4. MODEL VERIFICATION

4.1 INTRODUCTION

The purpose of this chapter is to prove that the mathematical models developed in the previous chapter are in fact valid. This is to be done by using live data gathered at Anglogold's Tshepong and Kopanang mines.

4.1.1 Measurement Accuracy

In order to successfully verify mathematical models, it is imperative that test data used is accurately measured and gathered. According to Dressler, Ferenczy, Olver and Turner [40, pp. 6 – 7], the ultimate accuracy achievable in South Africa, for any kind of measurement, is limited by the quality of the national measuring standard for the relevant unit of measurement. Since the most important user of calibrated measuring equipment is industry, the accuracies of the various national measuring standards are determined by industry's stated demands.

Measurements taken on the water reticulation systems in the gold mining industry vary greatly depending on the size, age and budget of the individual mines. These measurements range from crude plots on graph paper to electronically gathered data stored to four decimal places on SCADA systems. One such mine is Tshepong. Tshepong's SCADA system stores comprehensive data of the water reticulation system. The mine also has a three chamber pipe feeder system installed, making it the perfect case study to verify the generated models.

Kopanang mine in the Vaal River Region makes extensive use of turbines. They also have data available on-line, which can be used to verify the turbine model.

This study is aimed at a 90% accuracy so mines such as these which regularly maintain their systems to ensure that they are within the national measuring standards will easily provide data accurate enough to verify models aimed at a 90% accuracy.

4.1.2 Case Study Details

The philosophy, which is to be followed in the verification of the models, is to use two different time case studies of Tshepong Mine for all models except the turbines. The individual turbine models are to be verified using two different time case studies of Kopanang mine. Two full day's data is used for each case study. The particular case studies chosen were chosen randomly from sets of available archived data:

Case study 1 dates: 27 – 28 July 1999.
Case study 2 dates: 16 – 17 May 2000.

4.2 INDIVIDUAL MODEL VERIFICATION

4.2.1 Introduction

The individual models developed are building blocks of a much greater system. For the models to be valid in any configuration, it is important to verify that each one is individually valid. For this reason, this section confirms the validity of each model developed in chapter 3 with the exception of the Darcy model, which by definition must be used as an input to one of the other models. There is numerous literature validating the Darcy model, as mentioned in section 3.2.

4.2.2 Pumping Model Verification

A problem, which one is faced with when attempting to verify the pumping models, is the fact that the efficiencies of the pumps are not readily available. For this reason it is necessary to use one set of test data to determine the efficiency of the pump and then another set of data for the actual verification using the efficiency already determined. The second set of data should be of a similar pump, allowing the efficiency determined for one pump to still be valid. According to Garay [41, pp. 198 & 258], a range of efficiencies of 55% - 75% is seen as normal for centrifugal pumps.

Referring to figure 3.1 and figure 3.2, the following data was used to determine efficiencies:

Table 4.1: Tshepong 66-level pump 1 data to determine pump efficiencies

MODEL	INPUT	SYMBOL	VALUE
Darcy	Constant	f	0.02
	Pipe Length	L	640.1 m
	Flow Rate	Q	0.103 kl/s
	Pipe Diameter	D	0.35 m
Darcy Result	*Friction Head*	h_f	*8.6 m*
Pump	Water Density	ρ	1 kg/l
	Gravitational Constant	g	9.81 m/s^2
	Flow Rate	Q	0.103 kl/s
	Natural Head	h	640.1 m
	Input Power	P	1015 kW
Model Result	*Efficiency*	η	*65%*

Using the pumping and Darcy models, one can see from the table that the efficiency of the pump is well within the range mentioned above. This efficiency will now be used as an input to a pumping model verified on a similar pump working under different conditions.

Table 4.2: Tshepong 66-level pump 2 data to verify pump model

MODEL	INPUT	SYMBOL	VALUE
Darcy	Constant	F	0.02
	Pipe Length	L	640.1 m
	Flow Rate	Q	0.142 kl/s
	Pipe Diameter	D	0.35 m
Darcy Result	*Friction Head*	h_f	*16.4 m*
Pump	Water Density	ρ	1 kg/l
	Gravitational Constant	G	9.81 m/s^2
	Flow Rate	Q	0.142 kl/s
	Natural Head	h	640.1 m
	Efficiency	η	65%
Model Result	Input Power	P	***1,407 kW***
Actual Value	Input Power	P	***1,379 kW***

Table 4.2 shows us that using the generated model depicted in figure 3.2, the power of 66-level pump 2 is calculated to be 1,407 kW. This represents an accuracy of 98%.

