Best Available Technologies Economically Achievable (BATEA) to Manage Effluent from Mines in Canada

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ABSTRACT

Hatch was commissioned by the Canadian Mine Environment Neutral Drainage (MEND) Program to complete a study to identify best available technologies economically achievable (BATEA) for the augmentation of existing effluent treatment systems, to improve effluent quality from mines in Canada. The study was commissioned in order to provide reference information to policy makers, industry, and civil society organizations for use in evaluating potential forthcoming changes within the Canadian *Metal Mining Effluent Regulations* (*MMER*) to the types of regulated mining facilities (addition of diamond and coal mines), the list of regulated parameters, and the authorized limits of regulated parameter concentrations in effluent discharged to the environment. This paper presents the overall objectives and methodology of the study and the participatory process used to gather and validate information, an overview of the various Canadian mining subsectors examined (metal mining: base metal, precious metal, iron ore, and uranium; diamond mining, and coal mining), a summary of technologies considered to be best available technologies (BAT) for Canadian mine effluent treatment, and incremental costs of implementing and operating BAT. BAT are defined as those technologies which have been demonstrated through full scale operation to achieve the present *MMER* regulated parameter limits via treatment of mine effluent under representative Canadian climate conditions. Finally, the paper presents Hatch's findings on best available technologies economically achievable (BATEA) for augmentation of effluent treatment systems, interpreted as technologies that can improve effluent quality through upgrades to existing treatment systems for a given subsector, within reasonable incremental capital and operating costs, as compared with previous capital expenditures and current operating cost expenditures. The study largely focuses on the improvement of effluent quality at existing operations; however, some BATEA suggestions for greenfield operations are also made. Parallels between the Canadian mining jurisdiction and other major international mining jurisdictions are drawn.

INTRODUCTION

Environmental regulations for the mining industry are becoming more stringent in many jurisdictions, amplifying the need for effective and efficient effluent treatment systems that are also economically viable. In Canada, the quantity and quality of mining effluent discharged to the environment are regulated at the federal and provincial/territorial levels. Potential forthcoming changes to the federal *Metal Mining Effluent Regulations* (*MMER*) generated a need to examine conventional approaches to effluent treatment at mining and mineral processing operations, with a focus on concentrations demonstrated by conventional technologies and which technologies are economically and operationally viable at Canadian operations, considering site conditions such as remote location and seasonal climatic variability.

The proposed changes to the *MMER* are outlined in the Environment Canada 2012 discussion paper, "10-Year Review of Metal Mining Effluent Regulations," and include:

- The addition of total ammonia, aluminum, iron, and selenium to list of regulated parameters for metal mines (base metal, precious metal, uranium, iron ore).
- The reduction in authorized limits of regulated parameter concentrations in effluent for metal mines.
- The addition of diamond and coal mines to the types of regulated mining facilities[1], and,
  - the introduction of authorized limits for pH, chloride, phosphorus, total suspended solids (TSS), and total ammonia as regulated parameters for diamond mines,
  - the introduction of authorized limits for pH, aluminum, arsenic, iron, manganese, selenium, TSS, and total ammonia as regulated parameters for coal mines (Environment Canada, 2012).

Environment Canada is undertaking the review of the *MMER* within a context of multi-stakeholder consultation, whereby stakeholders including industry, industry associations, regulators, non-governmental organizations, and First Nations organizations are engaged in working groups in order to provide feedback on the proposed changes through a series of meetings and workshops. As part of this multi-stakeholder consultation process, Hatch was commissioned by the Mine Environment Neutral Drainage (MEND) Program, on behalf of regulatory and industry stakeholders, to complete a study of water management and treatment practices at mining operations in Canada and to identify best available technologies economically achievable (BATEA) for the augmentation mining effluent treatment.

Hatch's study identifies and describes best available technologies (BAT) employed at metal, diamond, and coal mine operations in Canada and proposes BATEA for each sector. BAT were identified and characterized via extensive questionnaires issued to mining operations and technology vendors, as well as independent research. BATEA were selected based on a comparative assessment of the benefits in terms of effluent quality improvement against the incremental implementation and operating costs for each applicable BAT. BATEA selections are generic, in that they are based on the augmentation of a sector model effluent treatment system and do not consider site-specific factors not captured by the model. BATEA selections are also neutral, in that

[1] The diamond mining and coal mining sectors are presently not regulated by the *MMER.*

Hatch is not a water treatment technology supplier and has no vested interest in technology selection.

