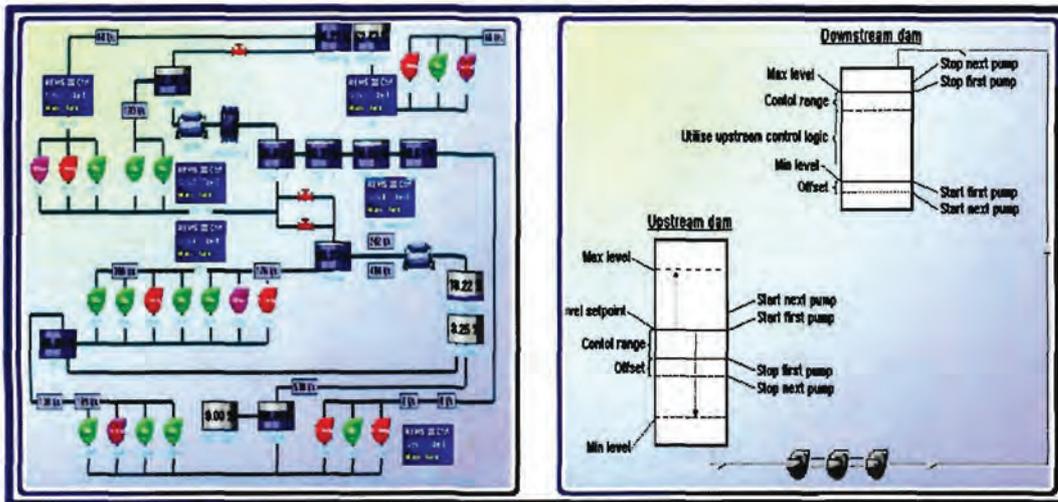


2. Developing a novel solution



A need for a simulation and control system for mine water pump systems was identified. This chapter explores the actual requirements of such a system.

2.1. Prelude

Chapter one clearly described the need for a novel control system that can be utilized to achieve electricity cost savings and shift electrical load. Also mentioned were the requirements that such a system should meet in order to fulfil those needs that will ensure its success in the industrial sector.

This chapter describes the development of a new control system that will answer the need identified in chapter 1. The system is called, and will from here on be referred to as REMS (Real-Time Energy Management System). The sub chapters of this section describe the development stages of the system and the philosophy and control algorithms that will ultimately realise the defined goals.

Section 1.2.5 summarises the problem statement devised in chapter one. Sections 2.3, 2.4 and 2.5 of this chapter describe the development of a solution engineered to solve this problem statement. The first step in engineering a novel solution is to list the required solution requirements, input and output.

2.2. Development goal

The goal of this chapter, and ultimately this research, is the development of a control system. The main result of this study will be a computer program focussed on the need as identified in chapter one. This computer program or control system is dubbed REMS.

This chapter is focussed on developing the philosophy behind REMS that will guide and control its thinking and abilities. The input and output of the system are discussed and the development specification is fabricated from the defined set of requirements.

The next chapter, chapter three, is focussed on taking the newly developed REMS philosophy and moulding it into a practical system that can be used in the industrial sector.

2.3. Ascertain solution requirements

2.3.1. Understanding the requirements

Chapter 1 concluded with the need for this study (Section 1.2.5) and listed the investigation into other possible systems that could have been used or claim the ability to control water pump system. Section 1.2.5 broadly sketched the need for a system with given attributes. Taking this list of attributes and building on it by looking at the properties of the systems discussed in chapter 1, it can be concluded that a new novel solution is needed that adhere to and combine the following specifications:

1. The solution must be able to realise electrical running cost savings in the operation of industrial water pumping systems by calculating optimised schedules for the pumps of the system.
2. It must also be able to shift electrical load in the automated control of industrial water pumping systems.
3. The system or solution must be engineered in such a way that it can predict or calculate the potential savings and load shifting potential of any proposed system or project before any implementation has commenced.
4. The solution or system must incorporate automated control. The system must be engineered to be capable of automated control of water pumping systems components in the industrial environment.
5. The system must perform control of the water pumping system while conforming to all safety and environmental constraints. The production and throughput of the system or plant must not be compromised.
6. This load shifting and running cost reductions must be realised through the scheduling of electrical pumps in industrial water pumping systems to utilise profiles of electricity pricing. This schedule must be continuously recalculated, based on real-time simulation results.

7. Any system has to take into account the cost of controlling pump equipment. The overall running cost, including maintenance, operator and electrical cost must be lowered.
8. A system that is unconditionally reliable and stable.
9. A system capable of simulation that can be used for optimisation and project investigations.
10. A system that can act upon real-time data such as unforeseen changes in the controlled environment.
11. A system that can keep track of its own performance in terms of load shifted and realised savings.
12. A system that incorporates an alert/alarm system to notify anyone in case of emergencies or malfunctions.

2.3.2. Evaluating the problem environment

An important step before developing a system or solution such as this, is to first understand the intended operation environment [96]. During the initial development of REMS most of the proposed projects were water pumping systems found in many typical South African deep level mines.

This section will explain the circumstances on a typical South African mine surrounding the water pumping system. This insight will ensure the feasibility of the solution in this unique environment.

