Technical Feasibility Studies and Uses of Treated AMD at Kingsmill Tunnel, Peru- “Emphasis on Supplement for Drinking Water Supply”

Nural Kuyucak✉[1], Jorge Chávez[2], Juana Rosa del Castillo[3] and Juan Ruiz[4]
[1] Corresponding author, Golder Associates, 1796 Courtwood Crescent, Ottawa, K2C 2B5 Canada
Tel: 1-613-224 5864; Fax: 1-613-224 9928; e-mail: nkuyucak@golder.com
[1] Golder Associates Perú S.A., Av. Jose Galvez Barrenechea 511, Lima 27, Peru
[1] CENTROMIN, Av. de la Poesía 155, Lima 41, Peru.
[4] SEDAPAL, Planta La Atarjea, Autopista Ramiro Prialé N° 210, Lima 10, Peru

Abstract

Environmental Impact Assessment (EIA) and Feasibility Studies (FS) were carried out to evaluate the potential use of treated acid mine drainage (AMD) occurring at the Kingsmill Tunnel in the Central Andes of Peru. The 11-km long tunnel drains the underground works of the Morococha Mining District and discharges about 1.25 m^3/sec of AMD directly into the Yauli River in the Amazon Basin. The communities living downstream cannot use the Yauli River water due to its low pH and elevated concentrations of metals (e.g., Cu, Zn, Fe, Mn, As, Cd) and sulfate. Studies carried out for this project included technical feasibility, EIA, economic viability and social impact assessment phases. During the “Technical Feasibility” phase, the treated AMD was produced by simulating a high density sludge (HDS) lime neutralization/ precipitation process and was evaluated for various potential uses. Mining companies located in Morococha, in particular Centromin Peru S.A., and the Water Works Company of the City of Lima (Sedapal) collaborated with Golder Associates during the studies. The Canadian International Development Agency (CIDA) provided the financial assistance.

The results of the physical, chemical, biological and toxicological analyses demonstrated that the AMD could be sufficiently treated to be potentially used to supplement the drinking water supply of Lima, and for agricultural (e.g., irrigation and livestock) and recreational purposes. Process design and scale-up parameters were also determined for implementation of the full-scale treatment facility at the site. The use of the treated AMD as a drinking water supplement would be economically feasible. The paper will discuss the studies conducted and results obtained, mainly from the “Technical Feasibility” phase.

1.0 INTRODUCTION

The “Kingsmill Tunnel” site is located in the district of Yauli, Junin Province, Perú. In the Yauli district, there are several mining areas such as Morococha, Andaychagua, San Cristobal and Carahuacra. These mines process mainly sulphide ores to produce copper, zinc and lead concentrates. Waste materials including overburden, waste rock piles and tailings that contain sulphide minerals have been placed in the same valley upstream of the Kingsmill Tunnel. The oxidation of sulphide minerals and subsequent generation of acid mine drainage (AMD or acid rock drainage “ARD”) at the site is of concern. The use of AMD management and prevention/control methods such as soil covers, water covers and/or amending the mining wastes with alkaline materials has been investigated and appropriate ones have been applied where possible (Kuyucak, 2001a). However, the generation of AMD at the site has already started and it is predicted that it will continue for a long time.

The 11.5-km long, 3-m wide and 3.40-m high Kingsmill Tunnel is constructed in rock with poured concrete end portals. It was constructed between 1929 and 1934 as drainage for the mines in the Morococha area. On the floor, a 1.2 m deep channel was excavated and covered with wood strips to discharge the collected acid water stream to the Yauli River. The tunnel serves three mining companies; the State Mining Company of Centromin Peru S.A., and two relatively small private companies. The acid water channel passes through the small town of Morococha and joins the Yauli River. Acid water coming from the San Cristobal Mine also discharges to the Yauli River upstream of the Kingsmill Tunnel. Currently, the

Yauli River water is not usable for any purpose because of pollution. A map for the study area is given in Figure 1.

If treated properly, the Kingsmill Tunnel AMD could be an important water source in the area and could help to improve the environment and human health. Golder Associates Ltd. (GAL) and the mining companies who use the Kingsmill Tunnel, in particular Centromin, developed a project to investigate the feasibility of treating the Kingsmill Tunnel AMD and the possible use of the treated AMD. The Canadian International Development Agency (CIDA Inc.) agreed to provide a financial contribution for the "Environmental Impact Assessment and Feasibility Study for the Use of the Treated Acid Mine Drainage (EIA/FS study for AMD) at the Kingsmill Tunnel in Peru" project. The project has included four major activities consisting of studies on technical feasibility, environmental impact assessment, economic viability and social impact assessment. The prime objective of the "Technical Feasibility" study was to produce treated AMD using an appropriate treatment method such as high density sludge (HDS) process and evaluate the quality of the treated AMD for its potential uses. Since the main interest was to investigate the possibility of the use of the treated AMD as a supplement for the City of Lima's drinking water resource, a collaboration was sought with "Sedapal" Water Works Company of Peru. Sedapal conducted physical, chemical, biological and toxicological tests to assess the quality of the treated AMD using the Peruvian Drinking Water Quality Standards and the quality of the Rimac River that is the water source for the City of Lima's drinking water treatment plant. Other possibilities for the use of the treated AMD include agricultural water for irrigation and livestock, recreational water, hydro-electric generation and process water for industries found in the vicinity of the Kingsmill Tunnel. The HDS process was simulated at a pilot scale to obtain treated water and sludge. The quality of the treated water and sludge generated were examined and the overall treatment efficiency was evaluated.

