Surface Water Treatment Plant for Mn, Ni and Cu at Morro da Mina, Brazil

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Abstract
The Morro da Mina site is a century old manganese mine impacted by acid mine drainage (AMD) originating from the waste rock dump (WRD) and, later, from the open pit. Loss of metals to the environment can be controlled by routing drainage from these two main sources of acidity and metal leaching to a single point for treatment and then discharge of the treated water to the local river (River Gigante). After completion of jar tests in 2007 and a pilot scale test in 2008, plans have been made for installation of a new water treatment plant (WTP) in the near future. Laboratory scale results demonstrated that a lime addition system is the most effective and efficient technique for removal of the majority of the metals and acidity. To be able to successfully implement the addition of a WTP, a water balance study was performed for this site using GOLDSIM software. This study was very important for the WTP layout determination and collection of surface water. It set up the technical basis for plant design. Pilot scale study results were used for the development of the WTP process flow diagram (PFD) and for definition of its footprint that will be needed.

Key Words: Mine Water balance, GOLDSIM and AMD management

Introduction
Morro da Mina is an open pit manganese mine owned by Vale Company. It is situated in the Paraopebas river basin, a traditional mining district in Brazil (Figure 1) where mining activities resulted in the establishment of several towns between the 17th and early part of the 20th century. This mine is an important part of mining history in this region of Brazil; it began as an artisanal enterprise in 1898 and became more industrialized in 1902.

From 1902 to 1969 the manganese ore was basically formed by of oxide minerals as a product of the intense weathering process typical of tropical countries. Approximately 8 million tons of manganese oxides were exploited during this time. There is no record of acid rock drainage up to the end of the 1990s. In the late 1990s the company exhausted its oxide ore and start to mine the silicon manganese carbonate ore (approximately 16 million tons) which is associated with sulfide minerals (Pyrite - FeS and Pyrrotite - $Fe_{1-x}S$). Then, surficial water quality in a pond (***Ipê*** lake) located at the foot of the waste piles (Figure 2) started to show signs of increasing water acidity (pH decreased down to 3.5) and metal leaching (Mn, Cu and Ni) concentrations increased up to 100.0; 0.11; and 0.45 mg/L respectively.

In October 2005 a preliminary site assessment of this area was developed to provide conceptual solutions to mitigate environmental problems caused by the AMD (Golder, 2006). As part of the environmental actions to mitigate the AMD there were suggestions such as: dry cover for the waste dump, review and install a new superficial water drainage system, and develop a feasibility study to find out the best available technology to treat the acidic water from ***Ipê*** Lake.

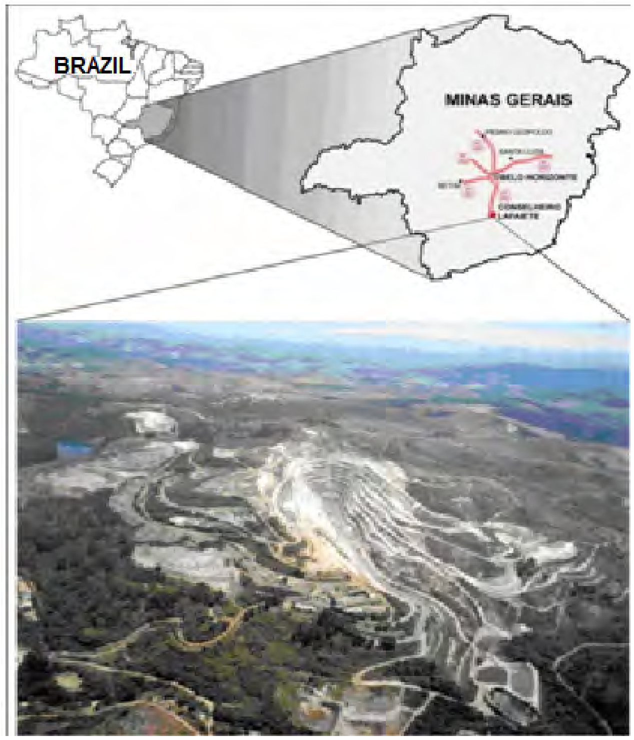

Figure 1. Morro da Mina location in Brazil, region of Minas Gerais state

This paper aims to present the last phase of the process to implement an acid mine drainage active treatment system. To be able to successfully implement the addition of a WTP, a water balance study was performed for this site using GOLDSIM software. This hydrological study was very important for WTP layout location at the site and evaluation of the technical basis for the establishment of plant design, considering that it provided the flows in different scenarios for the location of the WTP.

