In-Pit Batch Treatment of Arsenic

Laboratory Studies and Field Trial

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LABORATORY STUDIES & FIELD TRIAL

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EXECUTIVE SUMMARY

The mining industry has long recognized the potential value of open pits as a means to manage environmental liabilities with a focus on site closure. Typically, open pits have been used as a repository for mine wastes, specifically as a strategy to manage potentially reactive wastes. The use of open pits specifically within the context of water quality management for mine closure has received little attention despite water quality management representing a risk and therefore a focus of long-term care and maintenance activities at many mines globally. Moreover, water quality management can represent the greatest environmental liability for operations and the single highest cost factor associated with site activities. This is especially true in instances where water quality management must be achieved through traditional water treatment with a Water Treatment Plant (WTP).

In-pit treatment can represent a lower cost alternative with less infrastructure and more flexibility in water management that is aligned with more recent regulatory thinking on the approvability of perpetual water treatment via WTPs. In-pit treatment can be especially attractive for waters that marginally exceed discharge criteria with relatively small loadings of constituents. In such cases, the water treatment solids that precipitate as a by-product of treatment represent very small volumes and a pit can have a large capacity for retention of the treatment solids.

In pit treatment of various metals has been used at several mines with variable results. In-pit treatment of arsenic with ferric sulphate is an innovative approach to water treatment that was evaluated in this study. The overall objective of the investigation was to demonstrate that in pit batch treatment of arsenic represents a viable and economical alternative to traditional water treatment applications.

Phase 1 of this evaluation program included a laboratory or "bench-scale" study that was used to define the design criteria, including the attainable treatment efficiencies, the required reagent dosages and the sludge production rates. *Phase 2* of this study included a field scale treatment trial that evaluated the practicality and efficacy of in-pit batch treatment of arsenic within the Night Hawk Lake Mine (NHLM) open pit, as informed by the results in Phase 1.

Phase 1 of this investigation included testing of ferric sulphate dosing rates on water from Newmont Goldcorp's NHLM open Pit as well as the characterization of the water treatment solids that were formed. The molar ratio of iron (Fe) to arsenic (As) and pH were evaluated to assess optimal dosage requirements and resulting treatment solids stability. The results showed that total concentrations for both arsenic and iron were unaffected after ferric sulphate addition with only 5 minutes of reaction time; but were much lower after 24 hours of settling time. In contrast, dissolved concentrations of arsenic and iron were reduced within 5 minutes of reaction time after ferric sulphate addition; with little change after 24 hours of settling time.

There was a trend of decreasing concentrations for total and dissolved arsenic with increasing iron dosage in the tests after 24 hours settling time. The highest iron dosage of approximately 20:1 resulted in the most effective removal of arsenic from solution, to total and dissolved concentrations below 0.05 mg/L. Concentrations of cobalt and nickel were also examined in the ferric sulphate addition tests. The results showed that ferric sulphate addition increased concentrations of cobalt, initially, followed by lower concentrations after 24 hours of settling time. Final cobalt concentrations (total and dissolved fractions) did however exceed initial concentrations, likely due to the usage of reagent grade ferric sulphate that was associated with an elevated cobalt content. Total and dissolved nickel concentrations decreased below initial concentrations in all tests for all dosages. Cobalt and nickel were therefore also considered key parameters for assessment within the field trial.

A treatment solids settling test was completed to determine a minimum settling time and to generate enough solids for characterization. Based on total concentrations of arsenic and iron, the majority of settling occurred between 5 minutes and 30 minutes, after which concentrations were relatively constant up to 24 hours of settling time, and decreased slightly again between 24 and 120 hours of settling time. Results of the settling test also provide an indication of the relative stability of treatment solids. Concentrations over 120 hours were either stable or decreased

during that time. These results imply that the solids in contact with the water are relatively stable and that the observed concentrations are representative of those that would occur in waters in contact with the treatment solids. These results are consistent with other studies of arsenic treatment solids formed during the addition of ferric sulphate.

Phase 2 of this evaluation program included a field scale study that evaluated practicality and efficacy of in-situ batch treatment of arsenic within the NHLM open pit, as informed by the results in Phase 1.

The bathymetry survey showed that the water volume in the NHLM open pit is approximately 100,000 m^3 with an average depth of about 10 m and a maximum depth of 22 m. On average, water quality monitoring results exhibit measured arsenic concentrations of 0.6 mg/L representing a total of 60 kg of arsenic in the pit water. The Phase 1 lab testing indicated that a 20:1 molar ratio of iron to arsenic (Fe:As) will result in treated arsenic concentrations of 0.05 mg/L or less and that was the target ratio selected for dosing of the pit water. Therefore, about 900 kg of iron (Fe) was required to dose the entire pit. This represents about 6 totes of commercially available ferric sulphate solution (50% w/w) each containing 1,350 kg of solution with 12.25% Fe, or 165 kg of Fe each.

The field trial was designed to include circulation of about 10% of the pit water volume. The concept was to pump the minimum volume that allows mixing of the required ferric sulphate dose with pit water by dispersing the reagent with the pit water over a large area of the water surface. This was accomplished by the use of two water cannons stationed around the perimeter of the pit.

The pH, dissolved oxygen (D.O.), temperature and specific conductance were measured in the pit water profile to a maximum depth of 22 m, before and after ferric sulphate addition. The results show that the pH was typically in the range of 7.5 to 8.5 and overall values were slightly lower after treatment than before. The oxygen saturation values varied between about 100% near the water surface to less than 10% at depths greater than 16 m, with very little difference before and after treatment. The temperature of the water varied between 4 and 5° prior to treatment and 3 to 5° after treatment with near surface temperatures higher than those at depth. The specific conductance values in November before and after treatment, were in the range of 450 to 575 µS/cm, exhibiting lower values near the surface with abrupt increases at a depth of about 12 m below surface. The specific conductance values were slightly higher after treatment than before. The specific conductance profiles in November suggest that there may be a density layering at a depth below 12 m from surface with higher TDS water in the bottom layer.

The total and dissolved arsenic concentrations at three (3) depths within the pit were compared for the sampling event immediately prior to treatment and three (3) sampling events after treatment. The pre-treatment samples exhibited slightly lower dissolved concentrations at depth than the total concentrations. Immediately post-treatment, November 2018, the total arsenic concentration at the surface at NHP1 decreased from an original value of 0.6 mg/L total arsenic, on average, to a value of 0.01 mg/L total arsenic and the dissolved concentration was less than 0.002 mg/L. These results translate into an approximate treatment efficiency of 98% within the surface depths. The mid-depth samples for the same sampling event were approximately 0.03 and 0.01 mg/L for the total and dissolved arsenic concentrations, respectively. The arsenic concentrations at depth remained close to the initial concentrations prior to treatment. The arsenic concentrations in subsequent sampling events, post-treatment, exhibited similar trends with depth showing the lowest concentrations near the surface and that the highest concentrations at depth.

The study showed effective treatment of arsenic in the upper 10 m of the pit providing a positive effect that can be used for the management of water in similar pits in temperate climates. These results also suggest that pits having natural outlets for flow may allow for the management of treated waters, with near surface waters released to the environment at the values observed after this treatment trial.

Considerations of the practical implications of in-situ batch treatment were also explored as part of this investigation. An evaluation of the required frequency for treatment was completed using a quantitative modelling approach, for NHLM open pit. The post treatment monitoring data provided a basis for assessing the potential need for additional treatment in the future. MineMod™, a proprietary water quality modelling tool, was used to assess the need for and timing of in-pit treatment events.

A similar model was also developed for a much larger scale pit, using the McEwen Mining Inc. Black Fox Mine, near Matheson Ontario, as an example in order to compare the requirements for in-situ treatment at this scale. A comparison of capital and operating expenditures was also completed for this example, in order to evaluate the application of in-situ treatment versus the construction of a water treatment plant.

Modelling showed that after an initial treatment at the time of the pit filling, periodic in-pit treatment can maintain arsenic concentrations below a selected discharge limit of 0.15 mg/L with treatment on the order of every 7 years for the NHLM open Pit, and 32 years for the Black Fox Pit. This low frequency of treatment potentially represents substantial savings in operating costs compared to ongoing and continual treatment with a conventional water treatment plant.

SOMMAIRE

L'industrie minière reconnaît depuis longtemps la valeur potentielle des fosses des mines à ciel ouvert comme solution de gestion des passifs environnementaux en particulier lors de la fermeture des mines. Habituellement, on dépose les rejets miniers dans ces fosses, en particulier dans le cadre d'une stratégie de gestion des rejets potentiellement réactifs. L'utilisation des fosses des mines à ciel ouvert dans un contexte de gestion de la qualité de l'eau lors de la fermeture des mines n'a pas tellement attiré l'attention, malgré le fait que gérer la qualité de l'eau représente un risque et, par conséquent, nécessite un suivi à long terme et des activités de maintenance pour de nombreuses mines à l'échelle mondiale. De plus, la gestion de la qualité de l'eau peut représenter le plus important passif environnemental de l'exploitation et les coûts les plus élevés associés aux activités du site. Cela est particulièrement vrai dans les cas où ou l'on doit gérer la qualité de l'eau au moyen de méthodes traditionnelles de traitement dans une usine de traitement de l'eau.

Le traitement dans des fosses des mines à ciel ouvert peut constituer une option moins coûteuse nécessitant moins d'infrastructure et accordant plus de souplesse pour une gestion de l'eau qui s'articule sur les récents concepts réglementaires axés sur l'acceptabilité du traitement perpétuel de l'eau dans des usines de traitement. Le traitement dans les fosses en bassin de résidus peut s'avérer une solution particulièrement attrayante pour les eaux contenant des quantités relativement minimes de certains composants qui dépassent légèrement les critères de rejet. Dans ce genre de situation, les matières solides issues du traitement de l'eau qui se précipitent représentent de très faibles volumes et une fosse peut avoir une grande capacité de rétention des matières solides du traitement.

Le traitement dans les fosses des mines à ciel ouvert a été utilisé pour divers métaux dans plusieurs mines, avec des résultats variables. Le traitement de l'arsenic dans une fosse de mine à ciel ouvert à l'aide du sulfate de fer est une méthode novatrice de traitement de l'eau qui a été évaluée dans le cadre de cette étude. L'objectif global de cette enquête était de démontrer que le traitement en vrac de l'arsenic dans une fosse constitue une autre solution viable et économique au traitement classique de l'eau.

La *phase 1* de ce programme d'évaluation incluait une étude sur paillasse de laboratoire qui a servi à définir les critères de conception, y compris les gains d'efficacité possibles pour le traitement, les doses de réactifs requises et les taux de productions de boues. La *phase 2*, quant à elle, incluait des essais de traitement à l'échelle réelle qui évaluait l'aspect pratique et l'efficacité du traitement en vrac de l'arsenic dans la fosse désaffectée de la mine de Night Hawk Lake (NHLM), à la lumière des résultats obtenus à la phase 1.

La phase 1 de cette recherche comprenait les essais sur les dosages de sulfate de fer sur l'eau de la fosse de Newmont Goldcorp à la mine Night Hawk Lake ainsi que la caractérisation des rejets s solides résultant du traitement de l'eau. On a évalué les ratios molaires fer-arsenic (Fe:As) ainsi que le pH pour établir les besoins relatifs au dosage optimal et la stabilité des solides issus du traitement. Les résultats ont montré que l'ajout de sulfate de fer ne modifie pas les concentrations totales d'arsenic et de fer après un temps de réaction de seulement cinq minutes, mais que ces concentrations diminuent considérablement après une période de sédimentation de 24 heures. Inversement, on a constaté que les concentrations d'arsenic et de fer dissous sont réduites après un temps de réaction de cinq minutes suivant l'ajout du sulfate de fer, mais qu'elles changent très peu après la période de sédimentation de 24 heures.

Les concentrations totales d'arsenic et d'arsenic dissous ont tendance à baisser après une hausse du dosage de fer dans les tests suivant la période de sédimentation de 24 heures. C'est le dosage de fer le plus élevé, soit environ 20:1, qui a donné les meilleurs résultats en éliminant l'arsenic de la solution jusqu'à des concentrations totales d'arsenic et d'arsenic dissous inférieures à 0,05 mg/L. Les concentrations de cobalt et de nickel ont aussi été examinées lors des tests avec ajout de sulfate de fer. Les résultats ont révélé que l'ajout de sulfate de fer fait d'abord augmenter les concentrations de cobalt, mais les réduit après une période de sédimentation de 24 heures. Les concentrations finales de cobalt (fractions totales et dissoutes) ont toutefois été supérieures aux concentrations initiales, probablement à cause de l'utilisation de sulfate de fer de qualité réactif associé au contenu élevé de cobalt. Les concentrations de nickel total et dissous ont diminué et sont passées sous les concentrations initiales dans tous les tests, avec tous les dosages. Le cobalt et le nickel ont donc été considérés comme des paramètres clés pour l'évaluation des essais sur le terrain.

On a mené un test des éléments solides dans le cadre du traitement pour déterminer la période minimale de sédimentation et pour générer suffisamment de solides aux fins de caractérisation. En se fondant sur les concentrations totales d'arsenic et de fer, la majeure partie de la sédimentation a eu lieu dans un délai de 5 à 30 minutes, après quoi les concentrations sont restées relativement stables pendant une période de sédimentation de 24 heures, puis elles ont légèrement diminué de nouveau entre 24 et 120 heures de sédimentation. Les résultats des tests de sédimentation constituent également une indication de la stabilité relative des solides issus du traitement. Les concentrations après une période de plus de 120 heures sont restées stables ou ont diminué pendant cette période. Ces résultats portent à croire que les solides qui sont en contact avec l'eau sont relativement stables et que les concentrations observées sont représentatives de celles qui se produiraient dans des eaux en contact avec les solides issus du traitement. Ces résultats sont cohérents avec d'autres études portant sur les solides issus du traitement de l'arsenic qui se forment à l'ajout de sulfate de fer.