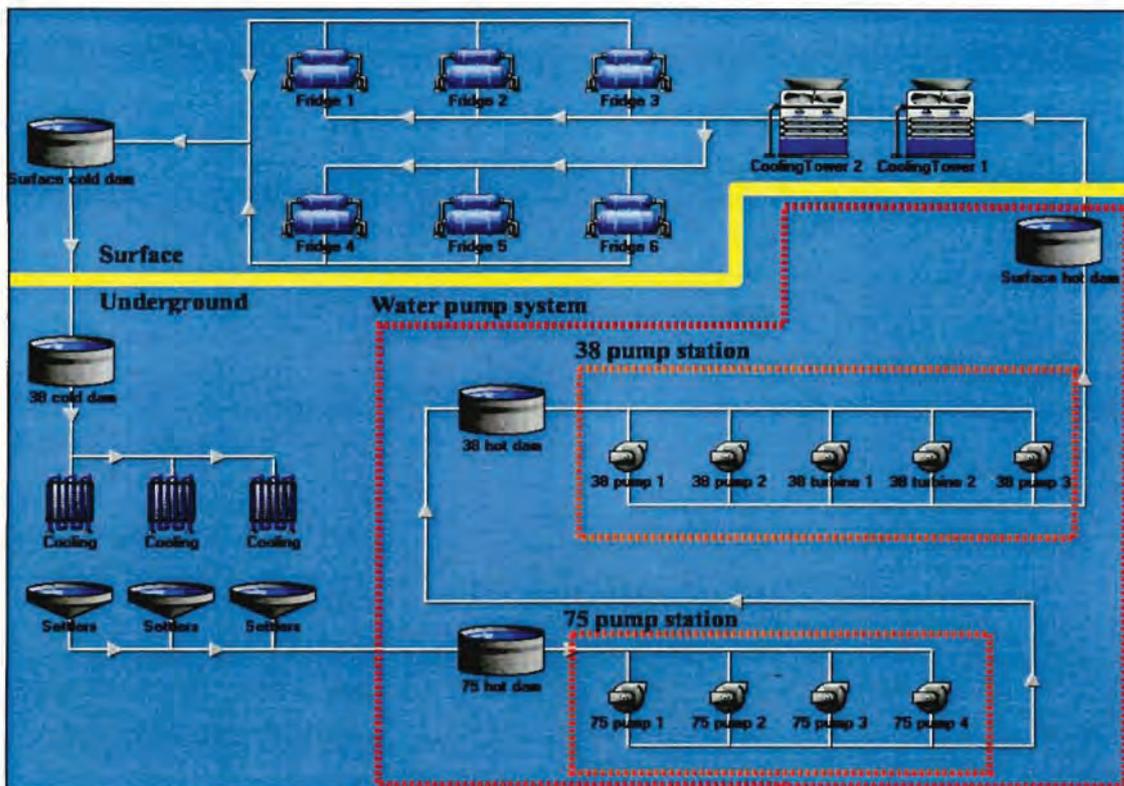


Figure 2-1 Water cycle of typical gold mine

Figure 2-1 displays the water cycle of a typical deep level mine. Section 1.2.2 gives a full discussion on the mine water cycle and its components. The water pumping system is a sub system of the water cycle. It is the system responsible for delivering the used water from the mine to the surface.

The water pump system is usually subjected to many control limitations, such as minimum and maximum dam levels, the maximum number of running pumps per pump station etc. These limitations have to be incorporated into the control philosophy and should not be violated.

2.3.3. Finding solution input

The system input is the information available to the system or solution in normal operational conditions. This information will drive the control algorithm and invariably influence the system output.

The input can be categorised into three groups. These are:

1. **Set input:** These input are once-off set values like the size of a pump, the capacity of a dam, the number of pumps present on a pump station etc. These inputs describe how the system ‘looks’ and do not change under normal operational conditions.
2. **Constraints (Constraining input):** These are the control and operational constraints. A typical example of this is the user defined maximum dam level for a certain dam or the maximum number of simultaneously running/operational pumps allowed on a given pump station.
3. **Live input:** These inputs change continuously under normal operational circumstances. This is live data portraying the current state of the controlled system and its components. These include real-time dam levels and pump statuses.

Set inputs:

System build-up	This information sketches the system setup. This include the number of pumps, dams, valves etc. and how these components relate to one another.
Pump information	Information on the flow, power usage and characteristics of the electrical pumps.
Dam information	Capacities and information regarding the dams.

Table 2-1 System set input

The system build-up input is supplied by the operator. The build-up of the system, in this case, is done by using the REMS interactive GUI (Graphical User Interface). The operator builds a representation of the water pump system in the GUI, supplying the information that dictate how the components of the system relate to one another.

The operator supplies pump information as well. This information is fed into the GUI as it is needed for calculating flow and effectiveness of the pump groups. Like the pump information, the operator also supplies dam information.

Constraints (constraining inputs):

Maximum dam levels	This specifies the maximum level for each dam in the system. This could be a single value or a profile giving a value depending on the time of day or week.
Minimum dam level	Same principle as the maximum dam level.
Maximum number of running pumps per pump station	This specifies the maximum running pumps per pump station. This could be a single value or a profile giving a value depending on the time of day or week.
Control philosophy settings	These settings dictate how the control philosophy reacts. See more in section 2.4 on the different control philosophies and the settings that dictate their behaviour and response.

