington, DC, United States of America, 2002.

[10] R. Wilkinson, G. Wolff, W. Kost, and R. Schwom, “An analysis of the energy intensity of water in California: Providing a basis for quantification of energy savings from water

system improvements," ACEEE Summer Study on Energy Efficiency in Buildings, vol. 12, pp. 123–133, 2006.

[11] Magalies Water, "Magalies Water: Annual report 2013," Rustenburg, South Africa, 2013.

[12] A. Arpke and N. Hutzler, "Domestic water use in the United States.," Journal of Industrial Ecology, vol. 10, no. 1–2, pp. 169–184, 2006.

[13] M. R. N. Vilanova and J. A. P. Balestieri, "Energy and hydraulic efficiency in conventional water supply systems," Renewable and Sustainable Energy Reviews, vol. 30, pp. 701–714, Feb. 2014.

[14] Eskom Holdings Limited, "Integrated report 2011," Megawatt Park, Sunninghill, Johannesburg, South Africa, 2011.

[15] M. Kleingeld, N. De Kock, and E. H. Mathews, "Real benefits of DSM projects on mines," Industrial & Commercial Use of Energy (ICUE), 2007.

[16] A. Botha, "Optimising the demand of a mine water reticulation system to reduce electricity consumption," Master's dissertation, Department of Electrical Engineering, North-West University: Potchefstroom Campus, 2010.

[17] G. Murray, "Energy and cost modelling of water reticulation systems in deep-level gold mines," Master's thesis, Department of Electrical Engineering, University of Pretoria, 2000.

[18] J. Vosloo, L. Liebenberg, and D. Velleman, "Case study: Energy savings for a deep-mine water reticulation system," Applied Energy, vol. 92, pp. 328–335, Apr. 2012.

[19] Department of Water Affairs (DWA), "Strategic overview of the water sector in South Africa," Pretoria, South Africa, 2013.

[20] Council for Scientific and Industrial Research (CSIR), "A CSIR perspective on water in South Africa 2010," Pretoria, South Africa, 2010.

[21] A. Nortje, “DSM strategy for national water pumping systems,” Master’s dissertation, Department of Mechanical Engineering, North-West University: Potchefstroom Campus, 2012.

[22] United States Environmental Protection Agency, “Primer for municipal wastewater treatment systems,” Washington, DC, United States of America, 2004.

[23] U.S. Energy Information Administration, “Independent statistics and analysis: South African energy overview.” [Online]. Available: http://www.eia.gov/countries/cab.cfm?fips=SF#note. [Accessed: 10 May 2014].

[24] Eskom Holdings Limited, “Fact sheet: Generation plant mix,” Megawatt Park, Sunninghill, Johannesburg, South Africa, 2012.

[25] Eskom Holdings Limited, “Integrated results for the year ended 31 March 2014,” Megawatt Park, Sunninghill, Johannesburg, South Africa, 2014.

[26] R. Cleetus, S. Clemmer, E. Davis, J. Deyette, J. Downing, and S. Frenkel, “Ripe for retirement: The case for closing America’s costliest coal plants,” Cambridge, MA, United States of America, 2012.

[27] Eskom Holdings Limited, “Integrated results presentation for the year ended 31 March 2013,” Megawatt Park, Sunninghill, Johannesburg, South Africa, 2013.

[28] K. Crowley, P. Burkhardt, and A. Janse van Vuuren, “Eskom says South Africa power pinch may run to month-end,” Bloomberg, Johannesburg, South Africa, 20 Nov. 2013.

[29] South African Press Association (SAPA), “Eskom declares power emergency, possible blackouts,” Mail & Guardian, Sunninghill, Johannesburg, South Africa, 06 Mar. 2014.

[30] South African Press Association (SAPA), “Eskom declares electricity emergency,” Times Live, Sunninghill, Johannesburg, South Africa, 20 Feb. 2014.

[31] L. Ensor, “Maintenance will not result in load-shedding, says Eskom,” Business Day Live, Cape Town, South Africa, 10 Jan. 2014.

[32] J. T. Cousins, “Using Time Of Use (ToU) tariffs in industrial , commercial and residential applications effectively,” Bryanston, Johannesburg, South Africa, 2008.

[33] J. Vosloo, “A new minimum cost model for water reticulation systems on deep level mines,” Doctoral thesis, Department of Electrical Engineering, North-West University: Potchefstroom Campus, 2008.