2.0 DESCRIPTION OF THE STUDY SITE

2.1 Socio-Economic Conditions

Presently, the area is considered rural and is in a hilly and mountainous terrain. Morococha and Yauli are two principal towns of the area. According to the Statistics and Data Processing National Institute of Peru, about 1,500 people live in each town, and although more than half of the population is considered potential workers, only a quarter of the population is actually working. The principal economic activity is the extraction of minerals (i.e., mining) and the majority of the population works in the mines. Basically, housing development is poor. An average house lacks some basic sanitary conditions such as sewage or water supply. In the high parts of the Yauli area, the Community of Pomacocha is located. In this region the raising of livestock and the cultivation of potatoes are considered as important economic activities.

2.2 Physical Setting and Climate

The area is located in the oriental part of the Andes, between 3,900 and 4,500 m.a.s.l. The relative humidity of the study area is always high reaching an annual average of 76.5%. Although the average daytime temperature can be as high as 19°C, a significant drop can occur at nights to as low as -8°C.

Heavy rainfall events bring two major seasons of rainy and dry to the area. The rainy conditions occur from December to March, while the dry season takes place from June to September. Calculations indicate that the annual average precipitation of the area is about 780 mm.

2.3 Hydrogeology

Within the study area, three main water bodies are encountered including Huacracocha, Huascacocha and Pomacocha lagoons. Downstream of the Kingsmill Tunnel, there is a hydroelectric plant that uses water from the Pomacocha Lake.

The core of the ore body in the area consists of filites from the Excelsior Group, followed by the volcanic rock from the Catalina Formation and lava flows of dacite and andesite which crosses the Kingsmill Tunnel. These rocks are superposed by limestones of the Pucará Formation that are composed of interbedded layers of limestone, stuffs, bituminous shales and cherts, that aflorate on the surface followed by the Goyllarisquizca Group. The Goyllarisquizca Group is represented by a sequence of a red conglomerate, followed by sandstones and red lutites, layers of cuarcites and gray sandstone, interbedded with lava flows or diabase dikes and basalt. The more permeable sedimentary rocks act as an aquifer and allow surface water flow over the riverbank of the Yauli River, which subsequently infiltrates into the Kingsmill Tunnel. The water infiltrates through veins and faults. 80% of the water that flows through the Kingsmill Tunnel comes from the Morococha area where the underground mining excavations, fractures and connected faults facilitate the flow of water coming from the surface into the tunnel. The rest of the water flows through the bedrock.

2.4 Existing Water Management Practices

Water required for the mining operations in the Yauli District are obtained from watercourses found in the area such as the Pomacocha Lake which is also the drinking water supply for the City of Lima with 8 million habitants. The mining and industrial operations in the Yauli District are subjected to PAMAS (Environmental Program Adaptation and Management) regulations which were promulgated in 1995. According to PAMAS, the existing companies had to develop an environmental management program and implement it at their site within five years in order to comply with the limits set for the mining effluents (i.e., wastewater). Projects having diversion channels for fresh runoff water and mines under development or construction are all included in PAMAS.

3.0 TREATMENT STUDIES

3.1 The Kingsmill Tunnel AMD and Suitable Treatment Process

As summarized in Table 1, the Kingsmill Tunnel AMD has a low pH and contains Cu, Zn, Fe, Mn, As and Cd in elevated concentrations. The pH ranged between 2.7 and 3; the SO_4 concentrations varied between 1716 to 2305 mg/L during the study. AMD contained as high as 9.6 mg/L of NO_3. The average flow rate of AMD is 1.27 m^3/sec (or 4,572 m^3/h), which is a substantial quantity for treatment. Hydrological investigations indicated that closing and flooding the mine by placing bulkheads could reduce the quantity of AMD, possibly by half. Even then, the treatment of a large quantity of AMD will be required. Therefore, there is a need for a cost-effective treatment process.

There are several alternative means of treatment including chemical, biological and physical/chemical methods and the mode of treatment process application may vary from the use of specifically designed and controlled reactors to passive systems. Alkaline neutralization and precipitation, in particular the use of lime as CaO or $Ca(OH)_2$ due to its relatively low cost and abundance, is the most preferred method in the mining industry for treating acidic effluents (MEND 1994; Kuyucak, 2001b). In lime neutralization processes, hydroxide ions (OH^-) neutralize the acidity and precipitate metals, such as $Fe^{(2+/3+)}$, Zn, Cu, Al, and Pb, in the form of metal hydroxides. Ca ions form $CaSO_4$ (gypsum) precipitates with SO_4 ions. The mixture of $CaSO_4$ (gypsum) and metal hydroxide, called "sludge", is separated and is disposed into a specifically designed impoundment. The principal reaction in lime neutralization can be expressed as follows (Eq. 1):

$$Ca(OH)_2 + Me^{2+}/Me^{3+} + H_2SO_4 \rightarrow Me(OH)_2/Me(OH)_3 + CaSO_4 + H_2O \qquad (1)$$