Table 2-2 System constraining input

The constraints of the system are also supplied by the operator. This information is usually changed more often than the set input. Altering these constraints can seriously affect the outcome and success of REMS. These settings usually dictate the trade-off between success and safety.

The maximum dam levels are specified by the operator, taking into consideration the size of the dam and the flow of water into the dam. Also the time it takes for the dam to overflow in case of pump station failure. The higher the allowed dam level, the higher the risk, but also the more buffer space available to the control system, which increases the load shift potential.

The minimum dam levels work on the same principle. Lowering this value increases the risk of pumps running dry etc. But lowering the allowed minimum dam levels also

increases the buffer capacity available to the control system, resulting in bigger load shift potential.

The maximum number of running pumps per pump station is usually determined by the maximum pressure the water columns can handle. When too many pumps are running or operational in a pump station the water column, into which the pump station feeds, runs the risk of bursting. Another factor that has to be considered is the supply stations that provide the pump stations with electricity. In some cases the supply capacity of the stations is not big enough to handle all the pumps running simultaneously.

The live inputs are:

Dam levels	Relays the actual dam levels.
Pump statuses	Reports on the statuses of the pumps.
Valve statuses	Reports on the statuses of the valves.
Electricity unit price	This information supplies the cost of a unit electricity for any time during the day, week and month.

Table 2-3 System live input

The live input is information that portrays the real-time status of the system. This information is read and measured by probes and measuring equipment and relayed to the SCADA (Supervisory Control and Data Acquisition) and control room. This dataflow network consists of a series of PLC's interconnected by a copper cable and/or optic fibre network.

2.3.4. Defining required solution outputs

REMS is primarily designed to realise electrical running cost reductions and to shift electrical load through the control of a water pump system. The first output of REMS is therefore instructions on how this water pump system elements must be controlled to realise these goals.

The instructions on how the water pump system must be controlled, come in the form of pump control schedules as suggested by Lane [47] and explained in chapter one. These control schedules dictate the on/off schedules for the electrical pumps in the water pump system.

REMS is also designed to calculate the potential of any project before implementation. This information is vital to investigate the feasibility of any proposed project. This will enable engineers to accurately predict if a project will be financially profitable in terms of needed capital inset over the financial gain resulting from implementation.

Thus, a second output required from REMS is detailed data and information that predict how a project will perform after the implementation of REMS. This information will come in the form of detailed daily real-time data on how the project will perform, including dam levels and pump status profiles.

How this data is processed to yield the success in terms of predicted electrical running cost reductions and load shifted, is fully explained in chapter 4.2. This chapter also explains how the success of a project is measured from real-time data detailing the dam levels and pump status profiles.

2.4. Engineering solution philosophy

The solution philosophy explains how the solution will prioritise the input and actions taken to ultimately reach the point where the output is generated. The solution philosophy of REMS is explained by the next figure (Figure 2-2) and sections 2.4.1 to 2.4.4.

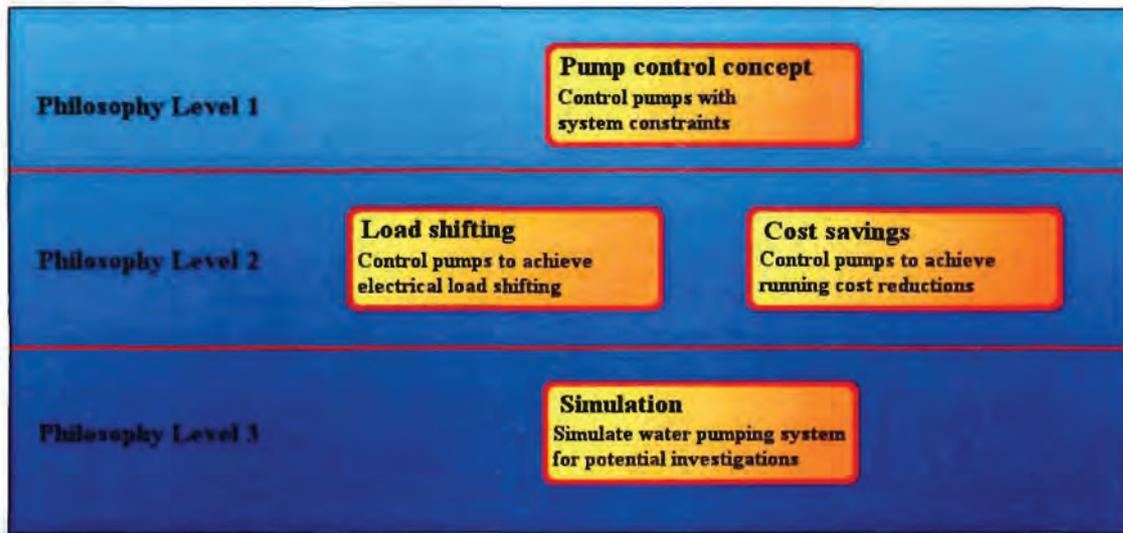


Figure 2-2 REMS control philosophy

2.4.1. Pump control concept

REMS is designed to control water pump systems. The first and most important factor that has to be considered in the design of this control system is the given control constraints. These constraints, for example, dictate the minimum and maximum dam levels and the maximum number of pumps that is allowed to be running simultaneously in any given pump station.

