OPENCAST MINE WATER SIMULATION MODELING

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Abstract

Opencast mining can generate large volumes of polluted water. A mine water model was developed to simulate water flow and salinity, using sulphate as salinity indicator, from an opencast coal mine in South Africa. The model was designed to combine different hydrological and geohydrological aspects including surface runoff, water storage in spoils and surface dams, irrigation disposal and groundwater flows. This was done to allow the analysis of water circuits. Model predictions indicated that 92 % of the sulphate pollutant load originated from the spoils material, while spoils also contributed 52 % of the water production in the opencast pit. A combination of irrigation land areas and evaporation/storage dam sizes were used to find an optimum solution for the discharge of pollutant waste loads to the public stream. The impact of different rehabilitation practices on pollution load mobilisation could also be determined.

Water systems modeling was demonstrated to be a valuable water management tool on an opencast coal mine.

Keywords

Water quality modeling, strip mining, coal mines, waste load.

BACKGROUND

Water quality management of the surface water resources of the Republic of South Africa is vested in the Department of Water Affairs and Forestry. The Department's policy to water quality management was recently broadened from the traditional *Uniform Effluent Standards* approach to now encompass:

- a *Receiving Water Quality Objective* approach to non-hazardous wastes.
- a *Pollution Prevention* approach to hazardous waste.

A water quality management plan (WQMP) was developed for the upper-Olifants River Basin in terms of the current approach to water resource management. Salinity and specifically sulphate have been identified as the water quality variables of most concern in this catchment. The WQMP caters for the allocation of **sulphate waste loads** which industrial, mining and municipal facilities are authorised to discharge.

Management of the controlled discharge of an allocated sulphate waste load from an opencast mining operation requires an understanding of the mine water circuits. Water quality simulation modeling is one of the management tools available to perform this control function. Such a model was developed for one of the opencast coal mines situated in the upper-Olifants River Basin.

2. REGIONAL LOCATION OF THE UPPER-OLIFANTS RIVER

The upper-Olifants River drains a catchment on the Eastern Transvaal Highveld which is endowed with rich coal reserves - refer to **Figure 2.1**. A diverse range of human activities including coal mining, power generation, agriculture and urban development impact on the water resources and specifically water quality.

A number of users abstract water from downstream impoundments for domestic use, irrigation, industrial use and cooling in thermal power stations. Recreation and aquatic life protection are also important considerations in the catchment.

The upper-Olifants River catchment is therefore not only of local importance, but also has an impact on the entire downstream river system.

3. OPENCAST MINE WATER MANAGEMENT

Opencast mine water management is fundamentally based on the separation of clean and dirty waters. Natural runoff (clean water) from the catchment upslope of the opencast mine is normally intercepted by a system of cut-off trenches and collection dams and diverted around the mining operation.

Dirty water is defined as any water in contact with waste rock, spoils and coal products. The dirty water circuits typically involve a system of opencast pits, impoundments, water conduits and pumping installations. The typical mine water system is conceptually illustrated in **Figure 3.1.**

Disposal options for the dirty water produced on an opencast mine include:

- evaporation / evapotranspiration.
- treatment and controlled discharge to the public stream.
- re-use within the mine water system.
- irrigation.

Water management on an opencast mine may be further complicated by the unpredictable and seasonal character of rainfall. The catchment of the upper-Olifants River is a summer rainfall region (October - March) with annual rainfall varying between 410 and 1 015 mm.

Due to the complex and dynamic nature of an opencast mine water system a computer model was developed to simulate water flow and water quality. The model was further employed as a management tool to analyse:

- different mine scheduling scenario's.
- the appropriate dirty water disposal options.