The neutralized treated water is discharged to the environment or recycled for use in the process. Depending on the site-specific requirements, lime neutralization facilities can vary greatly in degree of sophistication. They range from the simple addition of lime to acidic water lines to plants consisting of reactors, clarifiers, and sludge dewatering equipment as depicted in Figure 2. Sludge densities may vary from 1-30% solids depending on the sophistication of the treatment process and the quality of AMD. The current state-of-the-art lime neutralization process for treating AMD (or other acidic wastewaters) is called the "High Density Sludge (HDS)" process (Type III in Figure 2). The HDS process is capable of producing more compacted sludges and improved effluent quality than the traditional methods of liming (Aube and Zinck, 2000; Kuyucak, 2001b). The small quantity of sludge produced requires a small area for its disposal/storage, and reduces the associated monitoring requirements and liabilities. The HDS process offers a number of additional advantages such as increased quantity of recovered water, decreased quantity of lime used per unit of water treated and scaling, and less maintenance and labour. The recent tendency in the mining industry is to use the HDS method and, where appropriate, to upgrade the existing plants to the HDS method. The HDS lime neutralization technique was considered to be the most appropriate method for the treatment of the relatively high flow rate Kingsmill Tunnel AMD.

3.2 Treatment Tests: Test Equipment and Chemical Reagents

AMD was collected in $1m^3$ containers and transported from Kingsmill Tunnel site to Sedapal's facility in the City of Lima where the pilot-scale equipment was set up. This enabled quick delivery of the treated water samples to the laboratory for their analyses. First, the optimal treatment pH, lime requirements, and the type of polymer (flocculant) and its dosage were determined by bench scale tests. Then, pilot equipment simulating the HDS process was designed and constructed. As shown in Figure 3, the equipment consisted mainly of five tanks or reactors of different sizes and a clarifier. All tanks were instrumented with appropriate mixers and the neutralization tanks (Tank 6 and 7) were aerated as required. Aeration could oxidize Fe which could result in the production of a chemically more stable sludge. In addition, it could oxidize Mn and As, and improve their removal. The system was reasonably automated and the process control was achieved by controlling the alkaline reagent addition with pH values. A programmable logical control (PLC) system was used to control the process directly from a computer screen. The alkaline reagent contained a mixture of recycled sludge and lime slurry. Acid water, lime slurry and flocculant (polymer) were pumped into the reactors. Gravity flow was used between the reactors and clarifier, and for the discharge from the clarifier.

The principal neutralization and complete treatment took place in two neutralization tanks, which provided a retention time of 50-60 min for a flow of 1 L/min acid water. Sludge was recycled with the help of a pump as a volumetric ratio of inflow rate. The pH was controlled in the neutralization tanks in the range of 8.5 to 9.5, which was sufficient to reduce metals to below the regulated standards. The slurry from the neutralization reactors was treated with a flocculant solution prior to entering the gently agitated floc-mix (or flash-mix) tank. The pilot-scale treatment system used in the tests was a good simulation of a commercial-scale HDS process as used at other sites to obtain design and scale-up parameters for the construction of full-scale commercial treatment plants (Kuyucak et al., 1999; Kuyucak et al., 2001).

3.3 Monitoring and Analyses

The clarifier overflow (i.e., treated water) was monitored for physical/chemical parameters, such as pH, metals and SO_4, with samples taken several times daily for analysis at Sedapal's analytical laboratory. Metal concentrations were analyzed by an atomic absorption spectrophotometer and SO_4 concentrations were determined by the standard gravimetric method. Graphite furnace was used for the analysis of As. Thickened sludge from the clarifier underflow was sampled twice a day and was analyzed for its %S and chemical composition. Sludge settling rates were determined on the samples taken from the clarifier inlet by recording the distance of interface between the clarified water and settling solids vs. time in a graduated cylinder. Replicates for randomly selected samples were also taken and analyzed for physical/chemical parameters. A composite of about 24 samples was prepared for toxicological, biological and microbiological tests.

The insect *Chironomus callygraphus* was used for the toxicological tests, and LC_{50} tests were conducted using small (~2-3 cm) fish species of *Poecillia reticulata.* and alga *Daphnia pulex* for biological tests. Microbiological tests investigated the presence of *Coliform* bacteria in the treated AMD. The results were evaluated by the Sedapal staff according to the EPA-PROBITS statistical method and Munkittrick scale. A toxicologist in Canada assessed the methods and results and provided additional comments on the possible use of the treated AMD.

4.0 RESULTS AND DISCUSSION

4.1 Effect of pH on the Treated Water Quality and Lime Consumption

The bench tests indicated that the treatment pH had to be about 10 to be able to reduce the concentration of Mn to <1 mg/L (Table 1). The most effective polymer flocculant was weak-anionic Magnafloc 10 at a concentration of 2 mg/L. The results indicated that raising the pH of AMD from about 2.5 to 9 would require about 0.4 g lime per L of AMD.

The pH screening tests with the pilot tests indicated that a pH ranging from 8.5 to 9.5 would be feasible for treating the Kingsmill Tunnel AMD (Table 1). At this pH range all metals, except Mn, could be lowered below the regulated limits. The removal of Mn required a pH greater than 9. Otherwise, it was either on the borderline or slightly higher than the regulated limit of 0.1 mg/L. The pilot tests at about pH 9 resulted in a better Mn removal than the results of the bench treatment at ~pH 10. This could be due to the improved oxidation of Mn in the pilot system.