If these constraints are violated, dams could overflow, water columns could burst etc., resulting in system downtime, production loss, and ultimately, financial loss. This explains why the control constraints are the first priority in the control algorithm. This is illustrated in Figure 2-2.

2.4.2. Load shift philosophy

One of the primary factors that motivated the development of this control system is electrical load shifting. Second in priority to the control constraints, REMS is developed to achieve load shifting by calculating the pump control schedules in such a way that load is shifted from peak hours to off-peak hours. See Figure 2-2.

This is in accordance with Lane's [47] suggestion as discussed in chapter one. The principle of shifting load by optimising the control schedules of the electricity

consuming components of a system is not a new one. The load shift philosophy is engineered to utilise this principle.

2.4.3. Cost saving philosophy

REMS was also developed to achieve electrical running cost reductions. Note that the philosophy does not attempt to lower running cost by reducing workload or running time, but rather to re-schedule workload to inexpensive billing periods. An important property of this philosophy is that it will not have a negative impact on production whatsoever.

This principle is on the same priority level in the system philosophy as load shifting. This is illustrated in Figure 2-2. Realising electrical running cost, much the same as the load shift philosophy, attempts to re-schedule the workload from periods when the electricity costs peak, to periods where electricity costs are lower or ultimately the lowest.

2.4.4. Simulation element

A further requirement set to REMS is the ability to investigate the potential of any project before any implementation has commenced. This information enables engineers to calculate the feasibility of any project. Because this feature is not used or activated during live control of the water pumping system, it is at the bottom priority level of the system philosophy. See Figure 2-2.

Section 2.5.3 explains how predictions are achieved by the introduction of simulation structures, utilised to simulate proposed projects.

2.5. Solution algorithm

The solution algorithm is the heart of the engine that will calculate the pump control schedules that will be used to control the pumps. The algorithm is also responsible for achieving control within the set control constraints and boundaries set by the user.

The algorithm brings together the philosophy as set out in sections 2.4.1, 2.4.2, 2.4.3 and 2.4.4 of this chapter. The algorithm takes into account all the input as set out in section 2.3.3.

The final solution algorithm will consist of the components illustrated in the next figure (Figure 2-3) and discussed in sections 2.5.1 - 2.5.3.

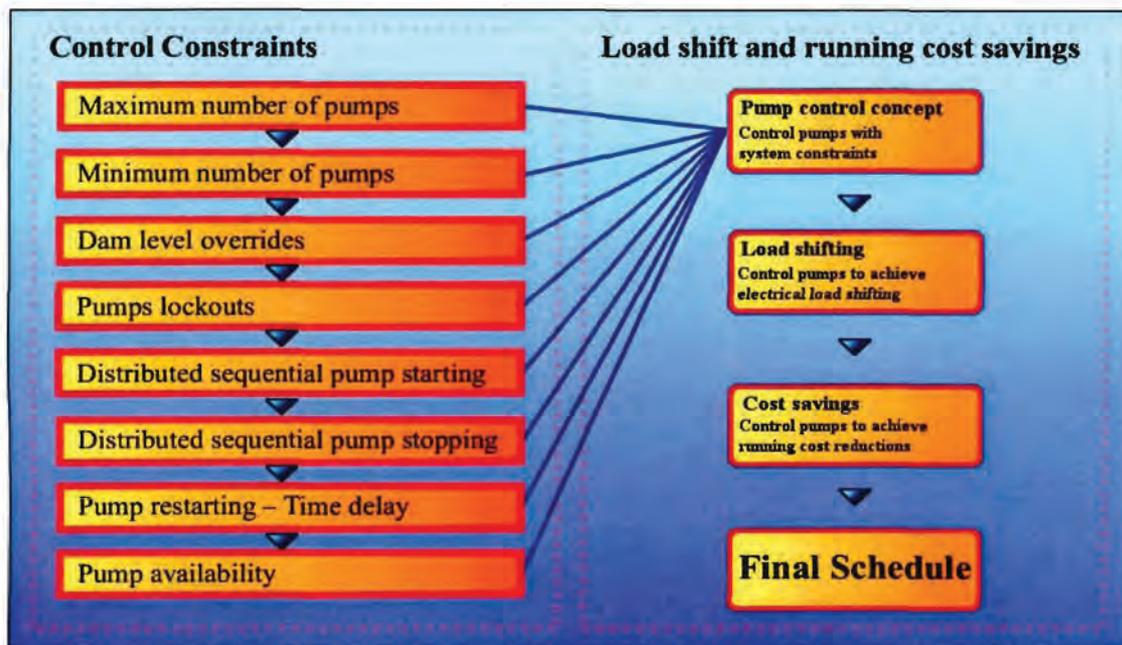


Figure 2-3 Control algorithm

2.5.1. Control constraints

Maximum number of pumps

The first constraint that is constantly checked by the control algorithm is the maximum number of pumps allowed to be running simultaneously on a given pump station. The user sets the setting, with the functionality provided by a composed value. The value of the composed value may change over a period of time.