[34] L. F. van der Zee, “Modelling of electricity cost risks and opportunities in the gold mining industry,” Doctoral thesis, Department of Electrical Engineering, North-West University: Potchefstroom Campus, 2013.

[35] Eskom Holdings Limited, “Schedule of standard prices for Eskom tariffs 1 April 2014 to 31 March 2015 for non-local authority supplies, and 1 July 2014 to 31 June 2015 for local authority supplies,” Megawatt Park, Sunninghill, Johannesburg, South Africa, 2014.

[36] Eskom Holdings Limited, “Integrated demand management,” Eskom Holdings Limited, 2014. [Online]. Available: http://www.eskom.co.za/CustomerCare/IDM/Pages/IDM.aspx. [Accessed: 15 Jul. 2014].

[37] Energy Services Companies Cape Town, “About energy services companies,” Energy Services Companies Cape Town, 2014. [Online]. Available: http://www.escos.co.za/index.php/about/overview. [Accessed: 21 Jul. 2014].

[38] A. J. Schutte, “Demand-side energy management of a cascade mine surface refrigeration system,” Master’s dissertation, Department of Mechanical Engineering, North-West University: Potchefstroom Campus, 2007.

[39] R. Pelzer, E. H. Mathews, D. F. le Roux, and M. Kleingeld, “A new approach to ensure successful implementation of sustainable demand side management (DSM) in South African mines,” Energy, vol. 33, no. 8, pp. 1254–1263, Aug. 2008.

[40] Wikipedia, “Industrial control system,” Wikipedia, 2014. [Online]. Available: http://en.wikipedia.org/wiki/Industrial_control_system. [Accessed: 29 Jun. 2014].

[41] K. Stouffer, K. Scarfone, and J. Falco, “Guide to Industrial Control Systems (ICS) security,” Gaithersburg, MD, United States of America, 2011.

[42] B. Galloway and G. Hancke, “Introduction to industrial control networks,” IEEE: Communications Surveys & Tutorials, vol. 15, no. 2, pp. 860–880, 2013.

[43] Advanced Micro Controls Inc., “What is a Programmable Logic Controller (PLC)?,” Advanced Micro Controls Inc., 2014. [Online]. Available: http://www.amci.com/tutorials/tutorials-what-is-programmable-logic-controller.asp. [Accessed: 29 Jun. 2014].

[44] D. Roberts, D. Kubel, A. Carrie, D. Schoeder, and C. Sorensen, “Costs and benefits of complete water treatment plant automation,” Denver, CO and Washington, DC, United States of America, 2008.

[45] F. Schutte, Handbook for the Operation of Water Treatment Works, 1st ed. Pretoria, South Africa: The Water Research Commission, 2006, pp. 3–24.

[46] Wikipedia, “Water purification,” Wikipedia, 2014. [Online]. Available: http://en.wikipedia.org/wiki/Water_purification. [Accessed: 25May. 2014].

[47] Magalies Water, “Water purification process,” Magalies Water: Vaalkop, 2009. [Online]. Available: http://www.magalieswater.co.za/index.php?option=com_content&view=article&id=7&Itemid=64. [Accessed: 25 May. 2014].

[48] B. Oram, “Ozonation in water treatment,” Water Research Center, 2012. [Online]. Available: http://www.water-research.net/ozone.htm. [Accessed: 06 Jun. 2014].

[49] IWA Water Wiki, “Coagulation and flocculation in water and wastewater treatment,” IWA Water Wiki: Information resource and hub for the global water community, 2010. [Online]. Available: http://www.iwawaterwiki.org/xwiki/bin/view/Articles/CoagulationandFlocculationinWaterandWastewaterTreatment. [Accessed: 28 Aug. 2014].

[50] Acquabella, “Coagulation and flocculation process fundamentals,” Chesterfield, NJ, United States of America, 2006.

[51] TutorVista.com, "Flocculation," TutorVista.com, 2014. [Online]. Available: http://chemistry.tutorvista.com/physical-chemistry/flocculation.html. [Accessed: 07 Jun. 2014].

[52] J. Freschi, "Bollman water treatment plant sedimentation basins," Contra Costa Water District, 2014. [Online]. Available: http://www.ccwater.com/photopages/. [Accessed: 06 Oct. 2014].

[53] "Safe drinking water is essential," National Academy of Sciences, 2008. [Online]. Available: http://www.drinking-water.org/html/en/index.html. [Accessed: 06 Jun. 2014].

