THE SIMULATION, VERIFICATION AND APPLICATION OF AN UNDERGROUND PUMPING SYSTEM

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ABSTRACT

The purpose of this research project was to modify an existing software programme, QUICKControl (which was originally designed for ventilation and cooling applications in the building industry), to be applicable to mine water pumping systems. The ultimate objective was to then use this modified programme to enable energy management and control of these systems.

The existing component models in this software program, i.e. pumps, valves, flow converges and diverges, were modified for the purpose of this study, and a new model of a thermal storage dam was incorporated into the software.

The predictions made by the simulation software were verified with the actual measured data from the system's operation. Measured data such as dam levels, water flow rates and active pumps were used for verification purposes. After completion of the verification study, various energy investigations were conducted to study the potential of Demand Side Management on the system's operation.

The total pumped volume of water from the underground workings to the surface dams were verified within a 1% error compared against the actual measured data. The various dam levels were verified with errors ranging from 0.19% to 8.08%. Total energy usage of the system was verified with an error less than 5% compared to the measured energy usage of the system. The energy studies revealed the potential of shifting a load of approximately 70000kWh (out of the peak tariff periods) from the daily operation, with a maximum demand shift of 14MW over 5 hours.

The study showed that it was possible to accurately simulate the operation of the pumping systems. This simulation was then used to predict the operation of the system when specific control strategies were implemented. Results showed that these new strategies would improve plant operation as well as save the mine significant energy costs.

SAMEVATTING

Die doel van hierdie navorsingsprojek was om die bestaande sagteware program QUICKControl (wat oorspronklik vir ventilasie en verkoelingstoepassings ontwerp is), aan te pas om aangewend te word op pompstelsels van myne. Die uiteindelike doel was om dan hierdie aangepaste program te gebuik om energie bestuur en beheer van hierdie stelsels te bewerkstellig.

Die beskikbare modelle in die program is verander om aan te pas by die toepassing van hierdie studie. 'n Nuwe komponent, naamlik 'n termiese bergingsdam, is ook in die sagteware geïmplimenteer.

Die voorspellings wat gemaak is deur die simulasie program is vergelyk met werklike gemete data wat verkry is vanaf die stelsel. Gemete data soos dam vlakke, vloei tempo's en pompgebruik is gebruik. Verskeie strategiese beheertoepassings is geïmplimenteer, en die potensiaal vir Maksimum Aanvraag Bestuur op die stelsel is ondersoek.

Die totale volume water wat daagliks vanuit die myn gepomp word is geverifieer met 'n foutwaarde van 1% vergeleke met die werklike gemete waarde. Die verskeie dam vlakke van die stelsel is geverifieer met fout waardes wat strek van 0.19% tot 8.08%. Die totale energie verbruik het met minder as 5% verskil van die werklike gemete energie verbruik van die stelsel. Die energie studies het bepaal dat daar 'n las van ongeveer 70000kWh verskuif kan word vanaf die daaglikse stelsel bedryf, met 'n maksimum aanvraag skuif van 14MW wat strek oor 5 ure.

Die studie het gewys dat dit moontlik is om die bedryf van die pomp stelsel akkuraat te simuleer. Die simulasie was gebruik om die stelsel se reaskie te voorspel onderhewig aan verskeie beheer strategië. Resultate het gewys dat hierdie nuwe strategië die bedryf van toerusting sal verbeter asook geldelike besparings vir die myn sal realiseer.

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Most importantly, I want to thank the Lord for His guidance, strength and love throughout my life, and especially throughout this study.

NOMENCLATURE

ENGLISH LETTER SYMBOLS

A	- Exposed area of dam	m^2
a	- Correlation coefficients for the K_h versus K_f relation	
b	- Correlation coefficients for the η_{pump} versus K_f relation	
C	- Mass flow constant	
c	- Specific heat	J/kgK
D	- Rotor diameter	m
dP	- Static pressure rise	Pa
G	- Irradiation	W/m^2
h	- Convective heat-transfer coefficient	W/m^2K
K	- Dimensionless coefficient for pumps	
k	- The number of pumps in cascade	
$\dot{m}$	- Mass flow rate	kg/s
n	- Rotational speed of the pump	rpm
Pwr	- Power required	W
Q	- Rate of heat gain	W
R	- Unit thermal resistance	m^2K/W
T	- Temperature	K
t	- Time interval	s
U	- Overall heat-transfer coefficient	W/m^2K
V	- Volume	m^3

SUBSCRIPTS

A	- Ambient
D	- Dam water
f	- Flow
h	- Pressure head
i	- Initial
i	- Inward
j	- j = 0 to k
l	- Liquid
li	- Liquid entering at inlet
le	- Liquid leaving at outlet
motor	- Motor
o	- Outside surface
o	- Outward
p	- Constant pressure
pump	- Pump
S	- Solar air
t	- Time

GREEK LETTER SYMBOLS

α	- Absorptance	
Δ	- Change in a quantity or property	
ε	- Emittance	
η	- Efficiency	
ρ	- Mass density	kg/m^3

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CHAPTER 1

MOTIVATION FOR THIS STUDY

1. MOTIVATION FOR THIS STUDY

1.1 INTRODUCTION

The United States Department of Energy predicts that the world primary energy consumption will increase by 59% over the period 1999 to 2020 [1]. The electricity used in developing countries during the 1980s has grown by more than 11% per year and is still increasing [2].

The overall reduction of energy usage is of relevance to Africa as a whole. South Africa uses some 40% of the total electricity consumed within the continent [3]. One of the reasons for this consumption is the electrifications of 3.5 million homes since 1993, which added an additional 750MW to the system [4].

Eskom, which is by far the largest supplier of electricity in South Africa (95%) [5], plans to electrify an additional 1 750 000 homes in the near future [6]. This will place additional strain on the electricity utility and is one of the main reasons why the peak demand is expected to increase within the next 5 years [7]. This means that the peak demand will become higher than the present delivery capacity of the system. Additional required capacity is expected by 2007 if the present demand growth prevails [3], [8].

Figure 1.1 shows the total demand profile of Eskom during the winter months of 2004. Peak energy usage takes place between 07H00 and 10H00, and again between 18H00 and 20H00. Eskom is attempting to reduce the energy peak occurring in the evening through various energy saving strategies.

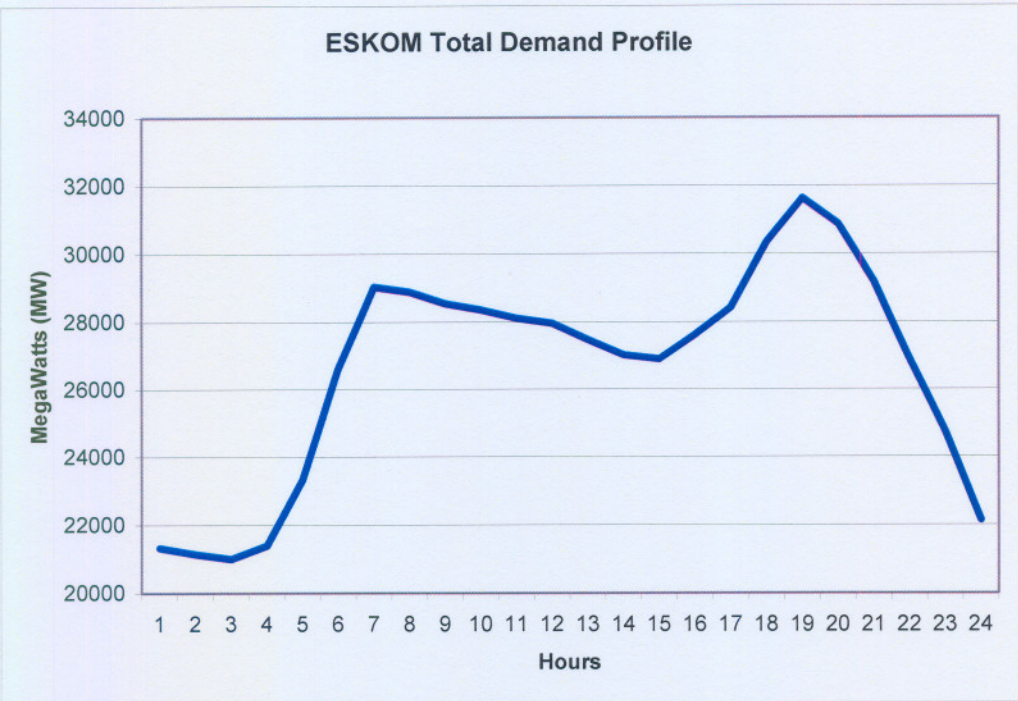


Figure 1.1 Eskom total demand profile.

In accordance to Eskom's latest planning, building a new peaking power station can take up to 7 years to build [9] at a cost of around R16 billion [10], and three years for the return of mothballed and gas-fired plants. It is therefore clear that there will be a potential peak demand shortage within the next 5 to 7 years if no corrective actions are taken soon.

As a short-term solution, Eskom has launched its Demand Side Management (DSM) initiative. The term DSM is used to describe the planning (scheduling) and implementation of activities to influence the time, pattern and amount of electricity usage in such a way that it produces a change in the load profile of the industry, while still maintaining customer satisfaction [9].

The two main areas of focus in this regard are Load Management and Energy Efficiency. It will be beneficial toward Eskom and large industries if DSM possibilities can be found in their systems.

Examples of previous ways to try and establish a successful load-shifting program were the implementation of different pricing structures. This was done to try and coax the consumers to rather use electricity during the off-peak periods when the tariffs are much lower than in the more expensive peak periods [11]. Many industries however do not effectively use these price offerings from Eskom.

One of theses pricing structures was the Real-Time Pricing (RTP) structure [12] which was introduced. The complete working and conditions as per supplier of Eskom's Real-Time Pricing billing system can be seen in reference [13]. Following is a short summary of how the RTP billing system works.

A Base Load is agreed upon between the electrical user and supplier. This Base Load is based on the historical use of the system applicable to an electrical user. The Base Load is set up to serve as a guideline from where the load shift and/or energy efficiency, and savings calculations can be done. This Base Load is a 24-hour profile of the expected MW of electricity to be used during each hour of the day.

The user is billed for this Base Load profile on a fixed c/kWh tariff. This fixed c/kWh differs for seasons and day types. The tariff is higher for the winter months, which are June, July and August. For the summer months, September to May, the tariffs are a bit lower. The same applies to the day types. The tariff rates are the highest for weekdays, lower for Saturdays and the lowest for Sundays.

The RTP price profile is updated for every day, which in turn is issued the previous day to the user. The user is billed for the deviation from the agreed Base Load. Whenever the real demand exceeds the Base Load the difference is billed according to the RTP. Whenever the real demand is lower than the agreed Base Load, the user's bill is debited according to the price of that deviation according to the RTP [14].

Another structure which is currently applicable to large energy users is the MegaFlex pricing structure. The complete working and conditions as per supplier of Eskom's MegaFlex billing system can be seen in reference [15]. Following is a short summary of how the MegaFlex billing system works.

MegaFlex is very simple and today more and more industries are utilising this pricing structure because of its simplicity. MegaFlex is widely known by the following table.

Defined Time Periods:	Weekday	Saturday	Sunday
Peak	07:00 - 10:00	N/A	N/A
	18:00 - 20:00		
	06:00 - 07:00	07:00 - 12:00	N/A
Standard	10:00 - 18:00	18:00 - 20:00	
	20:00 - 22:00		
Off-peak	22:00 - 07:00	12:00 - 18:00	Whole day
		20:00 - 07:00	

Table 1.1 MegaFlex – Demand Time Periods

The MegaFlex system divides the time of the week into three periods. These are:

1. Peak
2. Standard
3. Off-peak

Electricity is then priced according to these periods where in the peak period, electricity is most expensive and in off-peak periods the cheapest.

MegaFlex also differentiates between the different demand seasons:

1. High-demand season, which is June to August.
2. Low-demand season, which is September to May.

In table 1.2 the exact prices for each period can be seen.

High-demand season		Low-demand season
(June - August)		(September - May)
50.44c + VAT = 57.50c/kWh	Peak	15.45c + VAT = 17.61c/kWh
14.56c + VAT = 16.59c/kWh	Standard	10.23c + VAT = 11.66c/kWh
8.63c + VAT = 9.84c/kWh	Off-peak	7.72c + VAT = 8.80c/kWh

Table 1.2 MegaFlex – Tariffs according to season and demand period

The DSM provision in Eskom's current Integrated Energy Plan is for a peak load reduction target of 1.37GW by 2015. In addition, there is an interruptible supply agreement target of 1.511GW by 2007 and 0.409GW by 2015 [16]. This target is likely to change dynamically over time in response to the actual requirement for DSM in South Africa. It is also likely to change in response to the effectiveness of interruptible supply agreements.

Large and expensive equipment is needed for mining processes. Along with the capital cost, the energy usage of this equipment is very high. The mining and industry sector consumes about 40% of Eskom's total energy production. Mines alone use nearly 20% of the electricity provided by Eskom [17]. This amounts to approximately R3 000 million of electricity per annum just for the gold mines.

Mining is one of South Africa's biggest industries along with manufacturing, trade and agriculture [18]. It forms almost 20% of the gross domestic product of South Africa, with sales of R76.5 billion for 1999 [19]. Of this, gold sales were 33% of the total sales, or R24.99 billion for 1999. Platinum sales were 19.5% of the total sales, or R14.92 billion for 1999. In 2003 a total 373t of gold was produced in South Africa [20].

These prices vary with time and influence the profit margin of the mines. With the varying economy and mineral prices the need for retrieving the maximum amount of ore at the most energy efficient way has become apparent. One of the techniques employed to achieve this goal is deep-level mining with typical depths of between 3 - 5 kilometers.

For platinum, mining below 1400m will alter operations radically with the need for a lot more refrigeration and changes to the support systems [21]. For a gold mine, this crucial level is typically 3000m below the surface. At these depths the virgin rock temperature rises above the acceptable human endurance levels and special ventilation and cooling is needed [22].

This presents a difficult and potentially dangerous situation concerning the comfort and health of the workers. Satisfactory ventilation is needed, as well as a means to investigate the impact of machines in the ventilation cycle breaking or performing at lower efficiency [23].

Most mines use relatively standard ventilation and cooling layouts (see Figure 1.2). A conventional way of cooling the intake air is by placing the heat exchangers at the intake or down shaft. This is satisfactory for mines that are not too deep. When the mine becomes too deep, the air speed needed to convey the cold air to the stopes becomes too fast and uncomfortable.

For most mines these layouts consist of a surface cooling plant and an underground plant. This underground plant is typically between 1000m and 2000m below the surface. The surface plant contains the chillers or icemakers, water storage dams and cooling towers. The underground plant consists of a thermal storage dam and cooling coils or spray chambers.

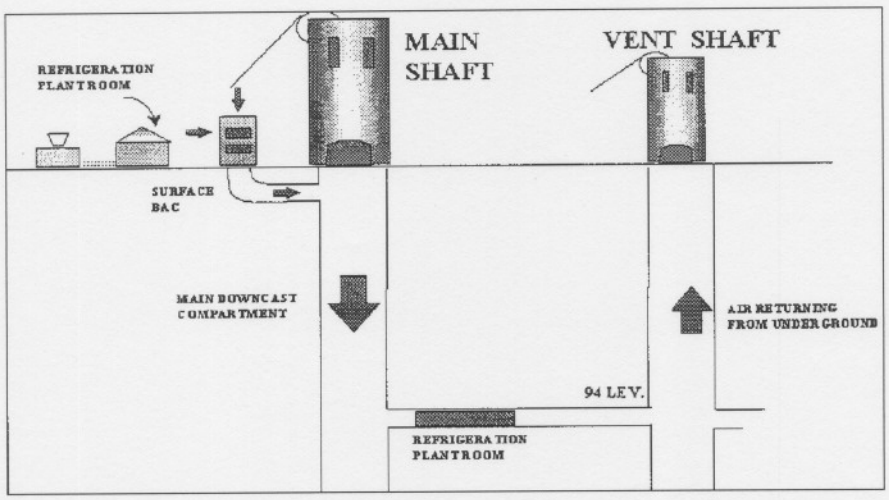


Figure 1.2 Typical layout of a mine's ventilation and cooling system.

If extra cooling is needed a further cooling plant or mobile plant can be installed below the surface. The warm intake air, heated by internal loads and the virgin rock, passes through the cooling coils or the chambers. Extraction fans, placed in the return airways, extract the warm air. Producing satisfactory cooling and ventilation for deep mines is a precise and necessary task.

The ventilation and cooling (VC) systems use approximately 25% or R750 million of this total amount of energy. The gold mines were recently in a crisis and some mines were threatening to close down. ERPM did close down in 1999. Every time the gold price drops, Eskom stands a chance of losing some of their biggest clients.

It will therefore be beneficial if the mines can be more energy clever to reduce their operating cost. Secondly, it will provide the Eskom with more DSM opportunities, e.g. energy efficiency, load shifting etc. A further benefit would be that with more efficient mining systems, the use of virtual power stations could be implemented [24].

The best, if not the only way, to effectively use the Eskom price structures without affecting operation is the better control of the VC and pumping reticulation systems for optimal use or for load shifting. However, this is difficult to predict, as a comprehensive, fully integrated, component based, dynamic simulation is needed to ensure that the safety of the miners is not compromised by any new DSM control strategy.

No such software could be found in the literature and through extensive discussions with specialists in the mining industry. Investigations into other fields of ventilation showed that such software used in large buildings, already exists. More than 50 man-years have already been invested in this software. One of these software packages is *QUICKControl.* This software has already been extensively tested and verified for building applications [25], [26].

To successfully apply this new software it needs to be modified and the results verified against actual measured data from a test mine. Such a mine was found in Placer Dome Western Areas Joint Venture, a gold mine producing about 140 kilotons a term in 2000. The average grade of the gold mined then was 6.99gm/t [27]. These values have since increased from the values above for March 2000, to 232 kilotons per term for September 2005. The average grade of gold mined was 8.34gm/t for this period [28].

The mine was divided into two sections namely the surface plant and surrounding equipment; and the underground pumping stations and dams. Mine water dams on the surface links these two systems to each other.

1.2 OBJECTIVE

The objective of this research project was to modify an existing software package (that was designed for ventilation and cooling applications in the building industry) to be used successfully in a mine pumping environment, and to test its application in a real life situation.

1.3 METHODOLOGY

- The existing software program QUICKControl designed for ventilation and cooling applications in the building industry was researched and investigated.
- The software was modified and upgraded to be applicable to mine pumping systems.
- The pumping system of a specific mine was then simulated.
- The simulation results from this modified package were then verified with actual measured operational data from the system.
- After such verification, the modified package was used to design reliable control strategies for the mine pumping system as far as energy management and cost minimisation was concerned.