La phase 2 de ce programme d'évaluation incluait une étude des traitements à échelle réelle visant à évaluer l'aspect pratique et l'efficacité du traitement en vrac de l'arsenic dans la fosse de la mine Night Hawk Lake (NHLM), à la lumière des résultats obtenus à la phase 1.

Le relevé bathymétrique a montré que le volume d'eau dans la fosse de la mine à ciel ouvert NHLM était d'environ 100 000 m^3, que la profondeur moyenne de la fosse était d'environ 10 m et que sa profondeur maximale était de 22 m. En moyenne, les résultats du suivi de la qualité de l'eau révèlent des concentrations mesurées d'arsenic de 0,6 mg/L, ce qui représente un total de 60 kg d'arsenic dans l'eau de la fosse. Les tests en laboratoire menés dans le cadre de la phase 1 ont indiqué qu'un ratio molaire 20:1 fer-arsenic (Fe:As) permet d'atteindre des concentrations d'arsenic de 0,05 mg/L ou moins après traitement, et c'est ce ratio qui a été choisi pour le dosage de l'eau de la fosse. Par conséquent, le dosage pour l'ensemble de la fosse a nécessité environ 900 kg de fer (Fe). Cela représente environ six réservoirs de solution commerciale de sulfate de fer (50 % en p/p), chacun contenant 1 350 kg de solution avec 12,25 % ou 165 kg de Fe.

L'essai en terrain a été conçu pour inclure une circulation d'environ 10 % du volume d'eau de la fosse. Le concept était de pomper un volume minimum afin de mélanger la dose requise de sulfate de fer avec l'eau de la fosse, en dispersant le réactif mélangé à l'eau de la fosse sur un grand périmètre à la surface de l'eau. Pour ce faire, on a utilisé deux canons à eau placés autour du périmètre de la fosse.

On a mesuré le pH, l'oxygène dissous (O.D.), la température et la conductance précise du profil de l'eau de la fosse à une profondeur maximale de 22 m, avant et après l'ajout du sulfate de fer. Les résultats démontrent que le pH se situait généralement dans un intervalle de 7,5 à 8,5 et que les valeurs globales étaient légèrement plus basses après le traitement qu'avant ce dernier. Les valeurs de saturation en oxygène ont varié entre 100 % près de la surface à moins de 10 % à des profondeurs de plus de 16 m, avec très peu de différence entre avant et après le traitement. La température de l'eau a varié entre 4° et 5° avant le traitement et entre 3° et 5° après le traitement, les températures près de la surface étant plus élevées que celles mesurées en profondeur. En novembre, les valeurs de conductance spécifique de l'eau avant et après le traitement se situaient entre 450 et 575 µS/cm, avec des valeurs moins élevées près de la surface et une hausse abrupte des valeurs à une profondeur d'environ 12 m sous la surface. Les valeurs de conductance étaient légèrement plus élevées après le traitement qu'avant celui-ci. Les profils portant la conductance spécifique de l'eau établis en novembre portent à croire qu'il pourrait y avoir des couches de densité à des profondeurs de plus de 12 m de la surface avec des taux de matières dissoutes totales (MDT) plus élevés dans les couches du fond.

Des échantillons prélevés à trois profondeurs dans la fosse immédiatement avant le traitement ont été comparés à trois autres échantillons prélevés après le traitement pour comparer les concentrations totales d'arsenic et d'arsenic dissous. Les échantillons prélevés en profondeur avant le traitement contenaient des concentrations d'arsenic dissous légèrement inférieures aux concentrations totales. Immédiatement après le traitement, soit en novembre 2018, la concentration totale d'arsenic à la surface NHP1 a diminué, passant d'une valeur totale d'arsenic de 0,6 mg/L au départ, en moyenne, à une valeur totale de 0,01 mg/L, avec une concentration d'arsenic dissous inférieure à 0,002 mg/L. Ces résultats se traduisent par un degré d'efficacité du traitement d'environ 98 % près de la surface. Les échantillons prélevés à des profondeurs médianes lors de la même prise d'échantillons étaient d'environ 0,03 et 0,01 mg/L pour les concentrations totales d'arsenic et d'arsenic dissous, respectivement. En profondeur, les

concentrations d'arsenic sont restées proches des concentrations initiales avant le traitement. Les concentrations d'arsenic relevées lors des prélèvements d'échantillons après le traitement ont révélé des tendances semblables, soit des concentrations moins élevées près de la surface et plus élevées en profondeur.

L'étude a révélé que le traitement de l'arsenic est efficace dans les dix premiers mètres de la fosse, soit un effet positif pouvant servir à la gestion de l'eau dans des fosses des mines à ciel ouvert en climat tempéré. Ces résultats portent également à croire que les fosses qui ont des exutoires naturels peuvent permettre la gestion des eaux usées, les eaux de surface étant relâchées dans l'environnement aux valeurs observées pendant cet essai de traitement. Nous avons également exploré des considérations liées aux ramifications pratiques du traitement en vrac sur place dans le cadre de cette étude. Nous avons effectué une évaluation de la fréquence de traitement requise à l'aide d'une approche de modélisation quantitative pour la fosse de la mine NHLM. Les données du suivi post-traitement ont servi de base pour évaluer le besoin potentiel de traitement additionnel à l'avenir. Nous avons utilisé MineMod^{MD}, un outil commercial exclusif pour la modélisation de la qualité de l'eau, afin d'évaluer le besoin de traitements ultérieurs de la fosse et la fréquence de ceux-ci. Un modèle semblable a également été mis au point pour une fosse de plus grande envergure en utilisant, pour ce faire, la Black Fox Mine de la McEwen Mining Inc., près de Matheson (Ontario), à titre d'exemple pour comparer les exigences de traitement sur place à cette échelle. Nous avons en outre comparé les dépenses d'immobilisation et d'exploitation pour cet exemple afin d'évaluer l'application d'un traitement sur place par rapport à la construction d'une usine de traitement de l'eau.

La modélisation a établi qu'après un traitement initial au moment du remplissage de la fosse, on peut maintenir les concentrations d'arsenic sous une limite choisie de rejet de 0,5 mg/L avec une fréquence de traitement d'environ sept ans pour la fosse de la mine à ciel ouvert NHLM et de 32 ans pour la fosse Black Fox. Cette fréquence de traitement plutôt faible représente des économies substantielles sur le plan des coûts d'exploitation par rapport au traitement continu et permanent d'une usine traditionnelle de traitement de l'eau.

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1 INTRODUCTION

The mining industry has long recognized the potential value of open pits as a means to manage environmental liabilities with a focus on site closure. Typically, open pits have been used as a repository for mine wastes, specifically as a strategy to management potentially reactive wastes, with both advantages and disadvantages being documented. For example, MEND (2015) conducted a review of in-pit disposal of reactive mine wastes and considered the relative success of in-pit disposal for twelve case studies in Canada, Spain, Australia, Germany, and Guyana. A similar review of "pit lakes" identified eighty-one pit lakes around the world, a subset of which (33) were assessed in some detail (Golder, 2017). In most cases, though not all, the primary function of open pits was to store reactive mine waste for the purpose of mitigating constituent source loads being mobilized to the environment. Alternative uses for open pits at closure have also been identified and implemented. These include uses ranging from the creation of fisheries and aquatic habitats, to recreation and cultural centres to bioreactors (Pearman, 2009).

The use of open pits specifically within the context of water quality management for mine closure has received little attention considering that water quality management represents a risk and therefore focus of long-term care and maintenance at many mines globally. Moreover, water quality management can represent the greatest environmental liability for operations and the single highest cost. This is especially true in instances where water quality management must be achieved through traditional water treatment with a Water Treatment Plant (WTP).

More sustainable and potentially cost-effective water quality management strategies that do not include a WTP warrant consideration. For instance, in-pit treatment can represent a lower cost alternative with less permanent infrastructure in water management. This is also in keeping with the spirit of the mine rehabilitation guidelines and/or codes for several provinces (e.g., Quebec, Manitoba and the Northwest Territories), whereby a permanent active water treatment plant cannot constitute a final reclamation measure for mining effluents.

In-pit treatment can be especially attractive for waters that marginally exceed discharge criteria. In such cases, batch treatment would be required infrequently with long times for the build up of concentrations after each treatment. In addition, the water treatment solids that precipitate as a by-product of treatment will represent small volumes and a pit can have a large capacity for retention of the treatment solids.

Mine-affected waters with arsenic (As) concentrations above a discharge criterion may be amenable to in-pit treatment and storage of treatment solids. Effective treatment of arsenic by addition of ferric sulphate in a WTP is a well-established.

In-pit treatment of arsenic with ferric sulphate is an innovative approach to water treatment at a mine site. In pit treatment of metals has been used at several mines. Various treatment methodologies have been applied, including organic carbon and/or nutrient addition to induce sulphide production and precipitation of metal sulphides (Highland Valley Copper, British Columbia) as well as pH adjustment to induce metal hydroxide precipitation (Selbaie, Quebec). To the best of our knowledge, the proposal to remove arsenic with ferric sulphate is based on a proven treatment process that had not yet been applied to in pit treatment.

The demonstration that in-pit treatment approach will work and can be readily managed at the scale of an open pit is key to both operational and regulatory acceptance. The proposed study represents a test of in-pit treatment that goes well beyond a bench scale application and provided a proof of implementation that is scaled to real open pit conditions. Successful results of this study may provide confidence to operators and regulators that in-pit treatment technology represents a practical, effective, economical and achievable water management option.

1.1 Objectives and Scope

The overall objective of this evaluation program was to demonstrate that in-pit treatment of arsenic represents a viable and economical alternative to traditional water treatment applications. Newmont Goldcorp's closed and reclaimed Night Hawk Lake Mine (NHLM) open pit was utilized to demonstrate this concept.

Phase 1 of this evaluation program included a laboratory or "bench-scale" study used to define design criteria, attainable treatment efficiencies, required reagent dosage, and sludge production rates.

Water samples were collected from various depths in the pit, representing surface, mid and bottom depth ranges and were analyzed for pH, conductivity, dissolved oxygen [DO], total and dissolved metals, and major anions.

A commercially available ferric sulphate solution was utilized for treatability test work. Results from the test work were used to determine the optimal ferric sulphate dosage and pH to attain arsenic concentrations of 0.05 mg/L or less. The molar ratio of iron (Fe) to As and pH were evaluated to assess optimal dosage requirements and resulting treatment solids stability.

Phase 2 of this evaluation program included a field scale trial to evaluate the practicality and efficacy of in-pit treatment of arsenic within the NHLM open pit, as informed by the results in Phase 1.

The field scale treatment system included a ferric sulphate storage and dosage system, and a recirculation pump and piping to and from the pit with a spray delivery system.

A monitoring program was developed to monitor arsenic concentrations within the pit and to evaluate batch treatment performance. Routine monitoring at the site is completed by Newmont Goldcorp personnel and was used to complement batch treatment performance monitoring.

Practical implications of in-situ batch treatment were also explored as part of this program. An evaluation of the required frequency for treatment was completed using a quantitative modelling approach. Post treatment monitoring data provided a basis for assessing the potential for additional treatment in the future. MineMod™, a proprietary water quality modelling tool, was used to assess the potential need for and timing of in-pit treatment events.

MineMod™ was also used to evaluate a much larger scale pit, using the McEwen Mining Inc. Black Fox Mine near Matheson, Ontario, in order to compare the requirements for in-situ treatment at a larger scale. A comparison of capital and operating expenditures was also completed for this example, in order to evaluate the application of in-situ treatment versus the construction of a water treatment plant.

Modelling suggests that following initial treatment at the time of the pit filling, periodic in-pit treatment (i.e., every 7 years for the NHLM open Pit, and 32 years for the Black Fox Pit) can maintain arsenic concentrations below a selected discharge limit of 0.15 mg/L. This frequency of treatment potentially represents substantial savings in operating costs compared to ongoing and continual treatment with a conventional water treatment plant.

1.2 Partnerships

Work presented herein represents a partnership between EcoMetrix Incorporated, the Mine Environment Neutral Drainage (MEND) secretariat, Goldcorp Canada Limited (now Newmont Goldcorp), McEwen Mining Inc., and Envirobay Inc.

The authors wish to acknowledge each of the research partners for their generous contribution and support in the completion of this work.

2 REVIEW OF IN-SITU BATCH TREATMENT CASE STUDIES

After mining operations cease, open pits represent potential resources for water management. Open pits are commonly used for water storage and at sites that require water treatment, an open pit can represent a reservoir for collection and storage capacity for water to allow for lower operating flow rates in a WTP. Open pits also present opportunities for in-pit treatment.

Treatment methods, which have been tested and documented for in-pit batch treatment include, but may not be limited to:

- Organic carbon and/or nutrient addition at Highland Valley Copper and Island Copper Mine, BC, to induce the precipitation of metal sulphides (Pelletier et al., 2018);
- Lime addition to adjust pH at the Selbaie Mine, QC, to induce metal hydroxide precipitation and the removal of zinc (Huls and Aubé, 2006);
- Lime addition to adjust pH and precipitate metals in Nero Lake at the former uranium mine at Lorado, SK[1];
- Combined lime and organic carbon addition at the Gilt Edge mine, South Dakota, to remove metals (Lewis et al., 2003); and,
- Organic carbon addition to the Grum Pit, Faro Mine, YK, to remove zinc[2].