[54] Ecologix, "Dissolved air flotation systems," Ecologix: Environmental Systems, 2014. [Online]. Available: http://www.ecologixsystems.com/system-dissolved-air-flotation.php. [Accessed: 06 Jun. 2014].

[55] OVIVO, "Dissolved air flotation," OVIVO, 2012. [Online]. Available: http://www.ovivowater.com/en/DissolvedAirFlotation. [Accessed: 06 Jun. 2014].

[56] Council for Scientific and Industrial Research (CSIR), "Chapter 9: Water supply," in Guidelines for Human Settlement Planning and Design, 2nd ed., Pretoria, South Africa: Council for Scientific and Industrial Research Building and Construction Technology, 2005, pp. 9.1–9.40.

[57] A. Vaccaro, "Water treatment," MyNewCastle.org, 2013. [Online]. Available: http://www.mynewcastle.org/index.php/departments/dept-of-public-works/101-water-treatment. [Accessed: 07 Jun. 2014].

[58] C. C. Ross, G. E. Valentine, J. B. M. Smith, and P. E. J. P. Pierce, "Recent advances and applications of dissolved air flotation for industrial pretreatment," Environmental Treatment Systems Inc., 2012. [Online]. Available: http://www.etsenvironmental.com/white-papers/recent-advances. [Accessed: 07 Jun. 2014].

[59] United States Environmental Protection Agency, "Technologies for upgrading existing or new drinking water treatment facilities," Cincinnati, OH, United States of America, 1990.

[60] E. Fewster and A. Mol, “Sand filtration: Rapid versus slow,” Biosand filter, 2004. [Online]. Available: http://www.biosandfilter.org/biosandfilter/index.php/item/316. [Accessed: 08 Jun. 2014].

[61] Wikipedia, “Rapid sand filter,” Wikipedia, 2014. [Online]. Available: http://en.wikipedia.org/wiki/Rapid_sand_filter. [Accessed: 08 Jun. 2014].

[62] J. Haarhoff, S. J. van Staden, J. Geldenhuys, M. Sibiya, P. Naicker, and N. Adam, “Assessments and improvement of filter media cleanliness in rapid gravity sand filters,” Johannesburg, South Africa, 2008.

[63] Michigan Tech., “Drinking water treatment: Filtration,” Michigan Environmental Education Curriculum. [Online]. Available: http://techalive.mtu.edu/meec/module03/Sources-Groundwater.htm. [Accessed: 07 Jun. 2014].

[64] J. Officer, J. A. Ostrowski, and P. J. Woollard, “The design and operation of conventional and novel flotation systems on a number of impounded water types,” Water Science and Technology: Water Supply, vol. 1, no. 1, pp. 63–70, 2001.

[65] EddieWaste, “Treating seasonal algal blooms,” EddieWaste, 1999. [Online]. Available: http://www.edie.net/library/view_article.asp?id=1815. [Accessed: 02 Sep. 2014].

[66] F. Kolbé and L. Meyer, “The first COCO DAFF waterworks in South Africa,” Civil Engineering/Siviele Ingenieurswese, vol. 6, no. 7, pp. 15–16, 1998.

[67] M. Rust and K. McArthur, “Slow sand filtration,” Water Treatment Primer, 1998. [Online]. Available: http://www.elaguapotable.com/WT - Slow Sand Filtration.htm. [Accessed: 11 Jun. 2014].

[68] L. Huisman and W. E. Wood, “Slow sand filtration,” Geneva, Switzerland, 1974.

[69] A. Ludwig, “Slow sand filtration,” Oasis Design, 1997. [Online]. Available: http://oasisdesign.net/water/treatment/slowsandfilter.htm. [Accessed: 11 Jun. 2014].

[70] Lenntech, "Membrane technology," Lenntech: Water Treatment Solution, 2014. [Online]. Available: http://www.lenntech.com/membrane-technology.htm. [Accessed: 13 Jun. 2014].

[71] Koch Membrane Systems, "Membrane filtration technology: Meeting today's water treatment challenges," Wilmington, MA, United States of America, 2013.

[72] Wikipedia, "Waterborne diseases," Wikipedia, 2014. [Online]. Available: http://en.wikipedia.org/wiki/Waterborne_diseases. [Accessed: 13 Jun. 2014].