1.4 BENEFICIARIES

In order to determine the value of this study the parties who will benefit the most from the work which was performed, must be identified. For the beneficiaries listed below, the criterion for a successful study is discussed, along with the manner in which the results could be implemented, and the potential impact thereof.

1. Consulting engineers

The Ventilation and Cooling of mines is a specialised engineering field and the work is usually contracted out to engineering firms with more experience in the field. Their design and installations are for static demand and is usually over designed for a dynamic system that changes its demand.

With a dynamic and integrated simulation tool it will be possible for the consulting engineers to design and install more cost effective systems. They can investigate the possibility for load shifting and other adjustments in equipment and the effect it will have in the mine's cooling and ventilation.

2. Mining companies and energy managers

To convince mining companies and energy managers to invest in, or install energy-efficient VC systems, the return must prove profitable. The prediction of energy consumption must therefore be accurate to establish the potential for energy savings of these energy-efficient options.

It is also important that there is no reduction in the comfort levels of the underground climate. This implies accurate predictions of the chilled water entering the mine by the simulation software.

3. Eskom

The postponement of the building of a new power station at a typical cost of about R16 billion can be achieved by promoting load shifting in mines nationwide. The integrated simulation tool will not only be a valuable tool but a necessity in realising load shifting and energy efficiency goals.

1.5 CONTRIBUTIONS OF THIS STUDY

The following contributions have been made by this study:

- The potential of load shifting in the pumping reticulation systems of mines have been investigated and proven possible.
- New system models have been incorporated into simulation software and some of the existing models upgraded.
- The new integrated simulation tool was extensively verified for the pumping reticulation system.
- The practical applicability of the simulation tool was successfully illustrated by means of showing the potential for load shifting.

1.6 OUTLINE OF THIS STUDY

The integrated simulation tool *QUICKControl* is presented in Chapter 2. The mathematical models incorporated into the software are briefly discussed. An overview of other software in the field of mining and building simulation is also discussed.

In Chapter 3 the various models were integrated into the new software and used for simulation purposes. Measurements were taken from the pumping reticulation system of Placer Dome Western Areas Joint Venture Gold Mine (South Deep). Measured data of the pumping reticulation system was used to verify simulated water-flows, dam levels and energy usage.

In Chapter 4 various control strategies were tested to establish the potential for load shifting. The effect of load shifting on the rest of the system parameters was also investigated.

CHAPTER 2

SIMULATION SOFTWARE AND MODELS

2. SIMULATION SOFTWARE AND MODELS

2.1 INTRODUCTION

The energy usage of the underground pumping reticulation system is dynamic and can vary over time each day. This is due to the varying operation of the underground working areas. The underground reticulation process needs to be simulated with dynamic, integrated computer software to fully investigate energy management options.

Software for dynamic, integrated simulations already exists for the same type of investigations in buildings [29], [30], and [31]. The software, named *QUICKControl,* can be adapted to mining applications because it is entirely component based. All that needs to be done is to integrate new component models specific to the mining industry, e.g. dams, with the existing software to create the new simulation model.

New, corresponding interfaces were created and the adjustments to the existing software were implemented. The simulation model was built using the component-based input interface. This simulation model represented the system according to the specifications of the actual system.

2.2 EXISTING SOFTWARE

Having found the need for a dynamic, integrated simulation software package that could investigate and solve pumping reticulation systems of mines on a component level, different software was evaluated. A short study into the available software in the mining industry was conducted.

The most commonly used simulation software in the mining industry is ENVIRON [32]. This software concentrates more on the design of mining systems and airflows below ground. This package is not a dynamic and integrated simulation software package. There was no simulation tool found in the mining industry that would suit the purpose of this study.

Other fields of study were also investigated. One of these fields was the building ventilation simulation field. It was found that a lot of work has been done in energy analysis and system simulation of large buildings. Some of the software available in this field is POWERDOE [33] and TRNSYS [34]. Integrated simulations with control strategies can be done with *QUICKControl* [35].

The software that best suited the purposes of this study was *QUICKControl.* It was found that this software had the ability to simulate integrated systems and provided the potential for the implementation of control strategies.

Some of the existing components, as required for this study, in the software include [36]:

1. Pumps.
2. Controllers.
3. Water sources.
4. Flow diverges.
5. Flow converges.

Previous results of simulations and energy predictions have proved to be accurate within 10% of actual measured values [37]. Due to the availability of the solver engine and basic input, it was decided to use *QUICKControl* for this study. The software package was modified and adjusted to incorporate the new components needed for the application of this study.

2.3 MODELS AND INTERFACES

Two of the most important components of the pumping reticulation system, the storage dams and pumps, will be discussed briefly in this section.

2.3.1 THERMAL STORAGE DAMS

A new component that was needed for the mining applications was the dams that serve as thermal storage capacity of the chilled water. Most mines use thermal storage dams to store thermal energy in water. This water can be used as needed by the mine refrigeration system. It is especially necessary for when there is a breakdown in the main cooling plant. With these water dams, the effects of these breakdowns can be limited or at least provide time for the workers to react and reach a safe depth [38].

This kind of storage can also be used to save on the energy usage of the system. Through the use of off-peak filling of the dams, a system can use the cool stored water during peak load periods. The cool storage can be produced during off-peak periods by the extra capacity of the refrigeration system.

These dams can also serve as mixing points for the control of water temperature [39]. These thermal storage dams can either be used to model cold-water storage or hot water storage.

The benefits of using thermal storage are:

1. *Reduced equipment size.* Because the peak loads can be met by the cold storage, equipment sized to meet the peak load can be downsized.
2. *Energy savings.* Cool storage systems allow chillers to operate more at night when lower condenser temperatures improve equipment efficiency.
3. *Energy cost saving.* A significant reduction of the time-dependant energy cost, like in-peak-time-of-use energy charges, can be saved on.

A schematic view of a dam can be seen in Figure 2.1. This schematic will be used for modeling [40] purposes.

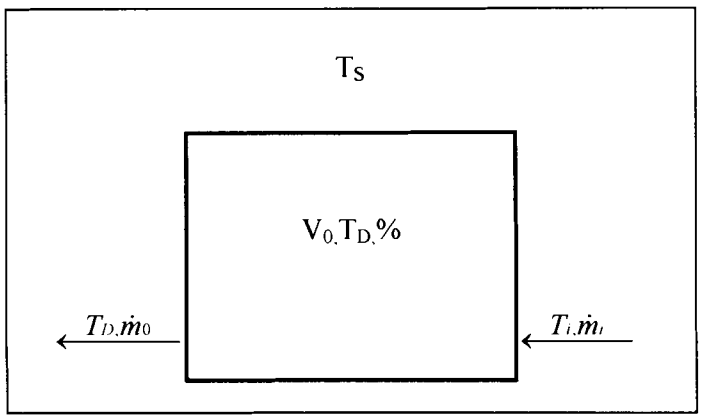


Figure 2.1 Schematic drawing of a thermal storage dam.

It can be assumed that the thermal storage dams react like an electrical capacitor [41]. The temperature within the tank is a function of initial temperature, initial volume, solar air temperature, which includes the emittance and absorption of the air on the dam wall, and the convection coefficient on the wall surface.

The exposed areas, horizontal and vertical, also need to be accounted for. Taking convection, emittance and absorptance into account, the basic equation for dams can be given by:

$$C.\frac{dT}{dt} = \dot{m}_i.c_p.(T_i - T_D) + UA(T_s - T_D) \qquad (2.1)$$

Where T_D is the water temperature in the dam. The main idea is to get T_D alone to be able to calculate the temperature within the dam. Furthermore, T_s is the solar air temperature given by [42]:

$$T_s = T_A + \alpha\frac{G_t}{h_0} - \frac{\varepsilon\Delta R}{h_0} \qquad (2.2)$$

This formula incorporates the atmospheric, dry bulb temperature T_A and the effects of absorption $(\alpha \frac{G_t}{h_0})$ and emittance $(\frac{\varepsilon \Delta R}{h_0})$ heat transfer by the air on the dam wall.

This value will be calculated for every hour, using the climate data that can be entered into *QUICKControl*. Multiplying the terms of Equation 2.1 and separating the variables gives the following results:

$$C.\frac{dT}{dt} = -T_D.a + b$$

With

$$a = \dot{m}_i.c_p + UA$$

$$b = \dot{m}_i.c_p T_i + UAT_s$$

$$C = C_0 + (\dot{m}_i - \dot{m}_0)c_p.\Delta t$$

$$C_0 = V_0.c_p$$

Separating the terms and rearranging the results to:

$$\int_{T_{D_0}}^{T_D} \frac{1}{T_D.a - b} dT = \int_0^1 \frac{-1}{C} dt$$

Using exponential rules after integration, the equation becomes:

$$\frac{1}{a}.\ln\left(\frac{T_D.a-b}{T_{D0}.a-b}\right)=\frac{-\Delta t}{C}$$

$$T_D=\frac{1}{a}\left((T_{D0}.a-b).e^{\frac{-a\Delta t}{C}}+b\right) \qquad (2.3)$$

With

$$C=\max, when C\geq \max$$
$$\dot{m}_0=0, C=0 when C\leq 0$$

The most important parameter of the thermal storage dam model, for the purpose of this study (the dams are used as hot water dams), is the volume or level of the dam. Due to variation in flow rates of the inlet and outlet water of the dam, the volume or level of the dam will change over time. For the simulation model the change in level is dependent on the flows in and out (l/s), and the time interval Δt. The model can be formulated by:

$$V_t=V_{t-1}+\frac{(\dot{m}_i-\dot{m}_o)\Delta t}{1000} \qquad (2.4)$$

With

$$\dot{m}_o=0, when V_{t-1}=0$$
$$\dot{m}_i=0, V_t=V_T, when V_{t-1}\geq V_T$$

To be able to use the model appropriately (as for the purpose of this study), the user needs to provide certain information pertaining to the model. This includes the basic design of the dam, the total volume of the dam and the initial conditions for the volume of the dam (volume fraction between 0 and 1). The user interface can be seen in Figure 2.2.

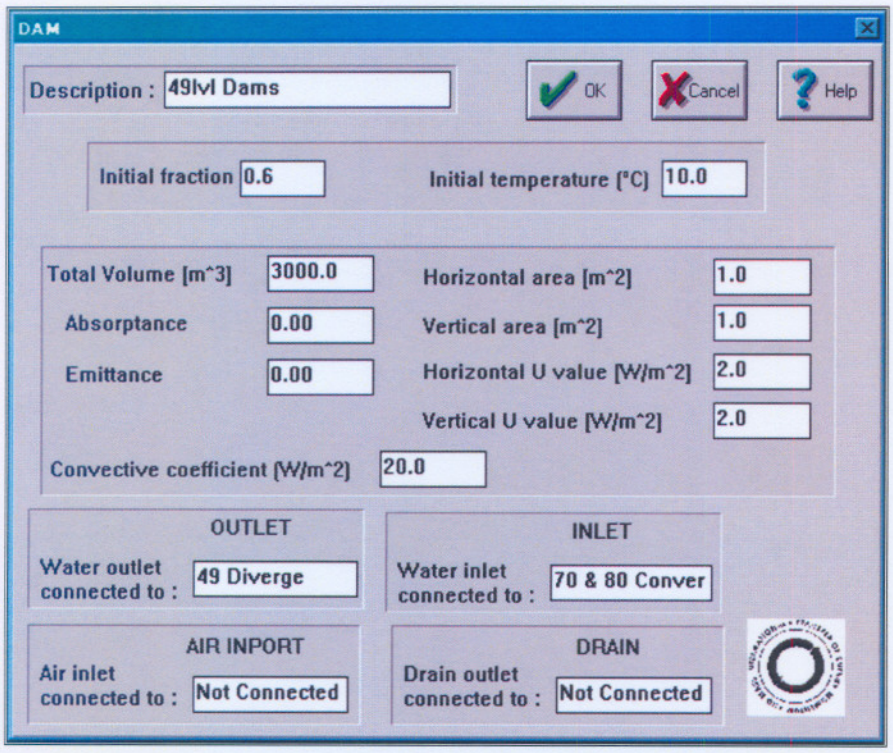


Figure 2.2 User input screen for storage dam.

2.3.2 PARALLEL PUMPS

A schematic view of a pump can be seen in Figure 2.3. This schematic will be used for modeling [43] purposes.

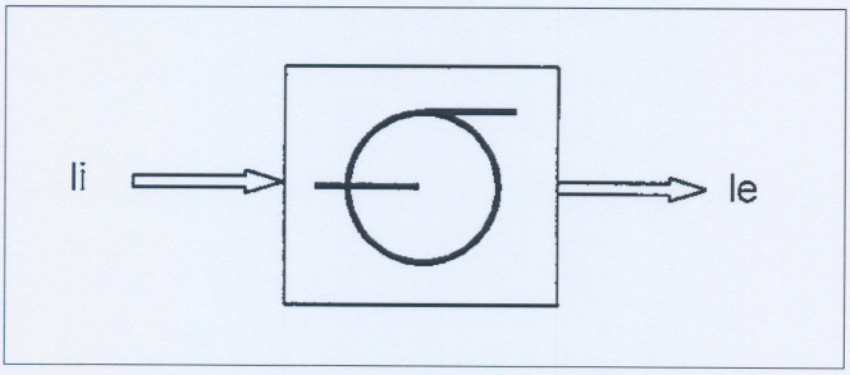


Figure 2.3 Schematic diagram of a pump.

The model is based on the following two non-dimensional variables, which can be derived by employing the Buckingham-Pi theorem [44]:

The flow coefficient defined as:

$$K_f = \frac{\dot{m}_l}{\rho_l n D^3} \qquad (2.5)$$

Where

$$\dot{m}_l = \frac{\dot{m}_l}{k} \quad \text{(parallel cascade only)} \qquad (2.6)$$

With ρ_l the fluid density (1000 kg/m^3), n the rotational speed of the pump and D the rotor diameter.

The pressure head coefficient is defined as:

$$K_h = \frac{dP_l}{\rho_l n^2 D^5} \qquad (2.7)$$

With dP_l defined as the static pressure rise.

Any specific pump is characterised by the relation between these two coefficients. Simple polynomial regressions will be used namely:

$$K_h = a_0 + a_1 K_f + a_2 K_f^2 + ... + a_k K_f^k \qquad (2.8)$$

With a_0 to a_k the k+1 correlation coefficients derived from the data sheets. The order of the polynomial equation may vary from model to model and will be determined by the shape of the K_h versus K_f relation.

Also

$$\eta_{pump} = b_0 + b_1 K_f + b_2 K_f^{\,2} + ... + b_k K_f^{\,k} \qquad (2.9)$$

Where

$$Q_l = \frac{(1-\eta_{pump})\dot{m}_l dP_l}{\rho \eta_{pump}} \qquad (2.10)$$

And

$$T_{le} = T_{li} + \frac{Q_l}{\dot{m}_l c_{pl}} \qquad (2.11)$$

With c_{pl} = 4187 J/kg°C.

The power required is defined by:

$$Pwr = \frac{k\dot{m}_l dP_l}{\rho \eta_{pump} \eta_{motor}} \qquad (2.12)$$

To be able to use the model appropriately, the user needs to provide certain information pertaining to the model. This includes the amount of stages, efficiency of the pump, static pressure rise and mass flow rate through the pump.

The user interface can be seen in Figure 2.4.

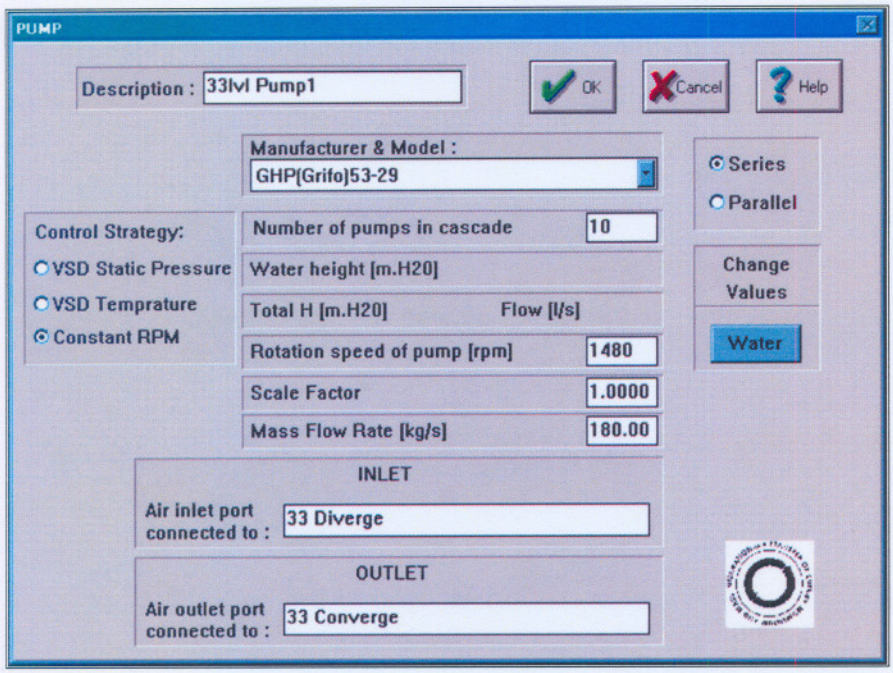


Figure 2.4 User input screen for pumps.

2.4 CONCLUSION

Due to dynamic and intricate interactions between the components of a cooling plant and a pumping reticulation system, there is a definite need for dynamic integrated software. Such software is furthermore needed to investigate the energy usage of the system. An existing software package, *QUICKControl*, is already used in the building industry.

This software needed some adjustments to incorporate mining equipment and components. One of these components was thermal storage dams. The mathematical model of this component was implemented into the simulation software.

This additional component, along with the existing components, is sufficient to simulate most of the pumping reticulation system's equipment. With the history of *QUICKControl* for building applications, the adjustments for mining applications should provide similar results.

CHAPTER 3

SIMULATION AND VERIFICATION

3. SIMULATION AND VERIFICATION

3.1 INTRODUCTION

To thoroughly investigate the pumping reticulation system of a mine, it is necessary to use integrated software that can model the different components and their interaction relevant to each other. Such software is only usable for investigations if it is properly verified, using proper verification procedures.

To verify the system properly it is required to physically measure the relevant information needed from the system. This information includes water flow rates, dam levels and electricity consumption measured over a period, at specified time intervals. Different measuring equipment is needed, either already installed in the system, or additionally provided.

By using simulation software, the system can be modelled by building the total system using the different model components in the software. Starting with a specific and typical day, the measured data of the system can be compared to the simulation data acquired from the simulation software, and verification is achieved. After the initial verification, a longer period e.g. a month or year's measured system data can be compared to the simulation data to further the verification process.

The measured and simulated data of the pumping reticulation system was compared and gave a good and accurate result. The accuracy of the simulated water flows is excellent (simulated total water flow from the underground workings to the surface dams verified with a 1% error against measured data).