Site water balance – Mathematical model (Goldsim)

The water balance model was developed using GOLDSIM, a dynamic simulation program, widely used for water and mass transport modelling on mine sites. GOLDSIM can accurately model hydrology and sediment transport with each project being set up with catchment specific data such as rainfall/runoff, sediment properties (SDP), network information (pipes, tanks, pumps, weirs), etc.

This project involved the development of a detailed GOLDSIM model based on accurate site and monitoring data, in order to determine an appropriate capacity for a proposed WTP for this mine site. A number of scenarios were evaluated – for both the existing mine site extents and proposed future extents (mine expansion).

Field data analysis and interpretation

Considering that there are two main sources of acid mine drainage (AMD) at this site, the waste rock dump (WRD) and the open pit (OP), a single point down-gradient from them would be theoretically the best place to set up a water treatment plant (WTP).

To be able to evaluate the technical viability of this location to establish a WTP, the existing WRD and the OP areas field data were analysed in eight groups: 1- Catchment area; 2- Storage area; 3- Rainfall and Evaporation Data; 4- Hydrology; 5- Groundwater inflow; 6- Site water consumption; 7- Water chemistry and 8- Ground water. Figure 2 below presents several catchment areas conceived for this site.

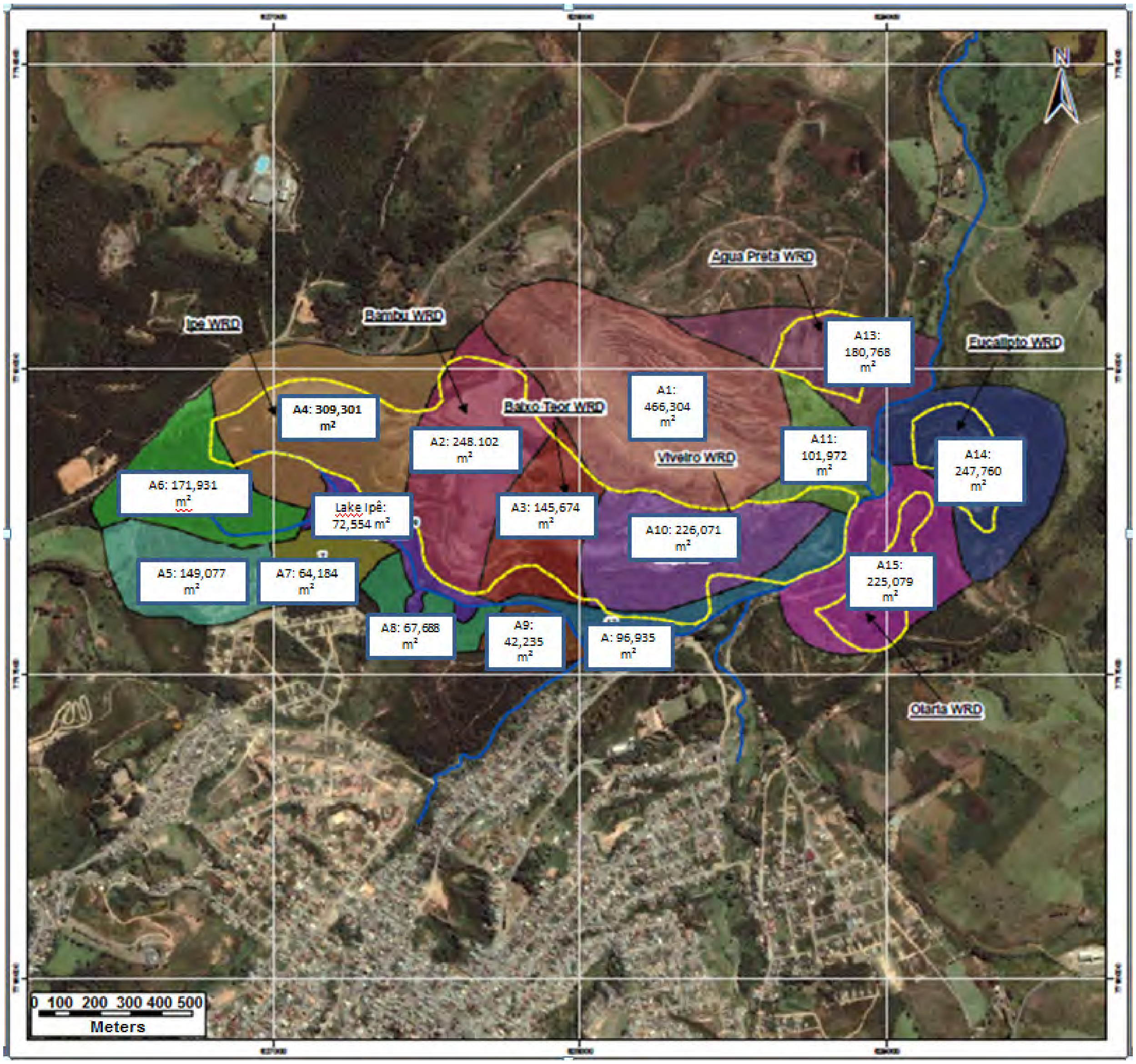

Figure 2. Morro da Mina site subdivided in several catchement areas

Catchment areas

Each catchment area was numbered and its surface area estimated as shown by the table below (Table 1). Land use varies between catchments and is also indicated on the map. As shown, each catchment predominantly has one land use type and it has been assumed that this land use characterises the runoff and contaminant transport for the entirety of each catchment. The contaminant runoff distribution for each land use has been determined from the ground water and surface water monitoring, which incorporates data gathered between 2001 and 2010. Each catchment and its land use, source contribution, runoff coefficient type, surface water contamination loading monitoring point(s) and ground water contaminant loading monitoring point(s) is identified in Table 1 below.

Preferential deposition of waste rocks with sulphide minerals may result in a waste dump area with a high acid potential AP area (Table 1).