[73] Lenntech, "Water disinfection," Lenntech: Water Treatment Solution, 2014. [Online]. Available: http://www.lenntech.com/processes/disinfection/what-is-water-disinfection.htm. [Accessed: 13 Jun. 2014].

[74] H. E. Hickery, "Water supply systems and evaluation methods," Washington, DC, United States of America, 2008.

[75] United States Environmental Protection Agency, "Distribution systems research," United States Environmental Protection Agency, 2013. [Online]. Available: http://www.epa.gov/nrmrl/wswrd/dw/dsr.html. [Accessed: 02 Jul. 2014].

[76] J. P. Guyer, "Introduction to pumping stations for water supply systems," El Macero, CA, United States of America, 2012.

[77] C. B. Jacobsen, "The centrifugal pump," Bjerringbro, Denmark, 2008.

[78] J. Evans, "Pump Ed 101: Centrifugal pump dynamics," Rhododendron, OR, United States of America, 2005.

[79] A. Kalmegh and S. Bhaskar, "Dynamic balancing of centrifugal pump impeller," International Journal of Emerging Technology and Advanced Engineering, vol. 2, no. 6, pp. 1–5, 2012.

[80] Engineers Edge, "Multi-stage centrifugal pump," Engineers Edge: Solutions by Design, 2014. [Online]. Available: http://www.engineersedge.com/pumps/multi_stage_pump.htm. [Accessed: 22 Jul. 2014].

[81] E. Butts, “Vertical turbine pumps: Fundamentals,” Water Well Journal, vol. 1, pp. 55–58, 2003.

[82] Goulds: Water Technology, “Vertical turbine pumps,” Lubbock, TX, United States of America, 2012.

[83] The Engineering ToolBox, “Pumps in parallel or serial connection,” The Engineering ToolBox, 2014. [Online]. Available: http://www.engineeringtoolbox.com/pumps-parallel-serial-d_636.html. [Accessed: 22 Jul. 2014].

[84] CheCalc, “Pump pperation series & parallel,” CheCalc, 2014. [Online]. Available: http://checalc.com/solved/pumpOp.html. [Accessed: 22 Jul. 2014].

[85] I. J. Karassik, J. P. Messina, P. Cooper, and C. C. Heald, “Chapter 6: Pump drives,” in Pump Handbook, 3rd ed., D. Fogarty, Ed. New York, NY: McGraw-Hill, 2001, pp. 6.1–6.35.

[86] CTi Automation, “Modern electrical motors,” CTi Automation, 2011. [Online]. Available: http://www.ctiautomation.net/About-Motors.htm. [Accessed: 23 Jul. 2013].

[87] A. T. Sayers, Hydraulic and Compressible Flow Turbomachines, 1st ed. Cape Town, South Africa: British Library Cataloguing in Publication Data, 1990, pp. 53–56.

[88] J. Anspach, “Solving a cavitation problem,” John Anspach Consulting, 2011. [Online]. Available: http://jacpump.wordpress.com/articles/. [Accessed: 23 Jul. 2014].

[89] Wikipedia, “Venturi effect,” Wikipedia, 2014. [Online]. Available: http://en.wikipedia.org/wiki/Venturi_effect. [Accessed: 24 Jul. 2014].

[90] J. Monsen, “Liquid flow in control valves: Choked flow, cavitation and flashing,” Valin Corporation, 2013. [Online]. Available: http://www.valin.com/blog/14-fluid-management-/305-liquid-flow-in-control-valves-choked-flow-cavitation-and-flashing. [Accessed: 24 Jul. 2014].

[91] M. Kay, Practical Hydraulics, 2nd ed. New York, NY: Taylor & Francis Group, 2008, pp. 118–122.

[92] Cycle Stop Valves, “Water hammer,” Cycle Stop Valves, 1994. [Online]. Available: http://www.cyclestopvalves.com/csvtechinfo_10.html. [Accessed: 24 Jul. 2014].

[93] B. Coelho and A. Andrade-Campos, “Efficiency achievement in water supply systems: A review,” Renewable and Sustainable Energy Reviews, vol. 30, pp. 59–84, Feb. 2014.

[94] M. Kleingeld, E. Mathews, and D. Krueger, “An overview of eight successful DSM projects on the clear water pumps of South African gold mines,” Industrial & Commercial Use of Energy (ICUE), 2006.

[95] N. De Kock, “Researching the long-term impact of load management projects on South African Mines,” Master’s dissertation, Department of Electrical Engineering, North-West University: Potchefstroom Campus, 2006.