Treatment technology development typically evolves from laboratory and modelling to pilot-scale testing, and full-scale application. These various phases are highlighted by the following case studies, which demonstrate the feasibility, including potential limitations and challenges, of in-situ batch treatment of mine pits.

Les Mines Selbaie (La Sarre, QC) is a decommissioned copper-zinc mine, with a pit lake containing 22 million cubic metres (Mm^3) of water (Huls et al., 2006). In 2005, a zinc concentration of 10 mg/L was measured, which exceeded typical tailings and site runoff contamination of less than 5 mg/L, and as well as the final discharge limit of 0.5 mg/L. The pH of the pit water was on the order of 7. It was hypothesized that raising the pH could remove zinc to levels that would allow passive discharge. Studies were then designed and implemented to support in-pit treatment.

This studied involved laboratory, in-pit limnocorrals (pilot-scale) and full-scale components. Tests involved the addition of ferric sulphate, aluminum coagulants, lime slurry, and/or Red Mud (i.e., bauxite tailings). Laboratory experiments demonstrated a positive correlation between lime consumption and pH, with a pH of 10 selected as a setpoint for further treatment. Pilot-scale tests demonstrated that surface lime addition only treated the epilimnion, with the need to mix and recirculate water in order to penetrate the thermocline at a depth of 5 m below surface. It was also reported that by injecting treated water at depth, the pH quickly increased up to the bottom of the thermocline. The concentration-pH relationship as well as lime consumption rates established during the pilot-scale corresponded well with laboratory results.

The full-scale conceptual design of in-situ batch treatment system included a lime injection rate of 0.5-1.2 g/L at a pH between 11.5 and 12. The treatment system consumed one 40-tonne truckload of quicklime per day, operating for 24 hours per day over a 52-day period, with only a 5% downtime. Overall, laboratory and pilot-scale testing ensured an effective treatment design. Field monitoring demonstrated excellent results with all discharge criteria met, including a zinc concentration of 0.2 mg/L after 35 days of treatment (Huls et al., 2006).

Lake Bockwitz (Leipzig, Germany) is an 18.4 Mm^3 water filled pit at an open-cast lignite mine. The pit is associated with a small watershed and limited groundwater inflow. The initial water in the lake was acidic, with a pH of 2.7, and iron and aluminum concentrations of 55 and 19 mg/L, respectively; all exceeding regulatory limits. Pit water was treated in-situ to overcome the acidity maintained by the stored acidity in the dissolved iron.

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[1] http://environment.gov.sk.ca/2009-041EISExecutiveSummary

[2] https://www.rcaanc-cirnac.gc.ca/eng/1480019546952/1537554989037

Soda ash (Na_2CO_3) was used to neutralize the lake water to a pH of 5, and was added to the lake just below the surface through a floating pipeline. Within a two-year period, 12,870 tonnes of soda ash was added and an overall neutralization efficiency of 90-95% was calculated (Ulrich et al., 2012). The in-situ batch treatment was considered more economical method, compared to the high-costs associated with an ex-situ method in the construction, operation, and maintenance of a WTP (Ulrich et al., 2012).

Treatment of mine-affected water at the Barrick Richmond Hill Mine at Lead, South Dakota resulted in the successful removal of selenium to concentrations of 0.012-0.022 mg/L by zero valent iron; which is able to neutralize acid and promote removal and immobilization of dissolved metals. This treatment system also incorporated ferric sulphate precipitation at a pH of 4.5 (EPA, 2014).

Remediation of the Barite Hill Pit Lake (South Carolina) involved addition of soluble organic carbon to treat 60 million gallons (227,000 m^3) of water with a pH of 1.5–2.3 and high concentrations of metals. Approximately 1,860 tonnes of hydrated and water saturated lime and 400 tonnes of soluble organic carbon were added into the pit lake between January and May of 2008, by means of a custom-designed aerated batch delivery system. Remedial costs were estimated to be 79-88% less than traditional treatment technology methods (ITRC, 2010). Monitoring results were not available.

A large-scale application of ferric chloride for on-site treatment of arsenic to address the contamination of Yangzonghai Lake in Yunnan Province, China (Chen et al., 2015). Arsenic concentrations in the lake reached 0.128 mg/L. With a lake volume estimated to be 604 Mm^3, 6-8 tonnes of ferric chloride was sprayed on the lake surface daily starting in October 2009. The average arsenic concentration declined to 0.021 mg/L after one year of treatment. After spraying over 4,000 tonnes of ferric chloride into the lake, iron and chloride concentrations were lower than 0.010 mg/L and approximately 13 mg/L, respectively. During the two-year treatment period by ferric chloride, pH of the lake water remained between 7.7 and 8.9. As demonstrated by Chen et al. (2015), in-situ batch treatment technology is associated with a high arsenic removal rate, simple operation and low-cost.

Overall, the results of this review suggest that open pits have largely been evaluated in terms of a waste disposal strategy with lesser focus on water management and treatment. Given that water quality is a key component of closure for mine operators, these results suggest that an opportunity exists to look at the pit from a water management perspective also. Although this approach may not be practical and/or feasible in all cases, these studies do suggest that in situ treatment should be considered amongst other options when evaluating closure strategies.

As a result, this study was intended to build upon the knowledge from other in-pit treatment investigations and strives to evaluate the relative success of in situ batch treatment for arsenic within a small-scale open pit, in terms of achieved water quality objectives, practicality of approach, frequency of batch treatment required, and scalability.

3 PHASE 1 – LABORATORY TESTING

The in-situ batch treatment of open pit waters is an emerging technology for treating Mine Influenced Water (MIW). This technology consists of the injection or placement of substances directly into pit water, to remove constituents of potential concern (COPCs) such as arsenic.

Of the various arsenic removal technologies, the process of coagulation and solids removal is considered as the leading method, with respect to cost and the associated handling of treatment residues (Kowalski, 2014). Water treatment that uses ferric salts to encourage the precipitation/settling process (MEND, 2014) is an effective method of arsenic removal treatment, and has been used extensively in both laboratory and field studies compared to other technologies (Vu et al., 2003). In particular, the precipitation of arsenic with trivalent iron salts (i.e., ferric sulphate) and lime (i.e., CaO, $Ca(OH)_2$) is a removal technique commonly employed for the treatment of MIW effluents (Pantuzzo and Ciminelli, 2010). Ferric salts, including ferric chloride, ferrous sulphate, ferric sulphate, are considered as low-cost materials that can effectively remove arsenic after mixing, with relatively short contact times. As reported by Kowalski (2014), the most efficient coagulant required for full-scale treatment would require the lowest dose and minimal pH changes to minimize associated treatment costs.

A study on the effects of major operating variables, including initial arsenic concentration, coagulant dose and pH, have shown that a lower initial arsenic concentration requires a higher coagulant molar ratio dose, leading to greater costs. Ferric salts have been shown to be more effective and economical reagent than ferrous salts, requiring a lower overall dose (Kowalski, 2014). The addition of ferric sulphate leads to the consumption of hydroxide ions during the precipitation of ferric hydroxide, which can decrease the pH (MEND, 2014; AMEC, 2017). Therefore, operations that use ferric sulphate as a coagulant and precipitant may consider pH adjustment (MEND, 2014). It has also been reported that ferric salts are more efficient on a mass basis and more effective over a wider pH range than alum as an arsenic removal or sorbent material (Vu et al., 2003).

The addition of a ferric sulphate solution was therefore selected for application within the Phase 1 bench scale studies. This selection complements the usage of the commercially available ferric sulphate solution currently used to treat arsenic in discharge waters from several gold mine operations with more traditional treatment systems or water treatment plants.

3.1 Field Collection of Pit Waters

Phase 1 of this investigation included testing of ferric sulphate dosing rates on water from Newmont Goldcorp's NHLM open pit as well as the characterization of water treatment solids that were formed. A detailed discussion of the NHLM open pit is provided in **Section 4.0**, with a general summary of waters collected for bench scale testing provided below.

Water was collected from the pit on March 27, 2018, representing approximately 40 L at 3 depths; shallow, middle (mid-depth) and bottom waters within the pit (**Figure 3-1**). Water samples were shipped to the EcoMetrix laboratory in Mississauga, ON, where they were stored at 4°C until further testing and analyses. A summary of water quality associated with each of the three depths, is summarized in **Table 3-1**.

Figure 3-1: Collection of Pit Water

Table 3-1: Pit-Water Chemistry at Three-Depths Sampled 27 March 2018

Measurement (mg/L)		Field Pit-Water Source		
		Surface	Mid	Bottom
Hardness (as CaCO$_3$)	Total	252	264	311
	Dissolved	269	262	307
Aluminum (Al)	Total	0.0046	0.0090	0.0267
	Dissolved	0.0109	0.0131	0.0043
Arsenic (As)	Total	0.672	0.671	0.858
	Dissolved	0.696	0.670	0.691
Cobalt (Co)	Total	0.00033	0.00144	0.00913
	Dissolved	0.00031	0.00132	0.00566
Copper (Cu)	Total	0.00281	0.00377	0.00309
	Dissolved	0.00338	0.00769	0.00187
Iron (Fe)	Total	<0.01	0.025	0.407
	Dissolved	0.011	0.017	0.290
Manganese (Mn)	Total	0.0091	0.0411	0.264
	Dissolved	0.009	0.0391	0.271
Nickel (Ni)	Total	0.0387	0.0411	0.0512
	Dissolved	0.0393	0.0424	0.0336
Calcium (Ca)	Total	55.4	57.2	69.7
	Dissolved	59.3	57.2	70.1
Magnesium (Mg)	Total	27.7	29.5	33.2
	Dissolved	29.4	28.9	32.2
Sulphate (SO$_4$)[3]	Total	112.8	110.7	137.4
	Dissolved	118.5	127.5	146.4

3.2 Ferric Sulphate Dosing Rates

A commercially available ferric sulphate hydrate solution was used to create the dosing stock, for the treatability test work. The stock solution was analysed and had a dissolved iron concentration of 966 mg/L.

The molar ratio of Fe to As, and pH are important in the evaluation of the optimal dosage rate requirements and resulting treatment solids stability. Molar ratios were adopted from AMEC (2017); with initial target ratios corresponding to 3:1, 5:1, 10:1, 15:1, and 20:1 based on an arsenic concentration of approximate 0.7 mg/L in the pit water. Actual ratios achieved during the series of tests, due to the observed variability in the prepared stock solutions are listed in **Table 3-2**. Samples from the surface (S) and mid (M) depths only were tested in order to limit the total tests completed.

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[3] Estimated from reported sulphur concentrations.

Table 3-2: Summary of Target and Actual Fe:As Molar Ratios

Target Ratios	Actual	
	Surface	Mid-Depth
3:1	2	2
5:1	3	3
10:1	7	6
15:1	10	10
20:1	14	13
	20[1]	19[1]

Note: 1-Denotes replicates completed to have ratio closer to target of 20:1

Beakers with 1 L of pit water were prepared. Ferric sulphate stock solution was added and the sample was agitated for 5 minutes to provide a reaction time. Sample agitation was discontinued and was allowed to settle for 24 hours. Water samples were collected, after the five-minute reaction time and after 24 hours of settling, and analyzed for dissolved and total concentrations of metals by ICP-MS (see **Appendix A** for complete list of analytes).

Figure 3-2 shows the particulate formation as the dose of ferric sulphate increases from left to right. This is followed by the subsequent settling captured in **Figure 3-3**, which shows a clear water column after the 24-hour settling period. Results were similar in the tests with the Shallow and Mid pit water samples.
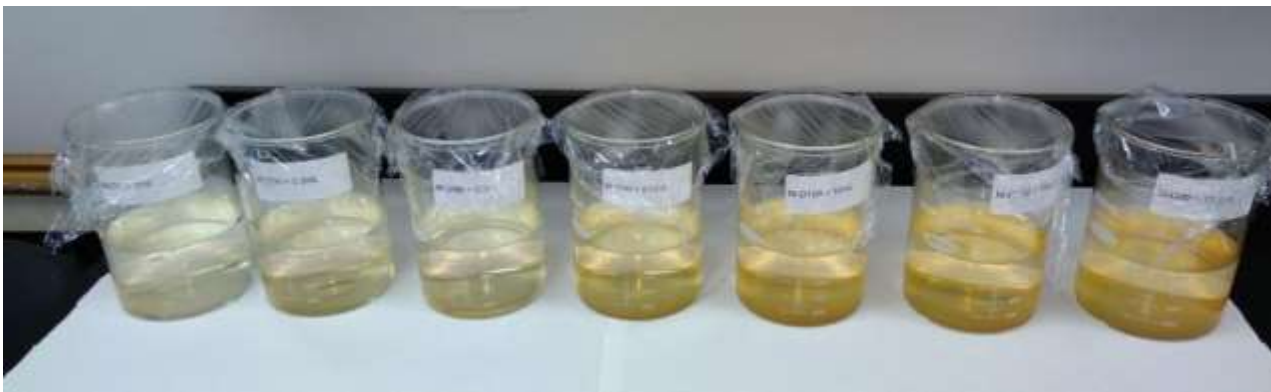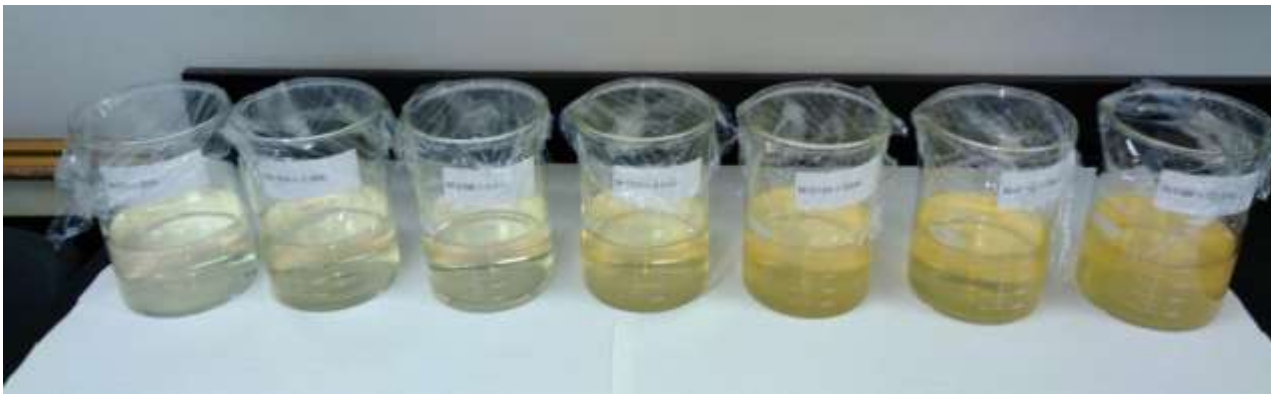
Figure 3-2: Pit-Water Settling Observations Before Addition (Top Photo),
After 5 minutes Reaction Time (Middle Photo) and After 24 Hours Settling (Bottom Photo).
An increase in ferric sulphate dosage can be observed visually from left to right.
Replicates are included in this photo, for the 5:1 and 15:1 dosages.

