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A Water Model for Water and Environmental Management at Mae Moh Mine Area in Thailand

T. Bhakdisongkhram · S. Koottatep · S. Towprayoon

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Abstract It is revealed that the water quality in Mae Moh Reservoir, Thailand, has been deteriorated by lignite mine drainage and power station effluent. This study aims to manipulate water quantity and quality to reduce environmental impacts in Mae Moh area through a model for water management. The model was constructed on the basis of materials balance to predict water flow, which includes concentrations of TDS and SO_4^{2-}. Data collected during 1996–2000 were used. Model validation showed that the mean of predicted and actual values of TDS and SO_4^{2-} load were significantly similar at 95% confidence limit. The test result is acceptable and the water model can be used as a tool for water system management in the area. In 2006, Mae Moh mine excess water will be discharged at 10.76 Mm^3, with a pH of 7.3, TDS and SO_4^{2-} concentrations of 2,547 and 1,803 mg/l, respectively. Mae Moh power station effluent will be 14.59 Mm^3, with pH of 7.1, TDS and SO_4^{2-} concentrations of 610 and 358 mg/l, respectively. Predicted results showed that the outflow of Mae Moh Reservoir will be 83.67 Mm^3 and the concentrations of TDS and SO_4^{2-} will be as high as 1,501 and 822 mg/l, respectively. Mine excess water management measures are recommended according to the following strategy. All mine excess water should be stored during dry season. During wet season, 50% of the excess water should be

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stored and the remaining treated at 90% of TDS removal before being discharged. The end result would be a significant improvement in water quality in the Mae Moh Reservoir over the 4-year period to 2010. Pollutants in terms of TDS would be reduced by 35% from 1,501 mg/l in the beginning of 2006 to 975 mg/l at the end of 2009.

Key words sulfate • total dissolved solids • pH • mine drainage • power station effluent • water model • water quality • water quantity • water management • water system

1 Introduction

Mae Moh Lignite-fired Power project is located in Mae Moh basin, Mae Moh district, Lampang province,Thailand, 630 km north of Bangkok and 26 km east of Lampang township as shown in Fig. 1. The basin area covers 135 km^2 with an average altitude of 320 m above mean sea level. The climate of the area is characterized by wet and dry seasons. The dry season starts in late October and lasts until April. The mean annual rainfall is 1,076 mm (Sompong et al., 1996). The project encompasses Thailand's largest open cast lignite mine and mine-mouth power stations, which generated approximately 18% of country's electricity need (2001). The proven lignite deposits are sufficient for a power generating plant capacity of 2,625 MW for 30 years. The project is of critical importance to Thailand not only because it fulfills a significant

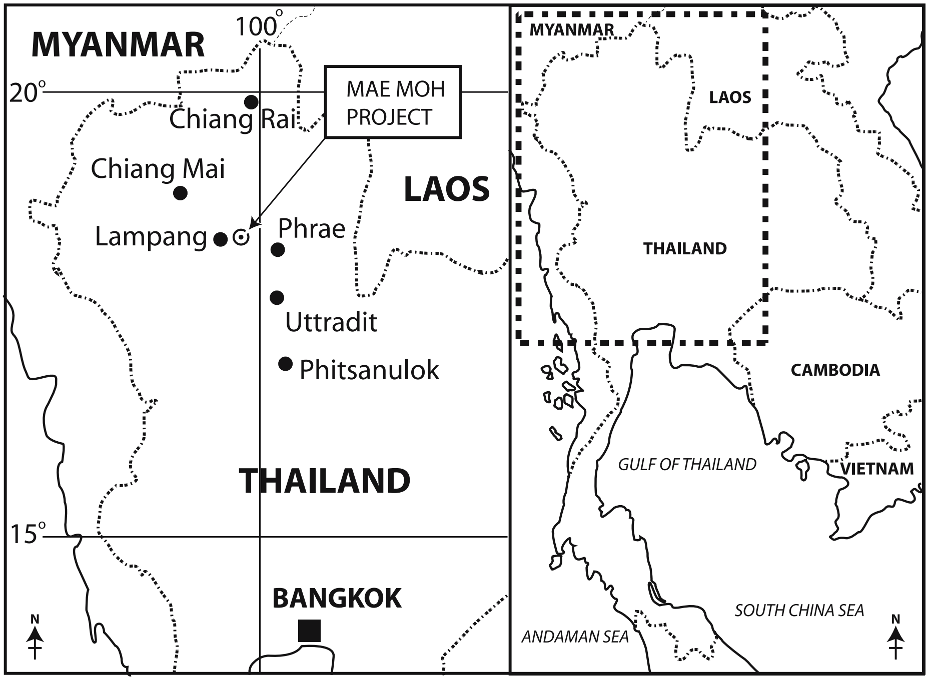


Fig. 1 Mae Moh project location

portion of electricity demand, but also because it burns indigenous, low price lignite, which helps save foreign exchange. Mae Moh project has been associated with a number of waste water drainage effects. As a consequence, the water quality in the downstream receiver (Mae Moh Reservoir) has deteriorated due to a considerable amount of contaminated water from mine drainage and power station effluent. This study aims to investigate both water quantity and quality through a constructed water model as a tool for water resources management and minimizing environmental impacts in the Mae Moh mine area.

2 Methodology

The fundamental water modeling procedure has been applied to construct the Mae Moh water model because of its simplicity and practicability for large and very complex water systems. Information and water system component linkage have been done by following the flow work as shown in Fig. 2. Mostly, secondary data and information collected by The Electricity Generating Authority of Thailand (EGAT) were used to infer the model such as detail of water system components, hydrological information, water sampling, laboratory data, descriptive data from literature, field knowledge and existing experience.