Table 1. Catchment area characterization and definition of runoff type (coefficient)

Catchment	Land Use	Contributes To	Runoff Type (Coefficient)	Surface Contaminant Point(s)	Ground Water Contaminant Points
C1	Pit	Pit Sump	Pit	M6	M6
C2	WRD	Lagoa do *Ipê*	WRD	M9	PZMM04, PZMM05, PZMM12, PZMM15, PZMM16
C3	WRD	*Ipê* Transfer Channel	WRD	M9	N/A
C4	WRD	Lagoa do *Ipê*	WRD	M10	PZMM04, PZMM05, PZMM12, PZMM15, PZMM16
C5	Urban	New Clean Water Storage	Urban	M11	PZMM04, PZMM05, PZMM12, PZMM15, PZMM16
C6	Undisturbed	New Clean Water Storage	Natural	M11	PZMM06, PZMM01, PZ0A4R(SUB07)
C7	Undisturbed	New Clean Water Storage	Natural	M11	PZMM06, PZMM01, PZ0A4R(SUB07)
C8	Undisturbed	New Clean Water Storage	Natural	M11	PZMM06, PZMM01, PZ0A4R(SUB07)
C9	Undisturbed	River Gigante	Natural	M11	PZMM06, PZMM01, PZ0A4R(SUB07)
C10	WRD	*Ipê* Transfer Channel	WRD	M9	N/A
C11	WRD	Detention Ponds	WRD	M6	N/A
C12	Undisturbed	River Gigante	Natural	M11	PZMM06, PZMM01, PZ0A4R(SUB07)
C13	WRD	New Storage	WRD	M9	
C14	WRD	New Storage	WRD	M9	
C15	WRD	New Storage	WRD	M9	

Storage areas

There are multiple water storage areas across the mine site that contributes to the water balance model. The existing storage areas contribute to the water balance areas at the Lake ***Ipê***, the Pit Sump and the

Open pit Detention Ponds. The accumulation storage and storage areas used for the mine process plant and site water demands do not influence the balance as the water is sourced from outside of the mine site and any seepage from the waste water is accounted for in the ground water inflow rate. The characteristics of each existing storage area contributing to the water balance is summarised below, including the depth, surface area and cumulative volume used in determining the reservoir activities:

The Open pit Detention Ponds storage areas are made up of three smaller storage areas which act as a series of sediment ponds with weirs overflowing to the neighbouring pond. For the purpose of the water balance model, the storage areas are represented by only large storage areas. The following information was provided for the existing ponds: No 1= 600m² surface area, 3m deep. It is assumed that the storage sides are vertical; No 2 = 1,200m² surface area, 3m deep. It is assumed that the storage sides are vertical; No 3 = 1,200m² surface area, 6m deep. It is assumed that the storage sides are vertical.

