Breaking the Toxicity Barrier: A Gold Mine's Journey to Sustainable Wastewater Treatment

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Abstract

In gold mining operations, contaminants such as cyanide species, ammonia, and metals can generate a toxic effluent. A Canadian gold mine operating in a very cold climate faced recurring toxicity issues and was pressed by regulations to address the issue. This case study highlights the journey to understand the sources of toxicity and identify a suitable solution, taking into account constraints such as climate and footprint. It presents the approach that leads to a compliant full-scale application, and demonstrates the effectiveness of the combined moving bed biofilm reactors (MBBR) and metals removal for toxicity remediation.

Keywords: Toxicity, mine water discharge, ammonia, thiocyanate, cyanate, biological treatment, MBBR

Introduction

In Canada, the federal regulation requires that treated mine effluent water meet specific criteria such as pH, TSS and concentrations of a few metals, and must not be acutely lethal prior to discharge to the environment. Two aquatic species, which are deemed representative of most of the native aquatic life in Canada, are used to evaluate the acute lethality potential of an effluent in freshwater discharge; *Oncorhynchus mykiss* (fish) and *Daphnia magna* (crustacean) (Metal and Diamond Mining Effluent Regulations, 2024).

With consideration of the Canadian regulation, a new mine must identify and eliminate any source of acute toxicity in its effluent prior to discharge. This is the story of a mine journey to understand and solve toxicity issues not addressed by traditional contaminants removal.

Context

A mine, located in the Canadian Shield, was being designed and was expected to produce a toxic effluent. It was located in an area with no other mine nearby, in a subarctic climate. Such climate results in long, cold winters with large quantities of snow, strong freshets, and warm summers.

During the feasibility study of the mine, detailed geochemical and hydrological studies tried to predict the composition and flow rate of mine effluent. Preliminary results from the studies led to the conclusion that copper and arsenic were concerns for toxicity, and that cyanide and explosive residuals would likely be at concentrations of no concern. The mine effluent treatment plant was therefore centred on metal removal (copper and arsenic). However, due to the uncertainties around the preliminary studies, the mine water treatment plant was designed to allow implementation of additional equipment at a later stage, once a better understanding of the water quality was achieved. At start-up of the mine effluent treatment plant, the treated water met all the metals criteria and was not acutely lethal (hereafter referred to as "non-toxic").

However, when the mine ramped up its production and started its concentrator, the mine effluent started to be toxic first to *Daphnia magna*, and then to *Oncorhynchus mykiss*. Within a year of starting production, the treated mine effluent was failing every toxicity test, no matter the modifications done to the concentrator operation or the mine effluent treatment plant.

Starting Point Hypotheses

The Canadian gold mine presented in this case study employs the MacArthur-Forrest process, which utilizes cyanide as a leaching agent for gold extraction in ore slurry. The resulting gold-barren solution is largely recirculated to the concentrator, but a portion must be purged to optimize the mill operation. This purged water contains high levels of cyanide, a highly toxic contaminant to wildlife (Pandey, 2013), necessitating detoxification at the source. The INCO Sulphur Dioxide/Air process provides such detoxification. It employs sulfur dioxide and a copper catalyst in the presence of air to oxidize cyanides to cyanates. In addition to copper, this process adds cyanates into the water. Furthermore, the interaction between the cyanide solution and sulfides in the ore generates another cyanide by-product, thiocyanates (Habashi, 1967).

Although cyanates and thiocyanates are less toxic compared to free cyanide, especially to mammals and birds, they remain toxic to crustaceans such as *Daphnia magna* (Dauchy, 1980, Hemming, 1989). In addition, cyanates and thiocyanates naturally hydrolyse/oxidize to ammonia, which is toxic to fish, particularly in its un-ionized form (Constable, 2023).

The treated effluent started failing toxicity tests first to *Daphnia magna* and then to *Oncorhynchus mykiss*. Ammonia being more toxic to fishes than to crustaceans, this indicates that while ammonia was likely a cause of toxicity, it was also likely not the only one. Analysis of the toxic treated water quality confirms that not only ammonia was present in concentrations to be a source of toxicity, but cyanate (OCN^-) and thiocyanate (SCN^-) were as well.