METHODOLOGY

Establishing Sector Models

A base case model for each sector representing the most commonly utilized water management practices and treatment process was established based on information collected from mine and mill operations. This model was utilized to identify and evaluate potentially augmentative technologies to improve effluent quality. To identify the most common practices, Hatch prepared a list of Canadian metal (i.e., base metal, precious metal, iron ore, and uranium), coal, and diamond mines. This list included the company, operation name, subsector classification by primary commodity, the location, and the operational status of the mine. After extensive revision and refinement of this list with the assistance of provincial, territorial, and federal industry associations, an operations contact list was generated. A comprehensive operations questionnaire was distributed to the contact list in order to solicit information on factors that impact treated effluent quality (i.e., mining, processing, and waste disposal practices, water management and effluent treatment systems, and untreated and treated effluent quality), as illustrated in Figure 1.

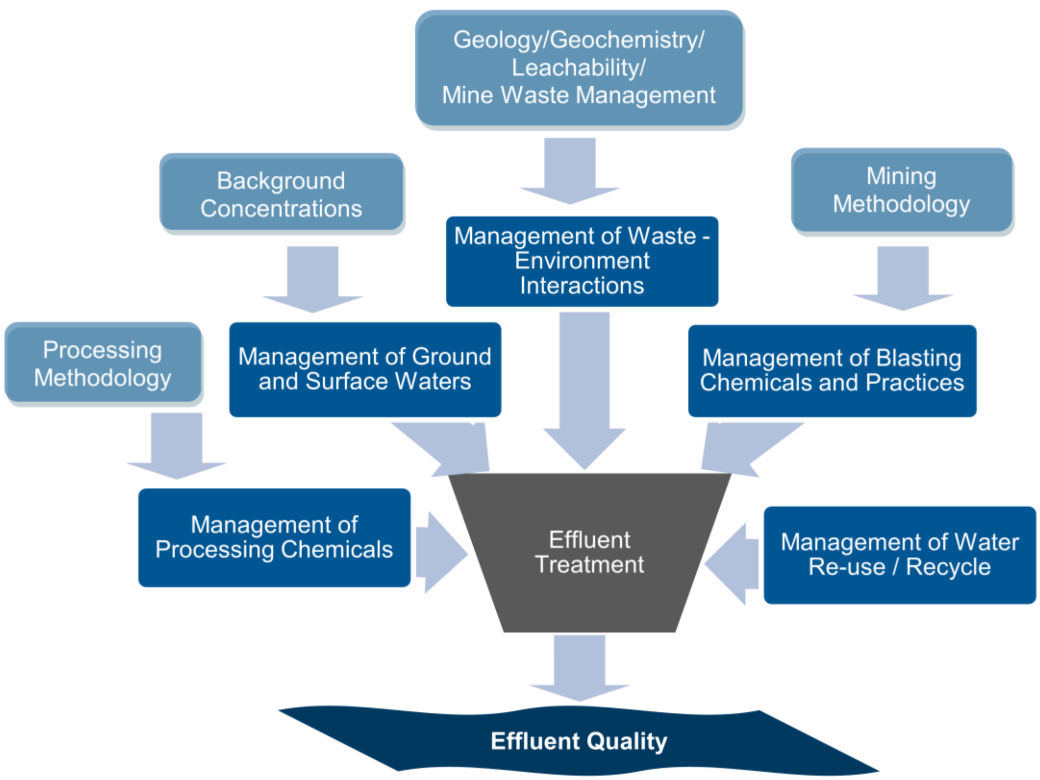

Figure 1 Factors of mine effluent quality

The questionnaire had an overall completion rate of 45% on an operations basis (i.e., 45% of individual operations identified as relevant to the study submitted completed questionnaires). This corresponds to 75 of the 164 operations contacted. By sector, the questionnaire completion rate varied between 32% and 75%. A more detailed summary of the questionnaire completion status by sector is provided in Table 1.