Lake Ipê captures the runoff from the largest waste rock dump on the mine site. The northern side of the catchment is predominantly waste rock dump, whilst the southern side of the catchment is mostly undeveloped, which includes a small area of urban land use. The storage area itself is long and narrow, approximately 5m deep and covers an area of 72,700 square meters at peak storage capacity. A shallow section in the middle of the storage could divide the storage into two smaller, separate water bodies, however, for the water balance it has been assumed that the storage will be joined. As the storage could have contaminants lying on the bed, it would be good practice to maintain a sufficient level of water in Lake *Ipê* to reduce the volume of sediments being oxidised, thus the assumption is likely to represent the actual operation of the water storage. Table 2 provides the properties of the Lake *Ipê* storage area used to model the behaviour of the detention ponds in the water balance. A concrete weir has been constructed at the downstream end of the Lake, which overtops into a channel and flows into the River Gigante. Once the treatment plant has been commissioned, the weir would not normally be overtopped and only relied upon during significant rain events.

Table 2. Lake *Ipê* Storage

Height (m)	Surface Area (m²)	Cumulative Volume (m³)
944.9	0	0
945	2,298	115
946	16,393	8,781
947	30,378	29,741
948	39,813	64,836
949	72,735	121,110

The main pit has a small sump constructed in the base of the pit to capture rainwater runoff and groundwater influx into the mining area and allow the mine to continue production. The pit provides a large storage capacity as it can fill up to the third bench before water is released to the neighbouring environs. The pit storage area has been calculated up to the third bench (data not presented). The intention is to keep the base of the pit dry by dewatering the sumps when necessary to allow production to continue, so the actual volume of storage used in the pit will be small except during extreme events. Thus the actual storage volume of the sump itself does not influence the water balance model.

Additional water storage areas are required to capture runoff which previously drained to the River Gigante and allow the treatment process to occur. The following new storage areas are required for the capture and treatment of contaminated water: (i) Treatment Plant inlet and outlet storages; (ii) Agua Preta Waste Rock Dump water storage; and (iii) Future Waste Rock Dump water storage.

Rainfall and Evaporation Data

Both hourly and daily rainfall data was obtained for the area. A number of rainfall gauges were assessed, and the following were chosen for the analysis: (i) Raingauge 02043013 – 1941 to 2010, daily data (shown below in Figure 3 alongside daily Acominas data); (ii) Acominas Gauge - hourly data from 2008 to 2010.

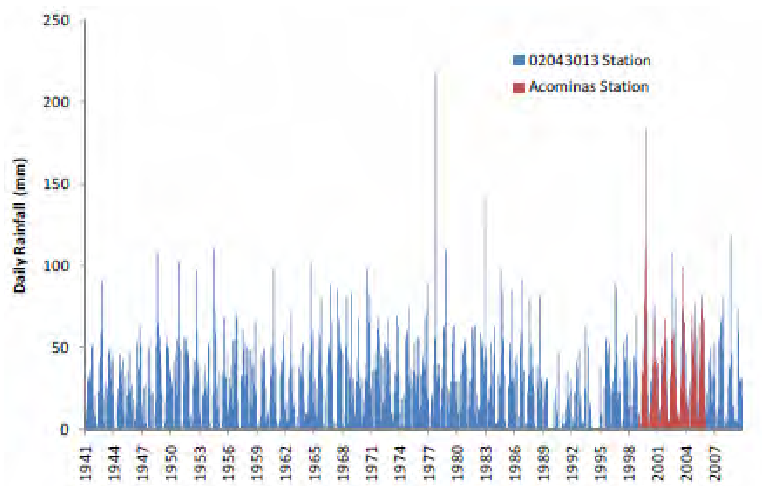

Figure 3. Daily rainfall data from station 02043013 and Acominas station

Average monthly evaporation data has been sourced from a previous hydrological report (Golder, 2009). No records of daily evaporation over a long time series is available, thus it has been assumed that the average monthly evaporation will occur for their respective months every year. A summary of the average daily evaporation for each month is provided in Table 3 below.