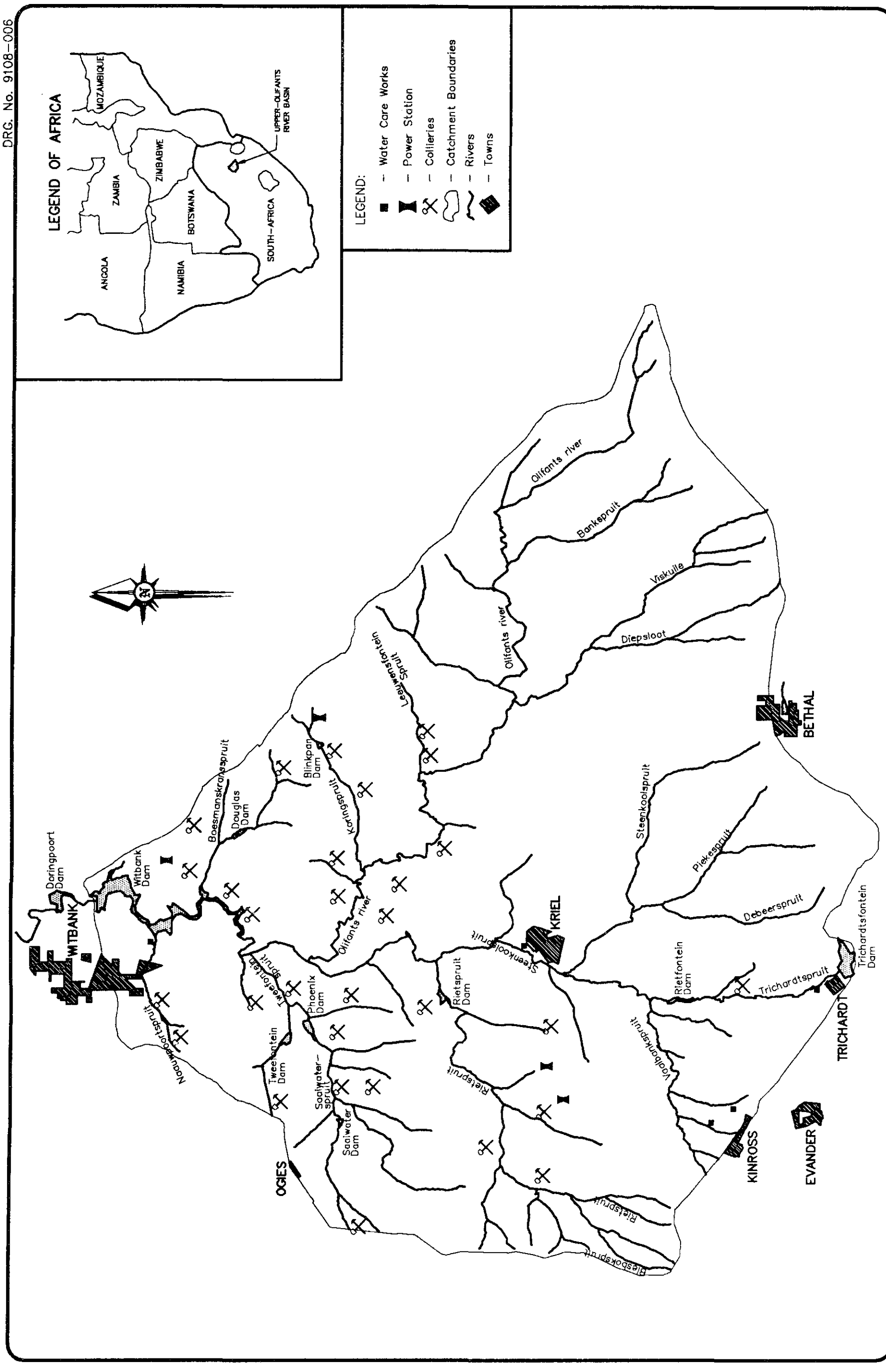
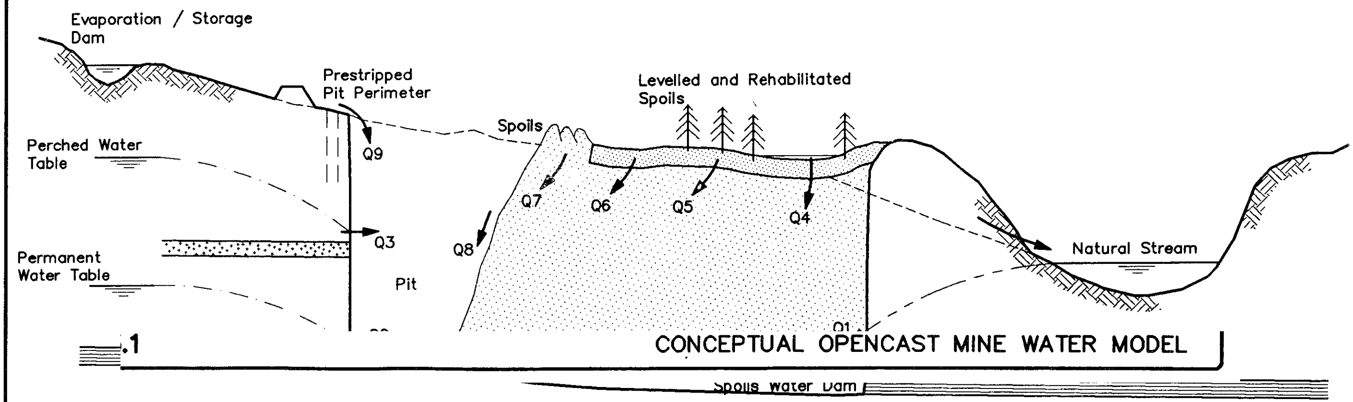