The results of the dam levels and the power consumption verified within reasonable values. The results showed satisfactory for verification purposes and the simulation model was therefore used for further investigations.

3.2 VERIFICATION PROCEDURES

To be able to verify the system model, built in the simulation software, it was needed to establish a proper procedure for the verification. This procedure needed to be systematic and incorporate various aspects. The procedure can be broken into the following steps:

1. The first step in the verification process was to identify a suitable mine that could serve as a test mine. The mine needed to have a fairly typical pumping reticulation system.
2. A detail description of the system was needed to establish the set up of the simulation model and to determine the various measuring points needed for the verification purposes.
3. The measurements needed for verification purposes included the measuring of all underground dam levels, water flow rate from the underground system to the surface dams, pumping status (active pumps) of all the pumps of each pumping station and the electricity usage of all the power consuming equipment.
4. Equipment that was already installed in the system and additional measuring equipment was used to perform all the necessary measurements. Typical equipment included ultrasonic flow meters and dam level measuring equipment.
5. A typical working day, week and month was selected along with an appropriate measuring interval to cover enough working conditions of the pumping cycle.
6. The measured data was collected and sorted into useful formats.
7. The simulations were set up for the measuring day, week and month. The simulations were run and the simulation data was compared to the actual measured data.
8. Corrections and modifications were made to the simulation models, and the simulations were repeated until the simulation data compared accurately to the measured data.

3.3 SYSTEM DESCRIPTION

Placer Dome Western Areas Joint Venture (previously South Deep Gold), a gold mine west of Johannesburg, was found to be a good test mine. The mine's underground pumping reticulation system is well maintained with an extensive measuring system implemented in the system.



Figure 3.1 South Deep Gold

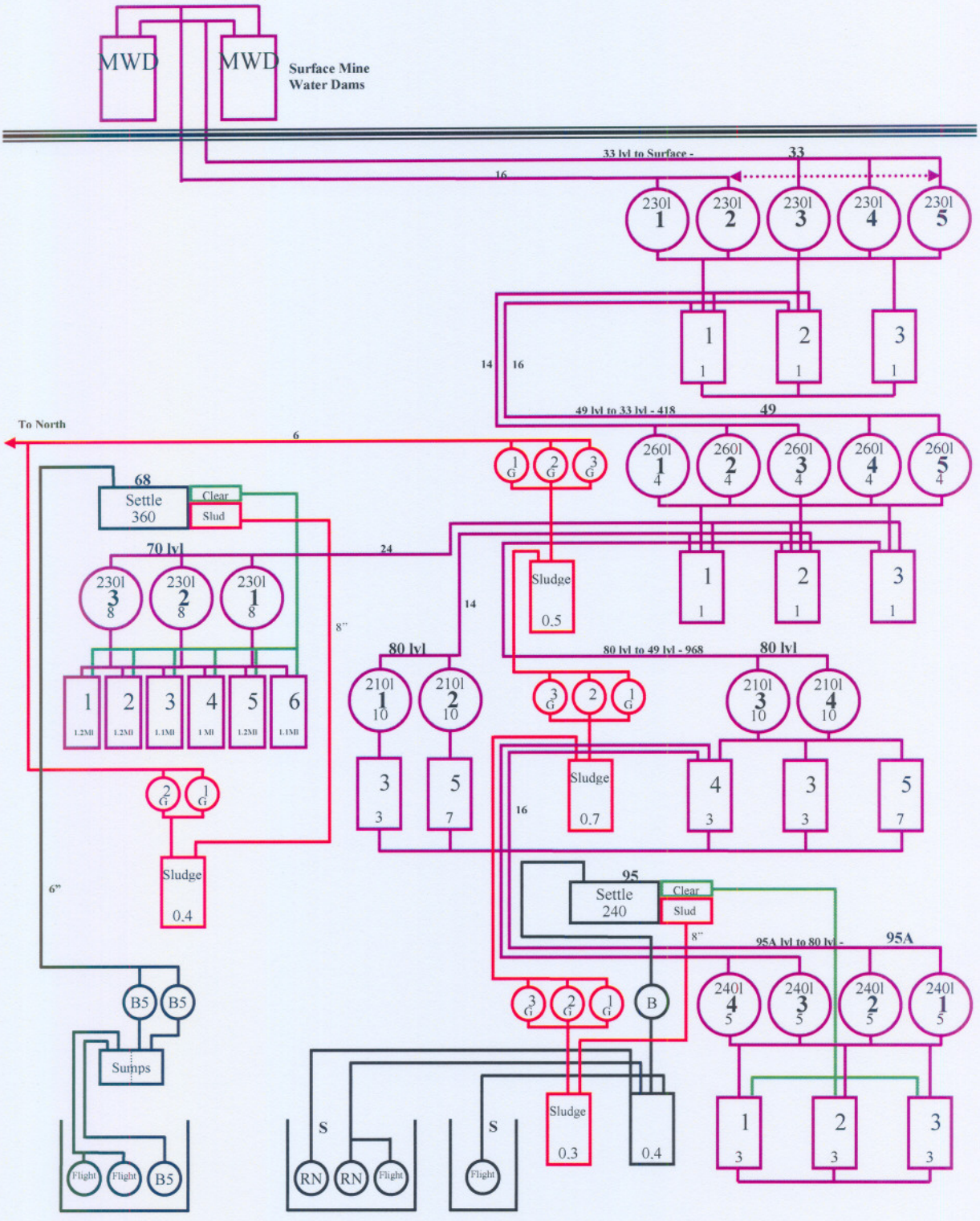


Figure 3.2 Schematic view of the underground pumping reticulation system. The purple lines represent the clear water reticulation path.

There are clear water dams on the levels with pumping stations, which serve as a buffer for the pumping chambers. For emergencies, such as power failures etc., the dams on 80level and 95level have a much larger capacity. The details of the various dams can be seen in Table 3.1.

LEVEL	DAMS	TOTAL CAPACITY
SURFACE	2	7Ml
33	3	3Ml
49	3	3Ml
70_{SV1}	6	6.8Ml
$80_{SV2\ \&\ 3}$	5	23Ml
95_{A}	3	9Ml

Table 3.1 Summary of the specifications of all the mine water (clear hot water) dams.



Figure 3.3 Photo of a typical underground dam.

It should be noted that measurements were taken on the clear water reticulation system, as it was decided that it would be this system that would be the major energy consumer of the total pumping reticulation system.

The clear water dams on 95_Alevel and on 70level SV1 receive their water from settlers on the 95 and 68 levels. A settler basically collects mine water (leakage refrigeration water, service water and fissure water), and separates the mud from the dirty mine water to provide clear water, which can be pumped by normal operating centrifugal pumps.

The muddy water is fed to mud dams from where the slurry is pumped to surface via the different levels which are fitted with slurry dams and pumps.



Figure 3.4 Mine water is pumped through a network of pipes to the different levels.

The mine has six underground pumping chambers situated on five different levels below surface. The details of each pumping station are shown in Table 3.2.

LEVEL	DEPTH	PUMPS	MANUFACTURER	TYPE	CAPACITY
33	919m	5	GRIFO 10-STAGE	GHP 53-29	230l/s
49	1337m	5	GRIFO 4-STAGE	GHP 58-29	260l/s
70_{SV1}	2000m	3	GRIFO 8-STAGE	GHP 53-29	230l/s
$80_{SV2\ \&\ 3}$	2305m	4	GRIFO 10-STAGE	GHP 53-29	210l/s
95_{A}	2794m	4	GRIFO 5-STAGE	GHP 58-29	240l/s

Table 3.2 Summary of the specifications of all the clear water pumping stations.

Note: The depth of each pumping station above is given in meters below surface. Each pumping station pumps to its neighbour, (the next station above its own level).



Figure 3.5 A typical pumping station.

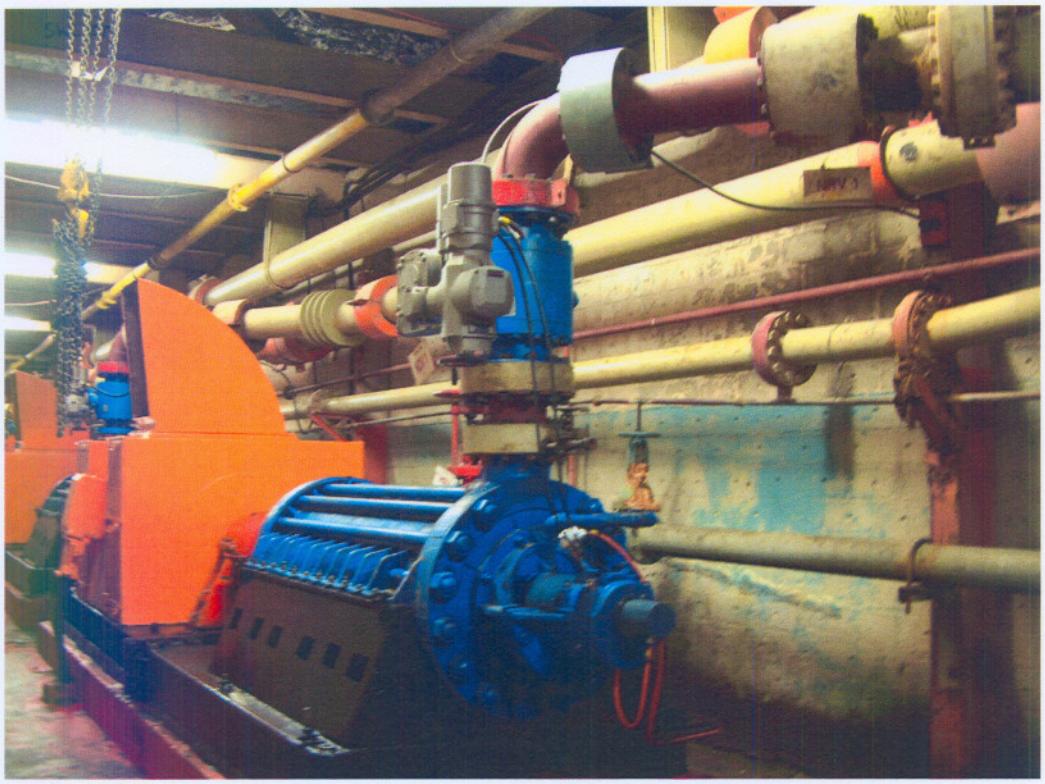


Figure 3.6 A typical multi-stage centrifugal pump.

The clear water is pumped from 95_Alevel to 80level, which is divided into two stations: SV2 and SV3. SV2 and SV3 each have two pumps in their chambers. The two pumping chambers SV2 and SV3 are connected to each other.

The water is pumped from 95_A to SV3 from where a valve regulates the water flow to SV2. From 80level the water is pumped to 49level. Clear water is also pumped from 70level SV1 to 49level. The water is then pumped from 49level to 33level from where the water is finally pumped to the surface mine water dams.

It was decided that the only water flow rate measured would be the total water flow from 33level to the surface mine water dams. Other flow rates could easily be calculated if needed.

The current control strategies, including operating times were obtained from the system operating manuals, operators and measurements. The layout of the simulation model can be seen in figure 3.7.

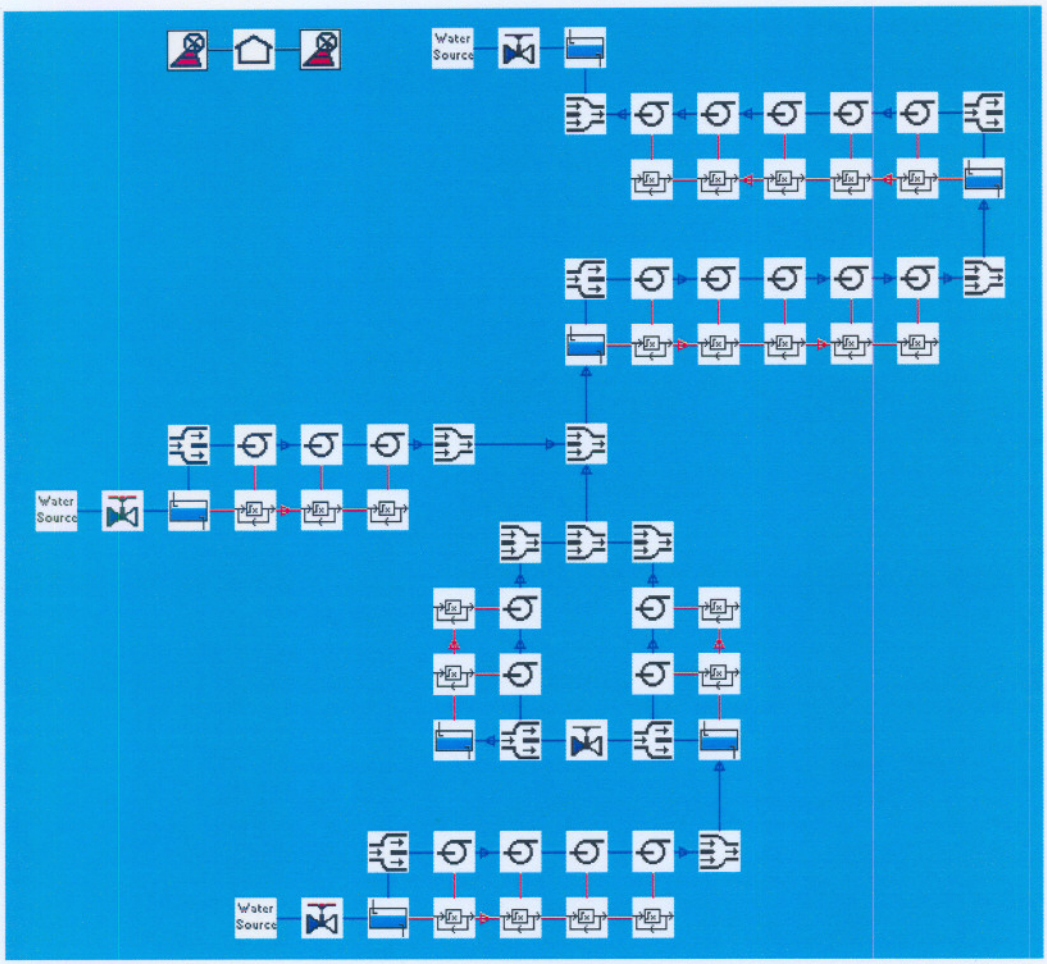


Figure 3.7 Layout of the simulation model.

3.5 SYSTEM OPERATION VERIFICATION

The actual measured system data was used to verify the predictions made by the simulation program. A representative specific typical 24-hour day of system operation was chosen for verification purposes.

3.4 MEASUREMENTS AND SIMULATION PROCEDURES

Measurements were taken over a four-week period to get familiar with the typical running of the system and to obtain a good typical day depicting the most common profiles of the equipment. From the downloaded data, a single representative day was selected, to be compared with the 24-hour day predictions provided by the simulation software.

The installed measuring equipment took the following measurements:

Water flow rates:

1. The water flow rate from 33level to the surface mine water dams, i.e. the total water flow leaving the underground workings.

Dam levels:

1. The dam levels of all the underground clear water (hot water) dams.

Pumps:

1. The activity of all the underground clear water pumps, i.e. specific times and durations when each pump was active.

Electricity usage:

1. The power consumption of each pumping station. With the measured hours of activity, the electrical units of each station could be calculated.

A simulation was done according to the operating schedules of the measured system. The predictions of this simulation were compared to a specific typical 24-hour day of normal operation, chosen from the measured data.

This 24-hour specific simulation was done to find out if it were possible to simulate the operation of the system accurately, i.e. it was necessary to simulate the "real life" operation of the system.

The predictions made by the simulation program were verified against the actual measured water flow to the surface, clear water dam levels and system energy usage.

These verifications showed that the capacities of the pumps were modelled correctly in the simulation program. The verification results are given graphically in this section.

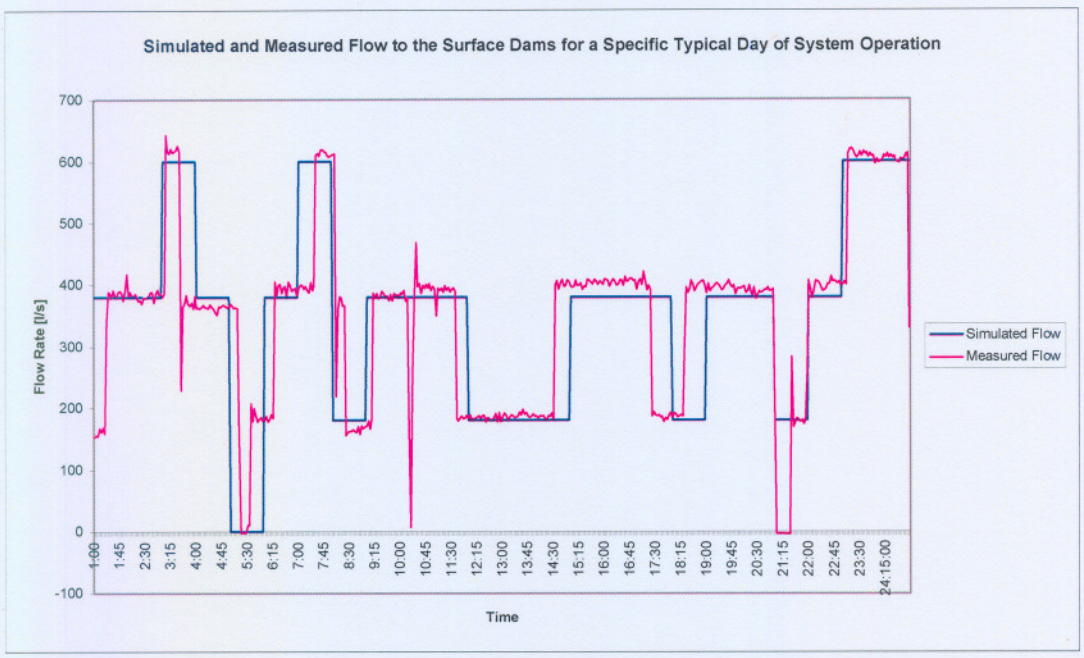


Figure 3.8 Verification results of the predicted flow rate from the underground workings to the surface mine water dams.

The excellent verification result of the total volume of water flow from 33level to the surface mine water dams are shown in Table 3.3.

TOTAL FLOW SIMULATED	TOTAL FLOW MEASURED	ERROR
30 204m^3	30 508m^3	1%

Table 3.3 Summary of the total daily flow from the underground workings to the surface compared to the actual measured flow for a specific typical day of system operation.

The daily dam levels of the system were measured, and this data was used to verify the dam level predictions made by the simulation program. The following figures will show the verification of the predicted dam levels against the actual measured dam levels.