2.1 The Water System

Water components of the Mae Moh water system around the project area consist of 12 pit and three out-pit mine sumps, three settling ponds, three wetlands, five reservoirs and one weir (see Fig. 3). The 13 main components from 27 components were considered as the important model components, which have been stated in the water model. The 13 main components consist of five reservoirs, one weir, three settling ponds, three wetlands, and one out-pit sump, which have been computed as a model database in each component for the model reference. The 13 main water resources could be categorized into three groups, based on the water quality.

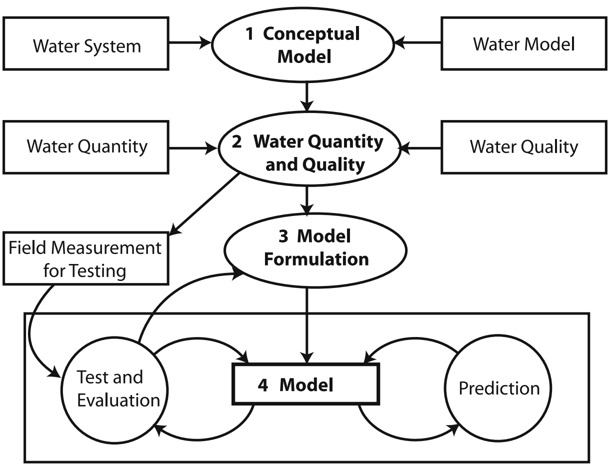
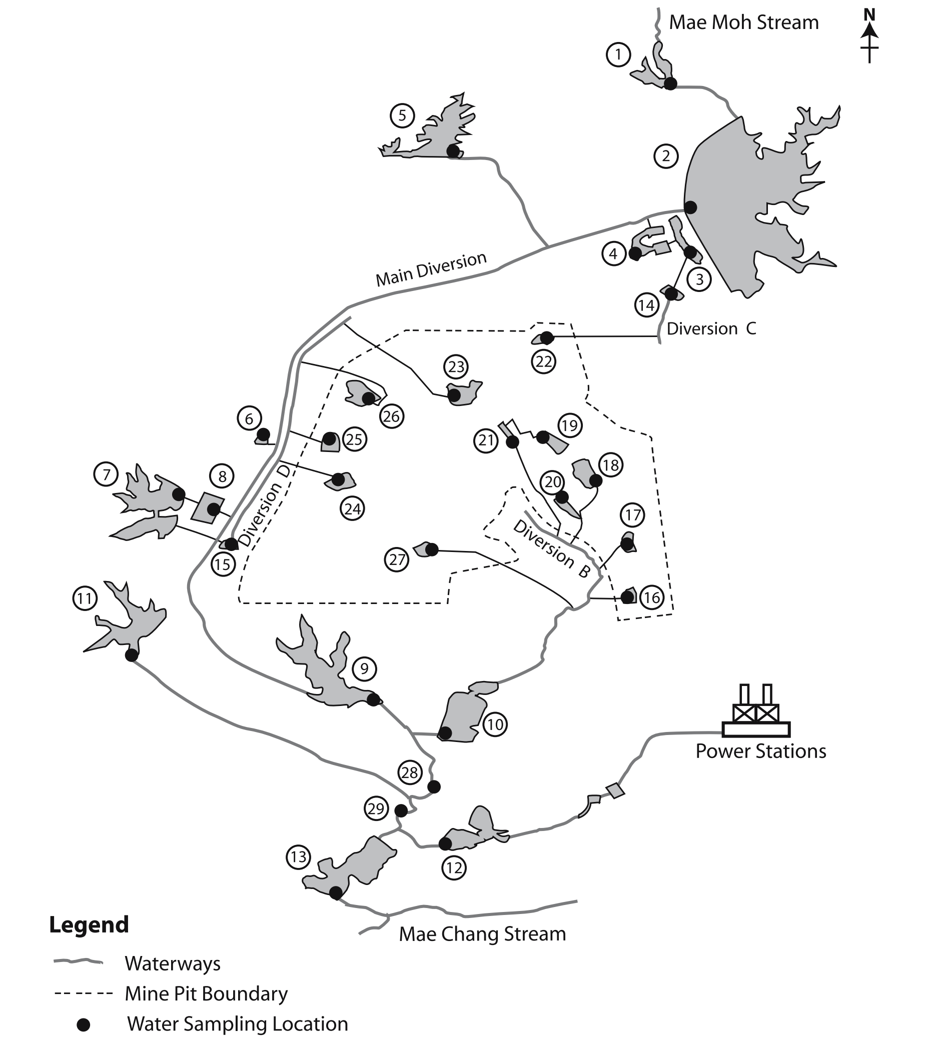


Fig. 2 The four successive steps of the water quantity and quality investigation and water model building processes



1. Tha Si Weir
2. Mae Kham Reservoir
3. North-east Settling Pond
4. North-east Wetland
5. Upper Huai Luang Reservoir
6. Sump E
7. South-west Settling Pond
8. South-west Wetland
9. Huai Sai Reservoir
10. South Settling Pond
11. Lower Huai Khing Reservoir
12. South Wetland
13. Mae Moh Reservoir
14. Sump C
15. Sump D
16. Sump Old
17. Sump 1 North-east
18. Sump 2 North-east
19. Sump 3 North-east
20. Sump 2 North-east Intermediate
21. Sump 3 North-east Intermediate
22. Sump 1 Sub-basin
23. Sump 1 C1
24. Sump 1 North-west
25. Sump 2 North-west
26. Sump 3 North-west
27. Sump 4 North-west
28. Hang Hung Bridge
29. Fang Kasaet Bridge

Fig. 3 Mae Moh water system (flow from north to south)and water sampling locations

Thus the three groups of water resources were natural water, drainage water and contaminated water as follow:

(1)	Tha Si Weir	Natural Water
(2)	Mae Kham Reservoir	Natural Water
(3)	North-east Settling Pond	Drainage Water
(4)	North-east Wetland	Drainage Water
(5)	Upper Huai Luang Reservoir	Natural Water
(6)	Sump E	Drainage Water
(7)	South-west Settling Pond	Drainage Water
(8)	South-west Wetland	Drainage Water
(9)	Huai Sai Reservoir	Contaminated Water
(10)	South Settling Pond	Drainage Water
(11)	Lower Huai Khing Reservoir	Natural Water
(12)	South Wetland	Drainage Water
(13)	Mae Moh Reservoir	Contaminated Water

During dry season, water in the Mae Moh Reservoir comes mainly from the power plant and to a lesser extent from Mae Moh mine and runoff. During wet season about half is due to runoff and the remainder from the mine pit and the power plant. The change of both quantity and quality of contaminated water discharging from the Project activities may affect the waterbody in reservoir. The excess water in the mine pit increases due to the expanded mine pit area. The effluent water from the power station remains the same, due to no change in the number and capacity of power plants. Mine drainage as a source of contaminated water and Mae Moh Reservoir as a final downstream receiver are the prime areas of this study. The discharged water from the reservoir flows to form a junction with the Mae Chang Stream and finally flows into the Mae Wang River, which is a branch of the largest river of Thailand, the Chao Phraya River. From the mine operation plan, the catchment area in the mine pit will increase up to 26.99 km^2 in 2006, which is greater than the catchment area of 25.22 km^2 in 2001 by 1.77 km^2 or 7.02%. The predicted annual rainfall in the project area in 2006 is 1,254 mm which is greater than the annual rainfall of 1,232 mm in 2001 by 22 mm or 1.79%. Thus, the volume of mine discharged water in 2006 is greater than the volume of mine discharged water in 2001.

2.2 The Water Model

The water model has been constructed from a number of Mae Moh water system components as shown in Fig. 3. The model consists of flow diagrams and symbols showing linkages between components as shown in Fig. 4. The information of water model were related and referred from water model calculation, which were designed to assist in solution, evaluation and prediction of both water quantity and quality for each of 13 main components of the water system.

2.3 Water Quantity

Rainfall is measured by using rain gauge, that is an automatic rainfall recorder (pluviographs). Evaporation is measured using a Standard United States Weather

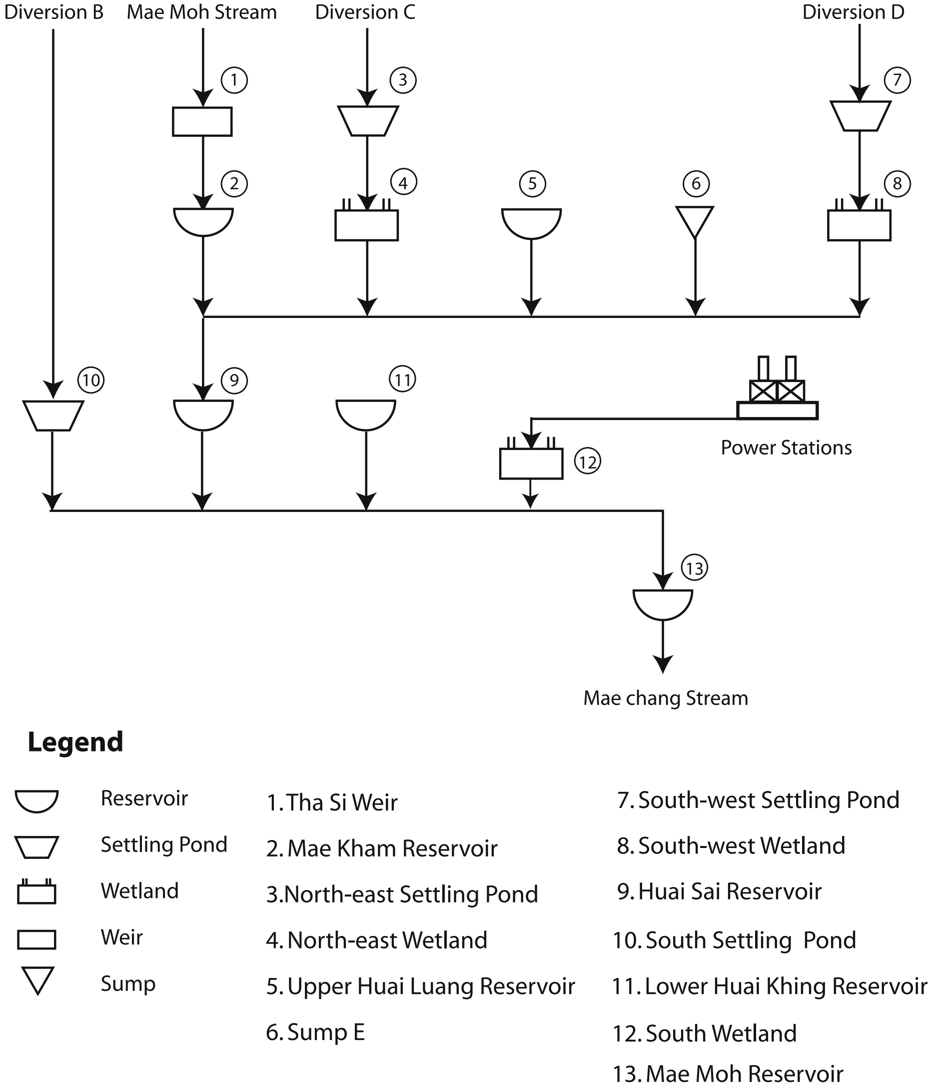


Fig. 4 Mae Moh water model

Bureau class A Evaporation Pan (Weeks and Dickie, 1993). The recorded rainfall and pan evaporation information were collected daily at the Old Lignite Mine Office (Weeks, 1994). The predicted rainfall was obtained by using time series (Kendall and Ord, 1990) for rainfall prediction for years 2001 to 2020. The estimated seasonal factors were assessed by using the seasonal decomposition procedure with a winter multiplicative model and all four points weighted equally. The exponential smoothing procedure with a winter model and seasonal factors were applied for predicted rainfall data. In order to test the normality of the distribution, the predicted rainfall data and the actual rainfall data have been computed. The distribution of rainfall data can be divided into two groups. The rainfall data from May to October is shown as normal distribution while that in other months could not be identified as normal distribution. The calculated rainfall data from May to October was performed by following the seasonal decomposition procedure. The others were calculated by using the exponential smoothing procedure with the Holt Model (Kendall and Ord, 1990), due to the positive trend of the rainfall data for January to April and negative trend for November and December.