FIGURE 2.1 DRAINAGE BASIN OF THE UPPER–OLIFANTS RIVER



LEGEND:

Q1 – Seepage from a public stream
Q2 – Primary aquifer recharge
Q3 – Perched aquifer recharge
Q4 – Seepage from on–spoils runoff storage dams
Q5 – Recharge from topsoiled and vegetated spoils
Q6 – Recharge from topsoiled and seeded spoils
Q7 – Recharge from unrehabilitated spoils
Q8 – Surface runoff from spoils
Q9 – Surface runoff from pit perimeter
Q10 – Surface runoff from pit floor

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- scheduling and implementation of dirty water disposal facilities.
- the waste load released to the public stream and the consequent impact on the downstream receiving water body.

4. STRUCTURE OF THE MODEL

4.1 Hydrology

Since rainfall is the most important determinant in water production associated with opencast mines, it is important to use a long rainfall record in order to quantify the risks associated with different hydrological cycles.

The mine water model was developed using a 70 year rainfall record, obtained from the South African Weather Bureau rain gauge in close proximity to the opencast mine. Although the opencast pit had an anticipated operational life of only 8 years, different rainfall sequences were used to quantify situations such as wet, average and dry rainfall cycles. Surface runoff was calculated using the Soil Conservation Services (SCS) methodology.

4.2 Opencast mine elements

From a water flow and water quality perspective, the colliery complex can be divided into a number of separate functional elements. Four typical elements are identified:

- catchments with certain quantifiable characteristics in terms of runoff generation and associated runoff quality.
- water storage facilities.
- irrigation land with a specific soil profile and crop cultivation pattern.
- geohydrological flows which consist of seepage through the spoils and ramps, as well as recharge from the natural aquifer.

The entire colliery complex could be described by the combination of and interconnection between elements which were modelled as one of the standard elements described above - refer to **Figure 4.2.**

4.3 Submodel description

Generic algorithms were developed to describe each of the typical model elements.