Figure 3-3: Settled Column of 20:1 Fe:As Molar Ratio Dosage After 24 Hours Settling

Results of the ferric sulphate addition with different dosages are summarized in **Figure 3-4** and **Figure 3-5** for the tests on the surface (SURF) and middle depth (MIDD) pit water samples, respectively. Total and dissolved concentrations of arsenic and iron are reflective of dosages on the final concentrations of both constituents. The dosages are shown as numbers ranging from 2. to 20 for the surface tests and from 2 to 19 the middle depth sample tests, respectively

Results show that the total concentrations of arsenic, five minutes after adding ferric sulphate represent the initial concentrations prior to treatment. In contrast, the total concentrations of iron, five minutes after ferric sulphate addition, represent the iron that was added, showing increases with increasing Fe:As ratios. The total concentrations for both arsenic and iron exhibit much lower values after 24 hours of settling time. The dissolved concentrations of arsenic, five minutes after ferric sulphate addition, were lower than the initial concentrations, consistently decreasing with increasing Fe:As ratios, and were only somewhat greater than those after 24 hours of settling time. The dissolved concentrations of iron varied somewhat across the iron dosage ratios at five minute and after 24 hours of settling and were all less than 0.2 mg/L

There is a trend of decreasing concentrations for total and dissolved arsenic with increasing dosage after 24 hour settling time. The highest dosage of ~20:1 resulted in the most effective removal of arsenic from solution. The resulting total concentrations of arsenic as a function of the Fe:As ratio during ferric sulphate addition are summarized in **Figure 3-6**. The final arsenic concentrations are highly correlated with the molar ratios with very high R^2 values for the log-linear relationships. The data show that ratios near 20:1 result in final concentrations on the order of 0.02 to 0.03 mg/L. At the next lower ratio of approximately 10:1, arsenic concentrations were approximately 0.1 mg/L. This suggests that, if economically achievable, the highest ratio tested will provide a benefit for lower treated concentrations of arsenic. Based on the Phase 1 investigations, the ratio of 20:1 for Fe:As was selected as the target ratio for the field testing.