2.3.1 Discharged Water from Mine Pit

The discharged water from the mine pit has been studied both ways: past water pumping recorded in 1999–2000, and by calculating the rainfall with the catchment area of each sump. Water pumping records were used for model testing only during the study year of 2001. Those calculated using discharged water from predicted rainfall and catchment areas is more reasonable for model prediction purposes because of its variable nature. The calculation formula is stated below (Weeks, 1996)

$$\text{Runoff}(\text{m}^3) = 0.35 \times \text{Rainfall(mm)} \times 1000 \times \text{Catchment Area}(\text{km}^2)$$

(0.35 is the average runoff coefficient used in Mae Moh mine pit.)

The discharged water from Mae Moh open cast mine was pumped during the rainy season, which starts late April and ends early November. Discharged water from the sub basin sump, north-east sumps and north-west sumps was pumped to sump C, diversion B and sump D, respectively. The water from sump C and sump D was pumped to the North-east Settling Pond and the South-west Settling Pond, respectively. The water in diversion B flowed to the South Settling Pond.

2.3.2 Effluent from Power Plants

The effluent from the power plants is a combination of used water from the power plants drainage (main drain) and ash water from the ash water lake. The waste water flows through a bio water treatment system for primary treatment before discharging to the South Wetland and finally to the Mae Moh Reservoir. The quantity of the effluent averaged 40,000 m^3/day in 2001. The value was obtained from automatic measurement station located at the entrance to the bio treatment and detention pond and was confirmed by field measurements at the South Wetland outlet using the rectangular weir formula (January–April, 2001). The effluent is of moderately high salinity and discharges at an almost constant rate.

2.4 Water Quality

In order to obtain an overall perspective on the characteristics of water quality and variation in quality through space and time within the project area, 29 sampling stations have been carefully identified for this study. Potential source pollutants discharging into the surface runoff system have been well covered. Sampling programs have been designed to embrace the seasonal variation of water quality throughout the year. Water analysis was done on the basis of Surface Water Quality Standards