Identification of the toxicity sources is a key for treatment, as many options exist for each of the contaminants of concern. Simultaneous removal of the three contaminants could be achieved either by biological hydrolysis of cyanates followed by oxidation of ammonia and thiocyanates or reverse osmosis separation. While reverse osmosis is a universal solution for many contaminants, the cost of evaporating and disposing of the final concentrated solution is often prohibitive and only used as a last resort solution. Therefore, an active biological treatment, requiring limited chemical addition and limiting the quantity of generated wastes, was selected to enhance the natural degradation of nitrogen contributors. The use of a biological system also gives better sustainability to the treatment plant, mainly due to its limited impact on the environment and its performance improvement in time with few maintenance over the years.

Moving bed biofilm reactors (MBBR) have been used for nitrogen removal in municipal and industrial applications for decades. Operation of MBBR has been done in challenging environments, such as conditions close to freezing and while experiencing recurring toxic shocks (Kwofie, 2021). MBBRs are fixed film biological reactors where suspended media (typically made of HDPE) serves as biomass support. Since the biomass is attached instead of free floating, its concentration within the reactor is stabilized even under fluctuating loads and flows. A structured biofilm also provides a protected environment for bacteria, providing higher resistance to toxic shocks, and ensuring optimal conditions for slow-growing nitrifying bacteria to develop and thrive in shorter retention times. Additionally, the MBBR technology facilitates the implementation of multiple reactors in series, each optimized for specific microbial communities required for the removal of pollutants at higher removal rates (Rusten, 2000). For all these reasons, it was selected as a prime solution for the mine water treatment plant.

Validation and Investigation

The first step of the validation was the confirmation of the nitrogen contributor induced toxicity at laboratory scale. During these tests, reactors with a volume of three to five litres were fed with the mine effluent. The objective was to validate the viability of the MBBR technology in such an application. The main conclusions from the laboratory test were the following:

- Biological nitrification is inhibited by copper. Copper concentration over 0.25 mg/L resulted in a slow start-up and ammonia and nitrites accumulation. Oxidation of cyanide and thiocyanates, as well as cyanate hydrolysis were not impacted by copper.

- When the MBBR reactors were the same size, ammonia and cyanides species were removed with over 99% efficiency once metal precipitation was implemented. However, nitrification was incomplete, resulting in nitrous acid inhibition for nitrite oxidation. The nitrite build-up resulted in a toxic effluent. The oxidation of nitrites to nitrates is the slowest of all the biological reactions. More time must be allowed for completion of both nitrification reactions in a single biological reactor.
- Once the MBBR reactors were sized to consider the nitrite oxidation kinetic, full removal of ammonia and cyanide species was achieved. The treated effluent was non-toxic.
- Biological activity decreased at lower water temperatures, as expected, but with the same removal performances. The effluent was still non-toxic.

Laboratory testing had proven the possibility of biological removal of the toxicity sources using the MBBR technology, resulting in a non-toxic effluent. There were still uncertainties related to process performance in fluctuating conditions. A six month pilot was therefore conducted to evaluate the response of the biological treatment in varying water composition and load, and operating during the cold season. The MBBR pilot was fed from the clarified water of the existing metal removal plant. The pilot was started up in early fall (water temperature of close to 20 °C) through late winter (down to 5 °C). The main observations and conclusions were the following:

- While the clarified metal removal effluent failed all toxicity tests (100% mortality), the MBBR effluent had no mortality for both *Daphnia magna* and *Oncorhynchus mykiss*.
- Complete oxidation of thiocyanates and cyanates, as well as the complete degradation of ammonia nitrogen to nitrates, was consistently achieved during six months of operation.
- The MBBR process can fail if not protected from biological offset, such as toxic shocks (chemical spills) and pH excursions. Both were experienced during piloting and resulted in biological oxidation failure, highlighting the importance of their early detection.
- Biological recovery to short-term toxic shocks is fast, recovering full capacity within a week.