Concentrations of cobalt and nickel were also examined in the ferric sulphate addition tests in order to assess potential treatment effects on these constituents that are known to correlate to arsenic regionally. Results of total and dissolved cobalt and nickel concentrations for the various dosages are summarized in **Figure 3-7** and **Figure 3-8**. The data show that ferric sulphate addition results in concentrations of cobalt above the initial untreated concentration, initially for all dosage ratios, followed by lower concentrations after 24 hours of settling time. Final cobalt concentrations (total and dissolved fractions) did however exceed initial concentrations, likely due to the usage of reagent grade ferric sulphate that was associated with an elevated cobalt content. Total and dissolved nickel concentrations decreased below initial concentrations in all tests for all dosages. Cobalt and nickel were therefore also considered key parameters for assessment within the field trial.
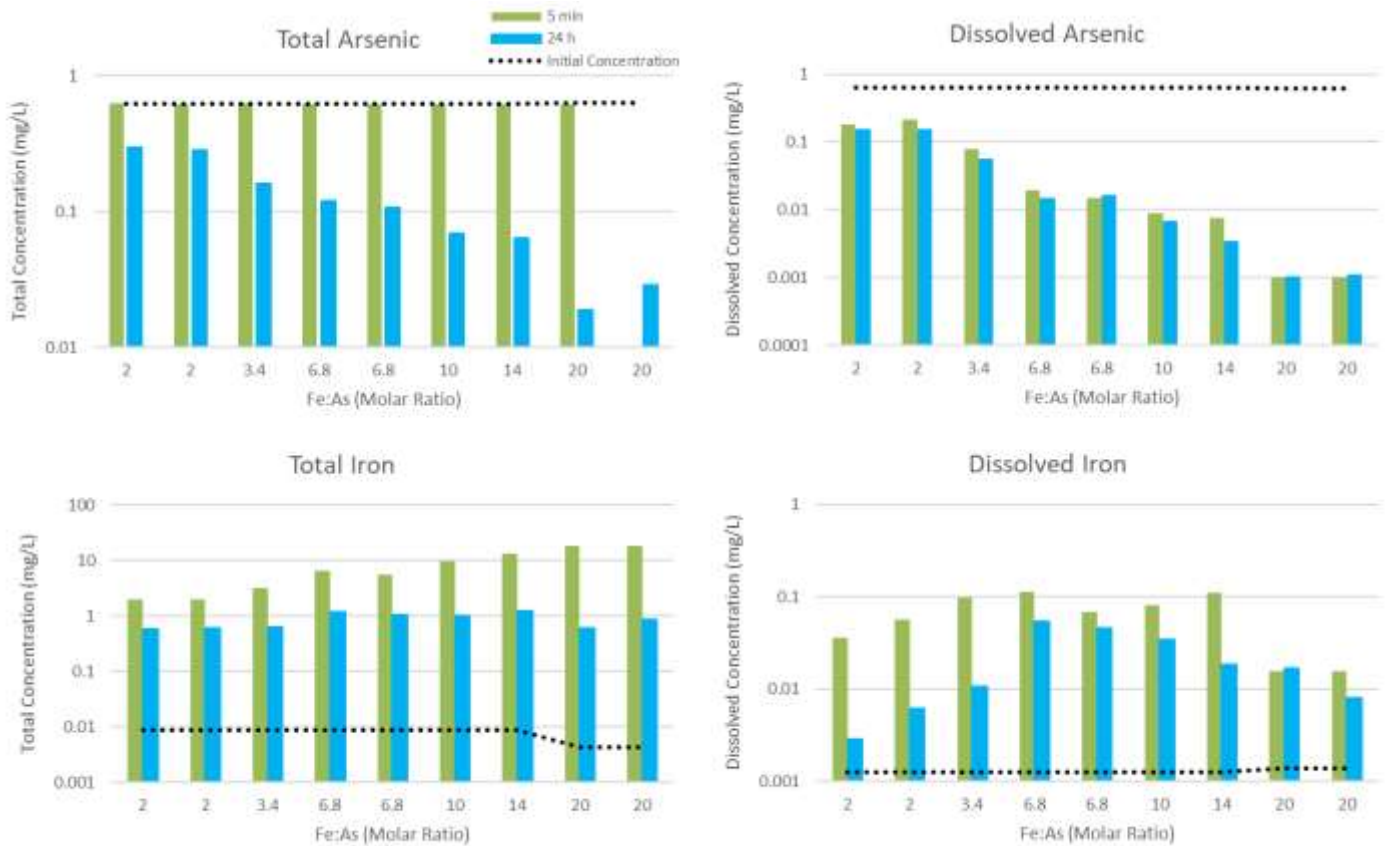
Figure 3-4: Total and Dissolved Concentrations of Arsenic and Iron After 5 minutes and 24 Hours for Selected Molar Ratios of Fe;As on Surface (SURF) Pit Sample. Note: the initial concentration for the 20:1 ratio differed from that for the other tests and is based on the analysis of the volume of pit water selected at a later date for those tests.
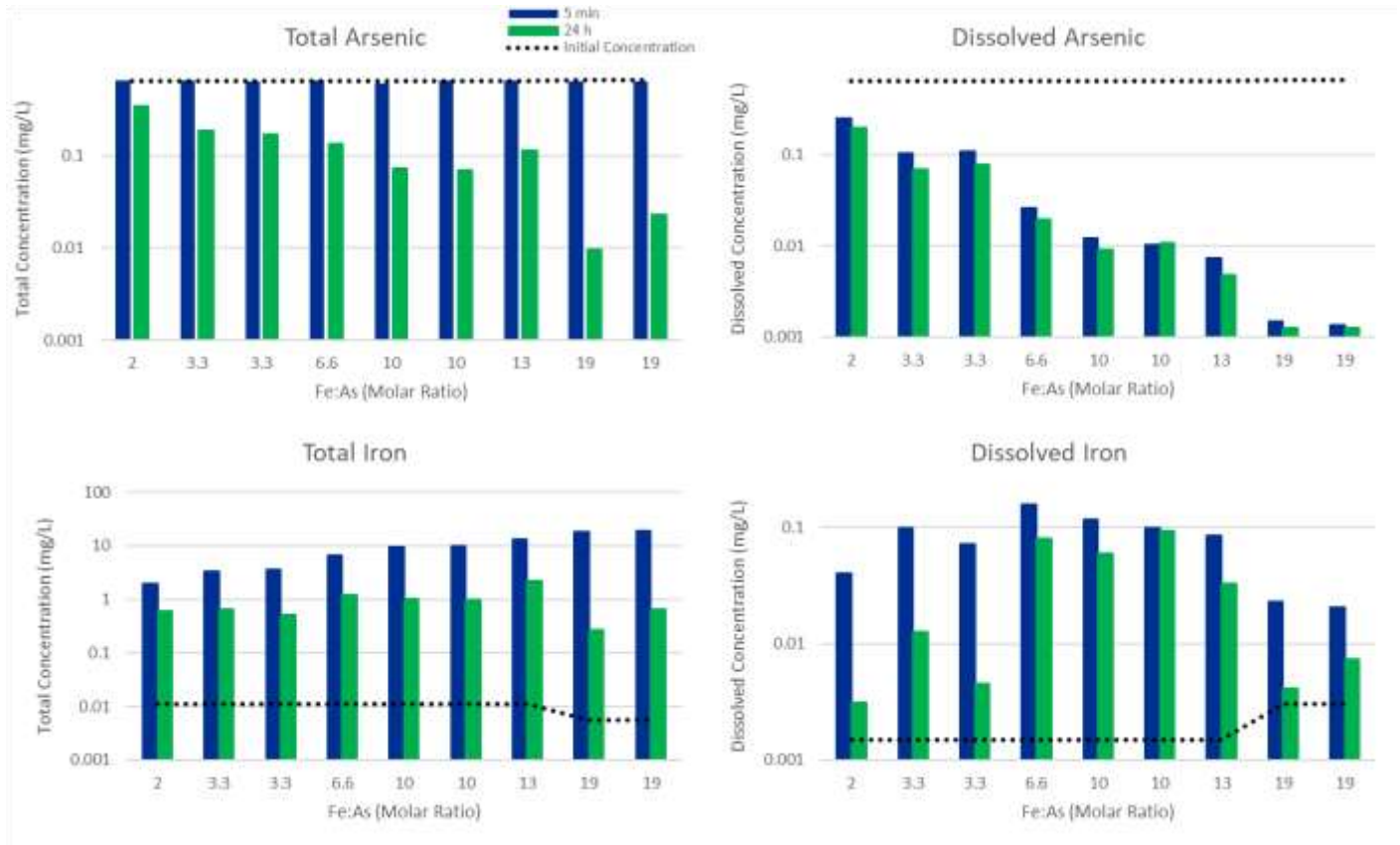
Figure 3-5: Total and Dissolved Concentrations of Arsenic and Iron After 5 minutes and 24 Hours for Selected Molar Ratios of Fe;As on Middle Depth (MIDD) Pit Sample. Note: the initial concentration for the 19:1 ratio differed from that for the other tests and is based on the analysis of the volume of pit water selected at a later date for those tests.
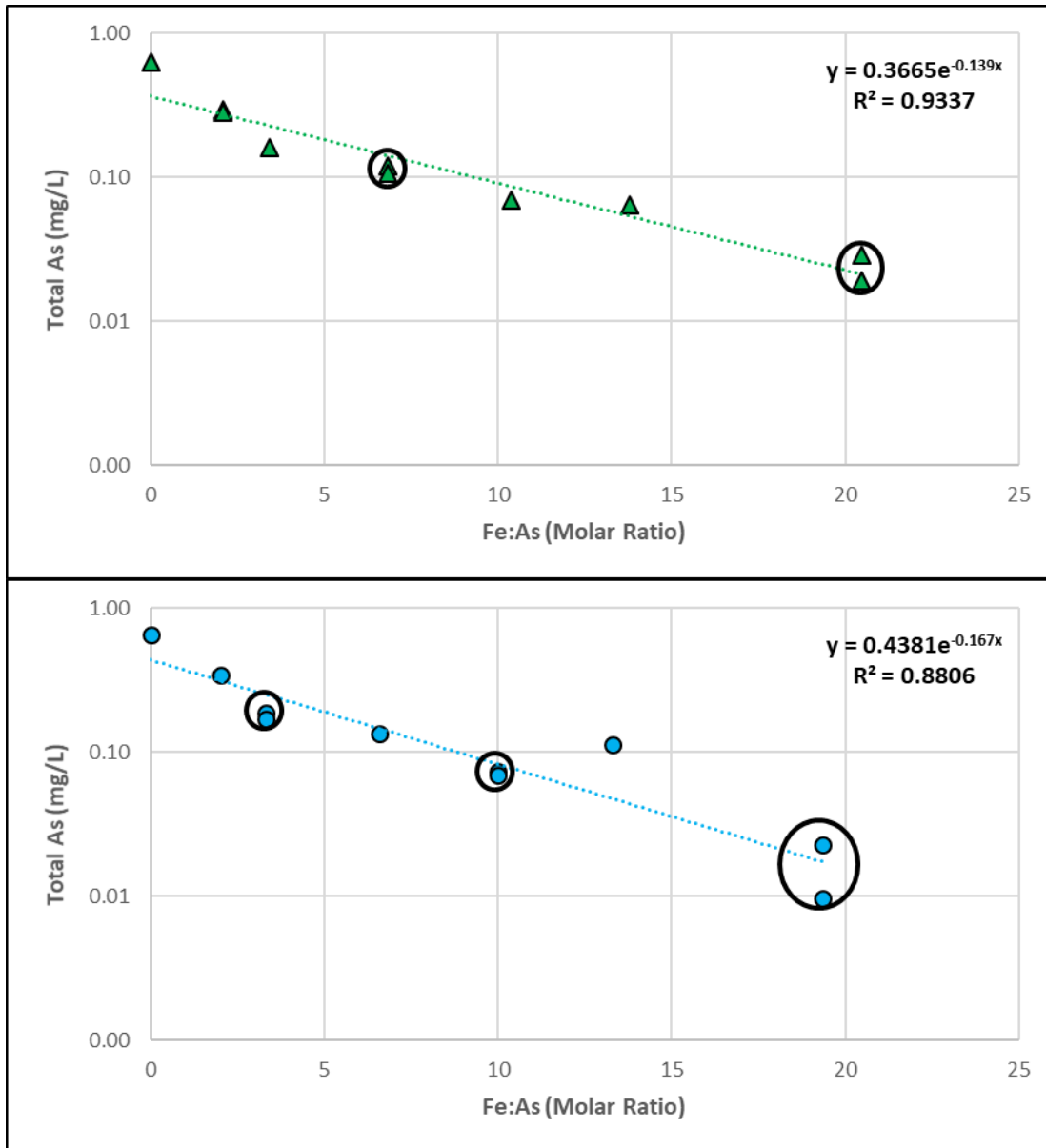
Figure 3-6: Relationships between Total Arsenic Concentrations to
Actual Fe:As Molar Ratios in the Surface (Top Plot) and Middle Depth (Bottom Plot)
Pit Samples after 24 Hours of Settling. Replicate samples are circled.
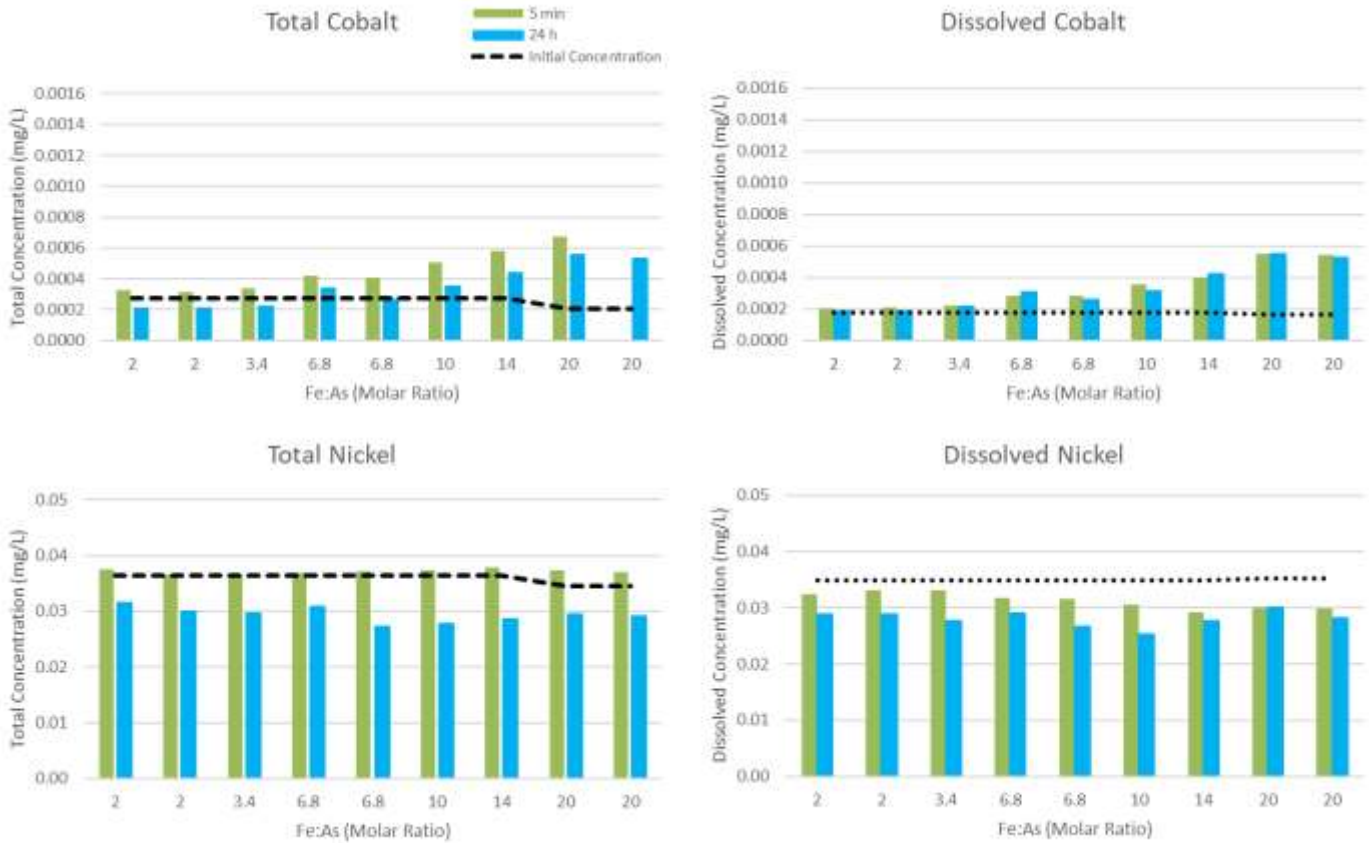
Figure 3-7: Total and Dissolved Concentrations of Cobalt and Nickel After
5 minutes and 24 Hours for Selected Molar Ratios of Fe;As on the Surface (SURF) Pit Sample
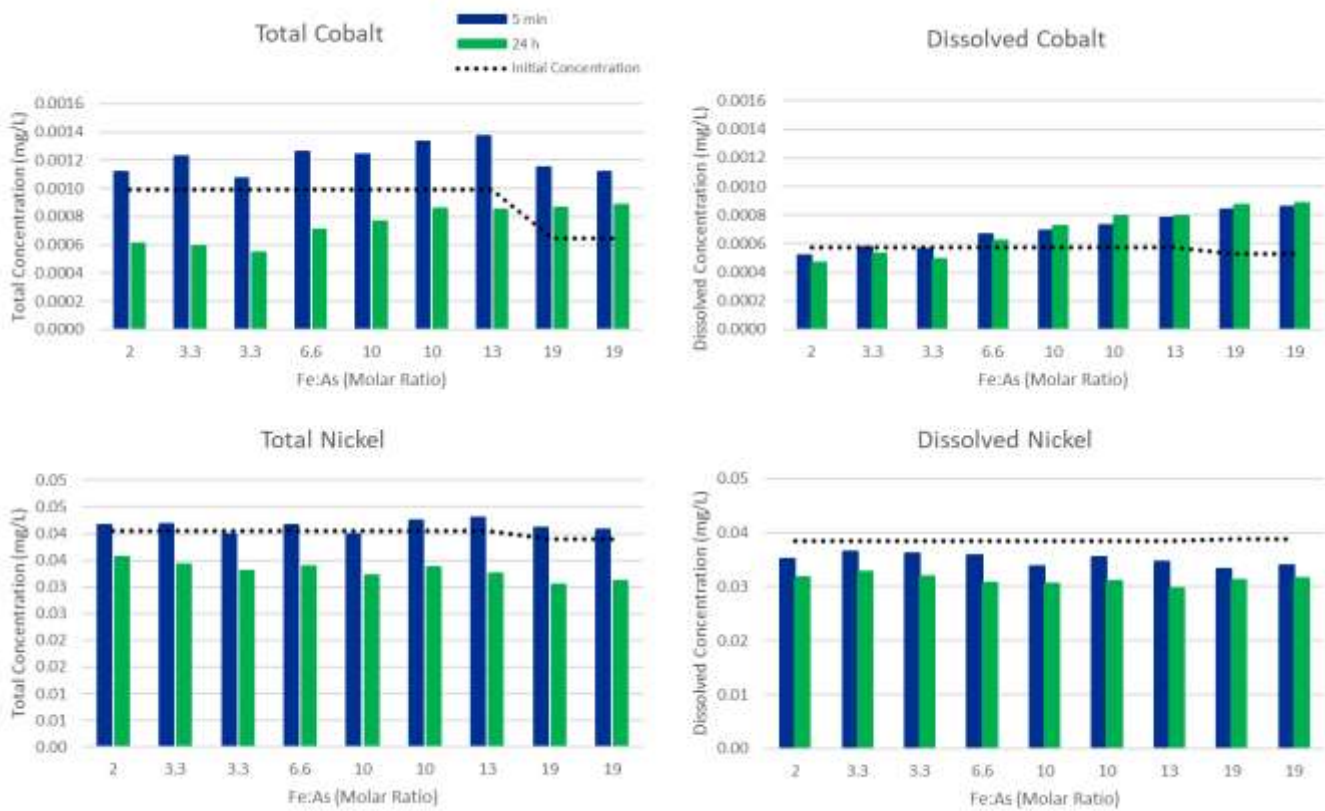
Figure 3-8: Total and Dissolved Concentrations of Cobalt and Nickel After 5 minutes
and 24 Hours for Selected Molar Ratios of Fe;As on the Middle Depth (MIDD) Pit Sample.
Note: the initial concentration for the 19:1 ratio differed from that for the other tests and is
based on the analysis of the volume of pit water selected at a later date for those tests.

3.3 Treatment Solids Analysis

A treatment solids settling test was completed to determine a minimum settling time and to generate enough solids for characterization. A 20 L volume of pit water was treated by the addition of ferric sulphate at a Fe:As ratio of 20:1. After ferric sulphate addition, water samples were collected periodically from the surface and analysed. The results for total and dissolved concentrations of arsenic and iron are summarized in **Figure 3-9**. The total concentrations of arsenic and iron were relatively constant between 30 minutes and 24 hours, indicating that most of the settling in 24 hours occurred in the first 30 minutes. The total concentrations were lower at 120 hours, indicating that further settling occurred after 24 hours. The results also showed that dissolved concentrations of arsenic and iron were relatively constant after 5 minutes of reaction time and were relatively constant through 120 hours for arsenic and 24 hours for iron. The dissolved iron concentrations declined by about a factor of 10 between 24 and 120 hours.