4.2.3 Multiple Pump Model Verification

The multiple pump model can be verified using values obtained with different numbers of similar pumps pumping together on 66-level of Tshepong mine. In order to test the validity of this model, the unknown constants, *A* and *k* of bounded exponential equation 3.5 need to be determined. There are two unknown variables in this equation and therefore two data points need to be used to determine the unknowns. The result can then be verified by using a third data point as a test point.

The two data points decided upon for determining the two unknowns, are data for running only one of the 66-level pumps, and data for running three of the 66-level pumps simultaneously. Once the unknowns have been determined, they are to be tested by substituting data for running two of the 66-level pumps into the bounded exponential equation, and comparing the flow rate calculated to the actual measured flow rate when two of the 66-level pumps are running. Equation 3.5 is repeated for ease of reading:

$$Flow = A(1 - e^{-k.(pumps)}) \tag{4.1}$$

The unknowns are *A* and *k*. The following data is used to solve these two unknowns as described above:

Table 4.3: Data for multiple pumps

DATA SET 1	DATA SET 2
Flow = 102.5 l/s	Flow = 270.5 l/s
Number of Pumps = 1	Number of Pumps = 3

From these values it was found that A = 817.3 and k = 0.314

When the model was tested using two pumps and the determined values of *A* and *k*, it predicted that that the flow rate would be 192.1 l/s. The measured flow rate of two pumps running together was 195.1 l/s. This represents an accuracy of 98.5%.

4.2.4 Turbine Model Verification

Tshepong mine does not make use of turbines at all due to the three chamber pipe feeder system in use there. For this reason data to verify this model had to be obtained from Kopanang mine. Kopanang does not have the same level of accurate, on-line data as Tshepong, but it does have accurate, manually measured data of the turbuines present on its 38-level. The data available from Kopanang, is basically flow rate through and power delivered by the turbines. This is sufficient for the model shown in figure 3.5 as all other required values are physical values, which can be measured or calculated.

The same philosophy will be followed as was in the verification of the pumping model to verify the turbine model. One set of data will be used to determine the typical efficiency of the turbines installed at Kopanang. This efficiency will then be used as an input to verify the turbine model using data of another turbine.

Table 4.4: Kopanang 38-level turbine 1 data to determine turbine efficiencies

MODEL	INPUT	SYMBOL	VALUE
Darcy	Constant	f	0.02
	Pipe Length	L	1161 m
	Flow Rate	Q	0.125 kl/s
	Pipe Diameter	D	0.4 m
Darcy Result	*Friction Head*	h_f	*11.8 m*
Turbine	Water Density	ρ	1 kg/l
	Gravitational Constant	g	9.81 m/s^2
	Flow Rate	Q	0.123 kl/s
	Natural Head	h	1161 m
	Output Power	P	986 kW
Model Result	*Efficiency*	η	*70%*

This efficiency will now be used as an input to a turbine model verified on a similar turbine working under different conditions. In the configuration present in Kopanang the turbines are used to directly drive pumps. This means that the 986 kW produced by this turbine can be used as the input to a pump model once all the other inputs are available. The next table shows data using the 70% efficiency, proving that the turbine models are accurate.

Table 4.5: Kopanang 38-level turbine 2 data to verify turbine model

MODEL	INPUT	SYMBOL	VALUE
Darcy	Constant	f	0.02
	Pipe Length	L	1161 m
	Flow Rate	Q	0.180 kl/s
	Pipe Diameter	D	0.4 m
Darcy Result	*Friction Head*	h_f	*24.5 m*
Turbine	Water Density	ρ	1 kg/l
	Gravitational Constant	g	9.81 m/s^2
	Flow Rate	Q	0.180 kl/s
	Natural Head	h	1611 m
	Efficiency	η	70%
Model Result	Output Power	P	***1,404 kW***
Actual Value	Output Power	P	***1,361 kW***

When the output value of the turbine model is compared to the actual value obtained when it was measured, we see that it is 97% accurate.

4.2.5 Three Chamber Pipe Feeder System Model Verification

The principle of the 3CPF system in that it does away with the natural head, *h*, that pumps usually have to pump against. Verifying this model promises to be very interesting due to the fact that the only remaining head is that of friction, which is usually much less that the natural head in similar vertical applications. This verification should help to prove whether or not the major loss in vertical-load pump applications can really be eliminated if it is balanced out.