On every control run, which occur every 1 to 5 seconds, the “maximum number of pumps” setting will be checked on every pump station to ensure that the settings are not violated.

Furthermore, the output of the control algorithm responsible for load shifting and reducing running cost is measured against this constraint. The algorithm can therefore not compose a pump group schedule that will violate this constraint.

Minimum number of pumps

The “minimum number of pumps” setting works on the same principle as the “maximum number of pumps” constraint. This setting is also determined by the functionalities provided by the composed value.

During every control run, every pump station is checked to make sure this constraint is not violated. The output of the control algorithm is also measured against this constraint.

Dam level overrides

The dam level overrides take over the control of the pump station if the dam levels exceed the “maximum dam level” setting or fall under the “minimum dam level” setting. When this happens the control is only focussed on correcting the error and no consideration is given to load shifting or reducing electrical running cost.

This feature is only intended for emergencies and is not part of the normal control philosophy.

Pump lockout

Pump lockouts occur when pumps fail, run a high risk of failing, or when pumps undergo maintenance. When a pump is locked out, it may not be started. This constraint is also checked on every control run. The output of the optimisation algorithm is measured to prevent schedules that dictate these pumps to be started.

Distributed sequential pump starting

This constraint, also set by the user, dictates the period that has to pass between the sequential starting of two pumps. It is not allowed for two pumps to start simultaneously. This is to prevent pump columns bursting and surge problems within

the power supply stations. This control constraint will activate when two pumps are scheduled to start simultaneously.

Distributed sequential pump stopping

This setting or constraint will act in the same way as the previous setting, preventing two pumps stopping simultaneously.

Pump restarting – time delay

In some cases it may happen that the starting of a pump fails. This control parameter will activate, prompting the pump to restart after the time period provided by the user. If the pump fails to start for a second time another pump will be started.

Pump availability

This constraint will continuously communicate to the SCADA, determining which pumps are available to start and which are not. The SCADA monitors a series of conditions on the pumps that include oil pressure, bearing temperature etc. When one of these measurements is not up to standard, the SCADA will publish the pump as not available to start. This functionality will then make sure that this pump is not prompted to start.

2.5.2. Load shift and running cost savings

REMS's pump control philosophy is applied to each pump station. The pumps in a given pump station pump water from a source dam, or further referred to as the upstream dam, to a destination dam, or further referred to as the downstream dam. The next figure illustrates this.

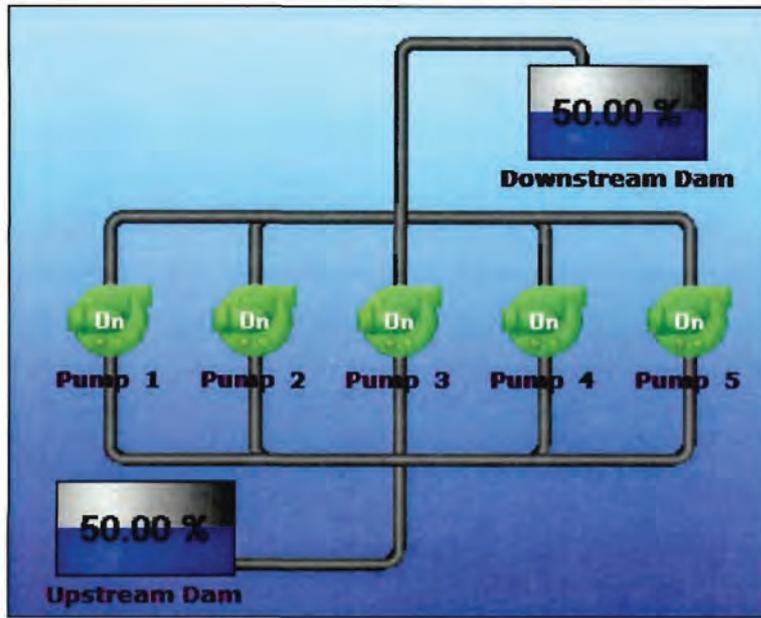


Figure 2-4 Pump station set-up

The pump group controller consists of two sections: the upstream controller and the downstream controller. The upstream controller is responsible for the water level in the upstream dam. The downstream controller is responsible for controlling the water level in the downstream dam. Consider the following figure for the sake of explanation.