Table 1 Operations questionnaire completion by sector

Sector/Subsector	Number of Companies	Number of Operations Contacted	Number of Questionnaires Submitted
Metal			
Base Metal	31	57	31 (54%)
Precious Metal	33	56	18 (32%)
Iron Ore	4	6	2 (33%)
Uranium	4	16	7 (44%)
Diamond	4	4	3 (75%)
Coal	12	30	13 (43%)

Questionnaire responses were processed into a database format so the data could be easily compared and analyzed. Where necessary, follow-up inquiries were made with questionnaire respondents to clarify information provided prior to inclusion in the database and study report, in order to limit interpretation bias.

The database was compared with regulatory reporting information provided by Environment Canada, which included effluent discharge volume and quality data for all of the operations subject to *MMER*, as well as effluent discharge volume and quality data for the diamond sector, and a summary of effluent treatment technologies employed by operations in Ontario. Similar data for the coal sector was provided by the Coal Association of Canada, however discharge volumes were not provided. Additionally, because the coal sector data was anonymous, effluent quality data could not be related to operational practices and other effluent-influencing factors.

Later, a short follow-up survey was distributed to collect additional information from operations about effluent treatment system flow rates, final discharge point names used in *MMER* reporting, treatment system process unit operations, mechanism of removal of targeted contaminants, and influent and effluent quality data.

In combination with the questionnaires and resources described above, Hatch also undertook independent research to collect supplemental information about mining operations. This independent research drew from in-house knowledge and publicly available information concerning mining operations and effluent treatment processes (e.g., environmental compliance approvals, certificates of authorization, permits, etc.).

Based on the information collected, Hatch established a generic effluent management and treatment base case model for each mining sector. Each base case consists of a model water management block flow diagram, a model water treatment block flow diagram, nominal and design treatment flow rates, and treated effluent quality produced by model or model-like effluent treatment systems. The effluent treatment model developed for the base metal subsector of the metal mining sector is provided as an example in Figure 2. The models represent the most common practices and treatment systems for the sector described to Hatch by industry via the information provided in the questionnaires, as illustrated in Figure 3. While more technologically advanced systems may be employed at Canadian mines, the model serves to exemplify the most common system as reported by industry.