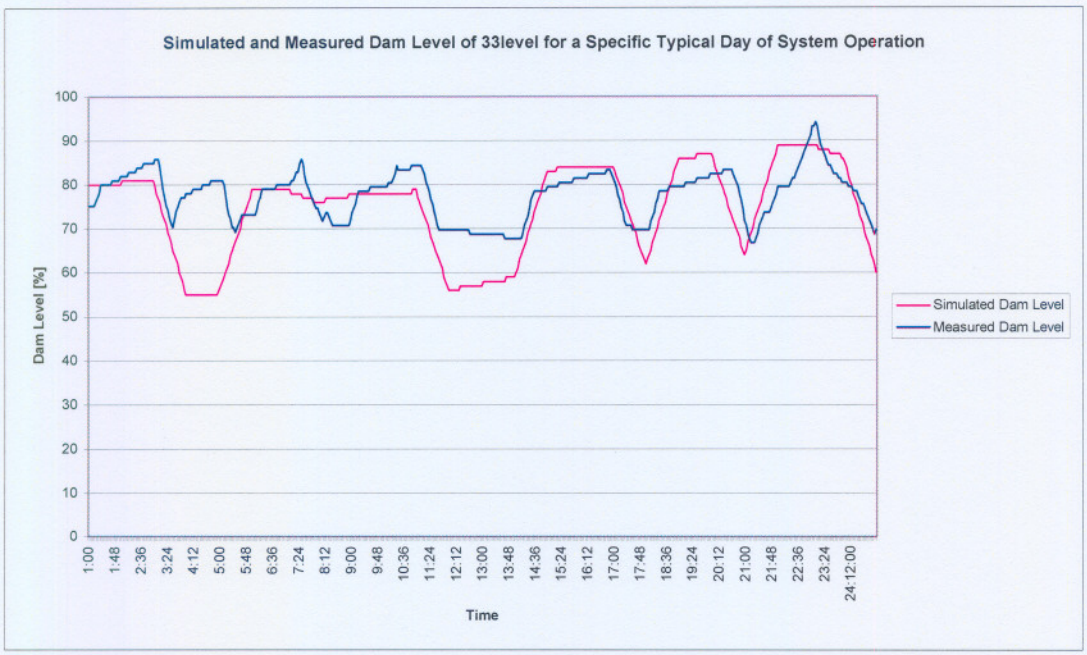


Figure 3.9 Verification of the predicted dam level of 33level against the actual measured dam level.

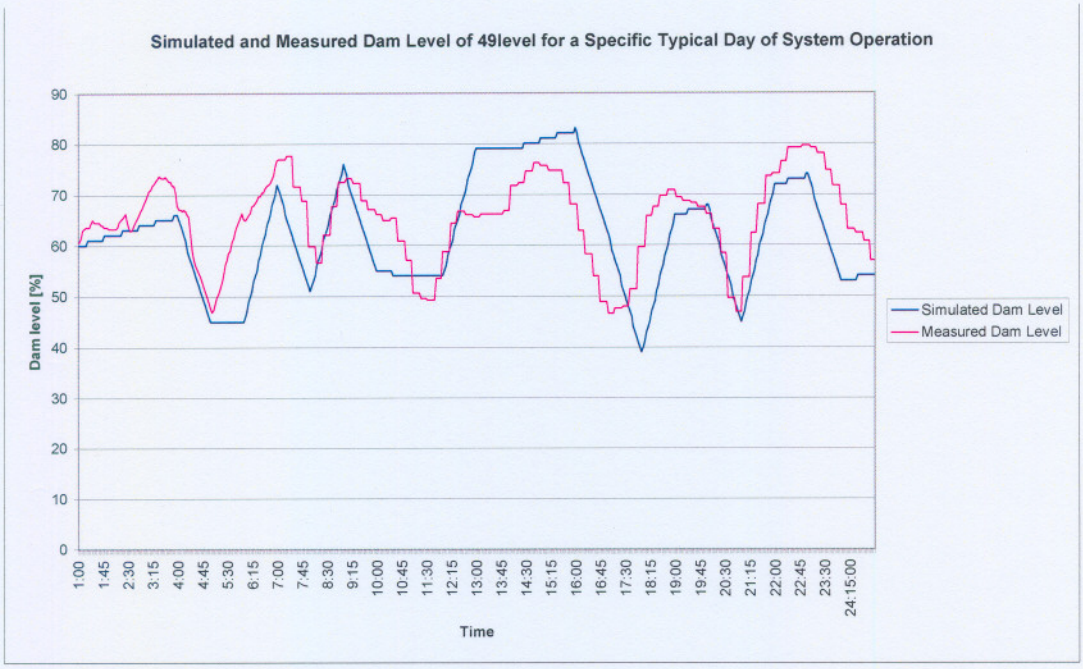


Figure 3.10 Verification of the predicted dam water level of 49level against the actual measured dam level.

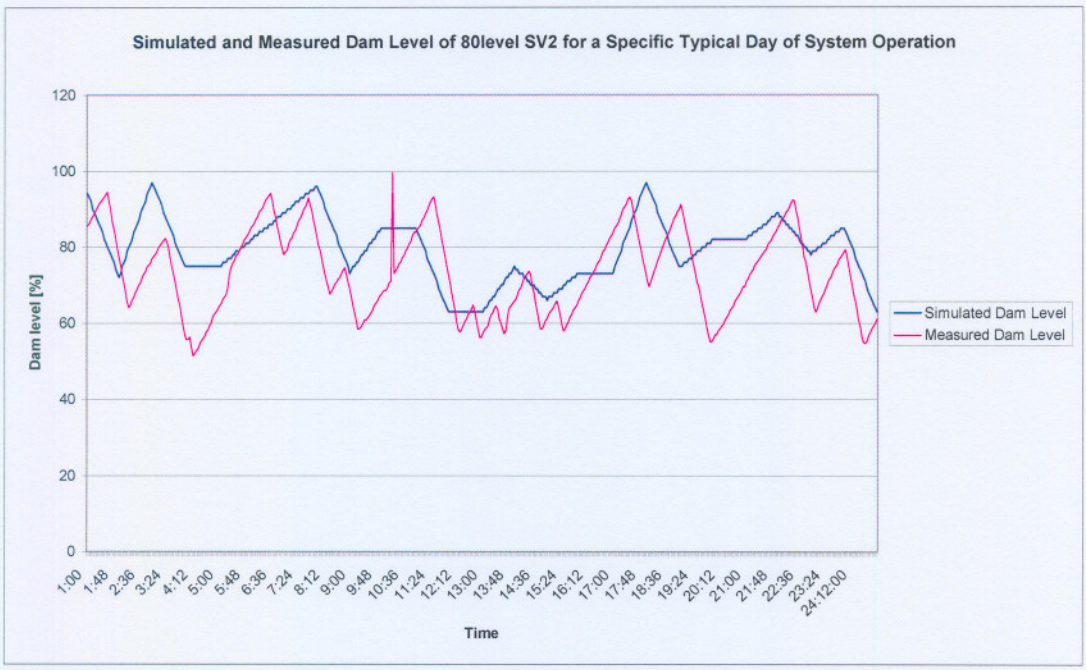


Figure 3.11 Verification of the predicted dam water level of 80level SV2 against the actual measured dam level.

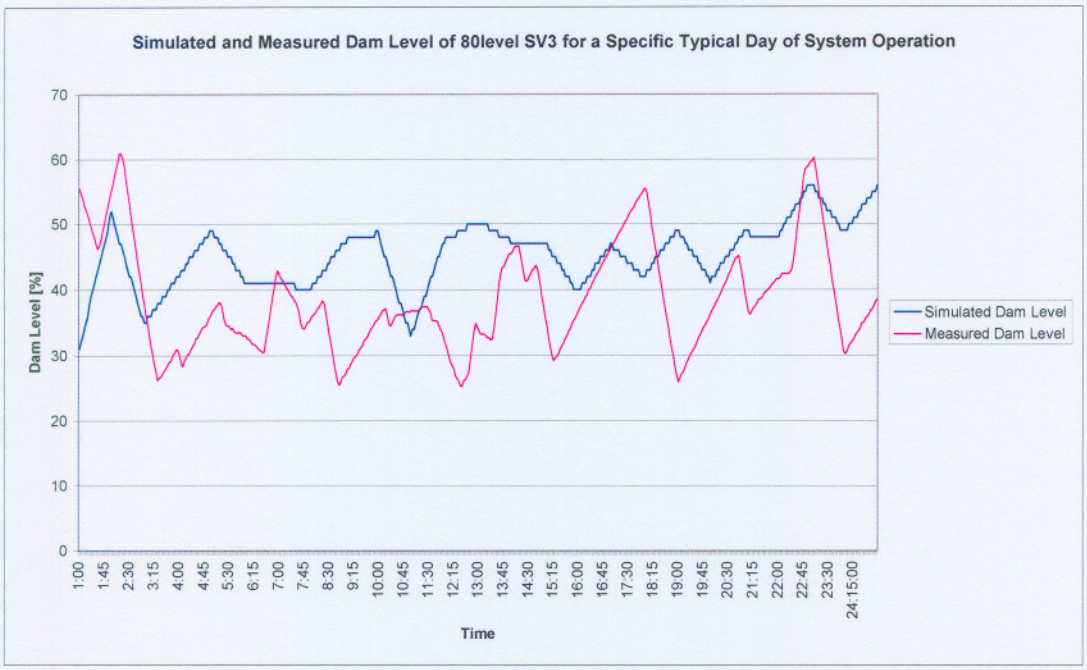


Figure 3.12 Verification of the dam water level of 80level SV3 against the actual measured dam level.

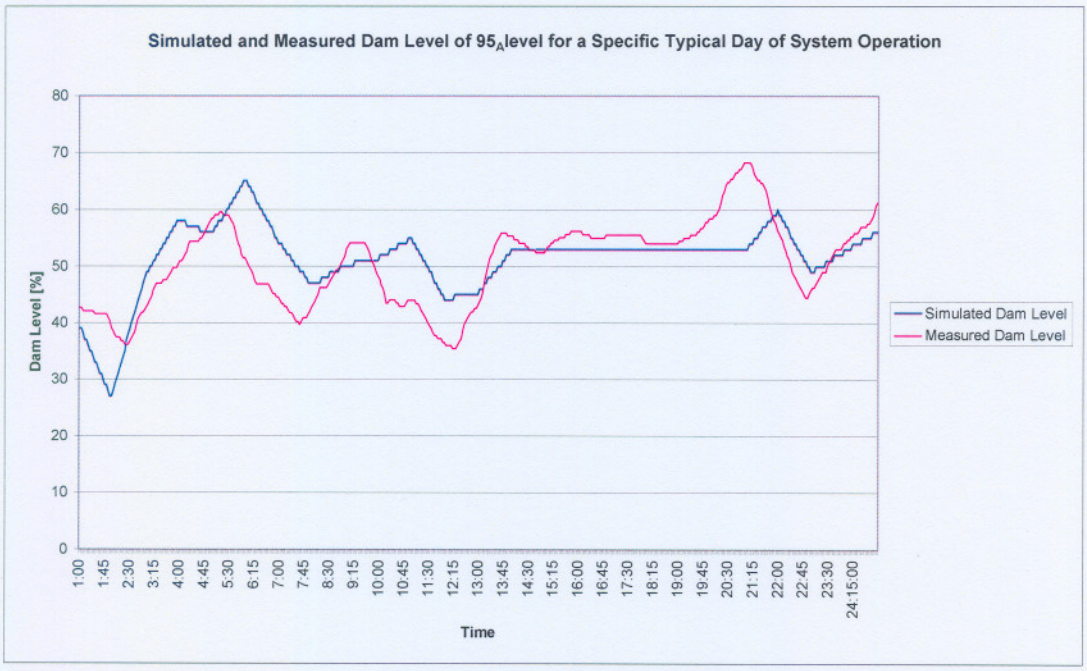


Figure 3.13 Verification of the predicted dam water level of 95_Alevel against the actual measured dam level.

The average daily dam level of each pumping station was calculated, and used for comparison purposes against the average daily simulated dam level of each pumping station. The verification results of the average 24-hour dam water levels are shown in Table 3.4.

LEVEL	AVERAGE ERROR
33	2.69%
49	2.86%
80 SV2	5.89%
80 SV3	6.62%
95_A	0.61%

Table 3.4 Summary of the verification results of the dam levels of the pumping reticulation system for a specific typical day of system operation.

From Table 3.4 it is clear that the verification results are satisfactory. These verification results are the first step in showing the accuracy of the simulation model.

The daily energy usage of the clear water pumps of the reticulation system was measured, and these results were used to verify the predictions made by the simulation program. The total active pumps on each level are shown graphically and the total energy usage of these pumps for each level is shown in Table 3.5.

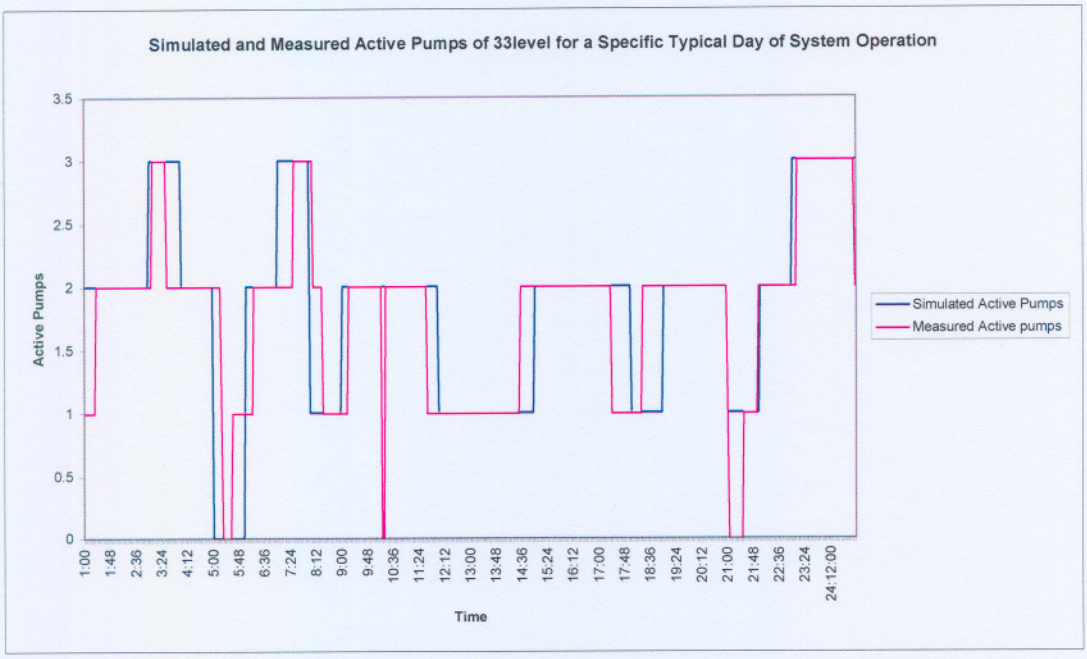


Figure 3.14 Verification of the predicted active pumps of 33level against the actual measured active pumps.

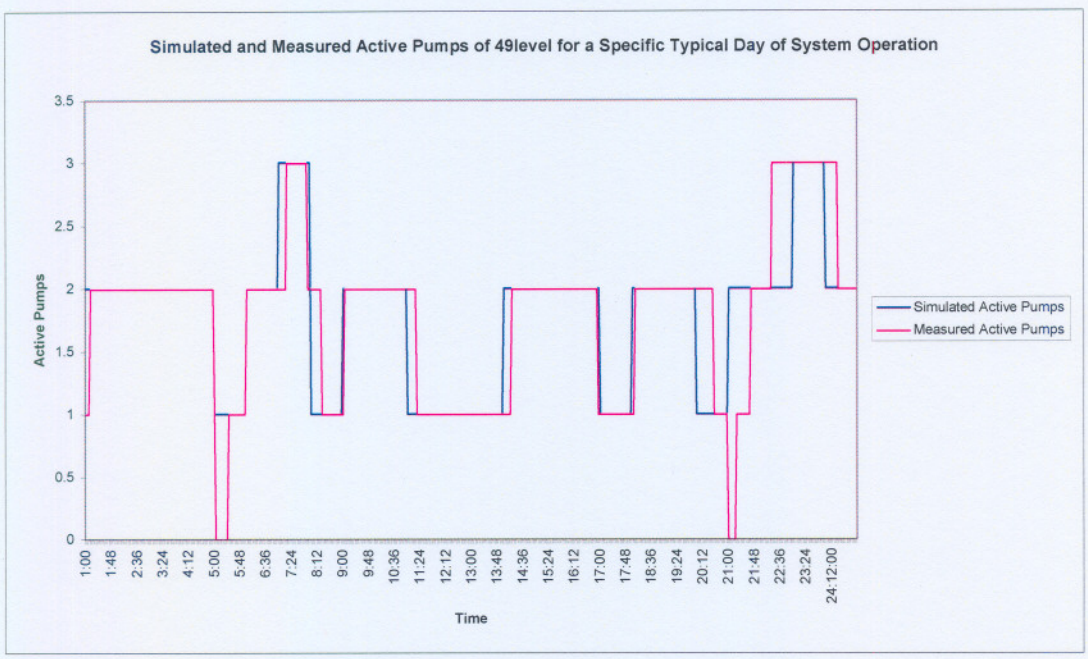


Figure 3.15 Verification of the predicted active pumps of 49level against the actual measured active pumps.

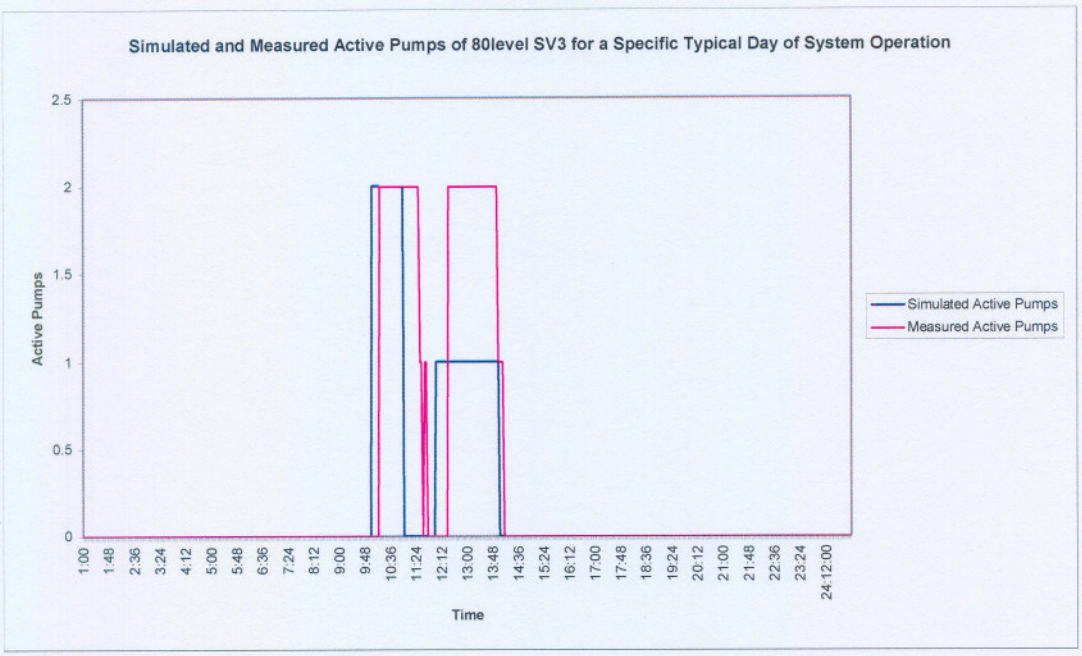


Figure 3.16 Verification of the predicted active pumps of 80level SV3 against the actual measured active pumps.