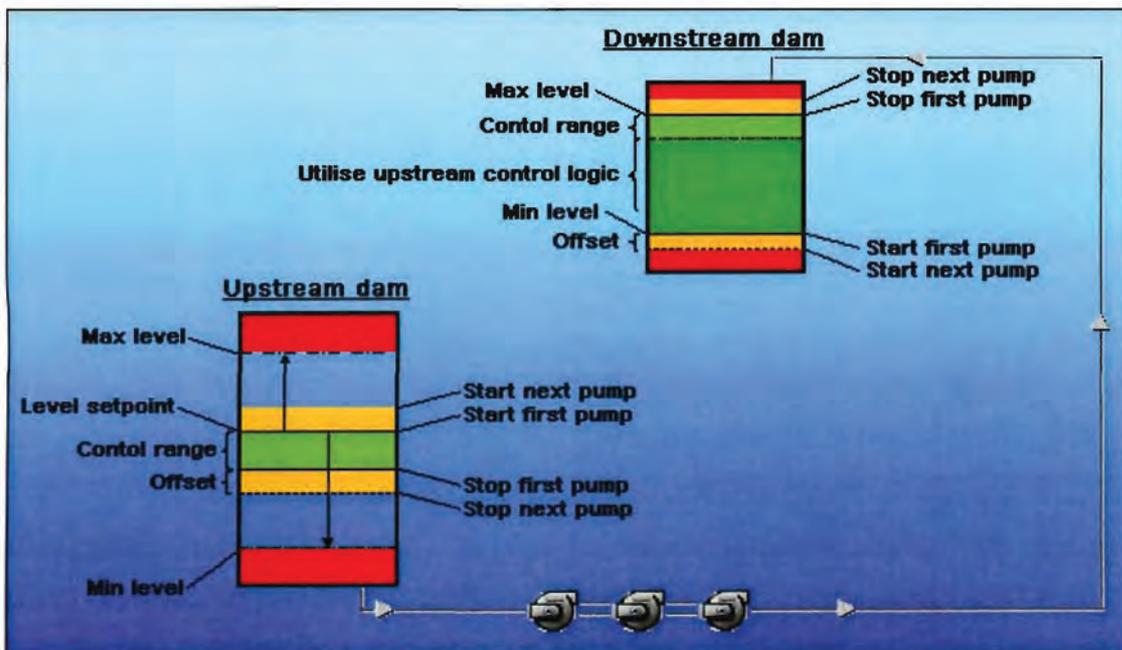


Figure 2-5 Schematic control philosophy

The downstream controller checks the downstream dam boundaries. The controller will stop the first of any running pumps in the pump group as soon as the water level in the downstream dam reaches the specified downstream maximum dam level. If the downstream dam level still keeps rising, pumps that are still running will be turned off one by one as the level rises in increments of the specified downstream offset.

The upstream controller works by using an upper bound control parameter. This will, from here on, be referred to as the upper bound. The upper bound is a profile consisting of 24 values. Each of the 24 values corresponds to an hour of the day. When the upstream dam level exceeds the upper bound for a specific hour, the upstream controller will start an additional pump in the pump station. If the upstream dam level exceeds the upper bound plus the upstream offset, the upstream controller will start another pump in the pump station.

When the upstream dam water level drops below upper bound, minus the upstream control range, the controller will stop a running pump on the pump station. When the upstream dam level drops below the upper bound minus the upstream control range, minus the upstream offset, the upstream controller will stop yet another pump in the pump station.

The upper bound profile is calculated using the electricity price profile. This profile, like the upper bound profile, consists of 24 values. REMS creates an upper bound profile for each of the pump groups.

The electricity price profile can be a fixed profile set by the user, or it can be a variable profile given by ESKOM. Currently REMS uses the Megaflex pricing profile as its electricity price profile. The mines where REMS is installed, are billed according to Megaflex.

On any given day, the 24 values of the upper bound profile are calculated using the following formula:

$$Upperbound_i = MinUB + \frac{(RTP_i - MinRTP) \times (MaxUB - MinUB)}{(MaxRTP - MinRTP)}$$

Where	MinUB -	Minimum Upper bound or Upstream Minimum Dam Level
	MaxUB -	Maximum Upper bound or Upstream Maximum Dam Level
	RTP _i	Electricity unit price for hour I
	MinRTP -	The minimum value of the electricity price profile
	MaxRTP -	The maximum value of the electricity price profile

Equation 1: Upper bound

In this way, if for a specific hour the electricity price is relatively high, the related Upper bound value will also be high. When the Upper bound value is high, pumps will be shut down. This also works the other way around, for times when the electricity price is low. In this way electrical costs are brought down by running more pumps when the electricity cost is low and running fewer pumps when the electricity cost is high.

ESKOM specifies a DSM high peak period, which is also called the peak period. It is the purpose of REMS to shift load out of this period. This is passively achieved by reacting to the Megaflex profile with the use of the Upper bound principle.