The pilot test highlighted the importance of control over operating conditions and pretreatment efficiency to prevent harm to the biomass. The test also demonstrated the ability of the MBBR system to recover from process offsets and toxic shocks. Interested readers are referred to a narrative of the case study by the authors of this paper (De Ladurantaye-Noel, 2025).

Full-scale application

Commissioning of the full-scale MBBR was completed in November 2017. The biological reactors are installed between the two existing metal precipitation stages; the first providing copper removal for biomass protection and the second removing sloughed biomass and excess of phosphorus in addition to metal polishing of the final effluent. A visual representation of the flow diagram is represented in Fig. 1.

MBBR thrive by optimizing natural biological reactions to enhance the biomass

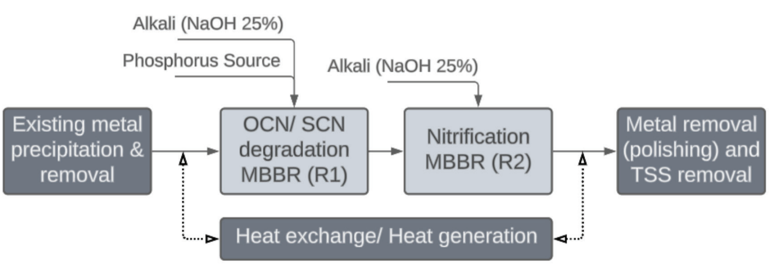

Figure 1 Full-scale plant process schematic

growth and efficiency. In order to help this optimization, some design considerations are implemented:

- Due to their size, the MBBR reactors are insulated field erected tanks to be installed outdoors. In winter, the water is close to 0 °C, being held in a large pond outside prior to treatment. For these reasons, water heating with heat recovery are used when required: it prevents freezing (tanks and pipes are not heat-traced) as well as having the capacity to quickly increase the biomass activity. An increase of the water temperature results in a 5% to 8% treated load increase per °C of water temperature increase.
- An alkali must be dosed in both MBBR reactors to control pH, as nitrification causes acidification of the mine effluent. While a calcium-based alkali could be used, sodium hydroxide was selected to avoid potential scaling issues (gypsum and calcite).
- A phosphorus source is supplemented in the first reactor as a nutrient to the biomass, since the mine effluent is devoid of an easily available phosphate source.

The base of design for the full scale application are the following:

- A hydraulic flow rate of 1 083 m^3/h.
- A nitrogen load of 147 kg N/d at 8 °C (17% as CN^-, 56% as SCN^-, 27% as OCN^-) in R1.