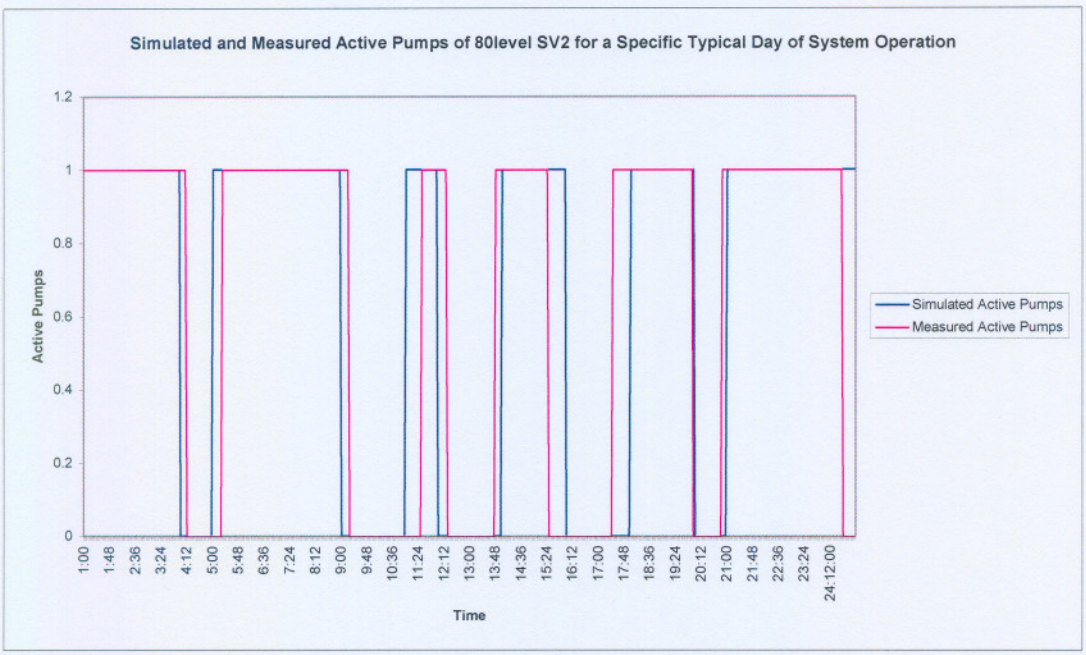


Figure 3.17 Verification of the predicted active pumps of 80level SV2 against the actual measured active pumps.

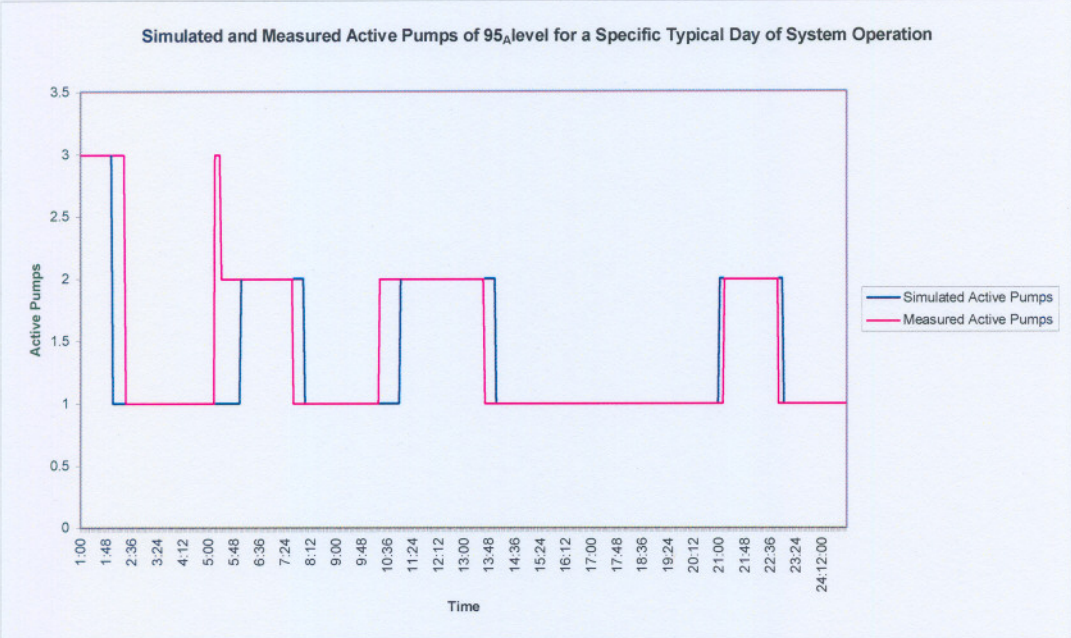


Figure 3.18 Verification of the predicted active pumps of 95_Alevel against the actual measured active pumps.

The verification results of the total daily energy usage of the various levels, for the specific typical day of operation, are shown in Table 3.5.

LEVEL	$TOTAL_{MEASURED}$	$TOTAL_{SIMULATED}$	% ERROR
33	113 683kWh	120 700kWh	5.81 %
49	61 894kWh	57 799kWh	6.62 %
70	21 383kWh	23 556kWh	9.22 %
80	118 923kWh	103 445kWh	13.02 %
95_A	49 970kWh	43 752kWh	12.44 %

Table 3.5 Summary of the total energy usage of the various pumping levels for a typical day of system operation.

The most important result for the purposes of this study is the total energy usage of the entire pumping reticulation system, i.e. the joint total energy usage of all the levels is investigated.

The total daily energy usage of the entire pumping reticulation system is given in Table 3.6. It should be noted that this is for a typical average day of operation.

$TOTAL_{MEASURED}$	$TOTAL_{SIMULATED}$	% ERROR
365 853kWh	349 252kWh	4.54 %

Table 3.6 Summary of the total energy usage of the entire underground pumping reticulation system for a specific typical day of system operation.

From Table 3.6 it is clear that the verification of the total daily energy usage of the entire pumping reticulation system is satisfactory. These verification results show that the energy using equipment in the system can be simulated accurately.

3.6 BASE YEAR VERIFICATION

A base year simulation (extended simulation run) was done to try and simulate the philosophy of the system's operators. It was found that the pumps of each pumping station were operated according to a certain trend of the dam levels of each pumping station's dams.

By using certain control parameters on the dam levels to keep them within certain boundaries, a base year simulation was done to see if the simulation model could accurately simulate the trend in the system's operation over a longer period of time.

A specific typical 24-hour day of system operation was chosen to use for investigation purposes. The results are given graphically in this section.

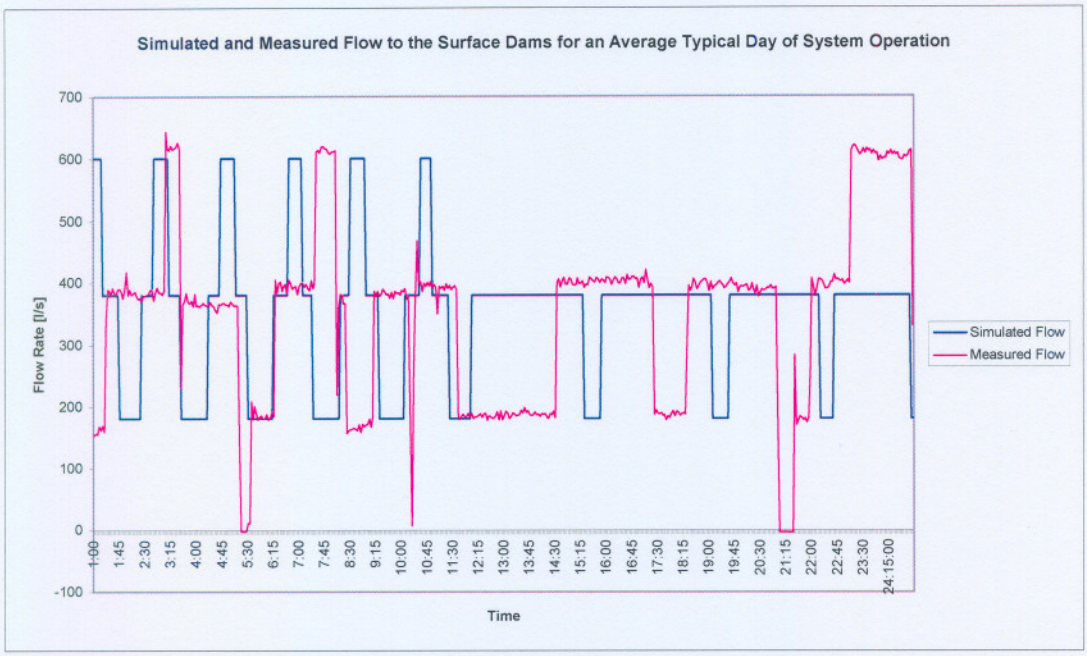


Figure 3.19 Actual and simulated flow rate from the underground workings to the surface mine water dams.

Although the flow pattern (Figure 3.19) does not look exactly like the measured pattern, the excellent verification result of the total volume of water flow from 33level to the surface mine water dams are shown in Table 3.7.

TOTAL FLOW$_{SIMULATED}$	TOTAL FLOW$_{MEASURED}$	ERROR
30 445m^3	30 508m^3	0.21%

Table 3.7 Summary of the total daily flow from the underground workings to the surface compared to the actual measured flow for an average typical day of system operation. The total flow from the underground workings, for the base year simulation, compares well to the actual trend of water flow to the surface dams.

The daily average dam levels of the system were used to verify the dam level predictions made by the simulation program, for the base year simulation. The following figures will show the verification of some predicted dam levels against actual measured dam levels.

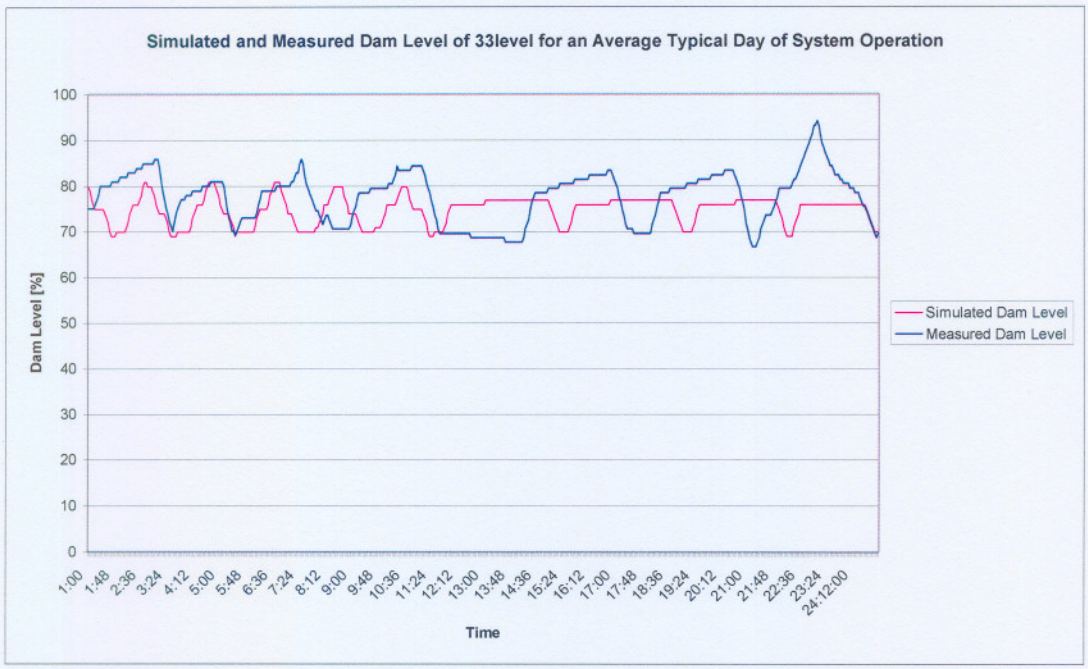


Figure 3.20 Base year verification of the predicted dam level of 33level against the actual measured dam level.

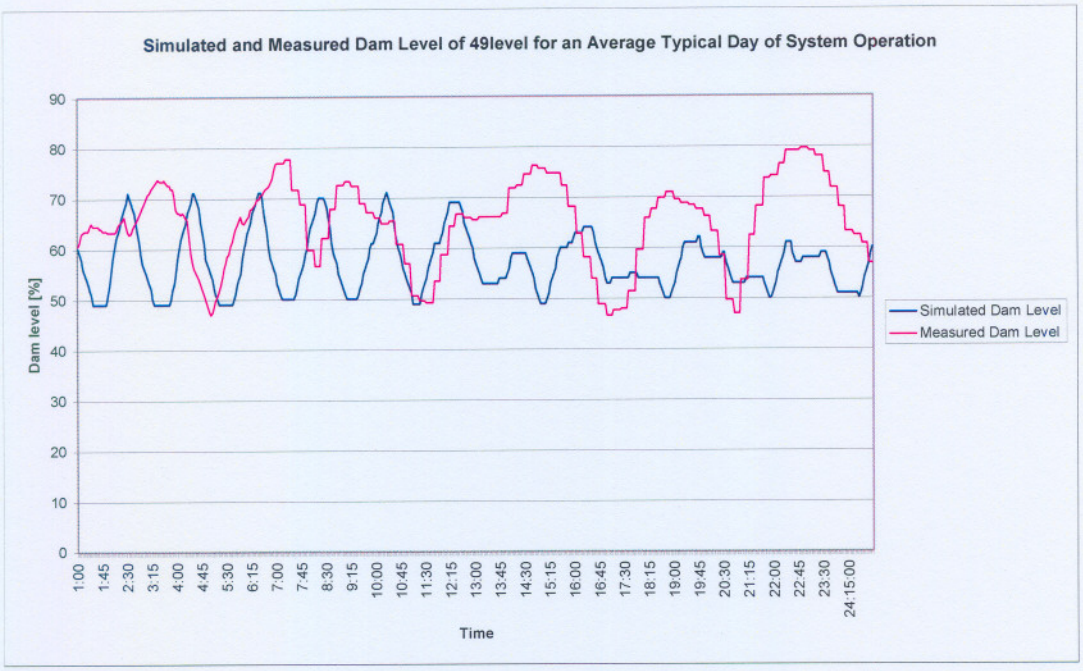


Figure 3.21 Base year verification of the predicted dam water level of 49level against the actual measured dam level.

The verification results of the daily average dam water level of each pumping station are shown in Table 3.8.

LEVEL	AVERAGE ERROR
33	2.68%
49	8.08%
80 SV2	8.71%
80 SV3	0.19%
95_A	4.09%

Table 3.8 Summary of the base year verification results of the dam levels of the pumping reticulation system for an average typical day of system operation.

From Table 3.8 it is clear that the verification is satisfactory. This verification results show that the trend (dam levels) of the system's operators could be simulated quite closely.

The daily average energy usage of the clear water pumps of the reticulation system was used to verify the predictions made by the simulation program. Because the control parameters of the base year simulation was set on the dam levels, the pump duration curves do not look the same, but it is the verification of their energy usage that is important in this section.

The base year verification results of the total daily energy usage of the various levels for an average typical day of operation are shown in Table 3.9.

LEVEL	$TOTAL_{MEASURED}$	$TOTAL_{SIMULATED}$	% ERROR
33	113 683kWh	121 513kWh	6.44 %
49	61 894kWh	58 605kWh	5.31 %
70	21 383kWh	23 099kWh	7.43 %
80	118 923kWh	105 667kWh	11.15 %
95_A	49 970kWh	54 154kWh	7.73 %

Table 3.9 Summary of the total daily energy usage of the various pumping levels for an average typical day of system operation.

It should be noted that although it was possible to simulate the trend of the system, there still was a human factor involved, i.e. sometimes the operators would operate their stations outside their normal trend.

The verification results of the energy usage of the various levels are quite satisfactory. The most important result for the purposes of this study is the total energy usage of the entire pumping reticulation system, i.e. the joint total energy usage of all the levels is investigated.

The total daily energy usage of the entire pumping reticulation system is given in Table 3.10.

$TOTAL_{MEASURED}$	$TOTAL_{SIMULATED}$	% ERROR
365 853kWh	363 038kWh	0.77 %

Table 3.10 Summary of the total daily energy usage of the entire underground pumping reticulation system for an average typical day of system operation.

From Table 3.10 it is clear that the base year verification of the total daily energy usage of the entire pumping reticulation system is satisfactory. These verification results show that the energy using equipment in the system can be simulated accurately for an average day of system operation, and that it was possible to simulate the philosophy of the system's operators very closely.

3.8 CONCLUSION

The integrated simulation tool, *QUICKControl*, discussed in Chapter 2, was used to conduct the simulation and verification study of the dam levels, pumping status, water flows and energy consumption of the pumping reticulation system.

Satisfactory results of all the equipment were obtained from the verification study. The total volume of water to the surface dams were verified with an excellent error value of less than 1%, while the various dam levels were verified with average errors ranging from 0.19% to 8.71%.

The predicted total daily (24-hour) power consumption of the entire pumping reticulation system was verified with results showing an error value less than 5%. It is this important result that successfully demonstrates the value of the simulation tool for energy studies.

CHAPTER 4

APPLICATION OF THE PUMPING SYSTEM

4. APPLICATION

4.1 INTRODUCTION

The pumping system of a gold mine is responsible for a very large portion of the mine's electricity bill. The mine can save money by operating the system outside Eskom peak tariff periods. This can be accomplished by Demand Side Management (DSM) opportunities, e.g. load shifting, etc.

The best, if not the only way, to effectively use the Eskom price structures without affecting normal operation, is the implementation of control strategies to optimally operate the system within the price structure boundaries, i.e. the potential for load shifting has to be investigated. The impact on the rest of the system and mine, however, has to be investigated to ensure the safety of the mineworkers. Using the simulation model verified in Chapter 3, the various impacts on the system can be studied.

Various simulations were investigated to find the potential period of load shifting per operational day. These investigations were made possible by implementing control in the simulation model of the system, and by means of a control strategy the DSM potential could be studied. The main impact of importance, the dam levels, carefully had to be monitored during this investigation process. It is necessary to ensure that the dams have a large enough capacity, to make it possible to shift load.