Table 3. Average daily evaporation per month

Month	Evaporation (mm/day)
January	2.65
February	2.82
March	2.74
April	2.20
May	2.06
June	2.03
July	2.35
August	2.97
September	3.17
October	3.03
November	2.87
December	2.71

Hydrology

A simple, but conservative hydrological assessment procedure was adopted for use in the study. Runoff estimates were made using volumetric runoff coefficients (VRC). This approach does not consider antecedent conditions or the effects of catchment lag, and is therefore an indicative hydrological approach. Excluding the effects of catchment lag is conservative because this will likely dampen the runoff peaks, particularly in the waste rock dump catchments where runoff is normally dampened significantly. This study has also adopted conservative VRC coefficients in light of the uncertainties in the hydrological procedure and gauging data. The adopted VRCs are presented in Table 4.

Table 4. Adopted volumetric runoff coefficients for this study

Height (m)	Surface Area (m^2)	Volume (m^3)
Urban	40%	60%
Pit	60%	80%
Waste piles – active	30%	50%
Waste piles - rehabilitated	10%	30%
Natural	10%	30%
Waterbodies	100%	100%
Land Use Type	Lower	Upper

The VRCs are represented in GOLDSIM by a uniform probability distribution. This means that combinations of VRCs between the lower and upper bounds were trialled in a Monte Carlo analysis.

Groundwater Inflow

A flow monitoring point is located at the Lake *Ipê* Weir. Flow measurements were taken approximately twice monthly in 2007 and 2009. Comparing the rainfall records over this period to the weir flow measurements indicated that during the dry season, when little to no rainfall occurred there was relatively consistent flow over the weir. This is indicated in Figure 4 below, showing data for 2007. These data indicate that Lake *Ipê* is continually recharged by groundwater seepage and runoff generated by the mine and catchment activities. Thus an average groundwater inflow rate of 4 l/s has been assumed, which corresponds to the average measured flow rate during the dry season.

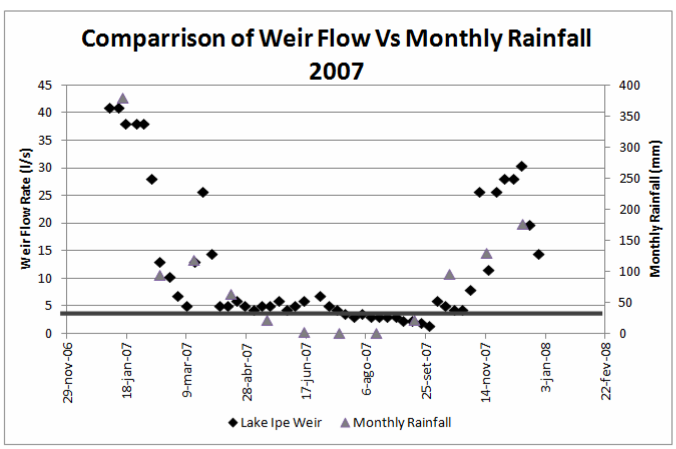

Figure 4. Weir near Lake *Ipê* flow vs monthly rainfall (2007)

The contribution of groundwater to Lake *Ipê* from the WRD and clean catchments feeding into the lake is considered relative to the catchment area. Thus the WRD (Catchments 2 and 4) contribute 53.5%, whilst the clean water catchments (Catchments 5 to 8) contribute 46.5%. This has been used to determine the contaminant loading of the ground water flowing into the lake.

In the open pit area, a more detailed study has previously been completed on the groundwater inflow into the pit by Golder in 2009. There is no metering of the sump pump, so estimation of groundwater inflow due to pump operation during dry months was not possible to estimate. This study identifies two sources of groundwater flowing into the pit sump. These are: (i) groundwater from recharge zones in the area of influence of the pit between 7 and 13 m^3/hr; (ii) groundwater stored within the rock mass within the area of influence of the pit which is released as the freatic surface drops and is related to the porosity of this material which enters the pit between 9 to 36 m^3/hr. This is predicted in increase linearly with the pit depth. This study subsequently applied a 1.5 factor of safety, giving a total inflow of between 24 and 73 m^3/hr. The existing Open Pit Detention Pond storage areas are at a higher elevation than the open pit base and River Gigante. It is assumed that the existing storage areas and the proposed storage areas and channels will have no groundwater transfer as they are at a higher level and would not interact with the ground water table. The new channels and storages should also be constructed in a manner that limits the amount of groundwater movement.