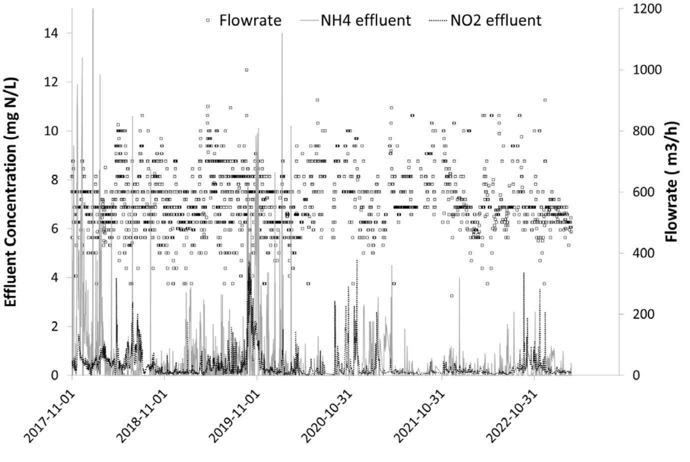

Figure 2 *Flowrate fluctuation and effluent ammonia and nitrite concentration.*

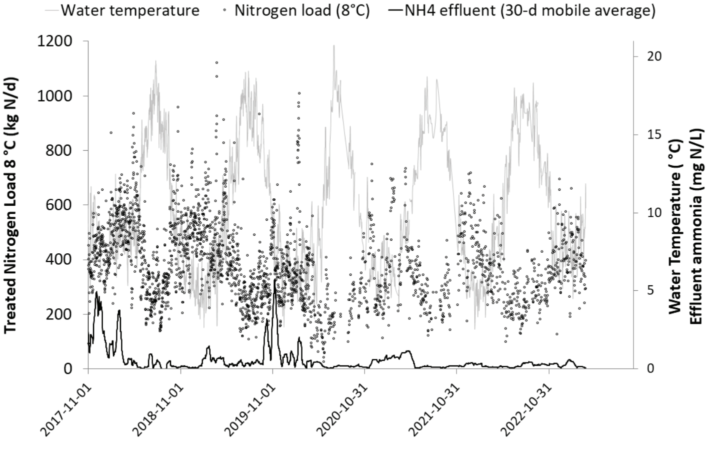

Figure 3 *Nitrogen treated load (corrected at 8 °C), water temperature variation seen and ammonia concentration at the effluent (represented as a 30-d moving average to lighten the graph).*

- An ammonia load of 462 kg N/d at 8 °C (combining mine effluent ammonia and by-product ammonia from the cyanide species degradation) in R2.

The conditions of operation were expected to vary based on the operation of the mine and on precipitations. The flowrate variation, as well as its impact on the biological treatment (effluent ammonia and nitrite concentrations) are illustrated in Fig. 2. Fig. 3 presents the variation of treated nitrogen load from the MBBR with the effluent ammonia concentration.

Main observations from five years of operation, as illustrated in Fig. 2 & 3, are the following:

- Substantial flow variations were observed over time. As expected, the fixed film biological treatment was not impacted through these hydraulic variations and provided robust nitrogen removal without harmful biomass entrainment.
- As the biomass matures, ammonia and nitrite peaks in the final effluent reduce in frequency and intensity. This is likely due to the increase in biodiversity in the biomass, which provides a variety of species that can respond to changes in condition.
- Load variations could be managed as long as the biomass is allowed to adapt through the increase. Sudden load variations (> 15% increase in 24 hours) have resulted in episodes of decreased performance until the biomass can stabilize its activity; this is illustrated in Fig. 3 with a small increase in ammonia concentration through fast load variations.
- Applied load was over the design load on several occasions. Nitrogen load up to 1 000 kg N/d (> 200% increase) was treated without impacting the effluent quality. This is due to biomass specialization and maturation, resulting in increased treatment capacity.
- The water heating system is used to boost bacterial activity, either to resolve a biological offset or to speed the load increase that could be managed by the biological system.
- Operation of the MBBR at 3 °C is possible with no impact on the system's performance. Limitations on lowering the temperature further are due to risks of freezing.

Previous analysis was mainly focused on the final effluent composition. It is however also interesting to look at the evolution of cyanate (OCN^-) and thiocyanate (SCN^-) through both MBBR reactors, as illustrated in Fig. 4, for a better understanding of the biological reactions.

Overall performance for cyanide species is high. Thiocyanate oxidation was complete in R1 shortly after commissioning. On the other hand, cyanate hydrolysis is not completed in R1 but in R2. Hydrolysis in R1