4.2 PROCEDURES

The following procedures were followed to ensure the successful investigation of the potential for load shifting in the pumping reticulation system of a gold mine:

1. The total period (total hours) of possible load shifting, without flooding any of the dams of the system, had to be determined by system simulation.
2. There is no current control on any of the system components, and the operators of the system use existing monitoring equipment of dam levels to determine when water should be pumped from the underground workings. Controllers were implemented into the simulation model to ensure that the pumps could be switched on, or off, at the pre-determined and specified times. By monitoring the dam levels the pumps can also be controlled to ensure that a certain level not be exceeded. After the final implementation of the various controllers, various simulations were studied.
3. A graphical presentation of the active pumps of the entire system was then compared to the original actual measured pumping status of the system.
4. The dam levels of all the dams were graphically monitored to ensure that they never reached their maximum capacities.

4.3 LOAD SHIFTING INVESTIGATION

The verification study of Chapter 3 provided us with the necessary evidence of the accuracy of the simulation model. In this section the simulation model was used to investigate various load shifting options, while the dam levels for each level were monitored to ensure that none of the dams reached their maximum capacity.

Various investigations showed that it was possible to shift maximum load for a period of five hours per day, with dam levels within acceptable limits. These five hours of load shifting could either consecutive, e.g. from 07H00 to 12H00, or could be separated into two sessions, e.g. from 07H00 to 10H00 and then again from 18H00 to 20H00. It was decided to shift load from the abovementioned times for the purpose of this study.

The layout of the simulation model can be seen in Figure 4.1.

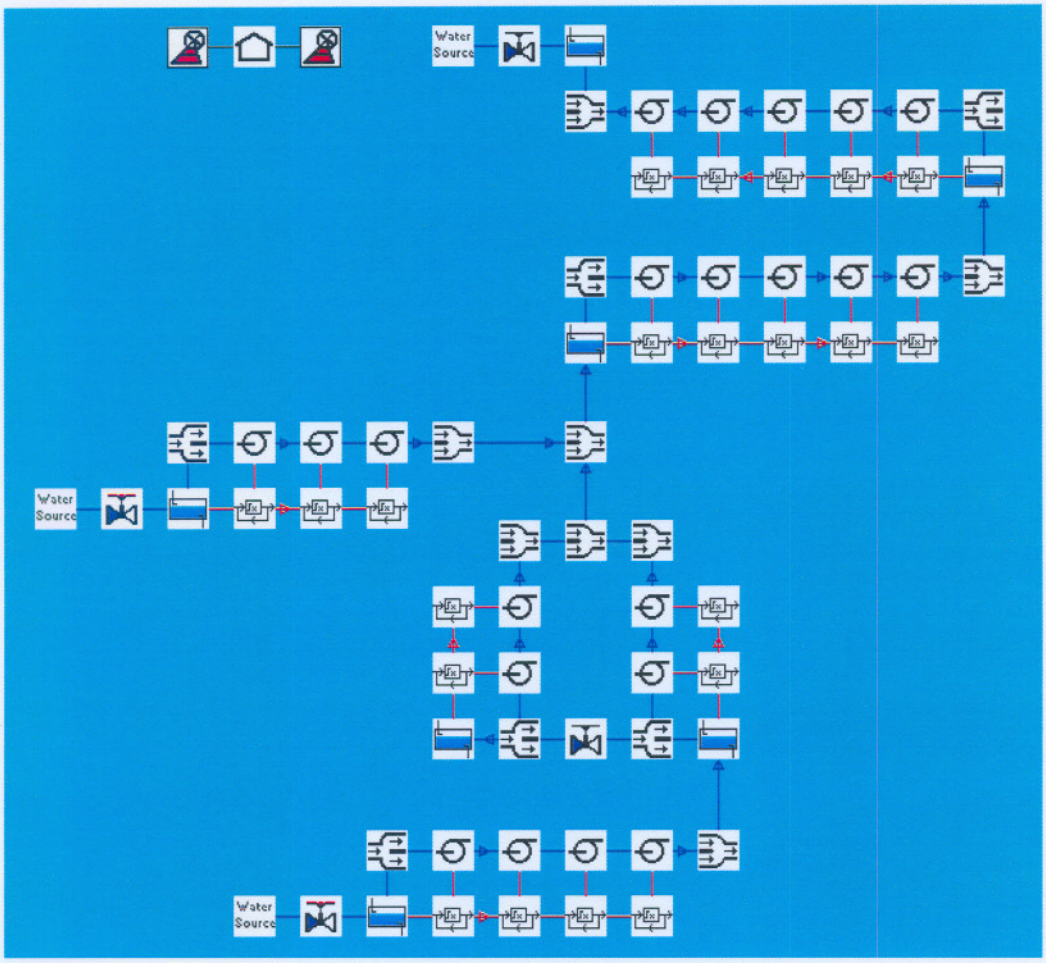


Figure 4.1 Layout of the simulation model.

- First control strategy:

The first control strategy implemented into the simulation model was the deactivation of all the pumps of the entire system for the specified consecutive five hours (07H00 to 12H00), while ensuring that no dams would overflow. This was done to find the maximum load that could be shifted. The total active pumps of the entire system and the various dam levels are shown in the following figures.

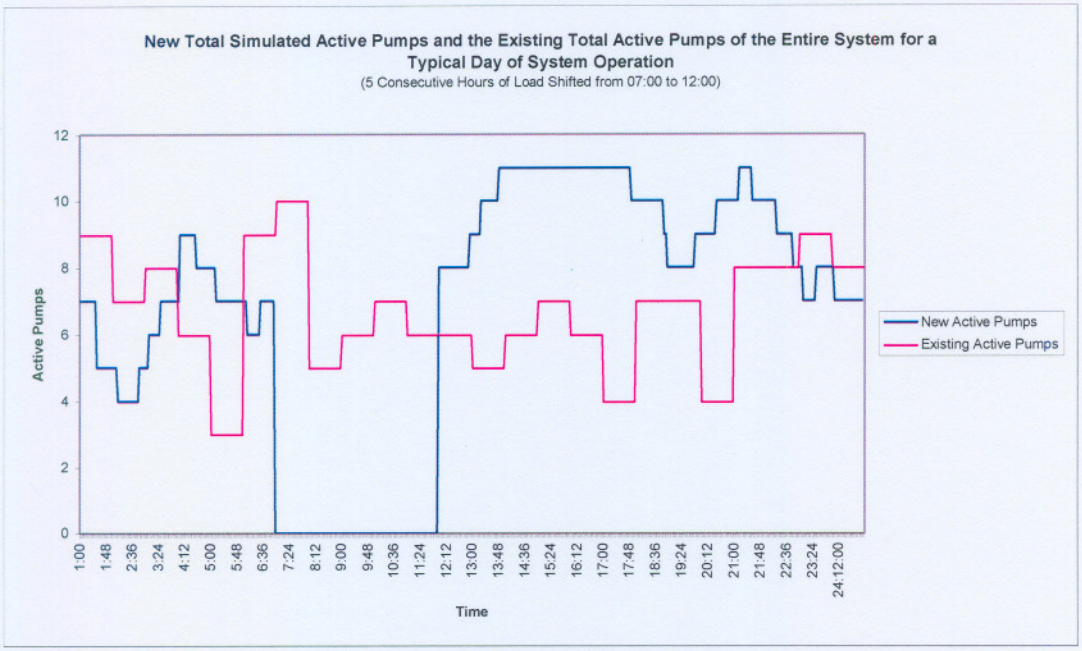


Figure 4.2 New proposed control total active pumps of the entire system and the total active pumps of the existing system. Five consecutive hours of load has been shifted from the 07:00 to the 12:00 slot.

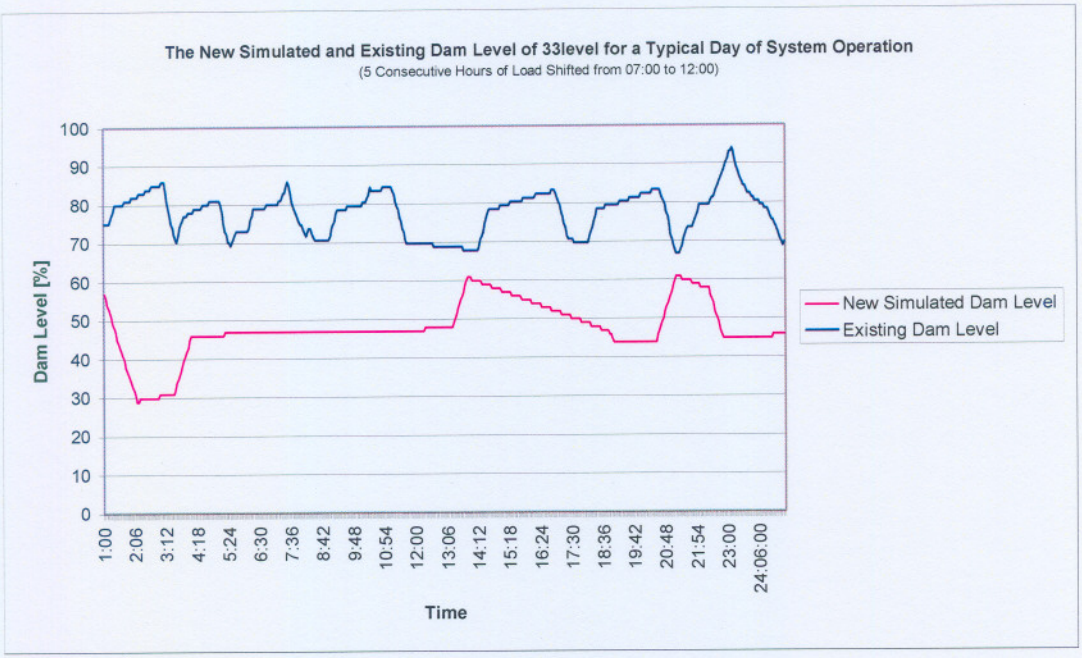


Figure 4.3 New proposed control dam level and the existing dam level of 33level, resulting from the five consecutive hours of shifted load from the system.

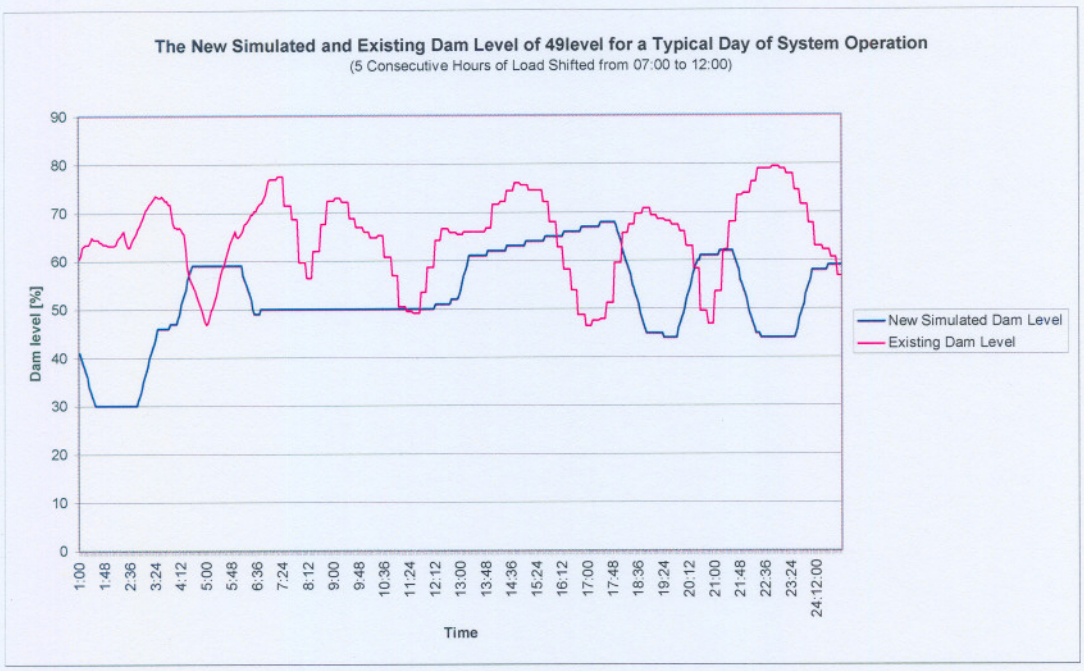


Figure 4.4 New proposed control dam level and the existing dam level of 49level, resulting from the five consecutive hours of shifted load.

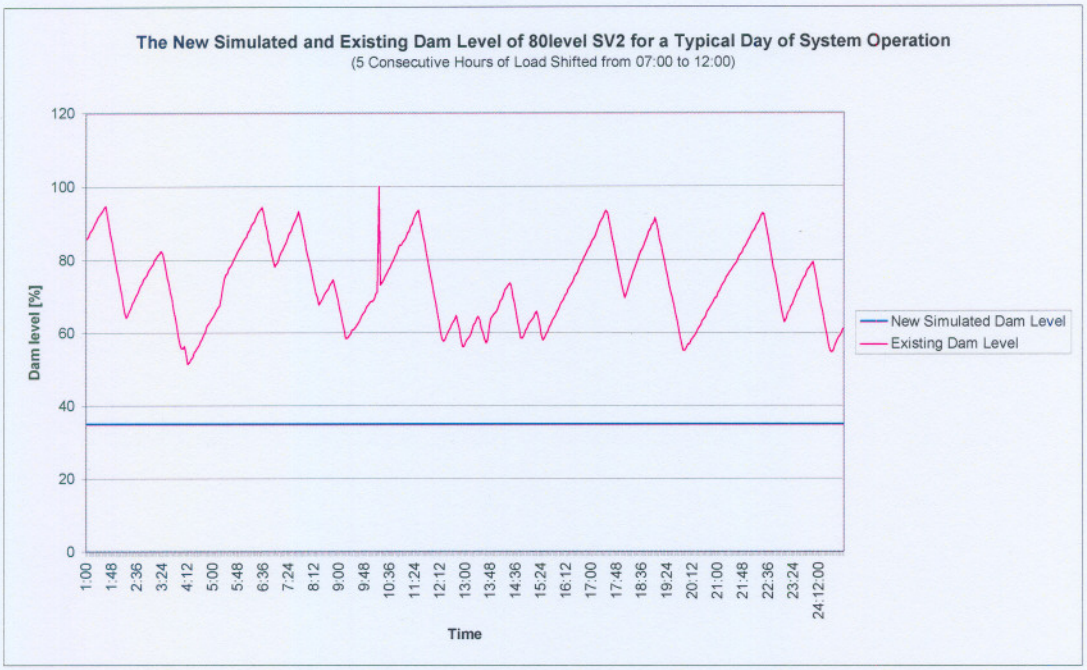


Figure 4.5 New proposed control dam level and the existing dam level of 80level SV2, resulting from the five consecutive hours of shifted load.

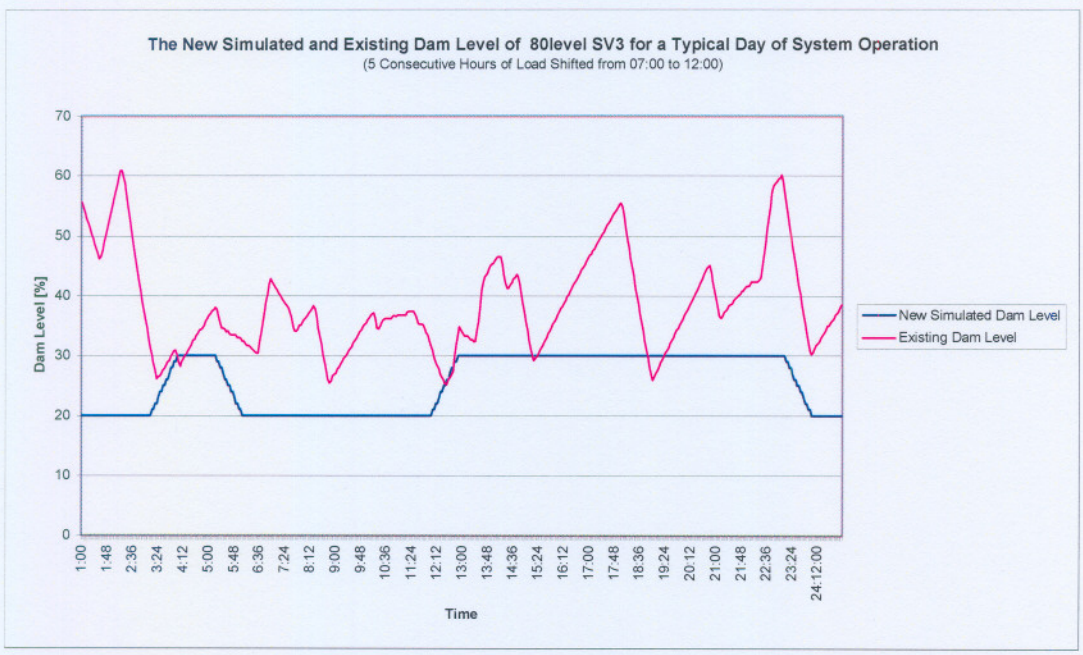


Figure 4.6 New proposed control dam level and the existing dam level of 80level SV3, resulting from the five consecutive hours of shifted load.

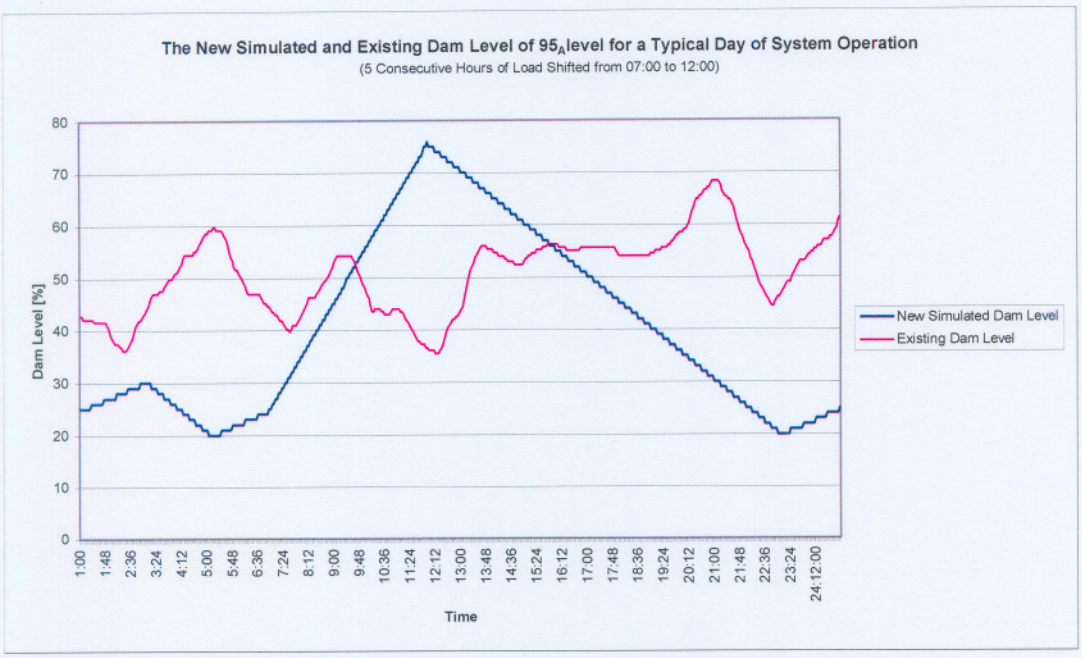


Figure 4.7 New proposed control dam level and the existing dam level of 95_A level, resulting from the five consecutive hours of shifted load.