The average lime consumption rate was about 0.25 g per L of AMD, which was lower than the quantity consumed in the bench tests. This could be due to the improved mixing and solubility conditions in the continuous system and the formation of oxidized Fe, Al and Mn hydroxide precipitates where their surfaces could serve as adsorption sites for other metal ions such as Zn, Cu, Cd, As, etc. Removal of these metal ions by means of adsorption not only results in more efficient use of lime but also improves the sludge compaction (Kuyucak et al., 1991).

When the treatment pH was about 9, the removal of As, Pb, Cu, Cd, and Zn was excellent being at least an order of magnitude lower than the regulated limits. As expected, removal of SO_4 was marginal and the average concentration of SO_4 was about 1,700 mg/L in the treated water. The pH in the clarifier always measured about 8.5. When the treated water was collected in a separate container and further aerated, the pH could drop and stabilize around 7.0. The drop in the pH could be due to natural carbonation of the treated water with CO_2 in air (Montgomery, 1985). Although removal of NO_3 with lime neutralization process is not normally expected, during the pilot treatment studies NO_3 concentrations were lowered from 9.6 to <1 mg/L.

There exists several methods for removal/reduction of SO_4 from waters. These methods include: precipitation with Barium (Ba); Ion exchange; Biological Sulphate Reduction (SRB process) and aluminium hydroxide ($Al(OH)_3$) precipitation (Kuyucak, 2000; Smith, 2000). In general, these methods are not used widely for the treatment of mining effluents. Even if they show technical feasibility, their application may not be economically feasible, especially for large flows.

Table 1: Physical/Chemical Characteristics of AMD and Rimac River Water, Selected Results of Bench and Pilot-Test Treatment, and Peruvian Drinking Water Standards

Parameter	Raw AMD	Bench Test	Selected Pilot-Test Results					Rimac River	Drinking Water In Lima	Peruvian Drinking Water Standards
		pH 10 *	pH 7 *	pH 8.2 *	pH 8.5 *	pH 9 *	pH 10 *	**	**	
PHYSICAL										
pH	2.73	9.21	6.95	8.18	8.82	8.99	10.07	8.19	7.14	6.5-8.5
Temperature (C)	21.30	24.60	25		25.8	20.8	21	19.03	21.19	
Tubidity (NTU)	8.27		4.28	2.09	4.22	1.12	3.79	249.50	0.87	5.00
Conductivity (mS)	3.18		2.67	2.65	3.02	2.62	2.68	321.50	365.17	
INORGANICS (mg/L)										
Total Alkalinity (CaCO3)	0.00		15.87	27.78	43.65	20.83	22.82	91.00	73.17	
Total Hardness (CaCO3)	1624.18		1772.32	1818.96	1912.24	1815.26	1815.26	230.00	226.83	
Ca - Hardness (CaCO3)	907.63		1212.64	1352.56	1539.12	1480.87	1576.41	202.00	203.67	
Mg - Hardness (CaCO3)	716.55		559.68	466.4	373.12	334.39	238.85	28.00	23.17	
Chloride (Cl)-1	25.48		5.42	8.23	7.33	4.01	2.61	18.32	22.52	600.00
Sulphate (SO4)-2	1715.80		1853.5	1922.35	1746.4	1868.8	1654.6	139.00	142.33	400.00
Nitrate (NO3)-1	9.605		0.709	0.455	0.367	0.089	0.152	1.641	1.855	45.000
Nitrite (NO2)-1	0.031		0.006	<0.001	0.001	0.012	0.008	0.068	0.001	
Phosphorous (PO4)-3	0.040		0.008	0.014	0.024	0.009	0.002	0.800	0.261	
Silicate (SiO2)	14.318		12.109	5.145	2.654	1.804	2.907	15.28	13.37	
METALS (mg/L)										
Total Iron (Fe)	151.330	1.054	0.679	0.286	0.148	0.259	0.166	4.994	0.035	0.300
Manganese (Mn)	42.380	0.787	37.346	3.094	0.148	0.143	0.169	0.248	0.009	0.100
Lead (Pb)	0.149	<0.005	<0.005	<0.005	0.022	<0.005	<0.005	0.131	0.005	0.050
Cadmium (Cd)	0.2345	0.0014	0.184	0.0086	0.0039	0.001	0.0043	0.0037	0.0023	0.0050
Copper (Cu)	13.673	0.155	0.187	0.118	0.142	<0.005	0.036	0.099	0.004	1.000
Zinc (Zn)	59.000	0.902	13.186	0.449	0.273	0.112	0.337	0.659	0.052	5.000
Aluminum (Al)	4.392	0.174	0.24	0.147	0.232	0.127	0.11	9.677	0.053	0.200
Sodium (Na)	7.190	7.256	7.425	5.155	5.198	5.075	5.325	13.005	13.278	
Potassium (K)	3.084	5.360	3.709	6.103	3.855	3.544	3.092	2.420	2.247	
NON METALS (ug/L)										
Arsenic (As)	1459.43	2.024	3.871	1.036	0.801	1.036	1.641	0.227	0.011	50.0000
III.- ORGANICS (mg/L)										
Total Carbon	3.92		4.8	5.83	5.37	5.83	4.08	19.14	17.67	
Inorganic Carbon	2.79		1.72	3.14	2.34	2.76	2.49	16.92	16.64	
Organic Carbon	1.13		3.08	2.69	3.03	3.07	1.59	2.47	1.03	

*Indicates adjusted treatment pH values. Clarifier overflow had always a pH less than 8.5; after aeration it was about 7.5. **Obtained from Sedapal, April 2000.