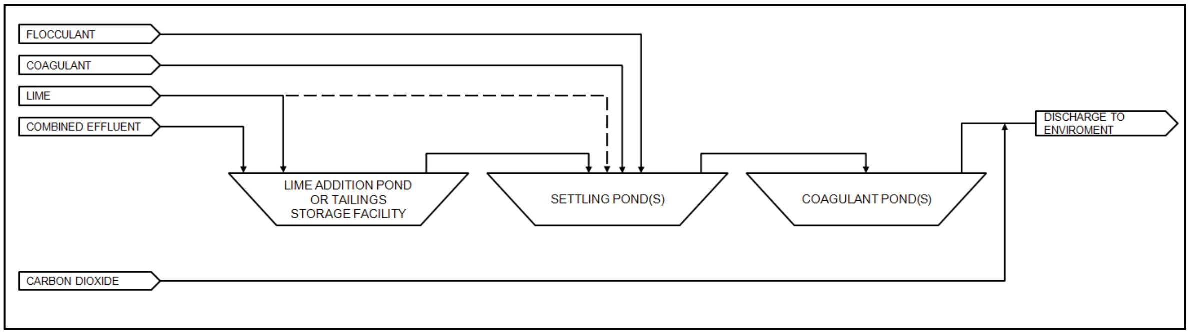

Figure 2 Base metal subsector effluent treatment model

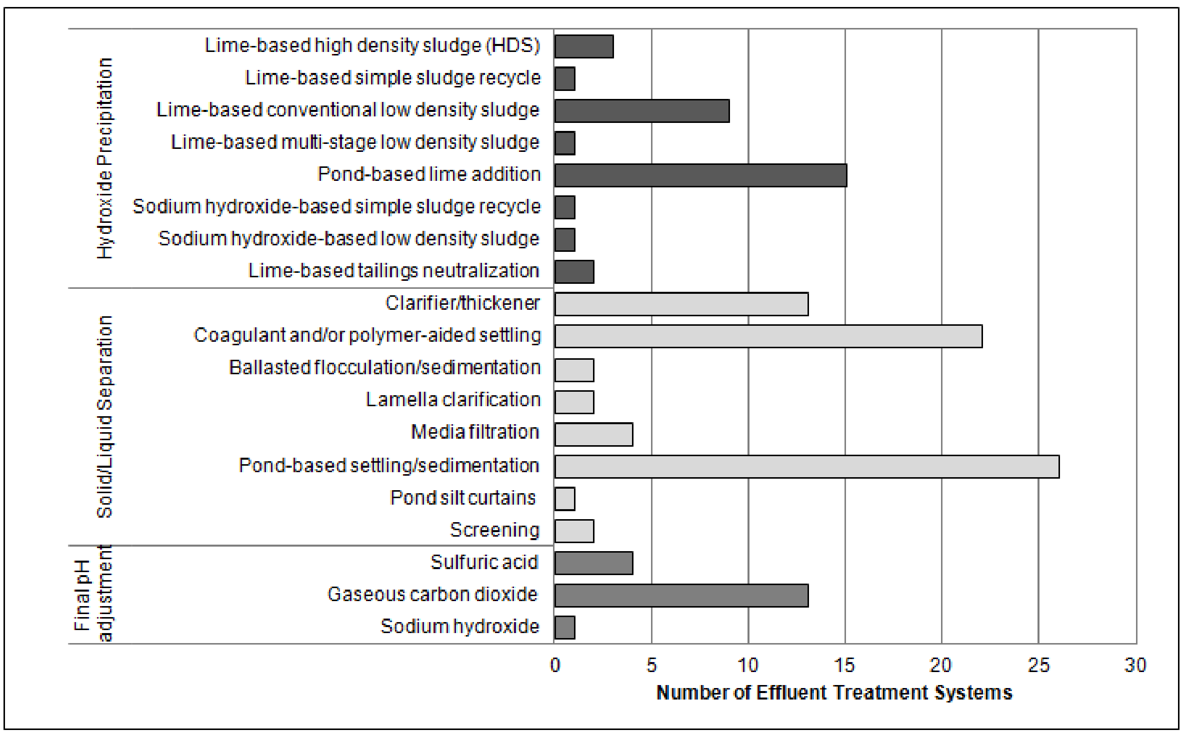

Figure 3 Distribution of hydroxide precipitation, solid/liquid separation, and final pH adjustment technologies for the base metal subsector

Model nominal and design treatment flow rates were generated from effluent discharge volume data and operations questionnaires, using a number of analytical approaches to generate statistical information and then applying judgment to select mid-range values. Model treated effluent concentrations for each current and proposed *MMER* parameter were determined by generating statistical treated effluent quality values for operations that employ model and model equivalent treatment systems and also self-identify as targeting the parameter for removal with treatment. This was done to minimize the statistical influence of operations that do not employ model or model-equivalent treatment systems and that do not target the specific parameter being analyzed for treatment (i.e., treatment is not required for parameter compliance with discharge limits).

Identifying BAT Technologies

To identify best available technologies, Hatch first compiled a list of treatment technologies currently available on the market, both active and passive, that are applicable to the control of effluent quality for those contaminants that are currently or potentially regulated by the MMER. A questionnaire was distributed to vendors to solicit input concerning proprietary technologies, including existing case studies of their use, and capital and operating cost information.

The technologies included in the preliminary technologies list were then screened against the following criteria questions:

1. Can this technique achieve current MMER discharge limits?
2. Has this technique been demonstrated at full scale on mining effluent?
3. Has this technique been demonstrated under representative Canadian climate conditions?

Technologies that met all three criteria were carried forward in the study as best available technologies (BAT) for the treatment of Canadian mining effluent. BAT technologies are summarized in Table 2.

Table 2 Best available technologies and targeted (X) and synergistically removed (+) contaminants