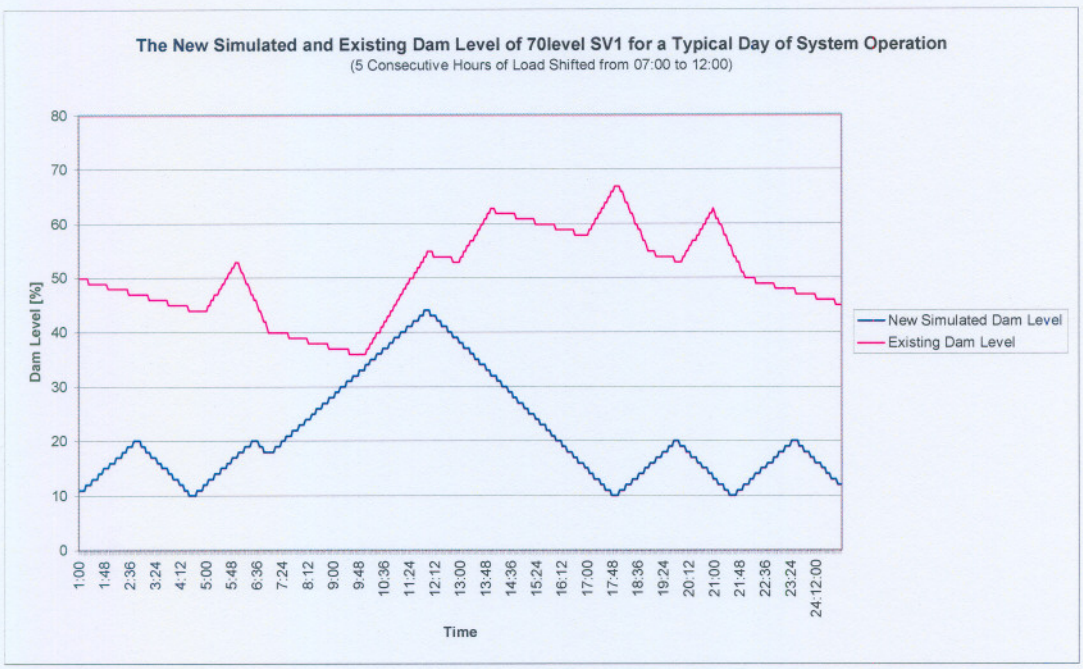


Figure 4.8 New proposed control dam level of 70level SV1 resulting from the five consecutive hours of shifted load.

The simulation showed that it was possible to shift a load of approximately 70000kWh while keeping all of the dam levels well within acceptable standards, with a maximum demand shift of 14MW over five hours.

It should also be noted that it was decided to use 9Ml, of the total 23Ml installed dam capacity on 80level, for emergency purposes. Table 4.1 shows the total energy usage of the system for a typical day of system operation.

$TOTAL_{EXISTING}$	$TOTAL_{NEW\ (SIMULATED)}$	% ERROR
365 853kWh	346 955kWh	5.45%

Table 4.1 Summary of the total energy usage of the entire system for a typical day of system operation. It can be seen that the system energy usage are slightly affected by the 5 consecutive hours of shifted load.

- Second control strategy:

The following figures represent the simulated total active pumps and various dam levels for the simulation where the total 5 hours of load shifted, was divided into two periods, from 07H00 to 10H00 and from 18H00 to 20H00. This was done to illustrate the possibility of shifting maximum load at different periods of the day.

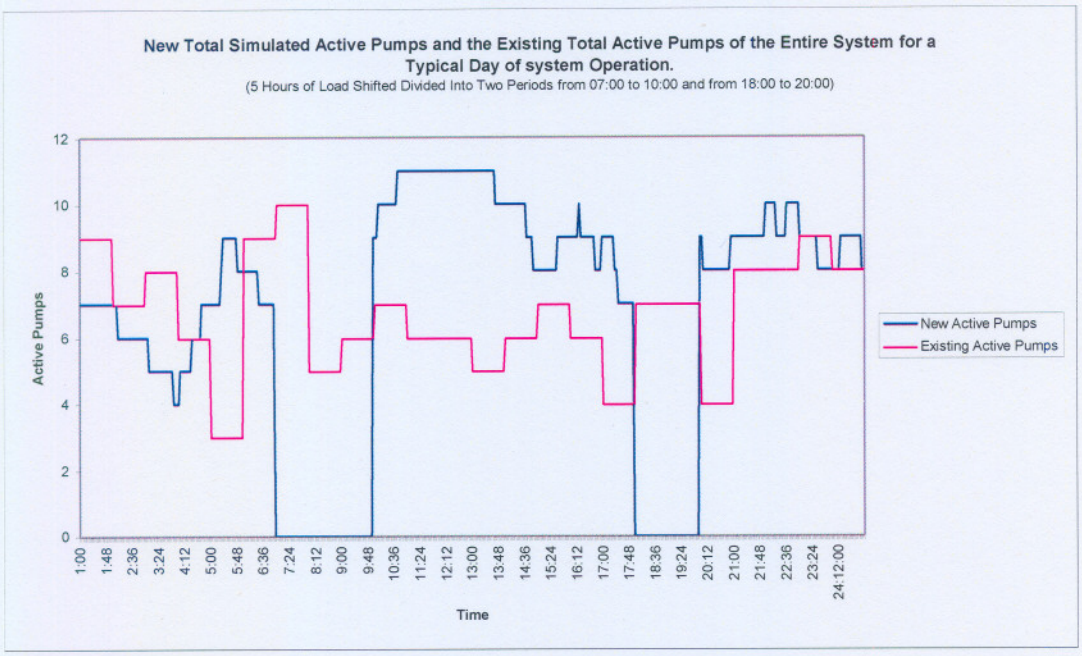


Figure 4.9 New proposed control total active pumps of the entire system and the existing active pumps for a typical day of system operation. Five hours of load has been shifted from two periods in the 24-hour operation.

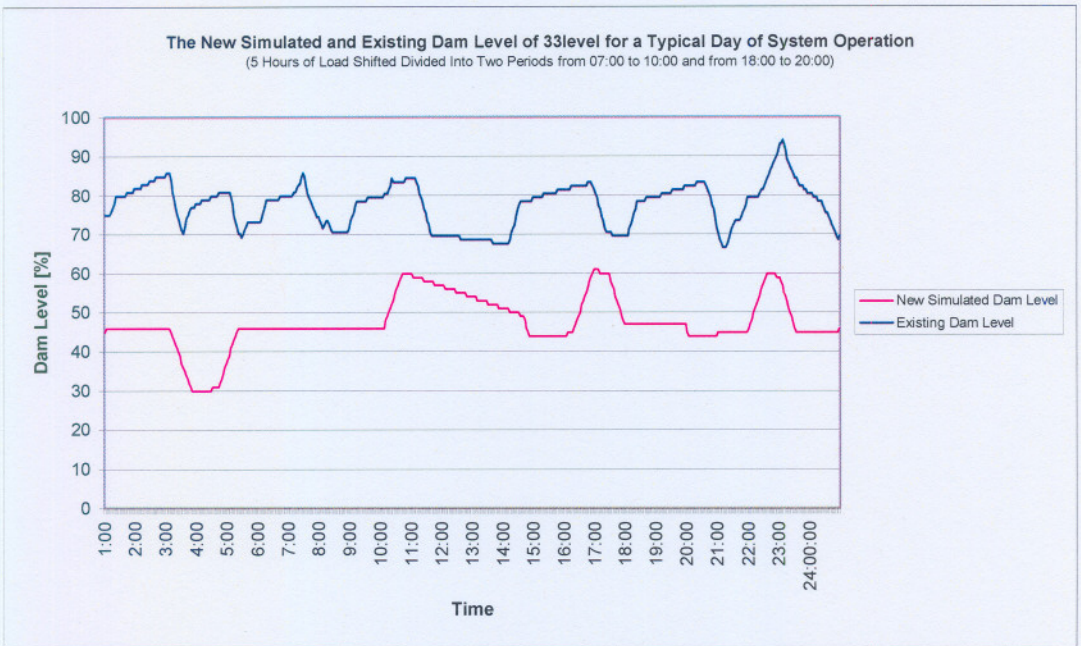


Figure 4.10 New proposed control dam level of 33level resulting from the shifting of 5 hours of load from two periods of time.

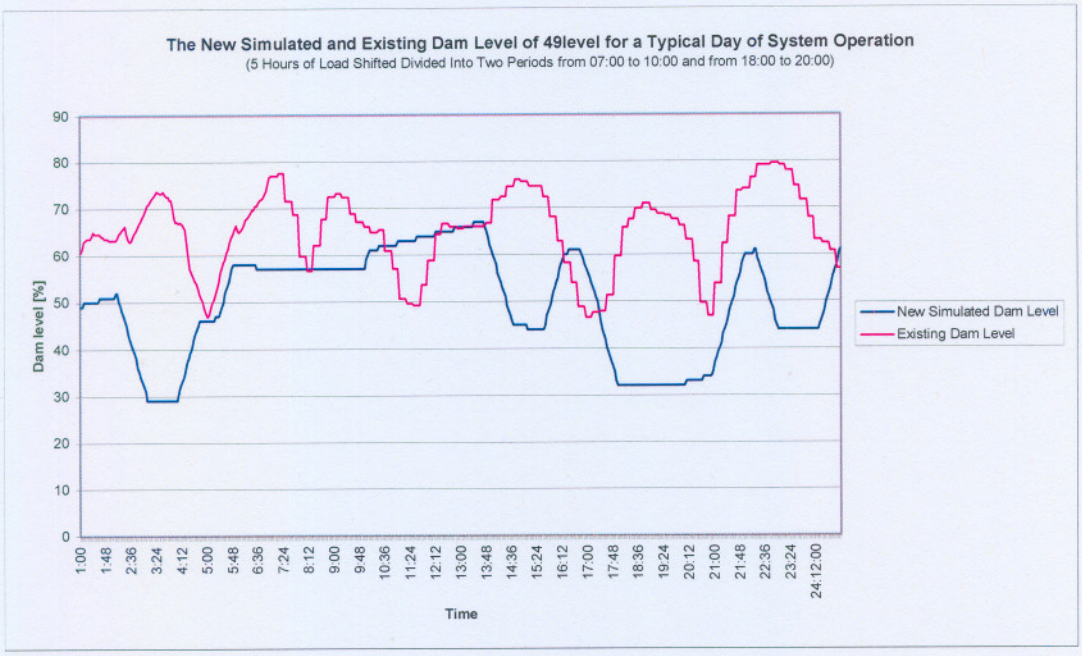


Figure 4.11 New proposed control dam level of 49level resulting from the shifting of 5 hours of load from two periods of time.

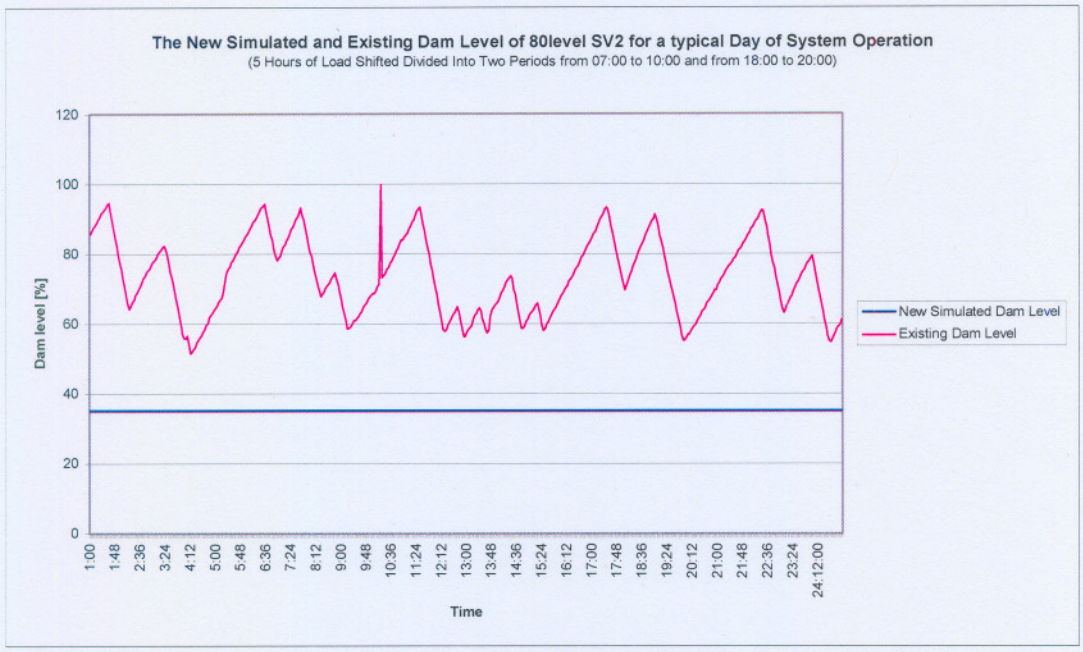


Figure 4.12 New proposed control dam level of 80level SV2 resulting from the shifting of 5 hours of load from two periods of time.

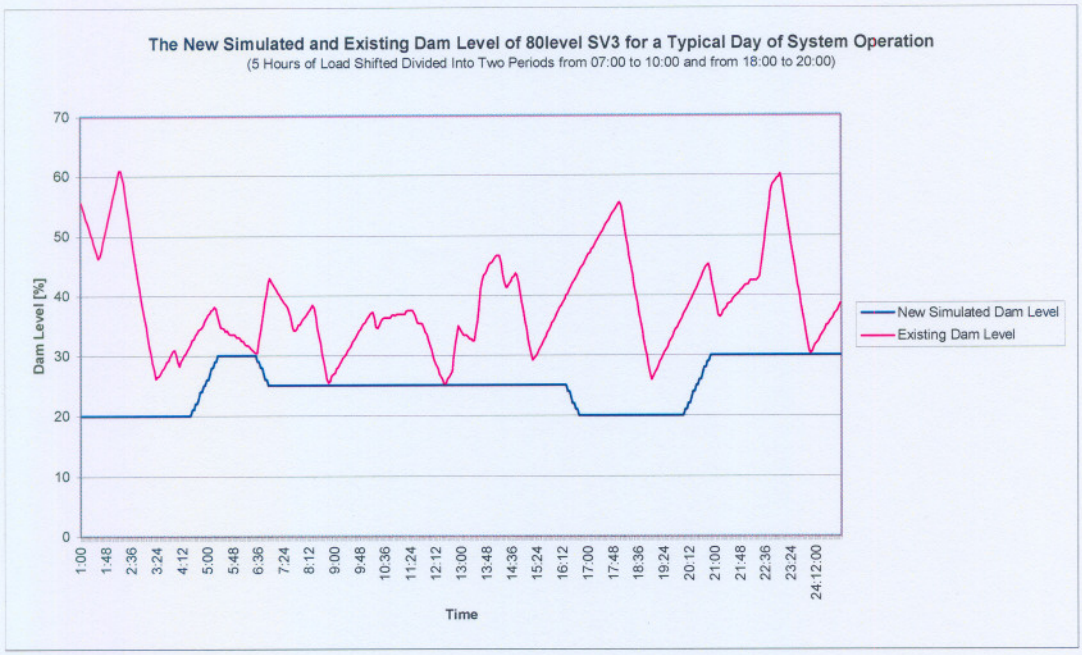


Figure 4.13 New proposed control dam level of 80level SV3 resulting from the shifting of 5 hours of load from two periods of time.

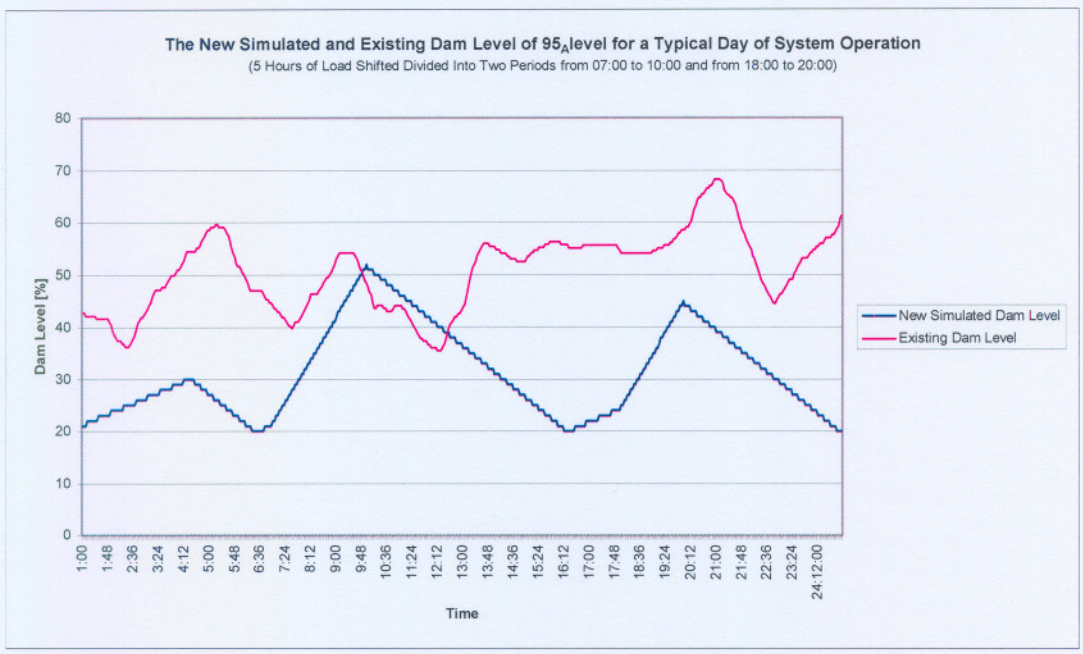


Figure 4.14 New proposed control dam level of 95_Alevel resulting from the shifting of 5 hours of load from two periods of time.