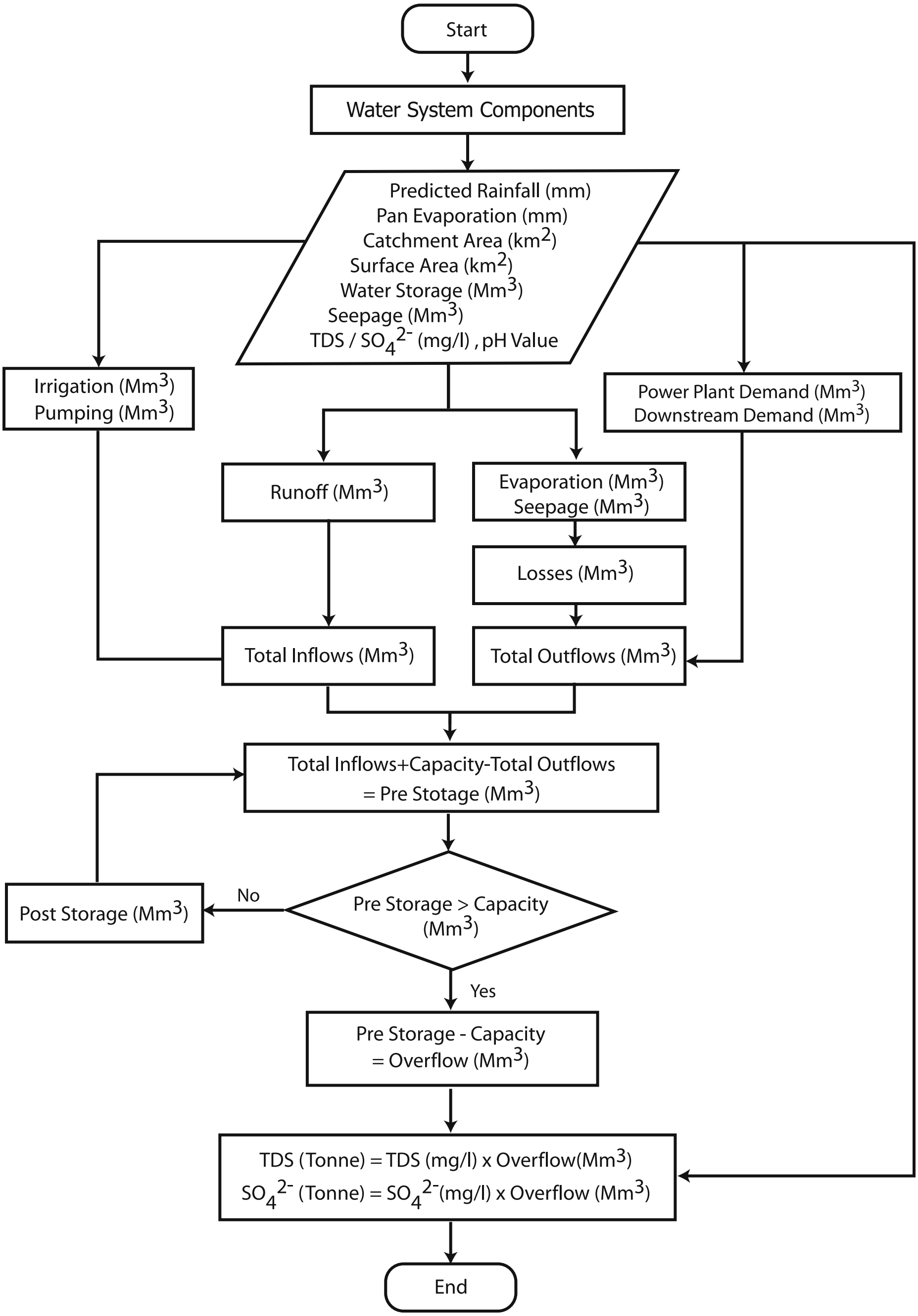


Fig. 5 The water model flow chart

(Water Quality Standards Notification of the Ministry of Science, 1995) and Standard Methods for The Examination of Water and Wastewater (American Water Works Association and Water Environment Federation, 1998). Approximately 1,505 samples were taken during year 1996–2000 (301 samples per year) from 29 locations shown in Fig. 3. Water samples were analyzed for different parameters at different frequency. Water characteristics considered were pH value, Total Dissolved Solids (TDS) and Sulfate (SO_4^{2-}), which are the most significant water pollutants resulting from the project activities.

2.5 Model Formulation

The water model flow chart is shown in Fig. 5. It shows the processes in calculating the water quantity and pH value as well as TDS and SO_4^{2-} concentrations and loading for each water component of the water system. Computations were made on a spreadsheet for the reference of monthly and annual information of the 13 components of the water model. The basic conditions and assumptions for constructing the model are stated below:

1. The water levels of reservoirs, settling ponds and other main components of the water system are at the normal high water level at the beginning of the first month of the year (after rainy season).
2. The mean annual seepage from reservoirs and settling ponds are 5% (Mae Moh Water Supply Project, 1998).
3. The summary of statistics of monthly and annual rainfalls were computed from selected station (Old mine office), which was the representative stations in the study area.
4. The rainfall data (1974–2000) was processed by using time series for rainfall prediction from 2001 onward.
5. Most of the secondary data and information for this study were sourced from EGAT (1996–2000).
6. The reactions of TDS and SO_4^{2-} on biological and physical process are negligible.

The formulae used for model calculation are as follow:

Water Quantity

Runoff (Weeks, 1996)

$$\text{Runoff} = \frac{\text{Rainfall}^{2.35}}{7300} \times \frac{\text{Catchment Area}}{1000}$$

$$\text{Runoff} = \text{Surface Runoff (Mm}^3\text{)}$$

$$\text{Rainfall} = \text{Predicted Rainfall (mm)}$$

$$\text{Catchment Area} = (\text{km}^2)$$

Evaporation (Weeks, 1996)

$$\text{Evap} = [(\text{Pan Evap} \times 0.7) - \text{Rainfall}] \times (\text{Surface Area} \times 10^{-3})$$
$$\text{Evap} = \text{Evaporation (Mm}^3\text{)}$$
$$\text{Pan Evap} = \text{Pan Evaporation (mm)}$$
$$\text{Rainfall} = \text{Predicted Rainfall (mm)}$$
$$\text{Surface Area} = 0.75 \times \text{Surface Area of Water Resource at Normal High Water Level (km}^2\text{)}$$

Pre Storage

$$\text{Pre Storage} = \text{Capacity} + \text{Total Inflow} - \text{Total Outflow}$$
$$\text{Pre Storage} = \text{Total Water Volume of Water Resource before Over Flow (Mm}^3\text{)}$$
$$\text{Capacity} = \text{Normal High Water Storage Capacity of Water Resource (Mm}^3\text{)}$$
$$\text{Total In Flow} = \text{Total Water Volume Flow into Water Resource (Mm}^3\text{)}$$
$$= \text{Irrigation Water (Mm}^3\text{)} + \text{Pumping Water (Mm}^3\text{)} + \text{Surface Runoff Water (Mm}^3\text{)}$$
$$\text{Total Out Flow} = \text{Total Water Volume out flow of The Water Resource (Mm}^3\text{)}$$
$$= \text{Evaporation (Mm}^3\text{)} + \text{Seepage (Mm}^3\text{)} + \text{Power Plant Demand (Mm}^3\text{)} + \text{Downsteam Demand (Mm}^3\text{)}$$

Overflow

$$\text{Overflow} = \text{Pre Storage} - \text{Capacity}$$
$$\text{Overflow} = \text{Excess Water Volume of The Normal High Water Storage (Mm}^3\text{)}$$
$$\text{Capacity} = \text{Normal High Water Storage (Mm}^3\text{)}$$

Water Quality

Chemical Load

$$NV = N_1V_1 + N_2V_2 + \ldots N_nV_n$$

$$N = \text{Concentration (mg/l), pH Value}$$

$$V = \text{Volume (Mm}^3\text{)}$$

$$\text{TDS (tonne)} = \text{TDS (mg/l)} \times \text{Overflow (Mm}^3\text{)}$$

$$\text{TDS (tonne)} = \text{Total Dissolved Solid in Weight (tonne)}$$

$$\text{TDS (mg/l)} = \text{Total Dissolved Solid Concentration (mg/l)}$$

$$SO_4^{2-} \text{ (tonne)} = SO_4^{2-} \text{ (mg/l)} \times \text{Overflow (Mm}^3\text{)}$$