Best Available Technologies	**pH**	**Al**	**As**	**Cl**	**Cu**	**CN**	**Fe**	**Pb**	**Mn**	**Ni**	**P**	**Se**	**Zn**	**Ra-226**	**TSS**	**NH_3/ NH_4^+**
Neutralization and Hydroxide Precipitation	X	X	+		X		X	X	+	X	+		X		+	+
Sulfide Precipitation			X		X		X	X	X	X		X	X		+	
Ferric Iron or Aluminum Salt Co-Precipitation			X								X	X			+	
Barium Chloride Co-Precipitation														X	+	
Metal Oxidation							X		X							
Reacidification	X															+
Solid/Liquid Separation		+	+		+		+	+	+	+	+	+	+	+	X	
Enhanced Coagulation and Settling		+	+	+	+		+	+	+	+	+	+	+	+	X	
Cyanide Destruction (SO_2/Air and/or H_2O_2)						X										
Air Stripping																X
Ion Exchange	+	X	X	X	X	+	X	X	X	X	+	X	X	+		X
Adsorption																
Zero Valent Iron			+				+	+	+			X	+			
Biological Oxidation/Reduction																
Aerobic Biological Oxidation						X										X
Active Anoxic/Anaerobic Biological Reduction			+		+		+	+	+	+		X	+			
Membrane Size/Charge Exclusion – Nanofiltration		X	X		X		X	X	X	X	X	X	X	X		
Membrane Size/Charge Exclusion – Reverse Osmosis		X	X	X	X	X	X	X	X	X	X	X	X	X		X
Passive Treatment																
Natural Degradation						X					+					X
Aeration Cascades							X		X							

For each best available technology, the following aspects of implementation and operation were elaborated: incremental capital and operating costs, removal efficiencies and/or achievable concentration levels, applicability to Canadian mining effluent treatment, and the synergies and challenges resulting from the application of the technology for the control of effluent quality.

For each sector, the list of BAT was assessed to identify which technologies could augment the model effluent treatment system and improve treated effluent quality. Order of magnitude capital equipment and installed cost and operating cost estimates were then prepared for each augmentative BAT technology for each sector. Cost estimates were generated through the use of in-house capital and operating cost information, vendor and operations questionnaires, and cost data reported in literature. It is acknowledged that actual costs could vary significantly from the presented figures, depending on numerous site-specific factors. Augmentative BAT that could improve treated effluent quality from existing treatment systems at a reasonable incremental cost were designated best available technology economically achievable (BATEA). For some subsectors, the model flowsheet was designated to be BATEA since BAT would either not improve treated effluent quality or could not be implemented at a reasonable cost.

RESULTS AND DISCCUSION

Review of the **base metal subsector** included a total of 43 operations. The model effluent treatment system for the subsector, as determined by the prevalence of questionnaire responses, consists of hydroxide precipitation for metals removal and pond-based settling for bulk TSS removal. Coagulant and flocculant are dosed to facilitate metal precipitate and TSS sedimentation. The pond-based system also enables passive natural degradation of ammonia which does not readily occur in reactor based lime addition/clarification systems. The pH of the settling pond decant is adjusted, most commonly with carbon dioxide to meet *MMER* pH limits and/or meet un-ionized ammonia/toxicity requirements prior to discharge to the environment. The design and nominal flow rates selected to estimate capital and operating costs for system augmentation for the model treatment system were 2 000 m^3/h and 870 m^3/h, respectively. Based on an evaluation of improvement in effluent quality relative to incremental capital and operating cost, BATEA was selected as sulfide precipitation with polymeric organosulfide chemicals for dissolved metals polishing and the model effluent management and treatment system for total ammonia, bulk metals, and TSS removal. The incremental capital cost and operating cost for augmenting the model flowsheet with the BATEA were estimated to be C\$550/m^3/h and C\$0.33/m^3, respectively. The incremental cost to implement this augmentative technology considers infrastructure not included in the model treatment system. Further details on the basis of the cost estimates are available in the full report.

Review of the **precious metal subsector** included a total of 40 precious metal operations. The model effluent treatment system for the subsector, as determined by the prevalence of questionnaire responses, consists of SO_2/air cyanide destruction on tailings and low density sludge lime hydroxide precipitation for bulk metal removal from effluent from tailings, mine, and waste rock areas. The design and nominal flow rates selected to estimate capital and operating costs for system augmentation for the model treatment system were 600 m^3/h and 180 m^3/h, respectively. Using the methodology outlined previously for the base metal subsector, BATEA was selected as sulfide precipitation with proprietary polymeric organosulfide chemicals for dissolved metals polishing, active aerobic biological oxidation for total ammonia removal, and the model effluent management and treatment system for cyanide, bulk metals, and TSS removal. The incremental capital cost and operating cost for augmenting the model flowsheet with the BATEA were estimated to be C$50/m^3/h and C$0.20/m^3, respectively, for the polymeric organosulfide chemicals, and C$32,670/m^3/h and C$0.60/m^3, respectively, for active aerobic biological oxidation. The incremental cost for implementation of this augmentative technology is less than for the base metal model system, as the precious metal model treatment system infrastructure is better suited for the use of this technology and thus less additional equipment is required. Further details on the basis of the cost estimates are available in the full report.