Site Water Consumption

Water is required for various activities across the mine site. These include process water, site activities (e.g. truck washdown), potable water from the water supply and dust suppression water. It has been assumed that the water discharged to the local environments from process plant and consumed by site activities once it has been used will be evaporated or recharge to the ground water storage. The contribution of the discharge water into the water balance is accounted in the ground water infiltration into Lake *Ipê* and into the Open Pit Sump.

Water for dust suppression is sourced from Lake *Ipê* and was metered for 4 months in 2009. It is assumed that the average extraction of water for dust suppression is representative of current and future monthly use at the site.

Surface Water Chemistry

Water quality monitoring reports over the past 3 years have highlighted that low pH levels are present in the lake water which indicates the presence of AMD. This in turn causes heavy metals from the waste dump area to mobilise, and monitoring has confirmed that these are present in runoff and groundwater on the site which subsequently enters into the stream and lake. Levels of manganese, copper, nickel and sulphates were all determined to be higher than acceptable limits relating to Brazilian environmental regulation for receiving waters (Class 2) (Mn = 0.1 mg/L; Cu = 0.009 mg/L; and Ni = 0.025 mg/L; SO_4 = 250 mg/L). Considering that sulfate is not mentioned by Brazilian environmental regulation (CONAMA 357, 2005) with a maximum limit of effluent discharge and metals are, the focus of this work was to treat metals and not sulfate. Contaminants like metals will enter the system via surface runoff and ground water seepage. Water monitoring data has been supplied from 2001 onwards. Surface water and ground water monitoring locations are provided in Table 5.

Table 5. Monitoring point location and description

Monitoring Point	Description of the monitoring point
M06	Out let from the open pit detention ponds
M09	Waste Rock Dump near catchment area 2
M10	Waste Rock Dump near catchment area 4
M11	Waste Rock Dump near catchment area 6

Each land use type (approximately based on each catchment) will have a range of contaminant runoff, which has been calculated from the monitoring data. Table 1 identified the monitoring points that were used to calculate these distributions for each catchment. This study is determining the inflow of four contaminants, Sulphates (SO_4), Nickel (Ni), Manganese (Mn) and Copper (Cu), from the mine site to the proposed WTP. The existing waste rock dump that spreads across catchments 2, 3, 4 and 10 will be capped in the future to reduce the levels of contaminants flowing to the WTP. A summary of the surface water monitoring points, the time over which samples were taken and number of samples for the monitoring points used in determining the catchment runoffs are provided in Table 6 below.

Table 6. Catchment Surface and Water Quality Monitoring Points

Monitoring Point	Sampling Duration	Number of Samples
M06	11/06 to 11/09	60
M09	1/09 to 9/09	10
M10	4/09 to 9/09	12
M11	12/06 to 11/09	25

A statistical analysis of the data for each point monitoring point was undertaken and a distribution fitted to the data to allow the variation in sampling results to propagate through to the model results to provide greater understanding of the range of contaminants flowing into the WTP. Where sufficient data has been gathered a log-normal distribution has been applied, otherwise a normal distribution is assumed. A summary of the analysis of the metal surface water quality data is presented in Table 7.

Table 7. Metal Surface Water Quality – Mean Concentration Data

Monitoring Point	Ni	Mn	Cu
M06	0.80	34.91	0.05
M09	4.04	448.33	0.55
M10	0.01	3.85	0.01
M11	0.02	0.34	0.006

Ground Water

The groundwater monitoring data collected has several test samples from each groundwater monitoring location. To better understand the data set and to determine the range of groundwater concentrations that may be observed, monitoring points from catchments with the same land use were grouped. It is assumed that these combined datasets are typical of the groundwater concentrations for that land use type. Table 8 below shows the total number of samples for each land use type.

Table 8. Ground Water Data Summary

Land Use	Number of Samples
Pit	60
WRD	20
Natural*	15

* Natural – Land use upstream from the mine site.

The natural land use has only fifteen samples, however the groundwater solute concentrations at these monitoring locations is very low (as expected) and therefore does not have a significant influence on the contaminant load. The WRD land use has twenty samples, which is sufficient to investigate the data distribution; however, additional data would improve the assessment. A summary of the results of the metal mean concentration used in the water balance model are provided in Table 9. The fitting of the ground water distributions is as per the surface water data analysis.

Table 9. Groundwater Quality - Mean Concentration Data

Monitoring Point	SO_4	Ni	Mn	Cu
Pit	370.41	0.80	34.91	0.057
WRD	1,627.18	5.28	195.44	0.18
Natural	21.7	0.01	0.008	0.005

Each of these mean concentrations was applied to the groundwater infiltration rate into each of the site water storage areas to determine the contaminant transport from groundwater sources into the site water storages.