$$SO_4^{2-} \text{ (tonne)} = \text{Sulfate in Weight (tonne)}$$

$$SO_4^{2-} \text{ (mg/l)} = \text{Sulfate Concentration (mg/l)}$$

3 Results and Discussion

3.1 Discharged Water

The project discharged water consists of mine drainage and power plant effluent. As shown in Tables 1 and 2, the mine drainage in 2001 was 8.14 Mm^3 with a pH of 7.3, and concentrations of TDS and SO_4^{2-} of 2,274 and 1,407 mg/l, respectively. The power station effluent was 14.60 Mm^3 with a pH of 7.2, and concentrations of TDS and SO_4^{2-} of 1,169 and 665 mg/l, respectively. The predicted mine drainage (2006) will be 10.76 Mm^3 with a pH of 7.3, and TDS and SO_4^{2-} concentrations of 2,548 and 1,803 mg/l, respectively. The power plant effluent will be 14.60 Mm^3 with a pH of 7.0, TDS and SO_4^{2-} concentrations of 610 and 358 mg/l, respectively. As can be seen the pH value is greater than 6 and alkalinity greater than acidity, the metal concentration is probably not significant. Coal mine drainage ranges widely in composition from acidity to alkalinity. The pH value is most commonly in the range of either 3 to 4.5 or 6 to 7.5 with fewer intermediate or extreme values. As a consequence, the quality of mine drainage discharged from the mine pit can be categorized in Type 5 Water (Skousen and Ziemkiewicz, 1996), which is neutralized acid mine drainage (AMD) with pH > 6 and high TDS, SO_4^{2-} concentrations.

Table 1 Water quantity and quality of Mae Moh project drainage (Actual 2001)

Locations	Volume (Mm^3)	Concentrations		
		TDS (mg/l)	SO_4^{2-} (mg/l)	pH
Mine drainage	8.14	2,274	1,407	7.3
Power plant drainage	14.60	1,169	665	7.2
Total	22.74	1,565	931	7.2

Table 2 Water quantity and quality of Mae Moh project drainage (Predicted 2006)

Locations	Volume (Mm^3)	Concentrations		
		TDS (mg/l)	SO_4^{2-} (mg/l)	pH
Mine drainage	10.76	2,548	1,803	7.3
Power plant drainage	14.60	610	358	7.0
Total	25.36	1,432	971	7.1

3.2 Model Validation

The Paired-Sample T Test was performed between the predicted model and the actual model in 2001. The testing was done for two pairs of mean TDS load (tonne) and SO_4^{2-} load (tonne). The first paired test result shows that the difference of TDS load from predicted model and actual model was in the range of 95% (±2 SD) confidence interval. The second paired test result shows that the paired differences mean of SO_4^{2-} load from predicted model and actual model was in the range of 95% (±2 SD) confidence interval. From these results it can be concluded that the test result was acceptable and the water model can be used as a tool for Mae Moh water system management.

3.3 Model Implementation

Three scenarios of the events and the interactions of mine drainage and water at Mae Moh Reservoir in year 2006 have been set for model implementation practice. The first scenario was "what will happen to the mine drainage system and Mae Moh Reservoir, if nothing has been done." The second scenario was "what will happen to water quality at Mae Moh Reservoir, if mine water quantity has been manipulated" and the third scenario was "what will happen to water quality at Mae Moh Reservoir, if mine water quality has been manipulated."

3.3.1 Scenario 1

Base on the actual model for 2001 and predicted model for 2006, the computed results are shown in Tables 3, 4 and 5. The mine excess water in 2006 will have to be discharged by pumping out through diversion lines B, C and D by 6.10, 1.18 and

Table 3 Comparative mine discharged water for 2001 and 2006

Location	Actual(1) Year 2001	Prediction(2) Year 2006	Difference(2)–(1)	
	Volume (Mm^3)	Volume (Mm^3)	Volume (Mm^3)	%
Diversion B	3.79	6.10	2.31	60.95
Diversion C	0.84	1.18	0.34	40.48
Diversion D	3.51	3.48	−0.03	−0.85
Total	8.14	10.76	2.62	32.19

Table 4 Water quality of Mae Moh mine drainage (Actual 2001 and Predicted 2006)

Location	Actual (2001) Concentration			Predicted (2006) Concentration		
	pH	TDS (mg/l)	SO_4^{2-} (mg/l)	pH	TDS (mg/l)	SO_4^{2-} (mg/l)
Diversion B	7.3	1,974	1,229	7.4	1,783	1,285
Diversion C	7.4	2,668	1,565	7.0	3,126	2,430
Diversion D	7.3	2,504	1,561	7.2	3,693	2,496
Average	7.3	2,274	1,407	7.2	2,548	1,803

3.48 Mm^3, respectively. The discharge through lines B and C in 2006 will be greater than that in 2001 by 60.95 and 40.48%, respectively. The total mine discharge in 2006 is predicted to be 10.76 Mm^3, or 32.19% greater than that in 2001. The average concentrations of TDS and SO_4^{2-} in year 2006 will be as high as 1,783 and 1,285 mg/l in line B, 3,126 and 2,430 mg/l in line C, and 3,693 and 2,496 mg/l in line D. Except for line B, all the predicted concentrations will be significantly greater than in 2001, with the averaged total of TDS and SO_4^{2-} in 2006 being 2,548 and 1,803 mg/l, respectively. The reservoir out-flow in 2006 will be 83.67 Mm^3 or 3.38% greater than that in 2001. The average concentrations of TDS and SO_4^{2-} will be as high as 1,501 and 822 mg/l, respectively, exceeding the guide line of industrial effluent for irrigation, which is equal to, or less than 1,300 mg/l.

3.3.2 Scenario 2

Mine pits cover a large area and the runoff from rainfall in them is very high, much higher than the runoff from an equivalent sized natural catchment. This high runoff is caused by the bare hard ground, steep slopes and limited vegetation. The quality of runoff in the mine pit is also very poor with some of the poorest quality water in the whole project area. Seepage also occurs in the mine pit. This is a much smaller volume than the surface water. Runoff and seepage in the mine pit all collects in sumps in the base of the pit. These sumps store water for dust suppression during the dry season, but much of the water is discharged from the pit. Water must be discharged rapidly before it damages equipment or disrupt mine operations.