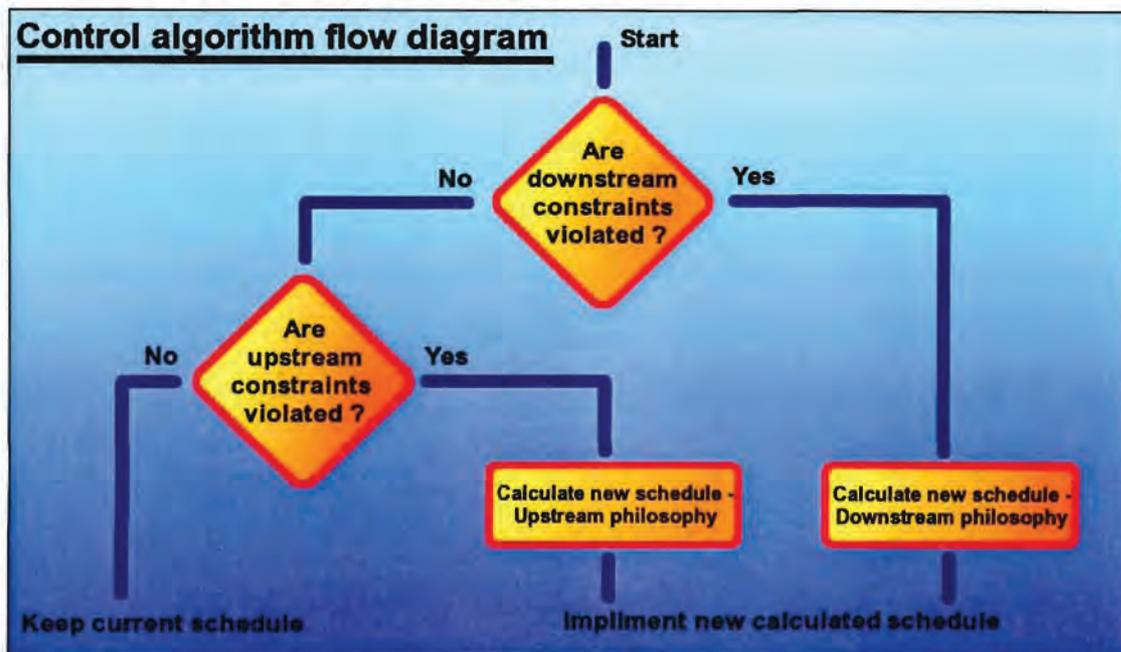


Figure 2-6 Control algorithm flow diagram

As shown in Figure 2-6, the downstream controller has authority over the upstream controller. This means that when the downstream dam does not meet its constraints, the downstream controller controls the pump station. When the downstream dam is between the given constraints, the upstream controller controls the pump station.

2.5.3. Simulation engine

REMS must be able to predict or calculate the potential of any project before implementation. This requirement was identified and explained in section 2.4. To achieve this, REMS was developed as both a control system and a simulation package. This enables REMS to simulate the water pump cycle.

When REMS is used to control the water pump system in normal conditions, the simulation element is disabled and the control philosophy is applied to the real-world water pump system. During project investigations the simulation element is used to simulate the water pump system, while the control philosophy is applied to this simulated system.

Doing this results in data recounting the performance of the system over a simulated time-period. Simulations can be done in faster-than-real-time. A month of simulated data can be generated in under an hour, speeding up the investigation process considerably.

The output data of the simulation session is processed in the same way the real-world control data is analysed to yield the success and potential of the given project. Many systems and procedures have been developed to process this data and are fully described in chapter 4 of this thesis.

Mainly two simulation elements are used to represent the water pumping system of the mine. These are the pump and the dam simulation components. The representation of the water pumping system is built-up by combining a number of these simulated elements.

Pump simulation element

The pump simulation element is used to represent an actual pump. The element's behaviour is dictated by mathematical equations. The following is a short discussion of the equations that are used in the pump simulation element.

Calculating the flow rate F [m^3/s] a pump delivers, is calculated as follows.

$F = V \times A$		
Where	F -	Flow rate [m^3/s]
	V -	Velocity [m/s]
	A -	Pump discharge cross-sectional area [m^2]

Equation 2: Flow rate [97]

In Equation 2 the V [m/s] represents the velocity of the water delivered by the pump, while A [m^2] represent the pump discharge cross-sectional area.

For a given pump we know that:

$$\frac{V^2}{2g} = h$$

Where V -	Velocity [m/s]
g -	Gravity Constant = 9.8 [m/s ²]
h -	Head of the pump [m]

Equation 3: Pump head [98]

In Equation 3, V is the deliver velocity of a given pump, while g (Gravity Constant) equals 9.8. h describes the head of the pump.

By rewriting equation 2 to the following, one can calculate the velocity (V) a pump delivers as:

$$V = \sqrt{h \times 2g}$$

Where	V -	Velocity [m/s]
	g -	Gravity Constant = 9.8 [m/s ²]
	h -	Head of the pump [m]

Equation 4: Pump deliver velocity

Therefore, substituting Equation 4 into Equation 2 yields the flow rate F (m³/s) of a pump as:

$$F = \sqrt{(h \times 2g)} \times A$$

Where	F -	Flow rate [m ³ /s]
	h -	Head of the pump [m]
	g -	Gravity Constant = 9.8 [m/s ²]
	A -	Pump discharge cross-sectional area [m ²]

Equation 5: Pump flow rate

The head of a system is calculated by taking into consideration the height of the location where the water has to be pumped and the height from where water is pumped. The head is calculated as follows:

$$h = h_d - h_s$$

Where	h -	Total system head [m]
	h _d -	Discharge head [m]
	h _s -	Suction head [m]

Equation 6: Total system head [99]

In Equation 6, h_d (Discharge Head) describes the height to where the water is pumped. If, for example, a pump is used to pump water up a tower into a reservoir at the top of the tower, h_d will be the height, in meters, from the pump to the water level in the reservoir. See next figure (Figure 2-7).

In Equation 6, h_s (Suction Head) describes the height from where the water is pumped. See next figure (Figure 2-7).