Water Transfer Operation

A water transfer philosophy is required to determine the operational parameters of the WTP operational storage areas and behaviour of water storage across the site. Considering the site water balance and the storage capacity of the each catchment area analysed here (e.g. open pit, open pit detention ponds and the Lake ***Ipê***) the best place to establish the WTP would be near the Lake ***Ipê***, and not near the open pit, as someone would imagine due to its down-gradient location in relation to the lake (Figure 5). This conclusion is supported by the fact that, according to GOLDSIM results, Lake ***Ipê*** water storage capacity is 18.75 times greater than open pit detention ponds and 1.135 times greater than the Pit storage. So, considering the fact that the waste dump will be covered and in a case of an intense storm event for a long period, then the design is based on a 2% risk of there being insufficient storage. Figure 5 presents the AMD water treatment system configuration for the site. Where, the water transfer operation would be: a- Water pipeline 1- capture impacted water from the open pit and pump to the Lake ***Ipê***; b- Water pipeline 2 – capture water from the lake and send it to the mill plant; c- Water pipeline 3 - capture water from the lake and send it by gravity to the WTP; and d- Water pipeline 4 – capture supernatant water from the filter pressure and send it back to the lake.

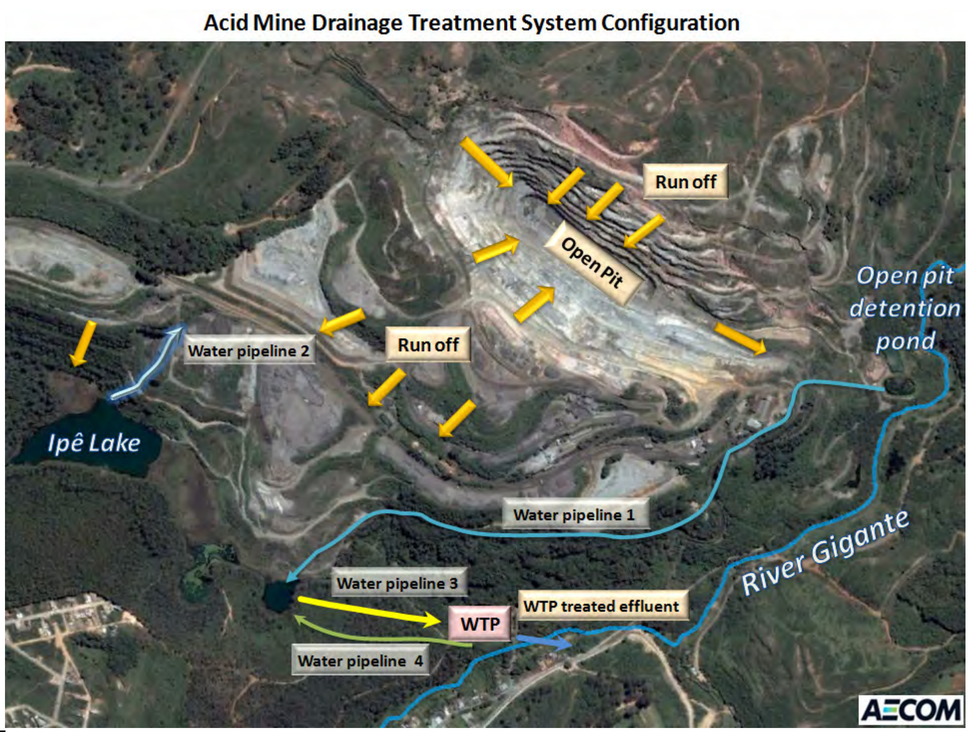

Figure 5. Water treatment plant footprint and lay out definition

Based on the water flow in the two basins: 1- Lake *Ipê*; 2- Open pit; the WTP flow capacity was conceived to operate by lime addition and to treat an average of 350 m^3/h. This plant will consume 3.6 tons of hydrated lime per day and produce 9.5 tons of sludge per day. This sludge will be composed of 55.7% MnO_2; 35.7% CaO; and 8.6% impurities. Considering the high concentration of manganese in the sludge and the proximity of this mine with some industries that would be interested in this type of material rich in manganese it is possible that the sludge that will be produced in this plant could be sold to reduce operational cost of this facility.