It is clear from the total concentrations of arsenic and iron that the substantial settling occurred between 5 minutes and 30 minutes, after which concentrations were relatively constant up to 24 hours of settling time with additional settling between 24 and 120. These results imply that a longer settling time than 24 hours has benefits and would be applicable to pit waters that typically have a hydraulic residence times on the order of years. The results of the settling test also provide an indication of the relative stability of the treatment solids. The concentrations over 120 hours were either stable or decreased during that time.
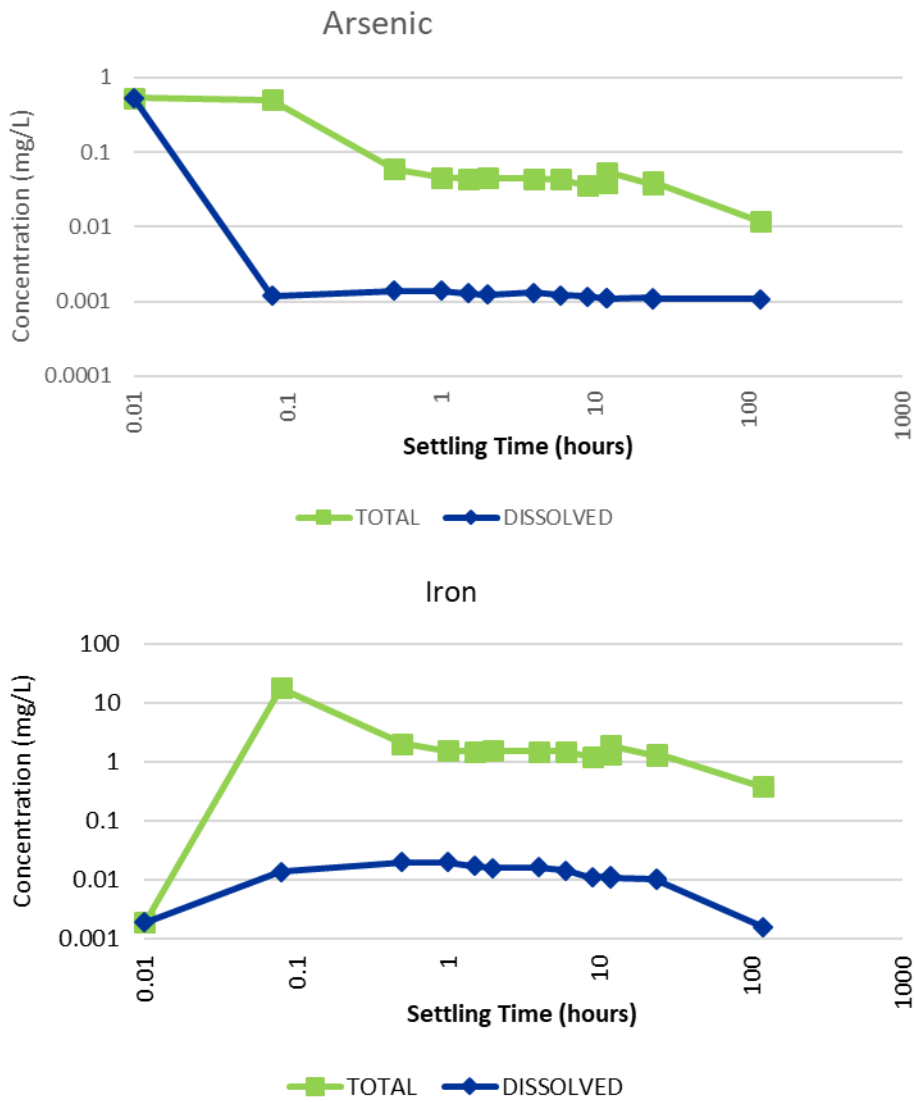
Figure 3-9: Total and Dissolved Concentrations of Arsenic and Iron in Surface Samples from a 20 L Volume of Treated Pit Water with Settling Time from 5 minute (0.08 Hours) to 120 Hours. Pretreatment Concentrations were Plotted at 0.01 Hours

The treatment solids from the settling test were collected, after 120 hours, by first decanting the overlying water and then filtering the slurry, and analyzed. Results of the analysis are summarized in **Table 3-3**. Treatment solids are characterized by percent levels of arsenic, calcium, iron and sulphur. The arsenic content was 8800 mg per kg (0.88% by dry weight) and the iron content was 430,000 mg per kg (43% by weight). The sulphur content likely represents sulphate that is a major component of the ferric sulphate added for treatment. The molar ratio of calcium to sulphate in the treatment solids is 1.8, compared to a ratio of 1.0 in gypsum ($CaSO_4 \cdot 2H_2O$) suggesting that there is excess calcium over that required to precipitate gypsum. However, adsorption of the sulphate onto the ferric hydroxides may also play a role.

Table 3-3: Chemical Composition of the Treatment Solids
with Ferric Sulphate Addition (Fe:As = 20:1)

Constituent	Concentration (mg/kg)
Aluminum	64
Antimony	7.6
Arsenic	8,800
Cadmium	0.15
Chromium	15
Cobalt	5.6
Copper	56
Iron	430,000
Lead	1.9
Manganese	36
Molybdenum	31
Nickel	200
Phosphorus	330
Selenium	1.5
Uranium	14
Zinc	39
Calcium	8,200
Magnesium	920
Potassium	48
Sodium	150
Sulphur	3,600

4 PHASE 2 – NIGHT HAWK LAKE MINE OPEN PIT AS A CASE STUDY

Phase 2 of this work surrounded the in-situ batch treatment of Newmont Goldcorp's Night Hawk Lake Mine (NHLM) open pit. An introduction to the study site is presented in the following sections, along with a discussion of treatment approach and pit water quality both pre- and post-treatment.

4.1 NHLM Open Pit Overview

The NHLM site is located nearshore on North Peninsula on the north side of Night Hawk Lake, and east of the City of Timmins, Ontario (**Figure 4-1**). The mine site is located within the Porcupine Gold Camp within the geological region referred to as the Abitibi Greenstone Belt, one of the most famous and prolific gold- and base-metal-producing areas in the world (https://magazine.cim.org/en/projects/quebecs-golden-pockets/). The site is currently owned and operated by Porcupine Gold Mines (PGM) a joint venture between Goldcorp Canada Ltd. and Goldcorp Inc., now Newmont Goldcorp.

Mining, as well as limited milling on the site dates back to the early 1900s. Underground mining occurred intermittently up to 1999, though the most active period of ore extraction was prior to 1950. An open pit was developed on site from 1995 and 1999. Records indicate ore was milled on site between 1923 and 1926. A site plan showing locations of historic and current mine aspects and support infrastructure is provided in **Figure 4-2**. Key site aspects include, or have included, the open pit and underground workings, the mill and mill site waste rock piles, mill tailings, and ore stockpile pads. The site, as of 2018, was at an advanced state of closure and on-site activities are limited to general care and maintenance and environmental monitoring.

The open pit of the NHL mine measures 70 m by 230 m by 20 m deep, filled with water to a level close to that of Night Hawk Lake (**Figure 4-3**). Small revegetated overburden and waste rock stockpiles exist around the pit.

The site Certificate of Approval (CofA) (4-0090-95-00), approves the use of ferric sulphate for water treatment. During the initial study design, personnel from the Ministry of Environment, Conservation and Parks (MECP) district office were integrated into discussions surrounding the research approach and application in order to ensure compliance within the CofA.

Figure 4-1: Location map of NHLM Site

Figure 4-2: Location of Key Site Aspects at the NHLM Site (modified from Golder, 2011)

Figure 4-3: Aerial view of the NHLM Open Pit Looking East.
The long axis of the pit is Approximately 225m

4.2 General Topography

Topography of the NHLM area is considered as a low relief, glaciolacustrine plain with occasional bedrock outcropping along the southern and eastern shoreline, as well as throughout the islands (Goldcorp, 2012). Elevations on both the peninsula range from approximately 275-m along the lakeshore to upwards to 295-m on few bedrock outcrops (Goldcorp, 2012). Historical topographic data suggests that over 50 percent of the land area is less than 15-m above lake level.

4.3 Waste Rock on Site

A small waste rock pile exists on the south side of the NHLM open pit that extends to the Night Hawk Lake shoreline (**Figure 4-4**). This pile is approximately 1 hectare (ha) in size is estimated to contain 150,000 tonnes of waste rock (Goldcorp, 2012).

Waste rock from the site has sulphur contents typically less than 0.5% S with carbonate contents greater than 15% $CaCO_3$. The rock therefore has neutralization potential (NP) to acid potential (AP) ratios greater than 10 and was classified as non-potentially acid generating (non-PAG). Arsenic was identified as potentially leaching at neutral pH values. Waste rock around the perimeter of the pit, as shown in **Figure 4-4**, is therefore likely to contribute to the observed concentrations of arsenic in the pit water.

Figure 4-4: A 2005 Image Showing the Waste Rock Areas Prior to Final Reclamation.

4.4 Surface Water

Local runoff drains into Night Hawk Lake within the closure plan boundary, which flows into the Frederick House River, then into the Abitibi River, and eventually discharging into James Bay. Surface drainage on the North Peninsula is generally overland and downhill into Night Hawk Lake via small, poorly defined ephemeral channels, or by sheet flow over flatter, smoother areas.

The NHLM open pit has a self-contained drainage area, covering an area of 5 to 6 ha. This open-pit specific drainage area captures runoff associated with about half of the area that comprises the one hectare reclaimed waste rock pile located north of the pit, as well as the runoff from the waste rock that was deposited around the perimeter of the open pit. The pit has filled naturally to a level consistent with the water level of the adjacent Night Hawk Lake. The water elevation in the pit is static well below the existing elevation of the lip of the pit and the pit is not connected to any water body on surface.

4.5 Surface Water Quality

Routine surface water quality monitoring is undertaken at the NHLM site, including sampling in nearshore areas in Night Hawk Lake, as well as locations within the former mine site. Data collected to date indicate that surface drainage associated with the site does not affect water quality in Night Hawk Lake.

Routine sampling in the open pit is completed for analysis of metals and a general suite of water quality parameters. Samples are collected on surface (NHLPS), at mid-depth (NHLPM) and in bottom (NHLPB) waters annually. Data for select constituents are summarized in **Table 4-1** for the period 2012 through 2018. Water in the open pit is circum-neutral to slightly basic, has total dissolved solids (TDS) levels that are in the range of 300 to 500 mg/L, hardness levels in the range of 250 to 350 mg/L (as $CaCO_3$) and sulphate levels in the of 100 to 150 mg/L.

In general constituent concentrations are higher in bottom waters than at the surface. Concentrations of total arsenic, dissolved arsenic and TDS at each sampling depth over the period 2012 through 2018 are shown in **Figure 4-5**, **Figure 4-6** and **Figure 4-7** to display this pattern. Total and dissolved arsenic concentrations are on the order of two times higher in bottom waters then in surface waters; whereas TDS values are on the order of 50% higher in bottom waters than in surface waters.

Overall, it appears that concentrations of arsenic as well as TDS have been declining from 2012 to 2018. This may be the result of limited loadings of constituents to the pit water and the ongoing input of precipitation and runoff with lower concentrations than those in the pit. The very gradual or small rate of decline in concentrations is related to the relatively small inflows and long hydraulic residence time in the pit water.

These data, with only three depths sampled do not provide a clear indication that the water column in the pit was stratified and formed a chemocline based on chemistry or density that is implied by the TDS values. There is evidence, however, of concentration gradients with depth that are likely the result of low TDS water entering the pit at surface from local runoff and direct precipitation.