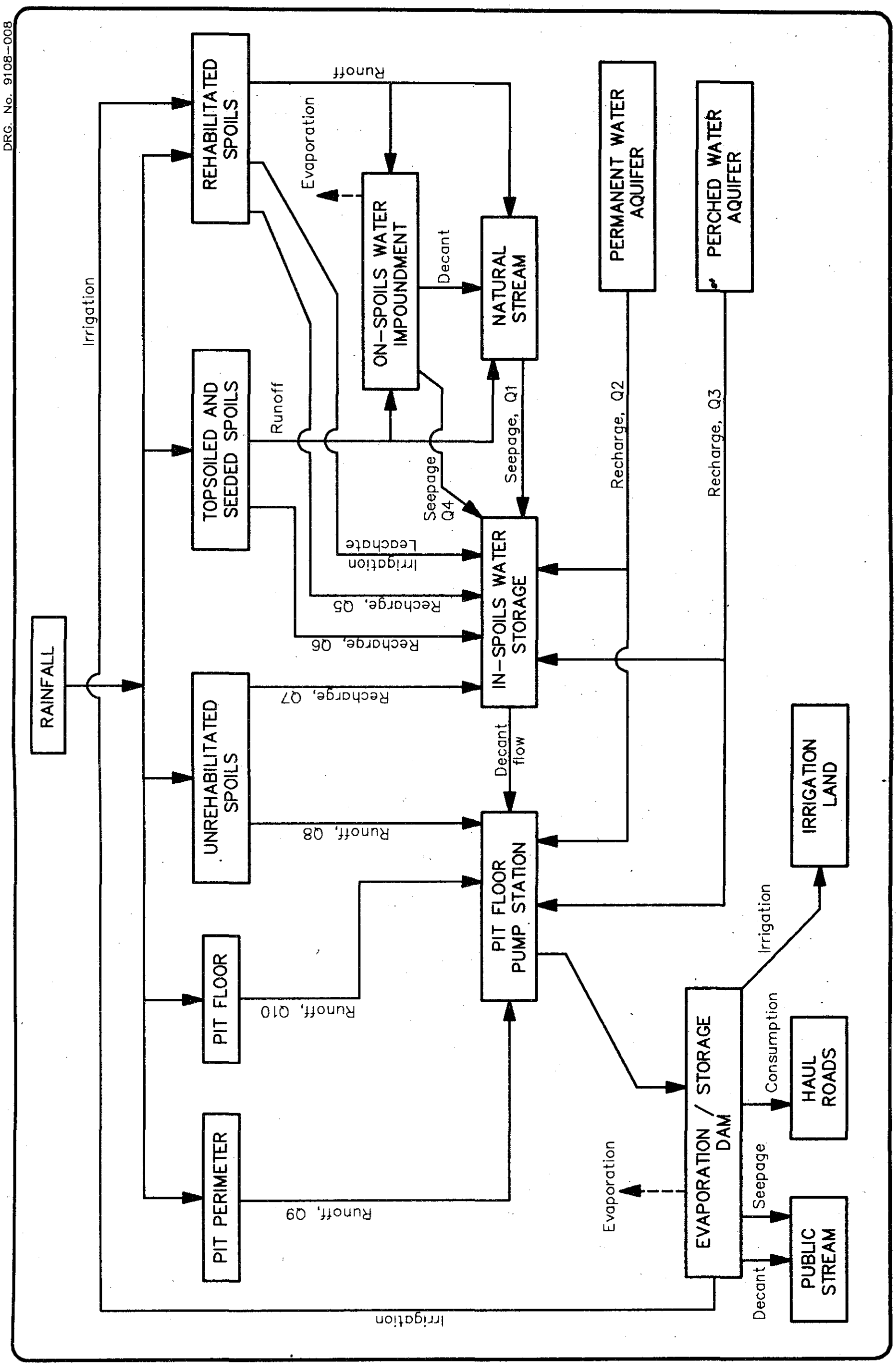

FIGURE 4.2 GENERIC WATER FLOW DIAGRAM OF OPENCAST MINE

4.3.1 Catchment submodel

The runoff generation from a defined catchment (e.g. pit floor) was simulated as the combination of direct surface runoff and interflow.

Direct surface runoff and interflow carry a sulphate load. The mobilisation of sulphate from a catchment surface is modeled using the differential equation:

$$\frac{dS}{dt} = BM - AM \times S \times R$$

where:

S = sulphate mass on the catchment surface ($kgSO_4/km^2$)

BM = sulphate generation for the specific catchment from atmospheric deposition, weathering and sulphide mineral oxidation ($kgSO_4/km^2/month$)

AM = kinetic coefficient which determines the rate at which sulphate is removed from the catchment surface (1/mm)

R = effective rainfall (mm/month)

4.3.2 Water storage submodel

Surface water storage

The generic water storage dam submodel is based on the assumption that the impoundment is well mixed. This assumption is based on the fact that the mine dams are relatively shallow with effective wind mixing. The sulphate concentration in the storage dam is modeled on the basis of flow and mass balance expressions:

$$dV/dt = Qin - [Qevap + Qseep + Qiros + Qirfl + Qcon + Qspill]$$

$$d(V.C)/dt = SQin - [Qseep + Qiros + Qirfl + Qcon + Qspill]C$$

where:

V = dam volume ($10^3 m^3$)

Qin = influent flow ($10^3 m^3/month$)

Qevap	=	nett evaporation from dam ($10^3 m^3$/month)
Qseep	=	seepage loss from the dam ($10^3 m^3$/month)
Qiros	=	abstraction for irrigation on vegetated spoils ($10^3 m^3$/month)
Qirfl	=	abstraction for irrigation on natural farm land ($10^3 m^3$/month)
Qcon	=	consumptive use, such as haulage road dust suppression ($10^3 m^3$/month)
Qspill	=	spillage in the event of overtopping ($10^3 m^3$/month)
C	=	sulphate concentration ($mgSO_4/\ell$)
SQin	=	sulphate mass load associated with influent to dam (kg/month)

The total flow entering a surface impoundment (Qin) will include runoff from the catchment of the impoundment, as well as the mine water discharges to the impoundment.