The foot print of the water treatment plant for this site, based on the water budget conceived by GOLDSIM, will be approximately 1 hectare (10.000 m^2) and the WTP process flow diagram is presented below in Figure 6.

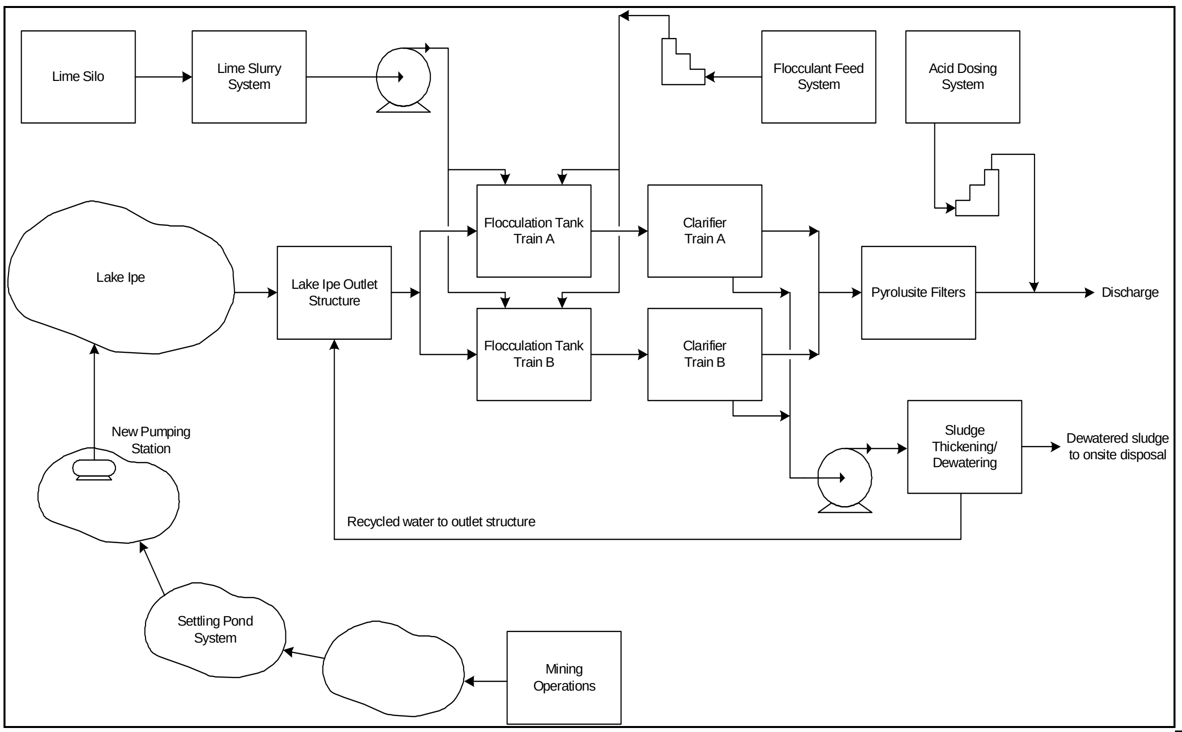

Figure 6. Schematic process flow diagram and map of the WTP for this site.

Findings and Comments

The findings and comments of the study are discussed below:

- A rational water balance at the Morro da Mina site was developed by AECOM technicians with a primary goal to characterize catchment areas, storage areas, and rainfall/evaporation data. From this data gathering and using GOLDSIM it was possible to determine the most appropriate location for the future water treatment plant.
- The water treatment system design for Morro da Mina was conceived with a 2% risk of failure in storage capacity.
- Ongoing and early rehabilitation could reduce the flow rates and treatment requirements, and reduce the treatment bypass risk profile. The assessment of existing and future development scenarios identified that the existing scenario is the critical scenario. The treatment plant duty could be reduced if early rehabilitation works and clean water diversions are possible.

- Lake *Ipê* sediments should remain water covered to prevent further oxidation of sulfides likely to be present on the lake bed.
- The required contaminant removal rates to achieve Class 2 water quality objectives are 96.9%-99.2% for Ni, 97.3%-99.9% for Mn and 96.1%- 98.8% for Cu. The WTP presented in this work should reach this performance and it will comply with Brazilian environmental regulations (CONAMA, 357/2005).

Acknowledgments

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