4.2 Results of Toxicological, Biological and Microbiological Tests

The results of all tests showed that properly treated AMD was not toxic to aquatic life. The treated AMD, where the flocculant is used, could be discharged to natural water sources such as lakes and rivers without any risks. As expected from the nature of AMD, the treated water did not show a presence of *Coliform* bacteria.

The toxicologist in Canada indicated that "if the water quality meets the Peruvian standards for drinking water quality, then they should be allowed to add it to the drinking water supply. The high sulphate and manganese concentrations, themselves, do not present a health risk. They will merely affect the aesthetic qualities of the water. Nevertheless, if these concentrations can be reduced through dilution, that will be much better for the drinking water. The Peruvian standards seem reasonable, compared to Canadian and US water quality guidelines".

4.3 Sludge Characteristics and Production Rate

After about three days of continuous operation, the colour of the sludge changed from yellow-brown to dark black-brown colour indicating improved oxidation of metals such as Fe and Mn. The settling of the precipitates was very rapid giving an initial sludge settling rate of about 1.2 m/h. As the continuous operation proceeded the fluffy texture of the sludge changed to granular rounded particles. The solids (S) content of the sludge increased to about 5.5% during a one-week operation period. The compaction of the sludge and drainage of the water through the sludge particles could be visually observed. The pilot-treatment system was operated for two one-week cycles. After each cycle (i.e., treatment period), the system was cleaned and the operation was restarted. The results were reproducible for all parameters evaluated. It is expected that if the system could be operated for a longer period of time, the sludge density could improve further, resulting in greater %S contents. Previous experience at different mining sites has shown that greater %S contents can be reached with the full-scale treatment systems in comparison to the %S contents obtained from the pilot tests (Kuyucak et al., 2001 and Kuyucak et al., 1999). Greater than 20% S contents can be obtained from the operation of full-scale HDS treatment plants. If the production of a sludge with 20% S contents is assumed, the treatment of 1 m^3 of AMD will produce 11 L of sludge. As mentioned above, because of low initial concentrations of SO_4, the sludge resulting from the lime neutralization/precipitation process mainly consisted of metal oxides and hydroxides (Table 2).

Table 2: Metal Contents in the Sludge Generated During Pilot Tests

Metal*	Al	As	Cd	Ca	Cu	Fe	Mg	Mn	Ni	Pb	Zn
Content (mg/Kg)	22807.6	126	252	39142.4	24349.2	58464.6	76647.8	73306.8	59.5	316.5	64860.7

*Selected metals are reported.

5.0 POSSIBLE USE OF THE TREATED KINGSMILL TUNNEL AMD

Possibilities for the use of the treated Kingsmill Tunnel AMD and associated potential constraints are summarized in Table 3. The suitability of the treated AMD from the Kingsmill Tunnel site for each specific application is discussed below.

5.1 Drinking Water Supplement

The Rimac River (Rio Rimac) originating from the Pomacocha Lake is the main source used at the drinking water treatment plant of Lima (i.e., Sedapal). The concentrations observed for Fe, Al and Pb in winter months can be as much as two orders of magnitude higher than those observed in summer and fall months (Table 1). For instance, in July 1998, the concentration of Fe, Al and Pb dropped from 142, 135.7 and 1.3 mg/L, respectively, to 1.7, 0.95 and 0.043 mg/L. The quality of the treated Kingsmill Tunnel AMD surpasses the quality of the Rimac River water and complies with the Peruvian drinking water standards for all metal ions (Table 1). The SO_4 concentrations are about 5 times greater than the required limit of 400 mg/L. Mn concentrations are dependent on the treatment pH which has to be greater than 9 to obtain the required Mn concentrations.

The Peruvian Drinking Water Standards compare well with the Canadian and the USA Drinking Water Standards except for SO_4, Mn and NO_3. The concentration of SO_4 and Mn are not regulated by the Canadian and the USA Drinking Water Standards (Canadian Water Quality Guidelines, 1998; Ontario Drinking Water Standards, 2000). They are considered to be secondary non-health related parameters and are for aesthetic reasons. For instance, SO_4 in high concentrations has been known to have laxative effects, while Mn shows staining and taste effects. The Peruvian limit for NO_3 is 45 mg/L, while Canadian and USA standards require 10 mg/L. The quality of the treated Kingsmill Tunnel AMD surpasses the standards and guidelines imposed by World Bank and WHO for the discharge of industrial wastewaters to surface water sources that are intended for drinking (World Bank, 1997; Global Drinking Water Standards, 1999).