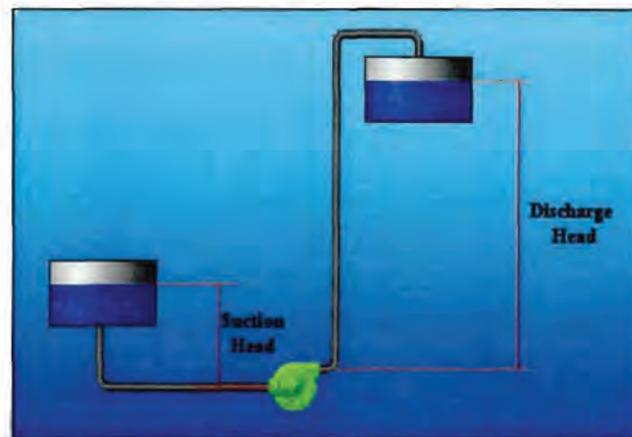


Figure 2-7 System head

In this simulation we simplified the mathematics by only calculating h_d and h_s by the heights as described above. For a more accurate solution the system head losses in pipes, bends, valves etc. must be considered as well.

Now the head of the system has to be overcome by the energy the pump exerts on the water. If a pump with specific head workload is applied into a system with a greater head (as shown in Figure 2-7), the pump will not be able to pump any water. If the head of the pump is bigger than that of the system, the flow the pump will deliver is calculated by inserting the delta head ($h_{pump} - h_{system}$) into Equation 5.

$$F = \sqrt{((h_{pump} - h_{system}) \times 2g) \times A}$$

Where	F -	Flow rate [m ³ /s]
	h_{pump} -	Head of the pump [m]
	h_{system} -	Head of the system [m]
	g -	Gravity Constant = 9.8 [m/s ²]
	A -	Pump discharge cross-sectional area [m ²]

Equation 7: Pump flow rate 2

Now, substituting Equation 6 into Equation 5 results in:

$$F = \sqrt{((h_{pump} - (h_d - h_s)) \times 2g) \times A}$$

$$= \sqrt{((h_{pump} - h_d + h_s) \times 2g) \times A}$$

Where	F -	Flow rate [m ³ /s]
	h _{pump} -	Head of the pump [m]
	h _d -	Discharge head [m]
	h _s -	Suction head [m]
	g -	Gravity Constant = 9.8 [m/s ²]
	A -	Pump discharge cross-sectional area [m ²]

Equation 8: Pump flow 3

Equation 8 was used in the simulation elements to calculate the flow delivered by each pump.

Dam simulation element

The dam simulation element was used to simulate the actual dams in the water pumping system. The level¹ [m³] of the dam simulation element was re-calculated during every simulation cycle. This was done by the following equation:

$$Level = Level_p + DeltaVolume$$

Where	Level -	New calculated level [m ³]
	Level _p -	Previous level [m ³]
	DeltaVolume -	Delta Volume during simulation cycle [m ³]

Equation 9: Dam Level

In Equation 9, *Level_p* (Previous Level) describes the level [m³] of the dam at the end of the previous simulation cycle. *DeltaVolume* [m³] describes the volume of water

¹ The term *level* is adopted from its usage in the mining industry. The *level* of a dam indicates the amount of water currently in the dam and is expressed as cubic meter [m³] or a percentage [%].

that flowed into the dam during the last simulation cycle. *DeltaVolume* is calculated as follows:

$$\Delta Volume = (TInFlow - TOutFlow) \times \Delta T$$

Where	$\Delta Volume$ - Delta Volume during simulation cycle [m ³]
	$TInFlow$ - Inflow of water during simulation cycle [m ³ /s]
	$TOutFlow$ - Outflow of water during simulation cycle [m ³ /s]
	ΔT - Time of simulation cycle [s]

Equation 10: Delta Volume

In Equation 10, *DeltaT* [seconds] is the time that passed since the previous simulation cycle. In our system, the simulation cycle was repeated every second. *TInFlow* (Total in-flow) [m³/s] and *TOutFlow* (Total out-flow) [m³/s] describe the inflow and outflow sources of the dam. In the simulation these are representations of pumps, settlers, cooling plants, etc.

Now substituting Equation 10 into Equation 9 results in:

$$Level = Level_p + (TInFlow - TOutFlow) \times \Delta T$$

Where	$Level$ - New calculated level [m ³]
	$Level_p$ - Previous level [m ³]
	$TInFlow$ - Inflow of water during simulation cycle [m ³ /s]
	$TOutFlow$ - Outflow of water during simulation cycle [m ³ /s]
	ΔT - Time of simulation cycle [s]

Equation 11: Dam level 2

Equation 11 was used to calculate the level of each dam during each simulation cycle.

On the interface of the system, the dam levels are rarely presented in terms of m^3 as yielded by Equation 11, but rather as percentages. The *PercentageLevel* [%] of a dam is calculated with the following equation:

$$PercentageLevel = \frac{Level}{Capacity} \times 100$$

Where	PercentageLevel -	Level as percentage [%]
	Level -	Level of the dam [m^3]
	Capacity -	Capacity of the dam [m^3]

Equation 12: PercentageLevel

2.6. Enrolling the solution algorithm into a feasible product

After the control philosophy is engineered, the following step would be to enrol this solution philosophy into a product that is feasible for the intended application and industrial environment. The next chapter of this thesis is devoted to this cause and explains the steps taken to engineer this control algorithm and solution into an automated package intended and optimised for the industrial environment.