Temperature data for the period 2012 through 2018 are shown in **Figure 4-8**. Temperature measurements over the last seven years cumulatively span the full duration (more or less) of the open water season and suggest that the water column likely becomes thermally stratified in the late summer and subsequently mixes fully in the late fall.
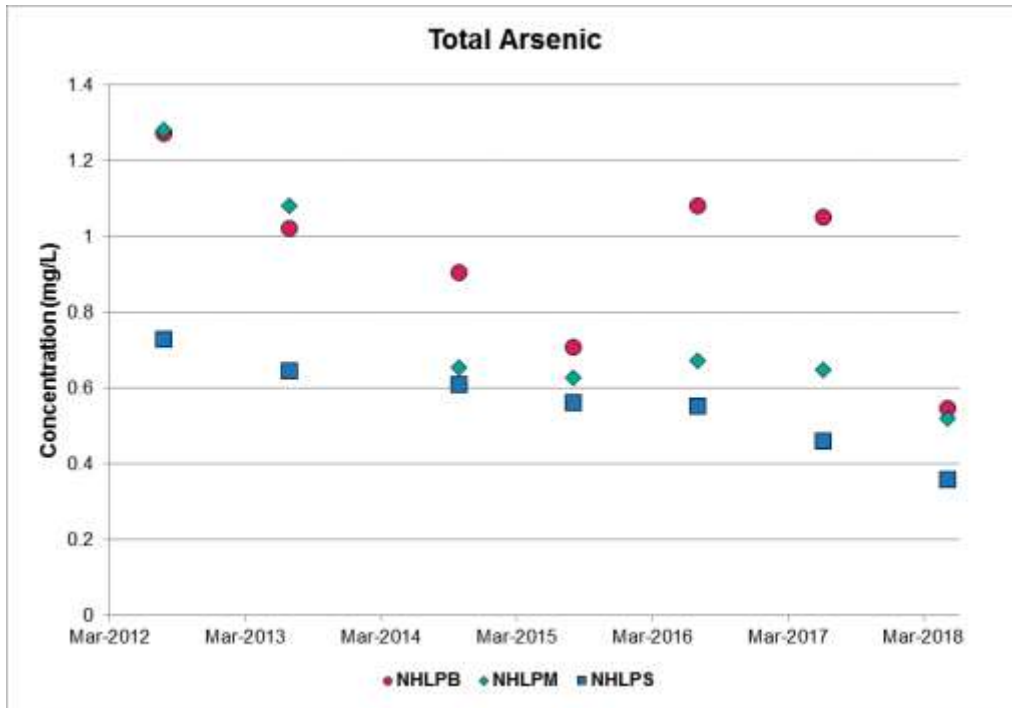
Figure 4-5: Total arsenic concentrations with depth in the NHLM Open Pit, 2012 through 2018
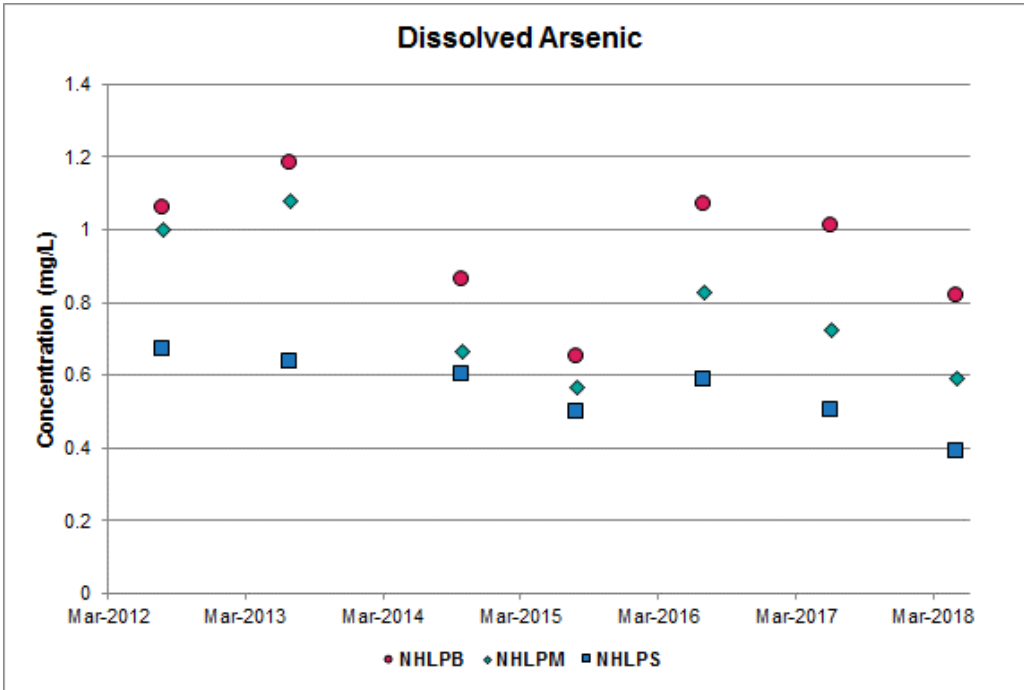
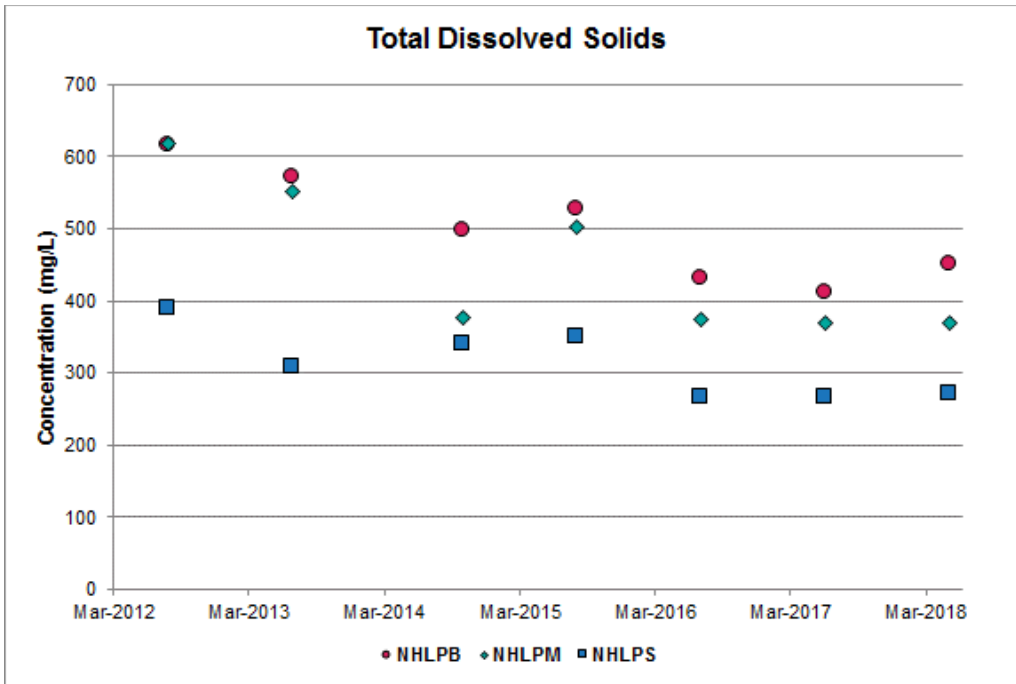**Figure 4-6:** Dissolved arsenic concentrations with depth in the NHLM Open Pit, 2012 through 2018

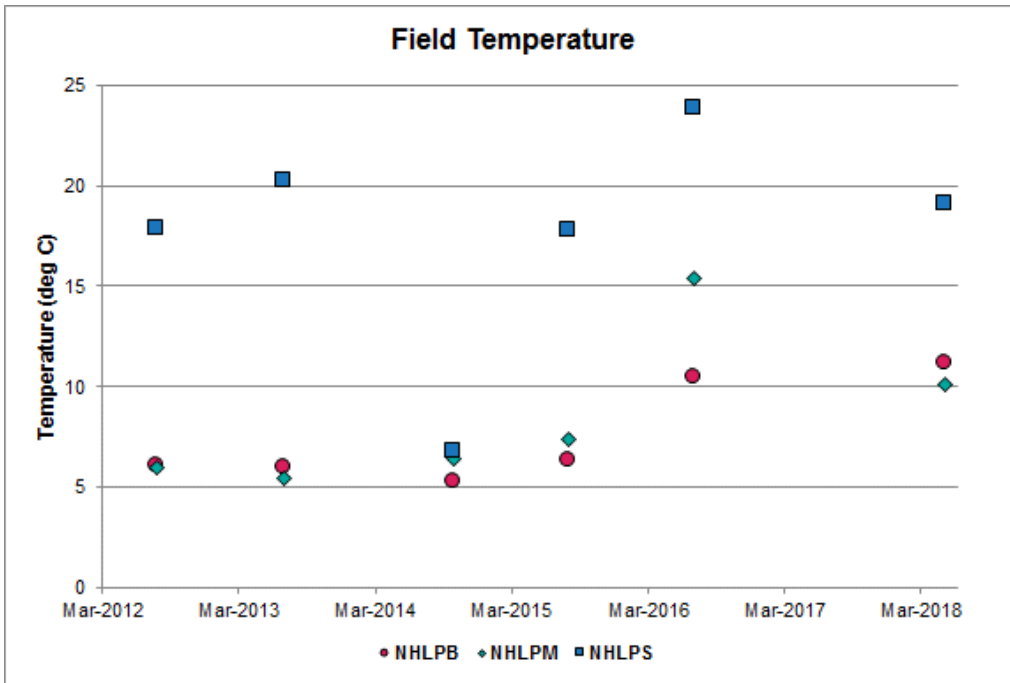**Figure 4-7:** TDS levels with depth in the NHLM Open Pit, 2012 through 2018

Figure 4-8: Water temperature with depth in the NHLM Open Pit, 2012 through 2018

Table 4-1: Summary of Water Quality in the NHLM open Mine Open Pit, 2012 through 2018

Location	Parameter		Units	Minimum	Percentile_5th	Percentile_50th	Percentile_95th	Maximum	Arithmetic_Mean
NHLB	Dissolved Metals	Dissolved Arsenic	mg/L	0.651	0.7005	1.01	1.147	1.18	0.94986
		Dissolved Cadmium	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
		Dissolved Copper	mg/L	0.0006	0.00081	0.002	0.00342	0.0036	0.0020429
		Dissolved Iron	mg/L	<0.003	<0.003	0.0074	0.0509	0.053	<0.019829
		Dissolved Lead	mg/L	<0.0001	<0.0001	<0.0008	<0.0008	<0.0008	<0.0006
		Dissolved Nickel	mg/L	0.0458	0.047	0.0727	0.09305	0.0959	0.069329
		Dissolved Zinc	mg/L	0.0026	0.00281	0.0093	0.01575	0.0159	0.0093571
	Total Metals	Total Arsenic	mg/L	0.546	0.5946	1.02	1.213	1.27	0.93957
		Total Cadmium	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
		Total Copper	mg/L	0.0026	0.00275	0.0051	0.00874	0.0088	0.0055857
		Total Iron	mg/L	0.0143	0.01562	0.053	0.3	0.3	0.12617
		Total Lead	mg/L	<0.0008	<0.0008	<0.0008	<0.00198	0.0024	<0.0010857
		Total Nickel	mg/L	0.0497	0.05051	0.0741	0.09581	0.101	0.072286
		Total Zinc	mg/L	0.0033	0.00384	0.0063	0.01547	0.0179	0.0082143
	Field Parameters	Field Conductivity	µS/cm	678	692.2	1060	8504	8580	3853.4
		Field pH	pH unit	7.7	7.725	7.86	8.325	8.4	7.9533
		Field Temperature	deg C	5.3	5.4675	6.18	11.025	11.2	7.555
	General Parameters	Total Dissolved Solids	mg/L	410	416	497	602.5	616	500
		Total Suspended Solids	mg/L	<1	<1.03	3.3	27.45	34.8	<8.2571
		Total Hardness (as CaCO3)	mg/L	254	280.4	378	422.8	424	372.57
		M-Alkalinity (pH 4.5)	mg/L CaCO3	178	183.7	217	261.9	267	218.57
		Nitrate (as N)	mg/L	<0.05	<0.065	1.49	5.933	6.44	<2.2643
		Nitrite (as N)	mg/L	<0.03	<0.03	<0.03	<0.03413	0.0359	<0.030843
		Phosphate	mg/L	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09
		Sulphate	mg/L	129	129.9	162	178.8	180	154.14
NHLM	Dissolved Metals	Dissolved Arsenic	mg/L	0.565	0.5731	0.725	1.0554	1.08	0.77914
		Dissolved Cadmium	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
		Dissolved Copper	mg/L	0.001	0.00106	0.002	0.00214	0.0022	0.0017286
		Dissolved Iron	mg/L	<0.003	<0.003	0.0063	<0.02294	0.0242	<0.011514
		Dissolved Lead	mg/L	<0.0001	<0.0001	<0.0008	<0.0008	<0.0008	<0.0006
		Dissolved Nickel	mg/L	0.0307	0.03289	0.0488	0.08186	0.0821	0.0542
		Dissolved Zinc	mg/L	<0.001	<0.00133	0.0034	0.01403	0.0152	<0.0064857
	Total Metals	Total Arsenic	mg/L	0.518	0.5507	0.653	1.22	1.28	0.78229
		Total Cadmium	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
		Total Copper	mg/L	0.0024	0.00249	0.0033	0.02394	0.0318	0.0075857
		Total Iron	mg/L	0.0057	0.00747	0.0208	0.158	0.17	0.066443
		Total Lead	mg/L	<0.0008	<0.0008	<0.0008	0.0012	0.0012	<0.00094286
		Total Nickel	mg/L	0.0372	0.03744	0.0518	0.0931	0.0967	0.058543
		Total Zinc	mg/L	0.0023	0.00242	0.0035	0.0154	0.0169	0.0065571
	Field Parameters	Field Conductivity	µS/cm	588	594.2	1006	8158	8160	3704.6
		Field pH	pH unit	7.36	7.41	8.05	8.6	8.7	8.0033
		Field Temperature	deg C	5.42	5.5675	6.9	14.075	15.4	8.455
	General Parameters	Total Dissolved Solids	mg/L	370	370	377	597.5	617	452
		Total Suspended Solids	mg/L	1.1	1.16	2.4	4.9	5.5	2.7286
		Total Hardness (as CaCO3)	mg/L	221	243.8	349	419.2	421	341.71
		M-Alkalinity (pH 4.5)	mg/L CaCO3	172	174.4	191	260.6	266	205.71
		Nitrate (as N)	mg/L	<0.05	<0.065	0.306	4.769	4.85	<1.4844
		Nitrite (as N)	mg/L	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
		Phosphate	mg/L	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09
		Sulphate	mg/L	109	111.1	125	174.4	175	135.43
NHLS	Dissolved Metals	Dissolved Arsenic	mg/L	0.391	0.4231	0.584	0.6601	0.67	0.555
		Dissolved Cadmium	mg/L	<0.0001	<0.0001	<0.0001	<0.00017	0.0002	<0.00011429
		Dissolved Copper	mg/L	0.0019	0.00193	0.0028	0.00374	0.0041	0.0026714
		Dissolved Iron	mg/L	<0.003	<0.003	0.0075	<0.02	<0.02	<0.0094
		Dissolved Lead	mg/L	<0.0001	<0.0001	<0.0008	<0.0008	<0.0008	<0.0006
		Dissolved Nickel	mg/L	0.0195	0.02079	0.027	0.03061	0.0307	0.026414
		Dissolved Zinc	mg/L	<0.0007	<0.0007	<0.001	0.00229	0.0028	<0.0011571
	Total Metals	Total Arsenic	mg/L	0.357	0.3876	0.562	0.7025	0.728	0.55843
		Total Cadmium	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
		Total Copper	mg/L	0.0025	0.00253	0.0038	0.00466	0.0049	0.0036143
		Total Iron	mg/L	0.02	0.02072	0.0296	0.0643	0.076	0.035614
		Total Lead	mg/L	<0.0008	<0.0008	0.0009	<0.001	<0.001	<0.00088571
		Total Nickel	mg/L	0.0227	0.02312	0.0285	0.03265	0.0337	0.027914
		Total Zinc	mg/L	<0.0007	<0.0007	<0.001	0.00487	0.0058	<0.0019143
	Field Parameters	Field Conductivity	µS/cm	399	425.8	712	5296	5400	2384.8
		Field pH	pH unit	7.6	7.805	8.545	8.8	8.8	8.4517
		Field Temperature	deg C	6.8	9.55	18.48	22.908	23.8	17.598
	General Parameters	Total Dissolved Solids	mg/L	265	265	307	377.7	390	312.14
		Total Suspended Solids	mg/L	0.5	<0.65	2.2	12.55	16.3	<3.9571
		Total Hardness (as CaCO3)	mg/L	214	218.2	244	288.1	292	248.57
		M-Alkalinity (pH 4.5)	mg/L CaCO3	120	121.8	128	156.8	161	135.29
		Nitrate (as N)	mg/L	<0.05	<0.05	<0.1	0.2145	0.225	<0.10997
		Nitrite (as N)	mg/L	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
		Phosphate	mg/L	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09
		Sulphate	mg/L	78.8	79.34	87.5	149.4	153	104.93
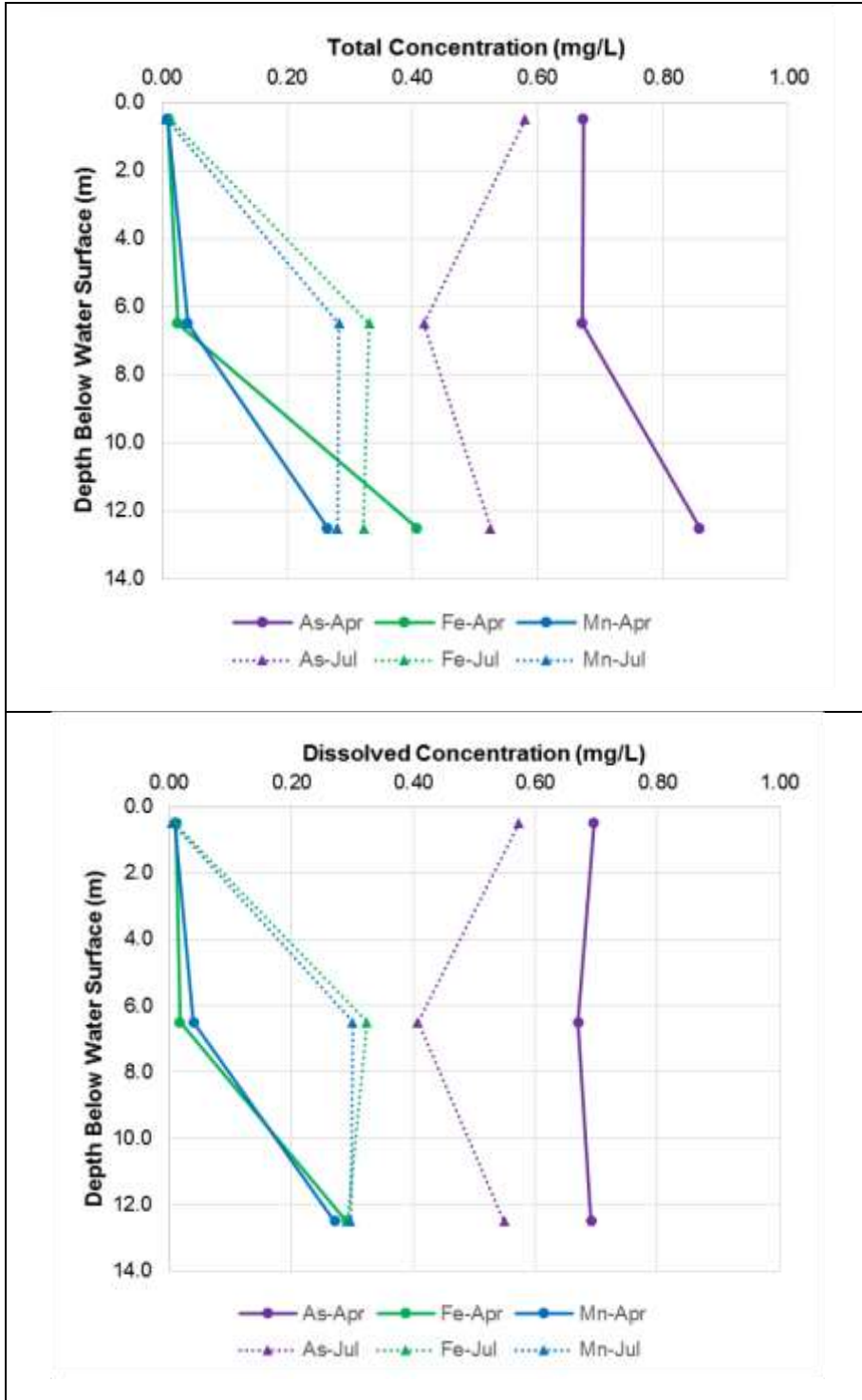
Figure 4-9: Total (Top) and Dissolved (Bottom) Concentrations of Arsenic, Iron and Manganese at Three Depths in the Pit in 2018 in April and July 2018