In-spoils storage

Several seepage and recharge streams percolate through the spoils before reaching the pit floor. The pit floor topography will change as mining progresses and local depressions form. These depressions will first fill before decanting to the pit floor.

Stagnant water which accumulates within the spoils usually have a higher salinity compared to water seeping through the spoils. In the case of coal strip mines in South Africa, it has been found that stagnant in-spoils water may take from 2 - 4 years to reach saturation levels of sulphate.

As a first approximation, the sulphate concentration of the in-spoils accumulated water can be modeled using the following differential equation:

$$V.dC/dt = SQinsp + (Ke^{1-C/Csat} - 1).V - SQdecant$$

where:

K = a kinetic constant

C = sulphate concentration in the in-spoil water storage impoundment ($mgSO_4/\ell$)

Csat = saturated sulphate concentration in the in-spoil water storage impoundment ($mgSO_4/\ell$)

SQinsp = sulphate mass flow entering the in-spoils water storage impoundment ($kgSO_4$/month)

SQdecant = pollutant/salt mass discharged from the in-spoils water storage impoundment ($kgSO_4$/month)

4.3.3 Irrigation submodel

The irrigation disposal of dirty water was modeled using the simple equation:

$$Qir = [Cf \times Pel - Er \times R] \, Air/Efi$$

where:

Qir = irrigation water demand ($10^3 m^3$/month)

Cf = crop factor for a specific month of the year

Pel = potential evapotranspiration for a specific month of the year (mm/month)

Er = precipitation efficiency to account for the non-uniform distribution of rainfall during a month (dimensionless)

R = precipitation (mm/month)

Air = irrigation land area (km^2)

Efi = irrigation efficiency, which depends on the irrigation practice (dimensionless)

Monthly evapotranspiration and crop factors can be modeled for any selected crop. The evaporative characteristics of a fodder crop were used in the model simulations.

4.3.4 Geohydrological flows

The geohydrological flow components associated with opencast mining include:

- seepage from a natural stream in close proximity to the opencast mine.

- groundwater ingress (from perched and/or permanent water aquifers).
- seepage through the spoils.

Different levels of spoils rehabilitation will have a significant impact on rainfall recharge. Three categories of spoils were modeled i.e. unrehabilitated spoils, topsoiled and seeded spoils and rehabilitated spoils with established vegetation.

The migration of water through the different spoils categories were investigated and quantified by the use of a finite difference geohydrological model developed at the Winand Staring Centre in Wageningen (Netherlands).

Recharge from the natural soils and coal aquifer surrounding the opencast mine was analysed with a finite element geohydrological model, developed by Technical Engineering Services (Pty) Ltd in Cape Town (South Africa).

5. CALIBRATION OF THE MODEL

Any model application requires formal calibration and verification prior to simulation of future scenario's. Usually limited field data exists to perform such a calibration.

The available data base can be extended by the use of accelerated spoils leach column tests. Water quality data from similar opencast mines operating under comparable geological and climatic conditions may also be used.

6. MODEL APPLICATION

6.1 Opencast mine water quality

The pit is the single most important element of the opencast mine water system. It is therefore imperative to develop an understanding of the relative contribution to the pit dirty water flow and pollutant mass generated by runoff, seepage through the spoils and recharge from the regional aquifer.

Table 6.1 contains the predicted generation of dirty water and associated sulphate loads by different sources on the coal mine during the first 8 years of the life of the mine. It is significant to note that the bulk of the pit water volume and sulphate mass loads are associated with seepage from the spoils. Seepage from the unrehabilitated spoils contributes 19 percent of the pit water generation, but contains 34 percent of the sulphate load.

Surface runoff from the topsoiled and rehabilitated spoils was diverted away from the opencast mine in the case of this investigation and was therefore not considered in the mass and flow balance.

The high sulphate loads mobilised by the rehabilitated spoils must be interpreted within the context of relative surface areas. The area of the unrehabilitated spoils increases until the onset of spoils topsoiling and seeding. The unrehabilitated area then remains constant, being followed at a fixed distance by topsoiling and seeding. The surface area of the rehabilitated spoils therefore increases steadily during the progression of mining and reaches an area approximately eight times that of the unrehabilitated spoils towards the end of the pit life.