Seeing that the 3CPF has two pumps in series, and the proposed model states that the load must be shared proportionally between the pumps, half the total friction head will be used for each pump. The 3CPF by definition has to have an equal amount of water moving up and down the shaft at any given time. Data from Tshepong mine however shows that on average that the chilled water flow rate passing down the shaft is 25 l/s higher than the warm water being pumped up the shaft. The reason for this is that a certain amount of extra water is allowed to flow down the shaft and emptied into the chilled water dams on 45-level through dissipaters. This water is used to make up water, which is lost to earth absorption. This water is continuously replaced by purchasing additional water from the Rand Water Board. This additional water passes through the surface pumps, increasing the flow rate of the surface pumps. The additional downward flow rate also confirms that the mine also does not have an increase in total water volume due to fissure water. Water is also lost due to evaporation in the pre-cooling towers. This loss however does not result in any additional flow rates because the Rand Water gets added at the same point in the system.

Once again, the philosophy of the verification process will be to use measured data to determine the efficiency of one pump. This efficiency will then be used as an input to the model to be verified when employed on a similar pump. The 3CPF system has two similar pumps installed and so this process will be possible. The data for the surface pump is as follows:

Table 4.6: 3CPF system surface pump data to determine pump efficiency

MODEL	INPUT	SYMBOL	VALUE
Darcy	Constant	f	0.02
	Pipe Length	L	1372 m
	Flow Rate	Q	0.299 kl/s
	Pipe Diameter	D	0.35 m
Darcy Result	*Friction Head*	h_f	*155.7 m*
Pump	Water Density	ρ	1 kg/l
	Gravitational Constant	g	9.81 m/s^2
	Flow Rate	Q	0.299 kl/s
	Natural Head	h	0 m
	Input Power	P	660 kW
Model Result	*Efficiency*	η	*69.1%*

As mentioned previously in paragraph 4.2.2, this efficiency is well within the reasonable range for centrifugal pumps. This efficiency will now be used as an input to the model when it is employed on the underground pump:

Table 4.7: 3CPF system 45-level pump data to verify 3CPF pump model

MODEL	INPUT	SYMBOL	VALUE
Darcy	Constant	f	0.02
	Pipe Length	L	1372 m
	Flow Rate	Q	0.274 kl/s
	Pipe Diameter	D	0.35 m
Darcy Result	*Friction Head*	h_f	*130.7 m*
3CPF Model	Water Density	ρ	1 kg/l
	Gravitational Constant	g	9.81 m/s^2
	Flow Rate	Q	0.274 kl/s
	Natural Head	h	0 m
	Efficiency	η	69.1%
Model Result	Input Power	P	***508.4 kW***
Actual Value	Input Power	P	***505.0 kW***

The model predicts an input power of 508.4 kW and the actual value measured was 505.0 kW. This represents an accuracy of 99.5%.

4.2.6 Storage / Buffer Model Verification

The process followed in verifying the storage and buffer model shown in figure 3.10 was to simulate the level of a number of the dams in Tshepong mine and then to compare the simulated results to the actual measured dam levels of the same time. The model basically integrates the total inflow and outflow rates of any storage device. In order to realistically implement this model in the mining environment, a computer algorithm was developed which integrated the resulting flow rate every minute and kept a running total of the resulting dam level. The algorithm makes provision for rather versatile scheduling and flow rate inputs. Operating schedules for the days that were simulated were obtained from Tshepong as well as actual data of the dam levels of interest.

The first set of conditions used to simulate this model were the 66-level hot water dam of Tshepong mine, over a period of 24 hours from 00:00 on 28 July 1999 to 23:59 on 28 July 1999. The results are as follows:

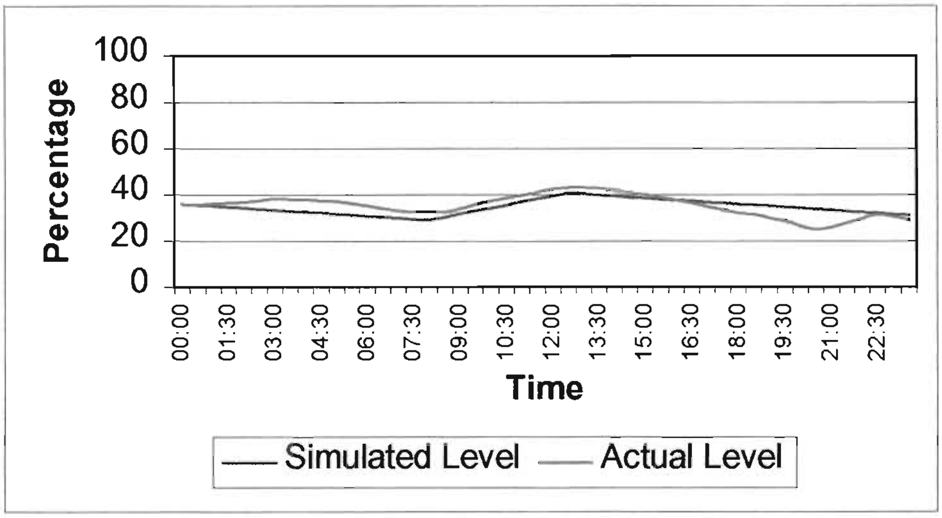

Figure 4.1: Simulated and actual Tshepong 66-level hot water dam level

As can be seen from the graph the simulated dam level is far more linear than the actual level. The main reason for this is that the flow rate from production, which actually fills the dam is not linear. It is dependent on a number of factors such as the delay time for the water to reach the shaft bottom from each different level and physical path, which the water has to follow from each level. In the simulation a constant flow rate into the dam was accepted. The overall simulated profile of the level seems to be reasonably similar to that of the actual profile. In fact, the average value of the simulated dam level is 34.53%, while that of the actual level is 35.36%. This represents an error of only 2.35%. Another important success of the simulation is that the final values of the actual and simulated conditions are very close. The actual final dam level is 29.1% and the simulated value is 30.8%.

The second set of conditions used to verify the model were the 45-level hot water dam of Tshepong mine, over a period of 24 hours from 00:00 on 16 May 2000 to 23:59 on 16 May 1999. The results are as follows:

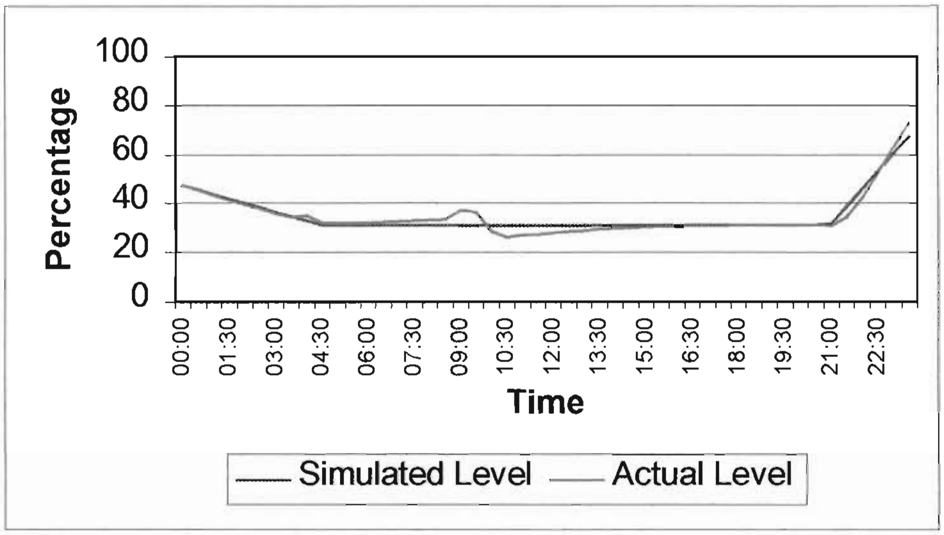

Figure 4.2: Simulated and actual Tshepong 45-level hot water dam level

From figure 4.2 it is apparent that the simulated profile follows the actual profile much more closely than the previous verification using the 66-level dam. The main reason for this is that the 45-level hot water dam does not have nearly as many unknown inputs as the 66-level dam. The profile of the 66-level dam is very subject to the delay of water from the workings as well as losses and gains from ground water. The 45-level hot dam basically has the 66-level pumps as an input and the three chamber pipe feeder system as an output. For this reason, as long as the flow rates of the pumps which are involved stay constant, the change in dam level will remain linear.

It is interesting to note that the average simulated level of the 45-level hot dam is 35.19% and the actual average level is 34.67%. The final level of the dam was once again also very successfully simulated. The simulated final level is 73.63, while the actual final level is 72.46%. Having a simulated value higher than the actual value is more desirable than visa versa. This is because the safety factor of the dam will be reached sooner, preventing overflows sooner.

It must be remembered that the main purpose of this model is to verify that the conditions for the rest of the models, which have been developed in this study, are valid. It is thus important for this model to in itself be accurate. From the findings in this section, it is clear that this is indeed so and the rest of the models developed in the study can be used with confidence once their operating validity has been checked by this model.

4.3 INTEGRATED MODEL VERIFICATION

4.3.1 Introduction

At this point, we have established that the models developed are indeed accurate when used individually. The point of the study however is to be able to use these models in any combination. This section provides verification that these models can indeed be used together to form a powerful tool.