Review of the **iron ore subsector** included all 6 operating iron ore operations. The model effluent treatment system for the subsector, as determined by the prevalence of questionnaire responses, consists of pond-based settling for bulk TSS removal with flocculant dosing to aid settling. The design and nominal flow rates selected to estimate capital and operating costs for system augmentation for the model treatment system were 7 000 m^3/h and 3 900 m^3/h, respectively. Using the methodology outlined previously for the base metal subsector, BATEA was selected as the model effluent management and treatment system for TSS, metals, and total ammonia removal. Hatch expects that with proper design and operation of water management infrastructure, a TSS concentration of 15 mg/L or lower can be achieved by the sector.

Review of the **uranium subsector** included a total of 12 operations. The model effluent treatment system for the subsector, as determined by the prevalence of questionnaire responses, consists of 2 stages: a high pH stage for precipitation of metals that precipitate in basic conditions and a low pH stage for metals and other parameters that precipitate or co-precipitate in acidic conditions. Between and after these pH stages, clarification and filtration are employed to separate precipitates from treated water. The design and nominal flow rates selected to estimate capital and operating costs for system augmentation for the model treatment system were 500 m^3/h and 350 m^3/h, respectively. Using the methodology outlined previously for the base metal subsector, BATEA was selected as active aerobic biological oxidation for total ammonia removal and the model effluent management and treatment system for metals and TSS removal. The incremental capital cost and operating cost for augmenting the model flowsheet with the BATEA were estimated to be C$31,800/m^3/h and C$0.45/m^3, respectively. Further details on the basis of the cost estimates are available in the full report.

Review of the **diamond sector** included a total of 4 operations. The model effluent treatment system for the sector, as determined by the prevalence of questionnaire responses, consists of settling pond(s), clarification, and media filtration for TSS removal. Coagulant is dosed into the clarifier. Prior to discharge to the environment, pH is adjusted using sulfuric acid to meet un-ionized ammonia/toxicity limits. The settling and polishing ponds enable passive natural degradation of ammonia and phosphorus. The design and nominal flow rates selected for the model treatment system were 3 000 m^3/h and 2 000 m^3/h, respectively. These flow rates were used to estimate capital and operating costs for system augmentation. Using the methodology outlined previously for the base metal subsector, BATEA was selected as the model effluent management and treatment system for chloride, bulk metals, ammonia, and TSS removal.

Review of the **coal sector** included a total of 16 operations. In the model effluent treatment system for the sector, as determined by the prevalence of questionnaire responses, bulk TSS is removed via pond-based settling and polishing which may be aided by the addition of flocculant. The settling and polishing pond(s) enable passive natural degradation of ammonia. The design and nominal flow rates selected for the model treatment system were 3 000 m^3/h and 1 000 m^3/h, respectively.

Using the methodology outlined previously for the base metal subsector, BATEA was selected as the model effluent management and treatment system for metals, total ammonia, and TSS removal.

It is important to note that BATEA cannot be applied universally to every mine in each subsector due to site-specific considerations. Factors such as feed water quality, flowrate, location, site conditions, legacy conditions, regulatory constraints, etc. will impact the cost of implementation and operation and may make these BATEA selections economically unattractive or their effluent concentrations technologically unachievable.

Hatch cautions that the use of polymeric organosulfide reagents should only be considered BATEA for operations that are capable of and dedicated to careful control of operating regimes to prevent effluent toxicity, as well as, careful control of residuals storage conditions to prevent long term instability and the potential generation of acid through sulfide oxidation and metals remobilization.

Table 3 provides a summary description of the model effluent treatment flowsheet, proposed BATEA, and achievable treated effluent quality with the proposed BATEA for each subsector. In the "Treated Effluent Quality" column, for those parameters not removed by the model treatment processes, the values presented are based on the 95th percentile of the final effluent concentrations for the entire subsector. The BATEA treated effluent concentrations are based on case study data and actual operating site data provided by vendors and industry as part of this study. Further details on the basis of treated effluent concentrations are available in the full report. These concentrations may not be achievable at every site due to local site conditions or operational factors which could affect the efficiency of the process. A pragmatic approach should be taken when assessing the probability of achieving these effluent target values under site-specific conditions.