This scenario simulates the 2006 water model to provide quality upgrading options at Mae Moh Reservoir by manipulating the mine discharged water. The model shows how mine discharged water will affect water quality at the reservoir. The criteria

Table 5 Mae Moh reservoir water quantity and quality

Year	Volume (Mm^3)	pH	Concentration (mg/l)	
			TDS	SO_4^{2-}
2001 (Actual)	80.93	7.0	1,042	531
2006 (Predicted)	83.67	6.5	1,501	822

Table 6 The Mae Moh water system situation for 2006 with various proportion of mine discharged water storage (Case: TDS)

Volume Stored (%)	Mine discharged water (Mm^3) Division B TDS 1,790 mg/l	Division C TDS 3,126 mg/l	Division D TDS 3,625 mg/l	Mae Moh reservoir Water quality Manipulation TDS Before (mg/l)	TDS After (mg/l)	Difference (%)
100	6.10	1.18	3.48	1,501	1,386	7.66
90	5.49	1.06	3.13	1,501	1,399	6.80
80	4.88	0.94	2.78	1,501	1,412	5.93
70	4.27	0.83	2.44	1,501	1,424	5.13
60	3.66	0.71	2.09	1,501	1,436	4.33
50	3.05	0.59	1.74	1,501	1,449	3.46

for keeping 100, 90, 80, 70, 60 and 50% of mine discharged water has been set for manipulation. The results are shown in Tables 6 and 7.

To meet the above criteria for maintaining the volume of mine discharged water, the TDS concentration at the reservoir will be reduced by 7.66, 6.80, 5.93, 5.13, 4.33 and 3.46%, respectively; while the SO_4^{2-} concentration will be reduced by 13.62, 13.50, 10.46, 9.00, 7.54 and 6.20, respectively.

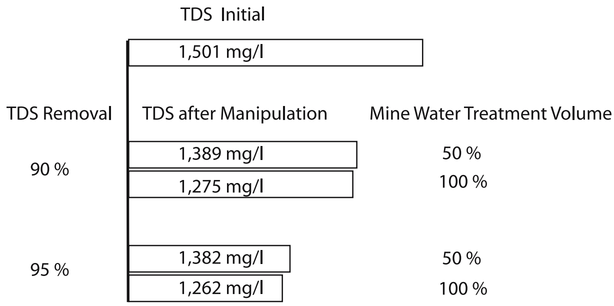
3.3.3 Scenario 3

Based on the water model, the Mae Moh water system in 2006 has been simulated. Water treatment is employed to upgrade mine discharged water quality, which will

Table 7 The Mae Moh water system situation for 2006 with various proportion of mine discharge water storage (Case: SO_4^{2-})

Keeping Volume (%)	Mine discharged water (Mm^3) Division B SO_4^{2-} 1,285 mg/l	Division C SO_4^{2-} 2,430 mg/l	Division D SO_4^{2-} 2,496 mg/l	Mae Moh reservoir Water quality Manipulation SO_4^{2-} Before (mg/l)	SO_4^{2-} After (mg/l)	Difference (%)
100	6.10	1.18	3.48	822	710	13.62
90	5.49	1.06	3.13	822	711	13.50
80	4.88	0.94	2.78	822	736	10.46
70	4.27	0.83	2.44	822	748	9.00
60	3.66	0.71	2.09	822	760	7.54
50	3.05	0.59	1.74	822	771	6.20

Fig. 6 Effect of mine water quality manipulation on TDS water quality in Mae Moh reservoir



affect water quality in the Reservoir. The amount of excess water in the mine pit will be treated at 100 and 50% by volume with 95 and 90% of TDS and SO_4^{2-} removal.

In the case of TDS, Fig. 6 indicates that, TDS in waterbody at Mae Moh Reservoir will be decreased from 1,501 to 1,262, 1,382, 1,275 and 1,389 mg/l, respectively.

In the case of SO_4^{2-}, Fig. 7 shows that, SO_4^{2-} in waterbody at Mae Moh Reservoir will be decreased from 822 to 652, 734, 660 and 742 mg/l, respectively.

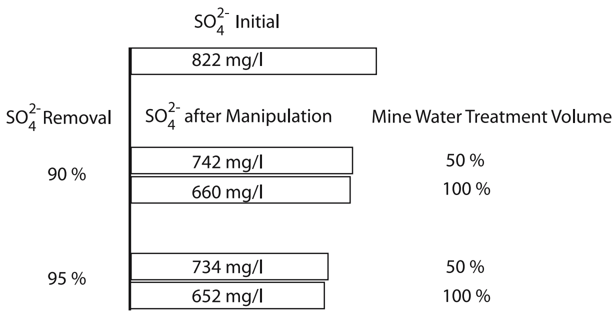
3.4 Mine Water Management Strategy

From the above three scenarios, water management strategy should take both water quantity and quality into account.

The mine excess water management options can be designed as follows:

- Total zero discharge measure The zero discharge measure of mine excess water will upgrade the reservoir water quality in terms of TDS reduction from 1,501 to 1,386 mg/l or 7.66% reduction. This measure poses limitation on water storage.
- The total treatment of mine excess water measure The treatment of 100% mine excess water at 90% TDS removal will decrease the TDS concentration in the reservoir from 1,501 to 1,275 mg/l or 15.06% reduction. This measure is apparently not feasible because of the very high cost.
- The integration of water quantity and quality control measures By keeping 100% mine discharge water during dry season and keeping 50% with 50% treatment at 90% TDS removal during wet season, the TDS will drop from 1,501 to 1,398 mg/l or 7% reduction. This measure is more likely to be achieved.

Fig. 7 Effect of mine water quality manipulation on SO_4^{2-} water quality in Mae Moh reservoir



From the above mentioned three measures, the suggested mine discharged water manipulation should be the combination of mine excess water quantity and quality controlled measures. For example, in 2006, the zero water discharge policy should be implemented during the dry season in the months of January to April and November to December, while the half-storage and half-treatment measure can be applied during the wet season in the months of May to October.