The method used to verify the models working together is to use the models in a combination representing the entire water reticulation system present at Tshepong mine in the Freestate. Once all the relevant model inputs have been obtained for a period of operation, the corresponding power usage values for the system will be determined from the models. These power usage values will then be summed together and applied to the tariff applicable for Tshepong mine. The total electricity cost will then be determined and compared to the actual electricity cost for pumping experienced by the mine for the relevant month.

Both case studies mentioned in section 4.1.2 will be used to ensure that the models work with entirely different sets of data.

4.3.2 Case Study: Tshepong 27-28 July 1999

Two full production days' data was used for this case study. The flow rates responsible for energy consumption are shown in the following graph:

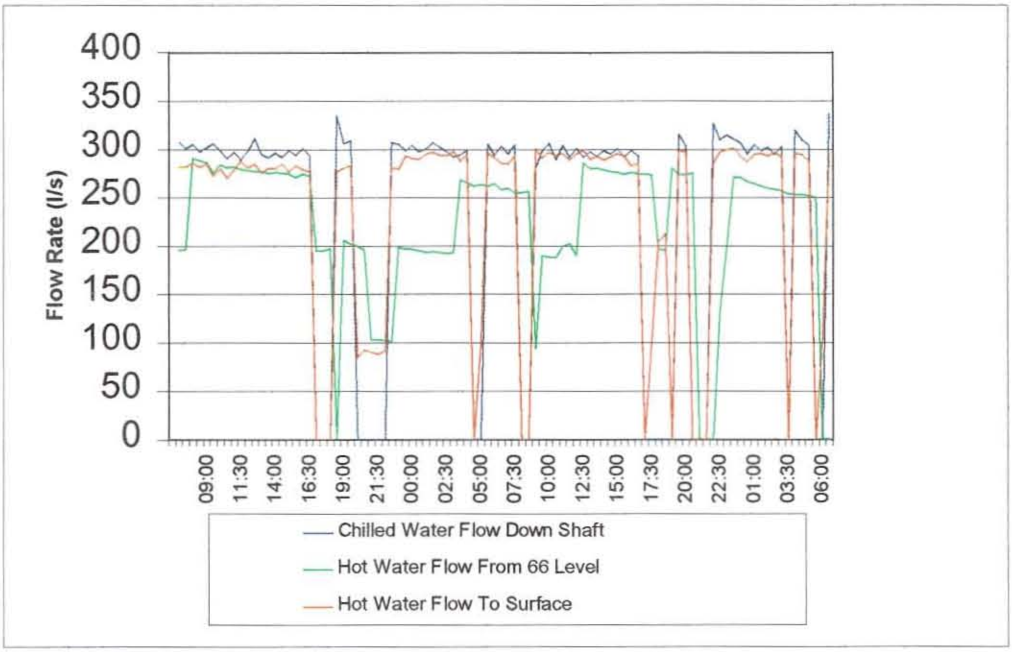

Figure 4.3: Flow rates responsible for energy consumption at Tshepong mine for 27 – 29 July 1999.

It can be seen in Figure 4.3 that the profiles of the water flowing to and from the surface correspond. This is naturally because they are both as a result of the operation of the three chamber pipe feeder system, which by definition has the two flows running together.

The number of pumps operating together on 66-level at any time is determined by inserting numerical filters at 150 l/s and 230 l/s. The number of pumps is then used in the bounded exponential relationship of equation 3.5 to determine the equivalent flow rate of a single pump. The energy consumption of one pump is then multiplied by the total number of pumps to obtain the total energy consumption at any particular time.

Using the models developed with the flow rates shown in figure 4.3 as well as all the other relevant physical model inputs, the following demand plot is obtained:

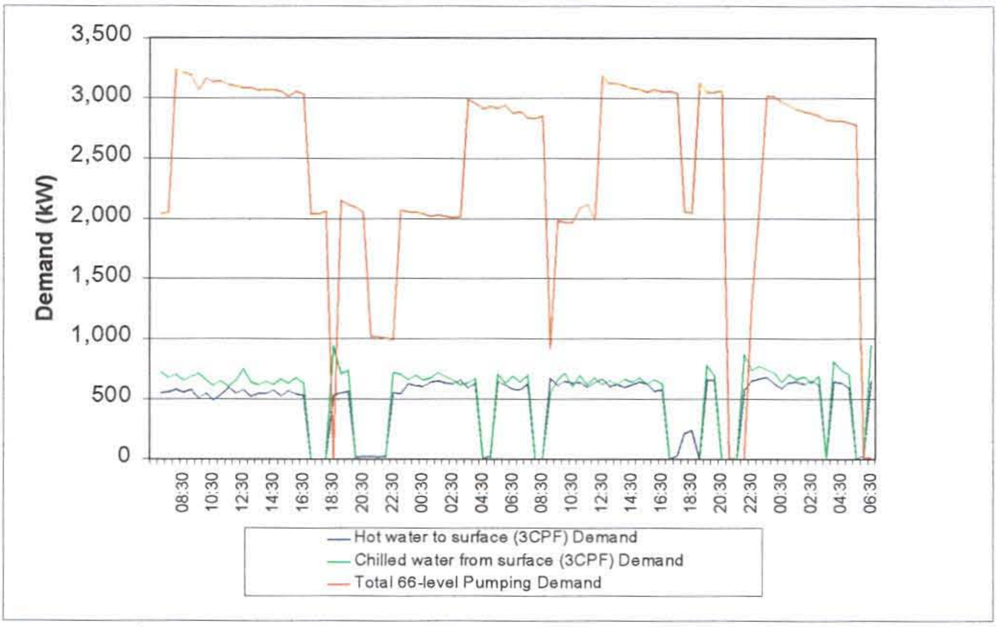

Figure 4.4: Demand plots of pumps for 27 – 29 July 1999

Summing these profiles produces the following disaggregated pumping load profile:

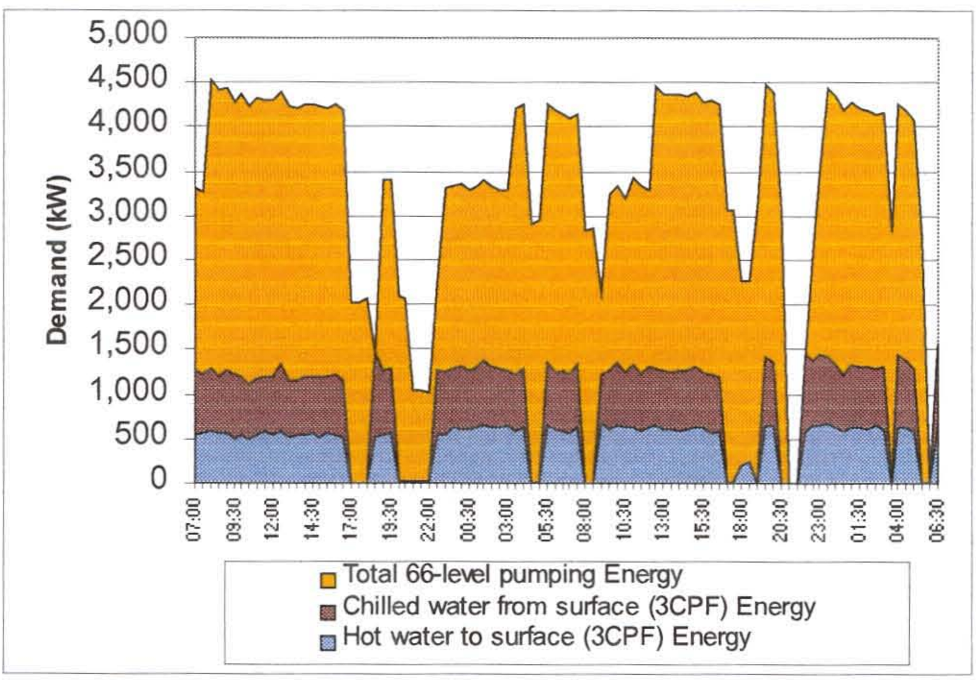

Figure 4.5: Total Disaggregated pumping energy profile for 27 – 29 July 1999

From the data presented in figure 4.5 one can see that the highest value is 4,520 kW, which represents the pumping maximum demand for the two days. Integrating the profile produces 163,435 kWh of energy used in the two days.

The energy that has been calculated is for two consecutive full-production days. To approximate a full month, this needs to be multiplied by 11 (for 20 full-production days and 2 half-production days per month). The total energy consumed per month for pumping at Tshepong under these typical conditions is thus:
163,435 x 11 = 1,797,785 kWh

The maximum demand should not change from the two typical sample days and so 4,250 kW will be used, seeing that it occurred in a peak time. At the time of the test data, Tshepong mine was on Eskom's Nightsave tariff. The following is a calculation of their total electricity costs:

1,797,785 kWh x 7.46 c/kWh	R134,114
4,520 kW MD x R46-26 / kW	R209,095
Sub Total	*R343,209*
Total After Voltage Discount (3.3%)	**R331,884**

Figure 4.6: Total simulated electricity costs

The actual cost of electricity used for pumping by Tshepong in July 1999 was R330,908. This figure is 99.7% accurate.

4.3.3 Case Study: Tshepong 16-17 May 2000

Once again two full-production days were sampled to obtain typical profiles of the flow rates that are responsible for most of the energy consumption of the water reticulation system of Tshepong.