Microbiological, biological and toxicological tests conducted by Sedapal indicated that the properly treated AMD would not pose toxic effects on the aquatic life and could be discharged into the natural water reservoirs. However, mixing of the treated AMD with the Rimac River water (or first with the Pomacocha Lake water) at a minimum ratio of one to six has been recommended to obtain suitable SO_4 and Mn concentrations in the final mixture. Treatment of the mixed water at the Sedapal Drinking Water Treatment plant could provide further polishing. In addition, it was suggested that the treated AMD quality must continuously be monitored for critical parameters (e.g., metal concentrations) and periodic toxicological, microbiological and biological tests must be conducted. An alternative water discharge plan for the site should be prepared for use in any events when the treated AMD quality does not meet the required standards. Especially, this plan should be available during the commissioning of the plant. Until the system reaches a steady-state condition and produces acceptable results, the treated water should not be discharged to the river.

5.2 Discharge to the Environment (i.e., river, lake, wetland)

Standards set for the protection of aquatic life are usually more stringent that those set for drinking water standards, because these standards aim to preserve and protect fish, fish habitat and the human use of fisheries resources at all mine sites (Metal Mining Req., 2001; Aquamin, 2001). Peruvian Water Quality Standards for fishing and protecting aquatic fauna are similar to Canadian guidelines for the protection of the aquatic life in which values for some metals such as Cd, Cu and Pb are lower than those limits regulated by the Peruvian Drinking Water Standards.

The comparison of the chemical composition of the treated AMD with the criteria given in the Peruvian General Water Law indicates that the treated AMD can be used for recreational, creative and commercial fishing purposes. The quality of water complies with the objectives required for the protection of aquatic fauna. The treated AMD could be discharged to surface water resources (i.e., river, creek, lake, wetlands) as practiced around the world, including Canada.

5.3 Industrial Recycle and Reuse

Mining and metallurgical processes require the use of large quantities of water. For instance, processing of one tonne of ore in the mill usually needs more than two m^3 of water (Kuyucak et al., 1999). Reuse/recycle of treated water is an accepted method which could reduce the need for fresh water sources and could avoid permit requirements for discharge. The tendency within the mining industry is to practice "zero discharge" as much as possible. Mining companies therefore prefer to recycle the treated water back to the process for reuse.

The chemical composition of the treated Kingsmill Tunnel AMD is considered to be suitable for milling processes in the mining and metallurgical industry. About 1,700 mg/L of SO_4 in the treated AMD is below the solubility limit of $CaSO_4$ (gypsum). Due to its low SO_4 and microbial concentrations, its use in pipes does not raise concerns about the formation of chemical scaling and biofouling. However, its high hardness may not be suitable for the preparation of food products such as baked food, beer, canned goods, confectionery and ice, and manufactured products such as leather, paper, paper pulp, clear plastic and textiles, or use in laundering (Montgomery, 1985). If the treated AMD is mixed with the Rimac River water, the resulting mixture will be softer and could be suitable for several applications.

5.4 Agricultural Use as Irrigation Water and Livestock Water

The treated AMD can be used for agricultural purposes including irrigation of crops, commercial nursery and landscapes, and raising livestock. According to the criteria given in Peruvian General Water Law, the quality of the treated AMD is suitable for agricultural uses including irrigation of vegetables to be consumed raw and for drinking by cattle. Only NO_3 concentrations are borderline. The value set for NO_3 in the General Water Law for agricultural use is 0.1 mg/L.

There are guidelines but, no regulated standards for agricultural waters in Canada and the USA. The quality of the treated Kingsmill Tunnel AMD compares favourably with the recommended values suggesting that its use for agricultural purposes would be suitable. However, maximum concentrations of trace elements in irrigation waters may pose concerns due to their potential accumulation in soil and crops. In addition, the presence of low sodium (Na) to calcium (Ca) and magnesium (Mg) results in a low Sodium Adsorption Ratio (SAR) in the treated Kingsmill Tunnel AMD and improves its suitability to be used as irrigation water (Metcalf and Eddy, 1991).

5.5 Recreational Water and Hydro-Power Generation

There are no guidelines regarding the water quality that can be used as a source for recreational (e.g., lakes, ponds, marsh enhancement, fisheries) or power generation purposes. Due to its improved properties and its suitability for aquatic and agricultural use, the treated Kingsmill Tunnel AMD could be used for recreational and hydro-power generation purposes.

6.0 CONCEPTUAL DESIGN OF THE TREATMENT FACILITY

A conceptual design of a full-scale plant for treating 4500 m^3/hr AMD and a sludge disposal/storage facility was prepared. The economical feasibility of the full-scale facility was evaluated and the appropriate “Siting” areas for the construction of the required facilities were determined using the conceptual design. The economical feasibility of the full-scale facility was evaluated mainly for the use of the treated AMD as drinking water supplement. Based on the current cost of energy and estimated sale price of the treated water, it is estimated that the construction and operation of the treatment plant would be economically viable. The total cost of the proposed project for the use of the treated AMD as a supplement for the drinking water supply was estimated to be about US$18 million including a capital cost of US$10 million and an infrastructure cost of US$8 million. Collection and treatment of the AMD occurring at the site would positively impact the environment. However, application of appropriate AMD prevention and control measures to the site is also required. Details of the “Environmental Impact Assessment” and “Economic Viability” studies will be discussed in other communications.