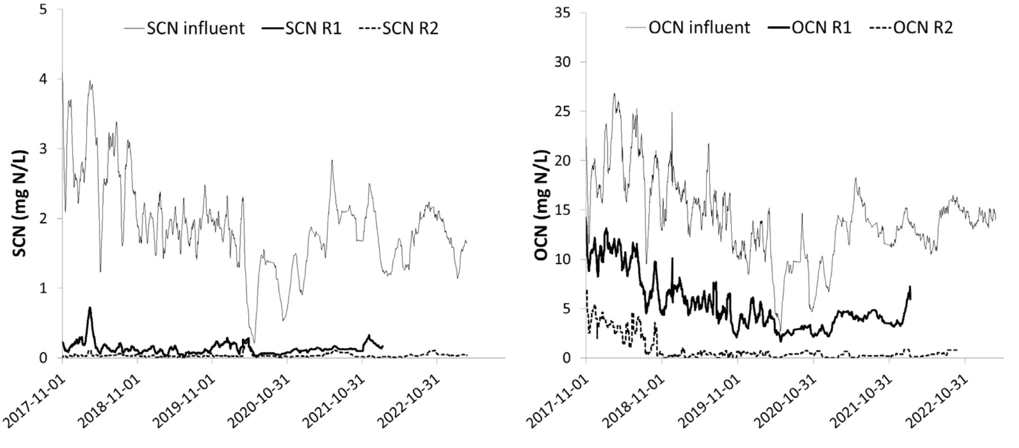

Figure 4 Cyanide species degradation evolution through the full-scale MBBR treatment; thiocyanate on the left and cyanate on the right (data shown as moving average, 30-d)

keeps improving over time after four years of operation. This cyanate hydrolysis evolution is a good example of biomass specialization and maturation over time.

The last element of concern is toxicity. Toxicity results from the full-scale operation are summarized in Table 1.

The following conclusions can be highlighted from the toxicity results:

- Prior to the MBBR installation, toxicity was a major issue with > 60% of mortality for both *Daphnia magna* and *Oncorhynchus mykiss*. An effluent is legally toxic when more than 50% of the test organisms die.
- During the commissioning of the MBBR, while the biomass is not yet acclimated, mortality dropped for both organisms to compliance and results show less variation.
- After completion of the commissioning period, mortality for both *Daphnia magna* and *Oncorhynchus mykiss* dropped significantly and results are stable over time. During this period, an improvement of arsenic removal was also seen, as shown by the reduction of the standard deviation, as arsenic is oxidized and easier to remove in the second metal precipitation following biological oxidation.

Conclusions

Mine development is complex and predicting its effluent water quality is challenging. When developing a water treatment plant, the mine's process chemistry needs to be considered from an early stage and should not be limited to metals. This case study highlights that no matter the water chemistry uncertainties, the possible sources of toxicity should be part of a contingency plan for the treatment plant and its integration should be thought of from the initial design.

This case study illustrates its benefices, as it started developing toxicity after the start-up of its concentrator. Investigations revealed a combination of ammonia, thiocyanate and cyanate in the mine effluent, none of which were removed by the existing physico-chemical treatment plant, to be causes for toxicity. A MBBR technology, which integration had already been planned in the initial design, was selected for the removal of these nitrogen species. Positive results from both laboratory and pilot tests led to its full-scale application, the performance of which confirmed its robustness, with no toxicity breach for years since its commissioning.

Mining effluent water treatment can be wrongly simplified to metal precipitation only, assuming that the toxicity of the process water is due to metals alone. This project demonstrated the removal efficiency of biological reactors for contaminants that can't be precipitated but are known to be biodegradable, such as cyanide species and ammonia.

This project focused on toxicity removal. However, to further increase the sustainability of the water treatment chain, nitrate removal should also be considered. While not toxic, it is a known source of eutrophication in receiving environments. Along the toxicity testing assessment, the pilot scale test did prove that biological denitrification was efficient to reach low total nitrogen concentration at the final effluent (< 5 mg N/L). Future implementation of a denitrification biological reactor was planned for in the design of the biological toxicity removal.

Table 1 *Toxicity evolution in time, from the mine start-up to stabilization of the MBBR process*

Effluent Water Parameters	Mortality *Daphnia magna (%)*			Mortality *Oncorhynchus mykiss (%)*			Total Arsenic (mg/L)		
	Average	*SD*	*Nb. data*	*Average*	*SD*	*Nb. data*	*Average*	*SD*	*Nb. data*
Metal removal only	61	45	137	69	423	137	0.025	0.062	202
Commissioning of MBBR	36	38	23	10	23	23	0.009	0.008	26
Stable MBBR Operation	0.7	3.2	57	0	1.9	57	0.006	0.005	390

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