[96] D. F. le Roux, “A New approach to ensure successful implementation and sustainable DSM in RSA mines,” Doctoral thesis, Department of Mechanical Engineering, North-West University: Potchefstroom Campus, 2005.

[97] S. Bunn and L. Reynolds, “The energy-efficiency benefits of pump-scheduling optimization for potable water supplies,” IBM Journal of Research and Development, vol. 53, no. 3, pp. 1–13, 2009.

[98] Derceto Aquadapt, “Overview of aquadapt software for water distribution,” Derceto, 2014. [Online]. Available: http://www.derceto.com/Products-Services/Derceto-Aquadapt/About-Derceto-Aquadapt. [Accessed: 11 Aug. 2014].

[99] Derceto, “Eastern municipal water district,” San Francisco, CA, United States of America, 2006.

[100] Y. Tang, G. Zheng, and S. Zhang, “Optimal control approaches of pumping stations to achieve energy efficiency and load shifting,” International Journal of Electrical Power & Energy Systems, vol. 55, pp. 572–580, Feb. 2014.

[101] K. E. Lansey and K. Awumah, “Optimal pump operations considering pump switches,” Journal of Water Resources Planning and Management, vol. 120, no. 1, pp. 17–35, 1994.

[102] G. McCormick and R. S. Powell, "Optimal pump scheduling in water supply systems with maximum demand charges," Journal of Water Resources Planning and Management, vol. 129, no. 5, pp. 372–379, 2003.

[103] D. F. Moreira and H. M. Ramos, "Energy cost optimization in a water supply system case study," Journal of Energy, vol. 2013, pp. 1–9, 2013.

[104] M. P. Slade, "Electricity cost optimisation for a surface potable water pump system," Master's dissertation, Department of Electrical Engineering, North-West University: Potchefstroom Campus, 2007.

[105] R. Pelzer and M. Slade, "Electricity cost optimisation of a surface potable water pump system," Industrial & Commercial Use of Energy (ICUE), vol. 5, 2008.

[106] Council for Scientific and Industrial Research (CSIR), "Guidelines for human settlement planning and design," Pretoria, South Africa, 2005.

[107] M. Feldman, "Aspects of energy efficiency in water supply systems," in Proceedings of the 5th IWA Water Loss Reduction Specialist Conference, 2009, pp. 85–89.

[108] C. Gellings, "Program on technology innovation: electric efficiency through water supply technologies: A roadmap," Palo Alto, CA, United States of America, 2009.

[109] O. Kiselychnyk, M. Bodson, and H. Werner, "Overview of energy efficient control solutions for water supply systems," Transactions of Kremenchuk State Polytechnic University, vol. 3, no. 56, pp. 40–46, 2009.

[110] R. Mobley, "Plant engineer's handbook," in Plant Engineer's Handbook, Knoxville, TN: Butterworth Heinemann, 2001, pp. 50/867–50/888.

[111] Ministry of Urban Development: New Delhi, "Operation and maintenance of water supply systems," New Delhi, India, 2005.

[112] ABB, "Low inrush current motors help to reduce disturbances to weak supply networks," Zürich, Switzerland, 2010.

[113] EATON, “Solid-state soft start motor controller and starter,” Cleveland, OH, United States of America, 2011.

[114] Rockwell Automation, “High efficiency motor protection: An overview,” Milwaukee, WI, United States of America, 1998.

[115] Foundation for Water Research, “Toxic algal blooms in drinking water reservoirs,” Buckinghamshire, United Kingdom, 2010.

[116] L. H. Odell, “The impact of water treatment plant processes on algae and algal toxins,” Bellingham, WA, United States of America, 2012.

[117] University of Florida, “Algae,” Plant Management in Florida Waters, 2011. [Online]. Available: http://plants.ifas.ufl.edu/manage/why-manage-plants/algae. [Accessed: 02 Sep. 2014].

[118] CH2MHILL, “2013 Water system plan update,” Bellingham, WA, United States of America, 2013.

[119] CH2MHILL, “Filter-clogging algae mitigation evaluation,” Bellingham, WA, United States of America, 2012.

[120] Google, “Google Maps,” Google Maps, 2014. [Online]. Available: https://www.google.co.za/maps/@-25.3250032,27.4891198,6480m/data=!3m1!1e3?hl=en. [Accessed: 25 Jan. 2014].