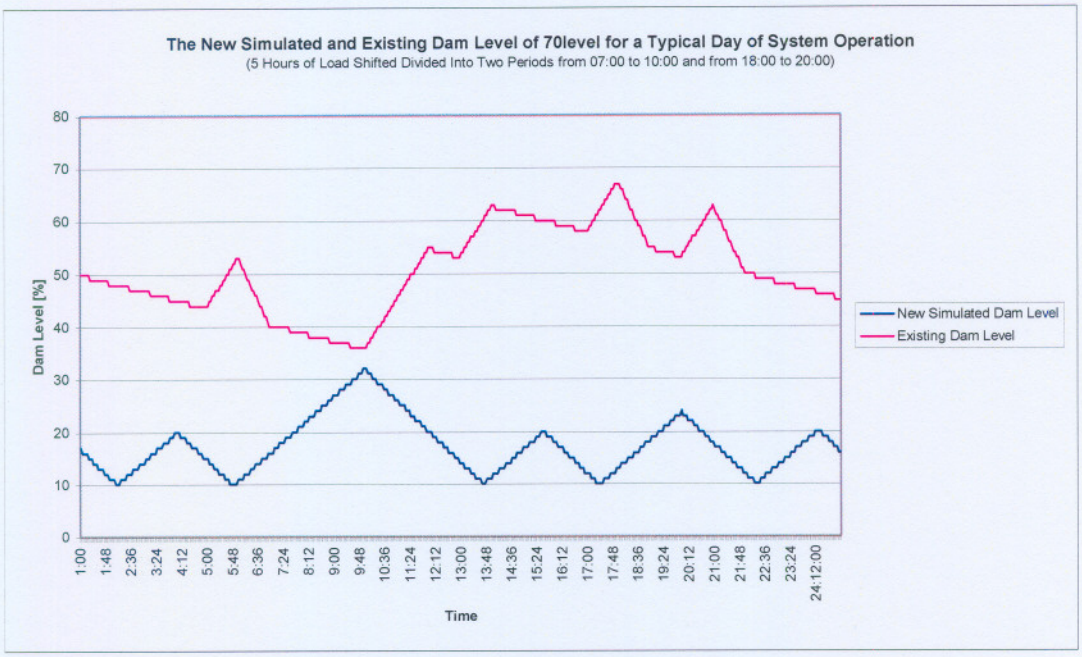


Figure 4.15 New proposed control dam level of 70level SV1 resulting from the shifting of 5 hours of load from two periods of time.

The simulation showed that it was possible to shift a total load of approximately 69 000kWh while keeping all of the dam levels well within acceptable standards, with a maximum demand shift of 13.77MW over five hours (divided into two periods). Table 4.2 the total energy usage of the system.

$TOTAL_{EXISTING}$	$TOTAL_{NEW\ (SIMULATED)}$	% ERROR
365 853kWh	343 049kWh	6.65%

Table 4.2 Summary of the total energy usage of the entire system for a typical day of system operation. It can be seen that the system energy usage are slightly affected by the 5 hours (divided into two periods) of shifted load.

The effect that these two control strategies have on the daily maximum demand (MD) of the total pumping reticulation system, for a typical day of system operation, are shown in Table 4.3.

LOAD SHIFT	ORIGINAL MD	NEW MD	% INCREASE
One-period	18.49MW	23.62MW	21.72%
Two-periods	18.55MW	23.84MW	22.19%

Table 4.3 Summary of the effect that the shifting of 5 hours of load has on the daily maximum demand (MD) of the entire system for a typical day of system operation. It can be seen that the maximum demand increases in both cases.

For the purpose of this study, the maximum possible load that could be shifted from the system was investigated (it was found to be 14MW), and two control strategies were studied. It should be noted that other control strategies could also be studied, i.e. various load shifting options could be studied according to a specific tariff structure of Eskom.

A specific tariff structure could for example require the shifting of load from certain peak times, but for a longer period than 5 hours. The effect that these kinds of RTP strategies would have on the rest of the system could easily be investigated. Examples of options are shown in Figure 4.16.

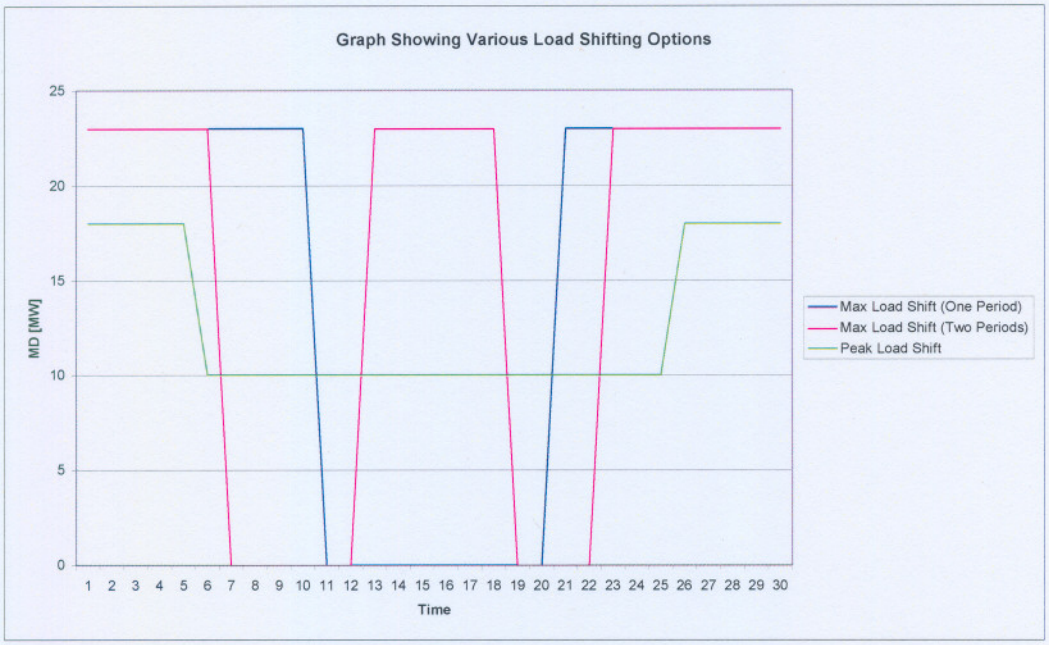


Figure 4.16 Load shifting options that can be followed. The purpose of this study was to find the maximum load that could be shifted without compromising the safety of the workers.

4.4 CONCLUSION

The application study of the pumping reticulation system showed that it is possible to shift load for either a single consecutive period, or more than one period of time. It was found that a total load per operational day of approximately 70 000kWh could be shifted without compromising the safety of the underground workers, with a maximum demand shift of approximately 14MW over 5 hours. If needed, other load shifting options (other than maximum demand shifts) can also be investigated, for RTP purposes.

It was decided, before starting any investigations, to use the 3Ml dam on 80 level SV2 and the two 3Ml dams on SV3 in the simulation model, thus leaving a total extra dam capacity of 14Ml. This extra emergency capacity will ensure that these critical dams will not overflow.

The study showed that it is possible to achieve load shifting via the implementation of control strategies using various physical controllers. The controllers used in the simulation were connected to the pumps and constantly monitored the dam levels. It was decided to restrict the dam levels of the entire system to 80% of their full capacity. The simulation showed that with the implemented control strategy most of the dams did not even reach 60% of their full capacity, thus ensuring the absolute safety of the system.

The total water flow from the underground workings amounted to approximately the same value as the original flow. The total energy usage of the system did not change dramatically, which show that the load shifting strategy did not really interfere with the normal system operation.

The shifting of load increases the daily maximum demand of the system. This result was expected because of the fact that the various dam levels rise when the system's pumps are de-activated. When the load-shifting period passes, the pumps of each level immediately attempt to reduce the water levels specified by the controllers. Most of these attempts will happen at the same time, and that is when a higher peak load of the system will be reached.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5. CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSIONS

This study proved that it was indeed possible to adapt the software package *QUICKControl* to a mining application.

The entire pumping reticulation system of a specific gold mine was simulated with the integrated simulation software tool, *QUICKControl*. The predictions made by the software program were verified with actual measured data from the system, such as dam levels, active pumps, water flows and energy usage.

Satisfactory results were obtained from the verification study for a typical specific day. The total daily pumped volume of water, from the underground workings to the surface mine water dams, were verified with an error of 1%.

The various dam levels of the system were verified with average errors less than 6% for a typical specific day of system operation. The total energy usage for a typical specific day verified with an error of less than 5% against the actual measured data.

A base year simulation was also conducted to try and determine the trend in the system's operation. By using control parameters on the dam levels, the philosophy of the system's operators was simulated. The predictions made by these simulations were verified against the actual measured data of an average typical day of system operation.

The total daily volume of water (for the base year), from the underground workings to the surface mine water dams, were verified with an error of 0.21%. The various dam levels of the system were verified with average errors less than 9% for an average typical day of operation. The total daily energy usage for this simulation of an average typical day verified with an error of less than 1% against the actual measured data.

It is these excellent verification results that demonstrate the success and accuracy of the simulation software program for simulation purposes. It should be noted that the verification results also provide proof of the potential of this simulation software for maintenance studies, e.g. by simulating water flows and comparing results to actual measurements, pumps operating under capacity could be tracked down. The verification results also show the value of the simulation tool for energy studies, e.g. load shifting, RTP etc.

The simulation program was also used to conduct various energy management studies. Various investigations showed that it was possible to shift a load of approximately 70000kWh from the daily system operation without flooding any underground workings, with a maximum demand shift of 14MW over a period of five hours. A saving of approximately R 300,000 per MW for load shifting could be possible (according to the MegaFlex tariff structure), resulting in a possible total annual monetary saving of R 4,200,000 for the mine.

Two control strategies were investigated: the maximum load could be shifted for five consecutive hours, or could be divided into more than one period and applied at different times of the day.

The most important parameter during the energy studies was the dam levels. These dam levels had to be constantly monitored, to ensure that none of the dams reach their maximum capacities. It is for this reason that an extra emergency dam capacity of 14Ml was made available on the critical 80level.

It was found that none of the dams reached their maximum capacities during the study. The total volume of water from the underground stayed approximately the same during the course of the investigation.

The daily energy usage of the entire system were compared with errors less than 7% for both control strategies, against the typical daily energy usage of the system. The maximum load shift, however, did have an increasing effect on the daily maximum demand (MD) of the system. The daily maximum demand of the system increased by approximately 22% (from 18.49MW to 23.84MW) for both control strategies.

5.2 SUGGESTIONS FOR FURTHER WORK

For the purpose of this study, the maximum possible load that could be shifted from the system was investigated, and two control strategies were studied. It should be noted that other control strategies could also be studied, i.e. various load shifting options could be studied according to a specific tariff structure of Eskom.

A specific tariff structure could for example require the shifting of load from certain peak times, but for a longer period than 5 hours. The effect that these kinds of RTP strategies would have on the rest of the system could easily be investigated.
Other pumping reticulation systems, e.g. smaller systems used in platinum mines, should be investigated to fully prove the accuracy and potential of the simulation program.

The energy investigations of this study should be verified by practically implementing the control strategies described in Chapter 4.

Although the daily MD of the system was not an active constraint during simulations, the control strategies to achieve maximum load shift should take MD into account (to keep it within acceptable boundaries) during practical implementation.

REFERENCES

CHAPTER 1

[1] US Department of Energy, Online, www.eia.doe.gov/oiaf/ieo/pdf/highlights.pdf, 25 October 2001.

[2] Lavine, M., Gadgil, A., Meyers, S., Sathaye, J., Stafurik, J., Wilbanks, T., "*Energy efficiency, developing nations and Eastern Europe: A report to the US working group on global energy efficiency*", International Institute for energy Conservation, Washington DC, June 1991.

[3] DME, "*White Paper on the Energy Policy of the Republic of South Africa.*" Department of Minerals and Energy, Pretoria, December 1998.

[4] Philip, B., "*Framework for improving energy efficiency in South Africa – the case of low-income household*", SEPCO Workshop, National Energy Regulator, November 2001.

[5] National Energy Regulator, "*Electricity supply statistics for South Africa: 1999*", NER, Postal address: PO Box 40343, Arcadia, 0007, 1999, p.4.

[6] Eskom, www.Eskom.co.za/main.asp?curl=faq%2Ftopicindex%2Easp%3Fcatid%3D1, 26 September 2001.

[7] National Energy Regulator, "*An integrated electricity outlook for South Africa*", NER, Postal address: PO Box 40343, Arcadia, 0007, 2002.

[8] Africa, A., "*Eskom: Demand Side Management, Short to medium term demand side strategy*", National Energy Conference, VW Marketing Conference Centre, Midrand, South Africa, July 2001.

[9] Eskom, "*Demand Side Management's information guide for Energy Services Companies*", Online, www.Eskom.co.za, Eskom, Postal address: PO Box 1091, Johannesburg, 2000, 2002.

[10] Kok, S., "*The impact of domestic solar water heaters on South Africa*", TEMM International (Pty) Ltd, Postal address: PO Box 55577, Arcadia, 0007, 1994, p.44.

[11] Eskom (DSM), Electricity Supply Statistics for South Africa, Electricity Demand Department, Postal address: PO Box 1091, Johannesburg, 2000.

[12] Eskom Tariffs, www.Eskom.co.za/tariffs.htm, 2002/2003.

[13] Kern C.F., "*Real Time Pricing Directive*", Key Customer Marketing, Eskom, May 1998.

[14] Pretorius, H.M., "*Scheduling of cogeneration facilities operating under Real Time Pricing*", Dissertation presented in partial fulfilment of the requirements for the degree Master of Engineering in the Faculty of Engineering, University of Pretoria, Pretoria, 1998.

[15] Eskom Tariffs, www.Eskom.co.za/tariffs/tariffs/megaflex.htm, 2004/2005.

[16] DME, 2004, "*Draft Energy Efficiency Strategy of the Republic of South Africa*" April 2004.

[17] DME, Energy balances, "*Energy balance for 1997*", www.dme.gov.za/energy/, Contact details: Tel: +2712 317 9000, Postal address: PO Box X59, Pretoria, 0001.

[18] Goldberg, I., "*South Africa's Mineral Industry*", DME, Pretoria, 1992, pp. 1-12.

[19] Statistics South Africa, "*Mining: production and sales, Statistical release P2041*", www.statssa.gov.za/Statisticalreleases, Contact details: Tel: +27 12 310 8095/839 0/8351, Postal address: PO Box X44, Pretoria, 0001, June 2000.

[20] Directorate: Mineral Economics, "*South Africa's Mineral Industry*", DME, Pretoria, 2003/2004, pp.15-30.

[21] Ryan, B., "*Impala Platinum: Jewel of the Bush*", Financial Mail: Corporate report, September 1999, pp. 21-22.

[22] Shone, R.D.C., Sheer, T.J., "*An overview of research into the use of ice for cooling deep mines*", Fourth International Mine Ventilation Congress, July 1988.

[23] Viljoen, R.P., "*Deep-Level Mining - A Geological Perspective*", Technical Challenges in Deep-Level Mining, 1990, pp. 411-427.

[24] Lane, I.A., Delport, J., "*Load Audits and Simulations to develop DSM Potential in the Mining Sector*", 1996.

[25] Mathews, E.H., Malan, A.G., Arndt, D.C., "*HVAC Control strategies to enhance comfort and minimise energy usage*", Energy and Buildings, Accepted for publication, 2000.

[26] Rousseau, P.G., Mathews, E.H.," *Needs and trends in integrated building and HVAC thermal design tools*", Building and Environment, Vol.28, No.4, pp.439-452, 1993.

[27] Placer Dome Western Areas Joint Venture, Production Results, "*Quarterly results for March 2000*", www.westernareas.co.za. Contact details: Tel: +2711 688 5000, Postal address: P0 Box 61719, Marshalltown, 2107.

[28] Placer Dome Western Areas Joint Venture, Production Results, "*Quarterly results for September 2005*", www.westernareas.co.za. Contact details: Tel: +2711 688 5000, Postal address: P0 Box 61719, Marshalltown, 2107.

CHAPTER 2

[29] Rousseau P.G., Mathews E.H., "*Needs and trends in integrated building and HVAC thermal design tools*", Building and Environment, Vol. 28, No.4, 1993, pp. 439-452.

[30] Van Heerden E., Mathews E.H., "*Applying an Integrated Building and HVAC Simulation Tool to Successfully Predict Energy Savings in Buildings*", Fifth International Conference for the International Building Performance Simulation Association, September 1997.

[31] Mathews E.H., Arndt D.C., Piani C.B., van Heerden E., "*Developing cost efficient control strategies to ensure optimal energy use and sufficient indoor comfort*", Applied Energy, Vol. 66/2, 2000, pp135-159.

[32] ENVIRON *2.5,* CSIR Mining Technology (Miningtek), 1997.

[33] Hirsch J.J., Winkelmann F.C., Bull W.F., Ellington K.L., "*POWERDOE, a windows-based visually oriented analysis tool*". In J.W. Mitchell and W.A. Beckman, Editors, Building Simulation '95 Fourth International Conference Proceedings, Madison, Wisconsin, USA, August 1995, IBPSA.

[34] Beckman W.A., Broman L., Fiksel A., Klein S.A., Lindberg E., Schuler M., Thornton J., "*TRNSYS the most complete solar energy system modeling and simulation software*". In A.A.M. Saying, Editor, Renewable Energy Climate Change Energy and the Environment: World Renewable Energy Congress, Reading, U.K., September 1994, Pergamoh.

[35] Mathews E.H., van Heerden E., "*A tool for integrated HVAC, building, energy and control analysis*", Part 2: control simulations with *QUICKControl*, Building and Environment, Vol. 34, 1999, pp. 451-467.

[36] Rousseau P.G., Moodie J.H.R., "*Computer program for energy policy support and energy savings in buildings: Appendix to the final report*", July 1995.

[37] Mathews E.H., van Heerden E., Arndt D.C, "*A tool for integrated HVAC, building, energy and control analysis*", Part 1: Overview of *QUICKControl*, Building and Environment, Vol. 34, 1999, pp. 429-449.

[38] Jansen van Vuuren S.P., "*A thermal storage system for surface refrigeration plants*", Journal of the Mine Ventilation Society, May 1983, pp. 36-52.

[39] Deichert J., Dorgan C.B., Elleson J.S., ASHRAE - Thermal storage, 1999.

[40] Els, R., "*Potential for load shifting in ventilation and cooling systems*", Dissertation presented in partial fulfilment of the requirements for the degree Master of Engineering in the Faculty of Engineering, University of Pretoria, Pretoria, 2000.

[41] Mills, A.F, "*Heat Transfer handbook*", IRWIN Boston, 1992.

[42] McQuiston, F.C., Parker, J.D., "*Heating, Ventilating, and air conditioning: Analysis and Design*", Fourth Edition, John Wiley and Sons, Inc., 1994.

[43] Rousseau, P.G., Moodie, J.H.R., "*Computer program for energy policy support and energy savings in buildings: Appendix to the final report*", July 1995.

[44] Daugherty, R.L., Franzini, J.B., "*Fluid mechanics with engineering applications*", McGraw-Hill, 1977.