CONCLUSION

For each subsector, utilizing the methodology presented herein to assess information compiled on the subsector and on effluent treatment technologies, Hatch selected BATEA for the removal of current and proposed contaminants under the Canadian federal *Metal Mining Effluent Regulations.* The study also provided valuable reference information to regulatory and industry stakeholders regarding subsector water management and treatment practices, the treated effluent quality achieved by model water management and treatment practices for each subsector, and effluent treatment technologies.

The study was published by MEND as Report 3.50.1 on their website at: ***mend**-nedem.org/wp-content/uploads/**MEND_3.50.1**_BATEA.pdf*

ACKNOWLEDGEMENTS

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REFERENCES

Please refer to the report for a complete listing of references (***mend**-nedem.org/wp-content/uploads/**MEND_3.50.1**_BATEA.pdf*).

Environment Canada (2012) *10-Year Review of Metal Mining Effluent Regulations Discussion Paper.*

Canada. *Metal Mining Effluent Regulations* (SOR/2002-222).

Table 3: Summary of proposed BATEA

(sub)Sector	Model Effluent Treatment Flowsheet	Proposed BATEA	Effluent Quality
Base Metal	• hydroxide precipitation for metals • coagulant and flocculant dosing and pond-based settling for TSS • natural degradation of ammonia • pH adjustment with CO_2	model +: polymeric organosulfide reagents for metals polishing	Al < 0.79 mg/L As <0.01 mg/L Cu <0.03 mg/L Fe <0.30 mg/L Pb <0.02 mg/L Ni <0.05 mg/L Se <0.04 mg/L Zn <0.02 mg/L TSS <10 mg/L NH_3/NH_4^+ <4 mg/L
Precious Metal	• SO2/air cyanide destruction on tailings effluent • reactor-based hydroxide precipitation for metals from tailings, mine, and waste rock • natural degradation of ammonia	model +: polymeric organosulfide reagents for metals polishing and active aerobic biological oxidation for ammonia	Al < 0.05 mg/L As <0.05 mg/L Cu <0.03 mg/L CN <0.1 mg/L Fe <0.30 mg/L Pb <0.01 mg/L Ni <0.05 mg/L Se <0.05 mg/L Zn <0.02 mg/L TSS <12 mg/L NH_3/NH_4^+ <2 mg/L
Iron Ore	• flocculant dosing and pond-based settling for bulk TSS • natural degradation of ammonia	model – no economically achievable augmentative technology	Al < 0.80 mg/L As <0.001 mg/L Cu <0.005 mg/L Fe <5.50 mg/L Pb <0.003 mg/L Ni <0.003 mg/L Se <0.005 mg/L Zn <0.04 mg/L TSS <62 mg/L[2] NH_3/NH_4^+ <8 mg/L
Uranium	• high pH hydroxide precipitation for metals • low pH hydroxide precipitation and co-precipitation for metals and metalloids • inter-stage clarification and filtration for TSS	model +: active aerobic biological oxidation for ammonia	Al < 0.70 mg/L As <0.06 mg/L Cu <0.04 mg/L Fe <0.50 mg/L Pb <0.002 mg/L Ni <0.20 mg/L Se <0.02 mg/L Zn <0.04 mg/L Ra-226 <0.11 Bq/L TSS <2 mg/L NH_3/NH_4^+ <2 mg/L
Diamond	• pond-based settling, clarification (with coagulant), and media filtration for TSS • pH adjustment with sulfuric acid	model – no economically achievable augmentative technology	Cl^- <1 240 mg/L P <0.1 mg/L TSS <7 mg/L NH_3/NH_4^+ <2.35 mg/L
Coal	• flocculant dosing and pond-based settling for bulk TSS • natural degradation of ammonia	model – no economically achievable augmentative technology	Al < 0.90 mg/L As <0.001 mg/L Fe <0.82 mg/L Mn <0.13 mg/L Se <0.38 mg/L TSS <77 mg/L NH_3/NH_4^+ <0.37 mg/L

[2] Proper design and operation of water management infrastructure can achieve TSS ≤ 15 mg/L.