The following is a plot of these flow rates:

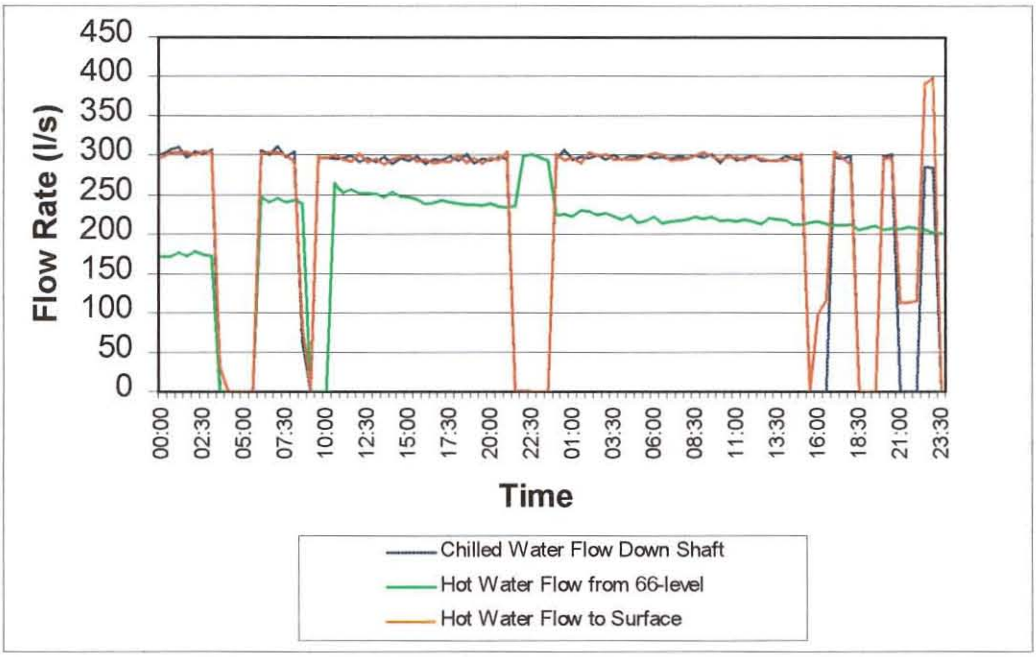

Figure 4.7: Flow rates responsible for energy consumption at the indicated times on 16 – 17 May 2000

Again, it is interesting to note that the flow rates of the cold water flowing down the shaft and the warm water flowing to surface match almost exactly because of the three chamber pipe feeder system.

The sudden rise in the hot water flow to surface shown in figure 4.7 at approximately 22:00 on 17 May 2000 can only be ascribed to a possible error in the data.

The number of pumps operating together on 66-level at any time is once again determined by inserting numerical filters. The numerical filters have been inserted at 190 l/s and 270 l/s for this case study. As before the number of pumps is then used in the bounded exponential relationship of equation 3.5 to determine the equivalent flow rate of a single pump. The energy consumption of the equivalent one pump is then multiplied by the total number of pumps to obtain the total energy consumption at any particular time.

Using the models developed, the following is a plot of the demand for the two sample days of the water reticulation system of Tshepong:

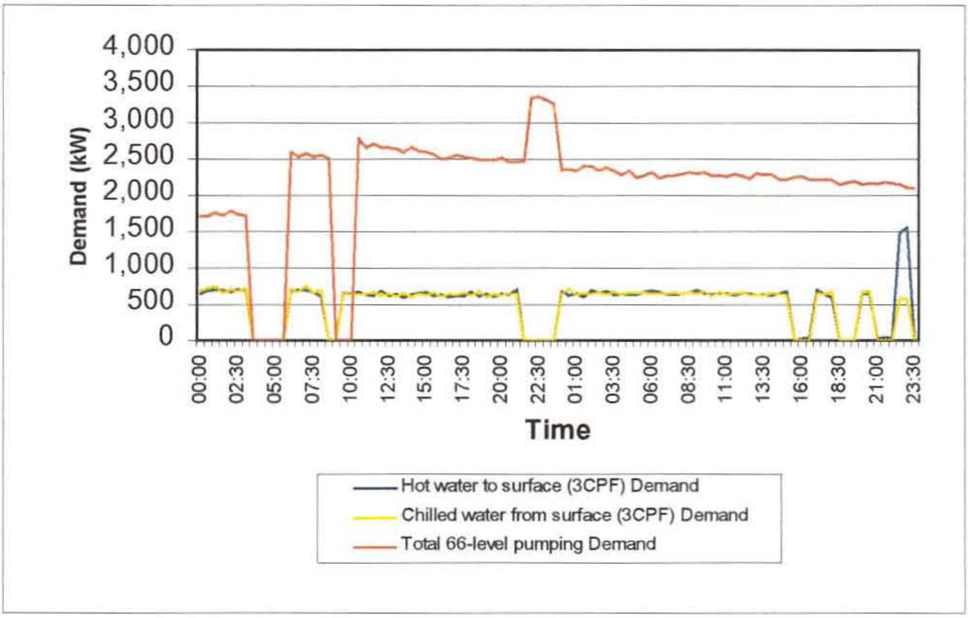

Figure 4.8: Demand plots of pumps on 16 – 17 May 2000

Summing these profiles produces the following disaggregated pumping load profile:

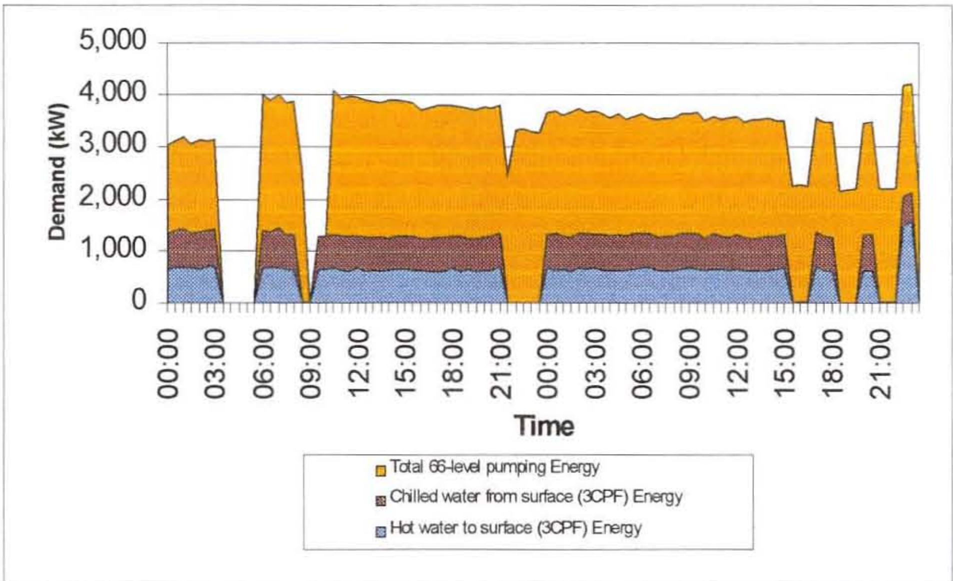

Figure 4.9: Total Disaggregated pumping energy profile for 16-17 May 2000

At the time of the case study, Tshepong mine was using the Eskom Nightsave tariff. According to this tariff, MD is only charged for load during peak times. As can be seen from Figure 4.9, the maximum demand of the water reticulation system during peak times occurred at 10:30 on 16 May 2000. This maximum demand was 4,087 kW. Integrating the profile produces 152,997 kWh of energy used in the two days.

As before, the energy that has been calculated is for two consecutive full-production days. To approximate a full month, this energy is multiplied 11 (for 20 full-production days and 2 half-production days per month). The total energy for the May 2000 is thus 152,997 x 11 = 1,682,967 kWh

The maximum demand is accepted to be 4,087 kW. The following is the calculation of the mine's total pumping electricity cost for May 2000:

1,682,967 kWh x 7.87 c/kWh	R132,449
4,087 kW MD x R49-46 / kW	R202,143
Sub Total	*R334,592*
Total After Voltage Discount (5.33%)	**R316,758**

Figure 4.10: Total simulated electricity costs for May 2000

The actual cost of electricity used for pumping by Tshepong in May 2000 was R327,460. This represents an accuracy of 96.7%.

4.3.4 Contribution to Maximum Demand

In both case studies (4.3.2 and 4.3.3), it was accepted that the maximum demand of the pumping profile can be used as the maximum demand figure used to calculate the cost of the maximum demand. This is in fact not entirely correct because the water reticulation system electricity usage is not billed separately to the rest of the mine. A more accurate method would be to calculate the *contribution* to maximum demand at the time that the whole mine experiences a maximum demand. This ties in with the adherence to the context of the models.

For the purpose of the case studies used in this verification however, the maximum demand of the pumping system occurs during the main production cycle of the mine. The energy consumption stays at reasonably constant maximum level for much of the production cycle and for this reason, using the maximum demand of the pumping system in these cases produces accurate results. Shifting this pumping maximum demand should be addressed for cost savings.