Source	Water flow (m^3/day)	% Flow	SO_4 Load (kg/day)	% Load
Unrehabilitated spoils runoff	10	1 %	91	1 %
Unrehabilitated spoils recharge	137	19 %	2 712	34 %
Topsoiled and seeded spoils recharge	88	12 %	1 742	22 %
Rehabilitated spoils recharge	147	20 %	2 901	36 %
Pit floor runoff	104	14 %	292	4 %
Pit perimeter runoff	188	26 %	144	2 %
Recharge from the permanent water table	33	4 %	30	0.4 %
Recharge from the perched water table	26	4 %	14	0.2 %
TOTAL	733	100 %	7 926	100 %

TABLE 6.1 RELATIVE CONTRIBUTION FROM DIFFERENT OPENCAST MINE ELEMENTS TO WATER FLOW AND POLLUTION LOAD.

The model simulation results reflected in **Table 6.1** assumed the following rainfall recharge rates through the spoils:

- unrehabilitated spoils - 15 %
- topsoiled and seeded spoils - 8 %
- rehabilitated spoils - 5 %

Rehabilitation practices will obviously also have an impact on the mobilisation of pollutants from the spoils. The simulation of mine water systems provides an excellent tool for the evaluation of different rehabilitation practices in terms of the generation of polluted seepage.

6.2 Water quality status in the colliery water circuits

The mine water model can be used to investigate the flow and sulphate concentration in any element of the mine water circuits. The response of a 20 000 m^3 capacity evaporation/storage dam, receiving the total excess pit water production, to an average rainfall cycle is shown in **Figure 6.2.**

The simulated water volume and sulphate concentration are depicted in this figure. It demonstrates how the evaporation/storage dam can be expected to fill with a corresponding drop in sulphate concentration during wet weather conditions. The beneficial use of this stored water, such as for fodder crop irrigation, can be evaluated on the basis of model predictions.

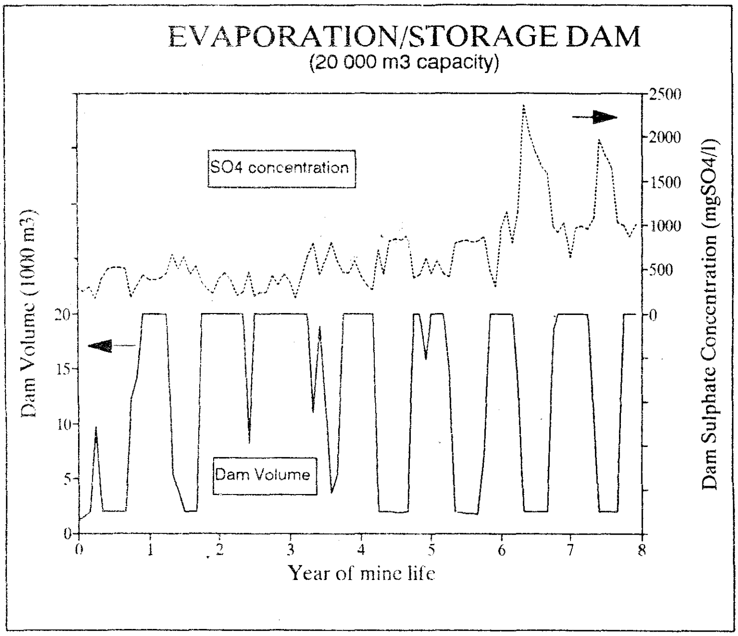

FIGURE 6.2 - WATER VOLUME AND CONCENTRATION OF A 20 000 m³ EVAPORATION/STORAGE DAM OVER AN 8 YEAR MINE LIFE

6.3 Waste load discharges

The timing of a waste load discharge to the public stream may have a significant impact on other water users, such as the aquatic life. If a waste load is released during periods of low base flow in the natural stream, the downstream water quality may be detrimentally impacted. Discharges during wet weather conditions normally have a much smaller impact on downstream water quality, even though the same pollutant mass load may be discharged. **Figure 6.3(a)** illustrates the predicted releases from a 20 000 m³ evaporation/storage dam in comparison to the situation with no evaporation/storage facility. During periods of low rainfall the pollution load is retained by the dam. A pollution load is however released to the public stream during wet weather events.

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In **Figure 6.3(a)** a positive trend can also be observed in the magnitude of discharged sulphate loads. This results from the increase in the pollutants mobilised as mining progresses and as the impact of the spoils increases.