TABLE 3: POSSIBLE REUSE OPTIONS AND POTENTIAL CONSTRAINTS FOR THE TREATED AMD

Agricultural Irrigation • Crop irrigation • Commercial Nurseries Landscape Irrigation • Park • School Yard • Freeway Median • Golf Course • Cemetery • Greenbelt • Residential	• Surface and groundwater pollution if not properly treated • Marketability of crops and public acceptance • Effect of water quality, particularly salts, on soils and crops • Public health concerns related to trace metals
Industrial Recycling and Reuse • Cooling • Boiler Feed • Process Water • Heavy Construction	• Constituents in reclaimed wastewater related to scaling, corrosion, biological growth and fouling
Groundwater Recharge • Groundwater Replenishment • Salt Water Intrusion Control • Subsidence Control	• Chemical composition of reclaimed wastewater and toxicological effects (e.g. total dissolved solids, nitrates)
Recreational /Environmental Uses • Lakes and Ponds • Marsh Enhancement • Streamflow Augmentation • Fisheries	• Health concerns • Toxicity to aquatic life
Nonpotable Urban Uses • Toilet Flushing	• Public health concerns • Effects of water quality on scaling, corrosion, biological growth, and fouling
Potable Reuse • Blending in Water Supply • Reservoir • Pipe to Pipe Water Supply	• Constituents in reclaimed wastewater, especially trace metals and their toxicological effects • Aesthetics and public acceptance • Health concerns
Adapted from Eddy & Metcalf, 1991.	

REFERENCES

Aquamin 2001. Aquatic Effect Monitoring of Mining Effluents. http://www.nrcan.gc.ca/aquamin

Aube, B.C., and J.M. Zinck, 2001. Evaluation of Lime Neutralization Methods. CIM Bulletine, January 2001.

Canadian Water Quality Guidelines, 1998. http://ec.gc.ca//ccrem

Global Drinking Water Quality Standards. http://www.ehl.cc/InfoPages/IntDW
Kuyucak, N., R.J. Mikula, and K. G. Wheeland,1991. Evaluation of Improved Lime Neutralization Processes- Part 3- Interpretation of Properties of Lime Sludge Generated by Different Processes. 2nd Int'l Conf. On the Abatement of Acidic Drainage Sept'91, Montreal, Quebec, Vol. 2, pp.31-35.

Kuyucak, N., M. Lindvall, J.A.R. Serrano, and A. F. Oliva, 1999. Implementation Of A High Density Sludge "HDS" Treatment Process At The Boliden Apirsa Mine Site, Clean Technologies – Wastewater Treatment Symposium, Sevilla, Spain. September 1999.

Kuyucak, N., 2000. Microorganism, Biotechnology and Acid Rock Drainage, Int. Minerals and Metallurgical Processing, Special Technology Review Paper, May 2000.

Kuyucak, N., 2001a. AMD Prevention and Control Options. Mining Environment Management Journal, January 2001, pp: 12-15.

Kuyucak, N., 2001b: Acid Mine Drainage (AMD) - Treatment Options for Mining Effluents. Mining Environment Management Journal, March 2001, pp: 12-15.

Kuyucak, N., M. Lindvall, T. Sundqvist and H. Sturk., 2001. Implementation of a High Density Sludge "HDS" Treatment Process at the Kristineberg Mine Site. Securing the Future 2001, Mining and the Environment Conference proceedings. June 2001.

MEND, 1994. Mine Environment Neutral Drainage Program (consortium between Canadian mining industries and the government) report on "Status of Chemical Treatment and Sludge Management", CANMET, NRCan, Canada. mend@nrnl.nrcan.gc.ca

Metal Mining Requirements, Environment Canada Publications, December 2001. http://www.ec.gc.ca/eem

Metcalf and Eddy, Inc., 1991. Wastewater Engineering: Treatment, Disposal and Reuse. 3rd Ed. McGraw-Hill Inc. Publication.

Montgomery, 1985. Water Treatment Principles and Design. John-Wiley Interscience Publication.

Ontario Drinking Water Standards, 2000. Reg 459/00, August 2000.
Smith, J.P., 2000. Potable Water from Sulphate Polluted Mine Sources. Mining Environmental Management Journal November 2000.

World Bank, 1997. Pollution Prevention and Abatement Handbook.