With this measure, the predicted TDS for the years 2007 to 2010 are shown in Table 8 , which indicate reductions of 7, 15, 25 and 35% with reference to 2006, respectively. The mine excess-water quantity control can be manipulated by storage in additional pit mine sumps or pumping into additional out-pit mine sumps and settling ponds. The mine excess water treatment can be done naturally by man-made wetlands and/or chemical treatment by several methods of sulfate treatment.

In order to manage the excess mine drainage in 2006, the measures for quantity control can be manipulated either individually or by integrated methods as follow:

1. The installed capacity of the pumping system should be increased by at least 61 and 40% for diversion B and C to cover predicted discharged water in 2006. A total of 10.76 Mm^3 should be pumped from the mine pit in 2006 compared with only 8.14 Mm^3 in 2001. The annual volumes of water pumped are listed in Table 3. The amount of water pumped from the mine pit will be much greater in 2006 than in 2001 considering the fact that the area of the mine pit has increased and the rainfall is greater.
2. Construct additional pit sumps or increase the existing sump capacity of 2.31 and 0.34 Mm^3 at north-east, east and north pit areas, respectively. The sumps must be large enough to store sufficient water for dry season and to allow the pumps to discharge water before they overflow.
3. Construct additional settling ponds/wetlands or increase the capacity of the existing settling ponds/wetlands to cover the additional excess water of 2.31 Mm^3 from diversion B and 0.34 Mm^3 from diversion C at south and north-east of the mine mouth area, respectively. The settling pond is a large dam, which is designed to allow sediment to settle out of the water. The ponds also store water for a considerable length of time and therefore provide for some measure of mixing and averaging of the salinity of the mine drainage. Water is released from the settling pond at a reasonably constant rate into wetlands, which contain a dense growth of aquatic vegetation. The performance of the wetlands and the runoff from mine pit areas needs to be managed. The main concern at Mae

Table 8 Predicted water quality result of TDS (mg/l) at Mae Moh reservoir year 2006-2010

Year	Status of TDS at the beginning of manipulation (mg/l)	Status of TDS at the end of manipulation (mg/l)	Difference of TDS with reference to 2006 (mg/l)	%
2006	1,501	1,398	103	7
2007	1,398	1,275	226	15
2008	1,275	1,132	369	25
2009	1,132	975	526	35
2010	975			

Moh is dissolved material, particularly TDS and SO_4^{2-} and the effectiveness of removing this material is unknown.

4. Recycle the excess water from the expanded pit sumps or settling ponds to use for dust control in mine operations and for plant vegetation on reclaimed land. The discharged water from the mine pit provides the largest contribution of salt. Part of this water can be disposed of and evaporated. However, because of the small area available for sumps in the mine pit, the water must be evaporated elsewhere. Extra water can be used for dust control in the pit, though it is not likely that this use can be expanded greatly. It is important that this water should be the first option selected for dust control since it is of the worst quality. Water from the mine pit could also be disposed of on the waste dumps. It is possible that a large amount of water could be disposed in this area to either evaporate or infiltrate. Water from the mine pit could also be used to infiltrate at explosive sites for dust control. Some further study is required before this option can be implemented.

In order to reduce the pollution from acid mine drainage the removal of sulfate from mine water is one of the important measures. There are numerous sulfate treatment methods, including the use of bacterial sulfite reduction (Hammack et al., 1998). Pilot results in that study, which involves a process that bacterially converts sulfate into elemental sulfur via a hydrogen sulfide intermediate for the treatment of mine water containing metal and sulfate, showed that it is capable of decreasing sulfate concentration from 1,800 mg/l to less than 0.03 mg/l.

4 Conclusion

The study provides a comprehensive analytical framework useful for long-term planning, development and management of conjunction use of Mae Moh water system. Applicability of the proposed methodologies is illustrated in a representative Mae Moh water system components, such as the upline natural water resources, the mine drainage system, power station effluent, other water used for Mae Moh project activities and downstream receiving reservoirs in Mae Moh basin. The study considers a conjunctive use system with a stream diversion, reservoirs, out-pit mine sump, weir, settling ponds and wetlands as the Mae Moh water model components. This study has considered several important issues related to the water quality and quantity of Mae Moh water system to create and construct a water model. The water model itself consists of a main diagram with symbols showing the major part of overall water system at Mae Moh basin and a series of water model databases to assist in information management, predictive capability and information presentation. Throughout the study, an attempt has been made to maintain an appropriate balance between simplicity and reality. The model validation has been done in year 2001 by comparing between predicted model and actual model. The result showed that at 95% ($\pm$ 2SD) confidence interval, the mean of predicted value and actual value of TDS and SO_4^{2-} loads at the Mae Moh Reservoir were equalized. It can be concluded that the test result was acceptable and the water model can be used as a tool for Mae Moh water system management. It is possible to apply the model for both source reduction and recycle/reuse methods in order to achieve waste water minimization. The water discharged from Mae Moh project consists of mine drainage and power plant effluent, with pH of 7.32 and 7.20, respectively. For pH value > 6 and alkalinity greater than acidity, the low metal concentration is probably not significant in estimating the environmental effects. The water model presented details of annual information of water flow, pH value, concentration and chemical load of TDS and SO_4^{2-}, which were significant water pollutants. According to the predicted water model for 2006, Mae Moh mine discharged water will be 10.76 Mm^3/year, with pH of 7.3, TDS and SO_4^{2-} concentrations of 2,548 and 1,803 mg/l, respectively. Mae Moh power station effluent will be 14.60 Mm^3/year, with pH of 7.0, TDS and SO_4^{2-} concentrations of 610 and 358 mg/l, respectively. At Mae Moh Reservoir, the out flow will be 83.67 Mm^3 and the concentrations of TDS and SO_4^{2-} will be as high as 1,501 and 822 mg/l, respectively.

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