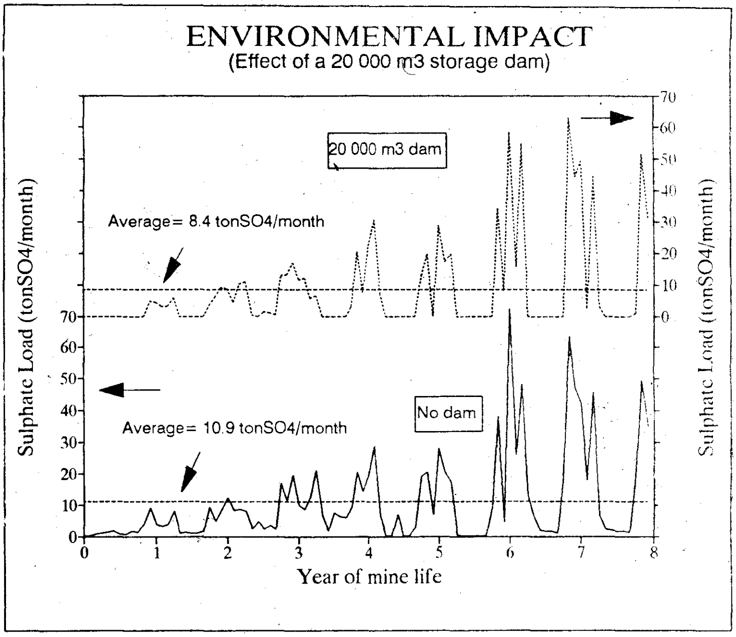

FIGURE 6.3(a) - EFFECT OF A 20 000 m³ EVAPORATION/STORAGE DAM ON THE SULPHATE LOADS DISCHARGED TO THE ENVIRONMENT.

The mine water model is a useful analysis tool in finding the optimum combination of evaporation dam size and irrigation land area to reliably achieve an allocated waste load. **Figure 6.3(b)** shows the average sulphate mass load which will be discharged to the public stream as a function of evaporation dam size and irrigation land area. Different combinations of dam sizes and land areas can achieve the allocated waste load. A techno-economic analysis can also be conducted using the simulation model results to find an optimum cost solution.

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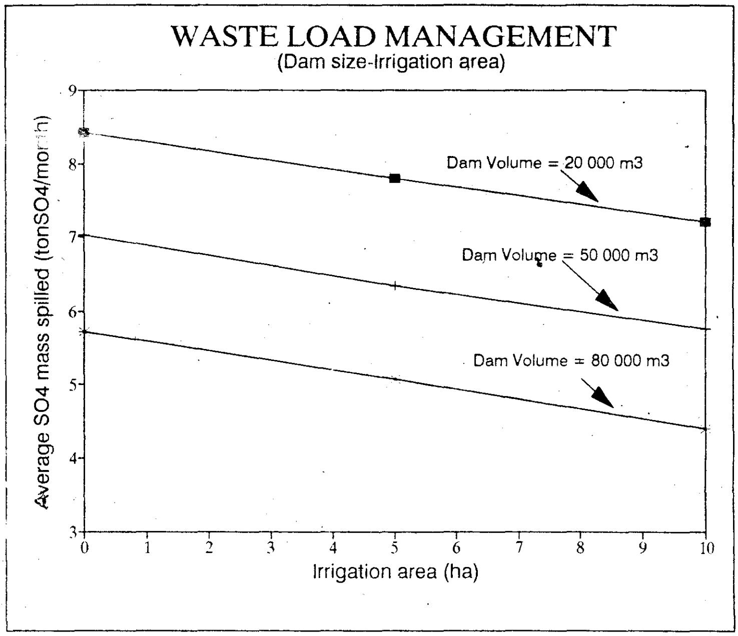

FIGURE 6.3(b) - INFLUENCE OF DIFFERENT EVAPORATION/STORAGE DAM SIZES AND IRRIGATION LAND AREAS ON THE SULPHATE LOAD DISCHARGED TO THE ENVIRONMENT

7. CONCLUSION

Opencast mining can generate significant volumes of polluted water and it is essential to understand the mobilisation of pollutants. An opencast mine is a complex environment and is furthermore subjected to the natural hydrological cycles. Modeling of the water circuits of an opencast mine presents a useful tool to assist the understanding and management of:

- the impact of activity scheduling (such as rehabilitation) on the water circuits.
- appropriate mine water disposal options.
- requirements for water handling facilities such as evaporation/storage dams etc.
- pollution waste load which could be released to the public stream.

Simulation modeling has been demonstrated to be a useful water management tool on opencast coal mines in South Africa.