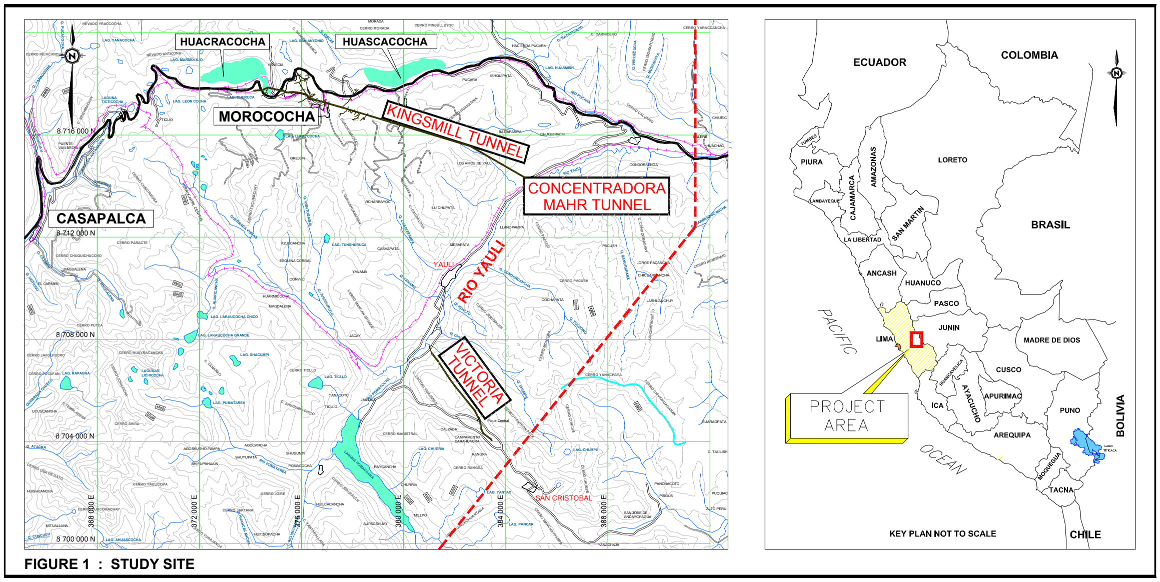

Figure 1

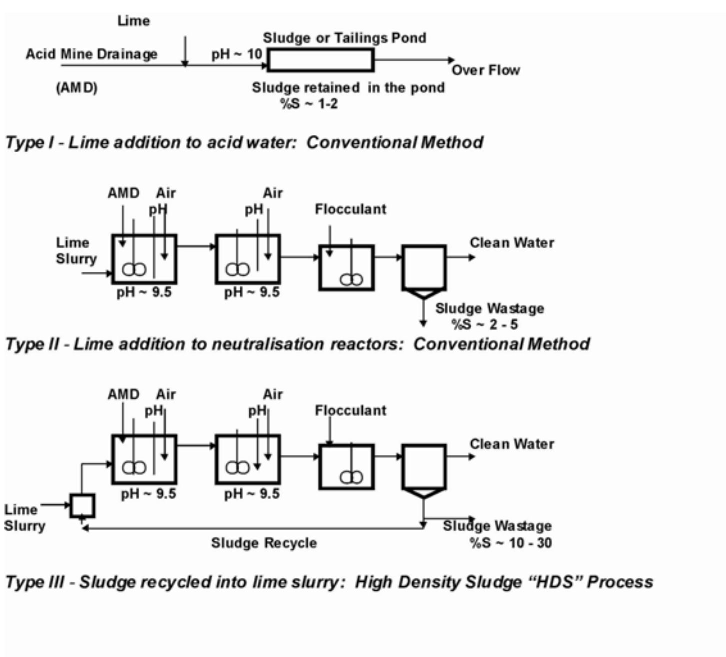

Figure 2

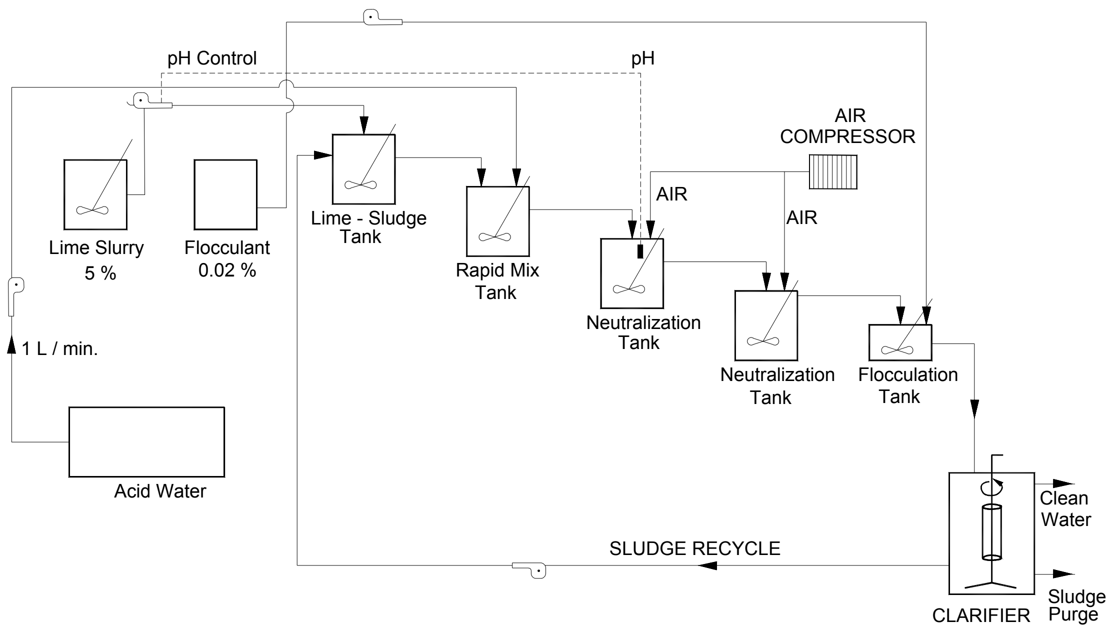

FIGURE 3 : SCHEMATIC PRESENTATION OF THE WATER TREATMENT TEST SET-UP " HDS LIME NEUTRALIZATION PROCESS "

NOT TO SCALE