Concentration profiles, in the pit, for arsenic iron and manganese are shown for July and April 2018 samples, prior to treatment, in **Figure 4-9**. Iron is included because of the potential for interaction with arsenic and both iron and manganese concentrations may reflect redox conditions. The plots show that there are only small differences between the total and dissolved concentrations. While the concentrations of dissolved arsenic varied slightly with depth in the July and April samples, iron and

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manganese exhibit very low concentrations at surface compared to those in the mid and deep samples in July and in the deep samples in April. The differences in concentrations of arsenic, iron and manganese between the April and July samples suggests that there may be some chemical dynamics occurring, likely related to redox conditions.

The lower concentrations of iron and manganese in the surface samples are consistent with oxic conditions and low solubilities of the oxidized forms of those metals as $Fe(III)$ and $Mn(IV)$, respectively. The higher concentrations of the metals at depth suggest anoxic conditions and that iron and manganese were in their more reduced forms of $Fe(II)$ and $Mn(II)$, respectively

4.6 Pit Bathymetry

A bathymetric survey was performed in the summer of 2018 prior to treatment. The contour presented in **Figure 4-10**, on a Northing/Easting scale. Dimensions of the pit correspond to a volume, area and average depth of 97,858 m^3, 10,032 m^2, and 9.8 m, respectively. These results were used for the design of Phase 2 of the study, in establishing the required ferric sulphate dosing and pumping volumes required.
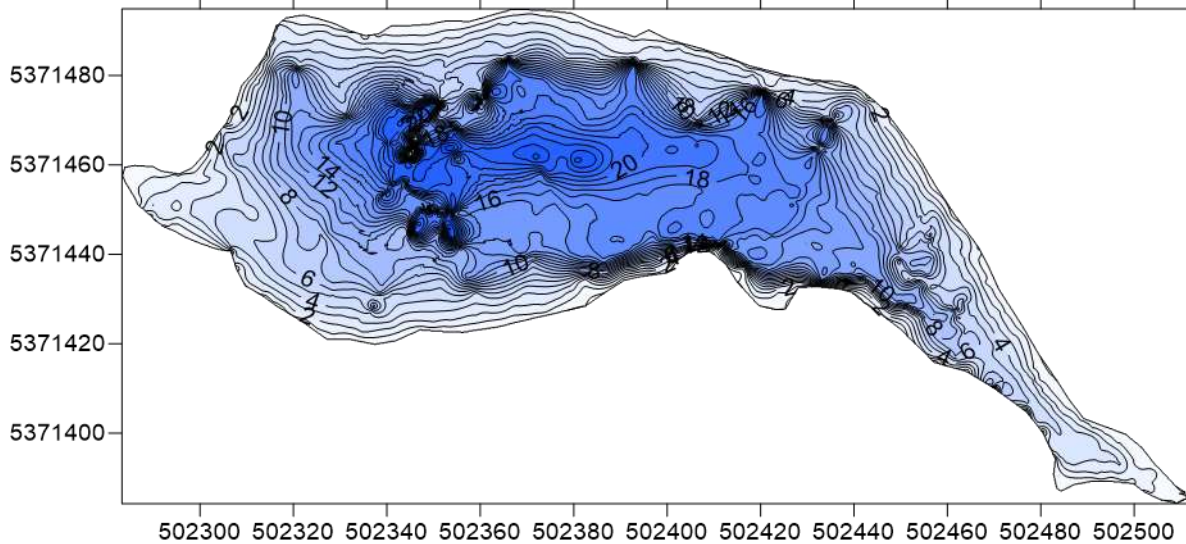

Figure 4-10: Bathymetry Contour Plot of NHLM Open Pit

4.7 Ground Water

The shallow groundwater surrounding the NHLM pit was considered here to determine the potential interactions between water in the pit and that in the shallow subsurface between the pit and Night Hawk Lake. The subsurface conditions suggest that there can be subsurface flow between the pit and the lake and that the higher water level in the pit infers that the flow will occur from the pit to the lake.

Hydraulic conductivity values in the shallow subsurface were reported to be in a range from 2.48×10^{-8} m/s to 5.1×10^{-7} m/s (Golder, 2011 and Goldcorp, 2012). This shallow groundwater flow is likely controlled by the local bedrock topography and the shoreline of Night Hawk Lake. Based on the flow directions and the calculated hydraulic conductivity values, the groundwater contribution to Night Hawk Lake was anticipated to be minimal.

In early-2011, PGM installed fifteen (15) monitoring wells at the NHLM site as shown in **Figure 4-11**. The well characteristics, including screened depths and geologic materials at the screened intervals are summarized in **Table 4-2**.

Figure 4-11: Groundwater Monitoring Locations at the NHLM Site

Table 4-2: Summary of monitoring well installation depths, screen intervals and sample locations

Monitoring Well ID	Well Depth (m)	Screened Interval	Sample Location
NH10-01D	13.3	Sandy Silt	Ore Pad
NH10-01S	9.2	Clay	Ore Pad
NH10-02D	14.9	Sandy Clayey Silt	Explosives Storage
NH10-02S	7.6	Clay and Silty Clay	Explosives Storage
NH10-03D	21.3	Silty Sand	Mine Site and Settling Pond
NH10-03S	10.7	Silt and Clay	Mine Site and Settling Pond
NH10-04D	13.7	Sandy Silt	Mine Site and Settling Pond
NH10-04S	7	Silty Clay	Mine Site and Settling Pond
NH10-05D	25	Sandy Silt	Mine Site and Settling Pond
NH10-05S	9.2	Silt and Clay	Mine Site and Settling Pond
NH10-06D	19.1	Silty Clay	Mine Site and Settling Pond
NH10-06S	10.7	Silty Clay	Mine Site and Settling Pond
NH10-07D	2.4	Sand	End of Pit
NH10-08	2.1	Fill	Peninsula (former Mill)
NH10-09	2.5	Fill	Peninsula

Sampling of these wells is completed annually, for analysis of dissolved metals and a general suite of water quality parameters. Data for select constituents at key locations surrounding the pit are summarized in **Figures 4-13** to **4-17**, for the period 2011 through 2018.

With the exception of two wells, sulphate concentrations were fairly low for the majority of locations, with values on the order of 20 mg/L (**Figure 4-13**). Sulphate concentrations were observed to be somewhat higher at locations NH10-02S and NH10-07, with values ranging from 50 to 200 mg/L. A decreasing trend was observed for location NH10-07, screened in the shallow overburden to the east of the pit. These wells are located within and downgradient of the waste rock that surrounds the pit and suggest the mobilization of oxidation or leaching products from these materials. Higher concentrations of calcium and magnesium were observed within the shallow wells surrounding the pit and also suggest the oxidation of sulphide minerals followed by neutralization by dissolution of carbonate minerals in the waste rock (**Figure 4-14 and 4-15**).

Dissolved arsenic concentrations were fairly consistent throughout the monitoring period for the majority of wells, with values ranging from 0.001 to 0.01 mg/L. (**Figure 4-16**). Values, on the order of 1mg/L were observed at location NH10-07 and are similar to the concentrations in the pit water (**Figure 4-5**). This well is screened in the shallow subsurface, within loose till and sand, with refusal at bedrock noted on installation at the screened depth of 2 meters below ground surface (mbgs). It is therefore likely that there is some lateral migration of shallow subsurface waters outwards toward the lake, although no increases in arsenic concentrations have been noted within the lake.
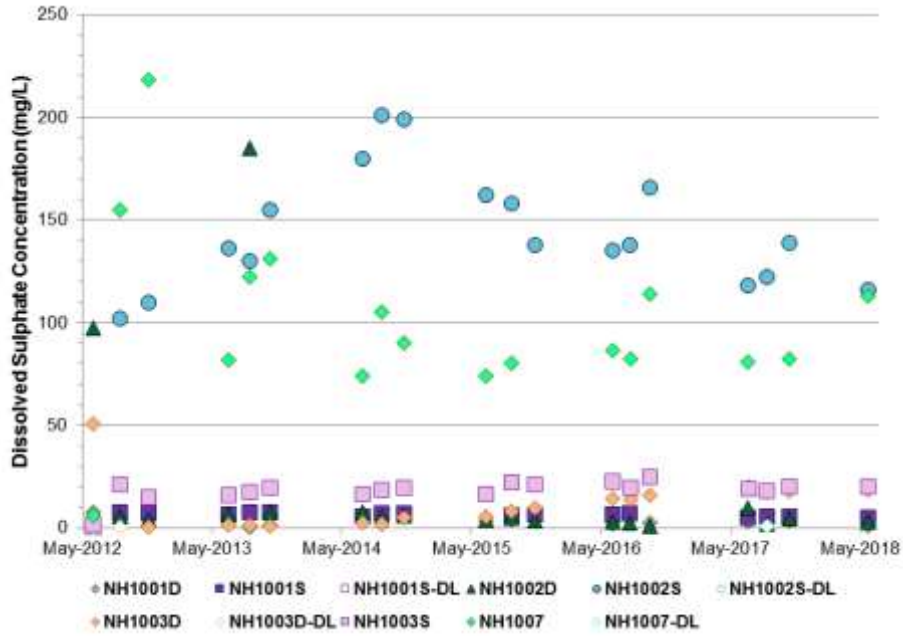
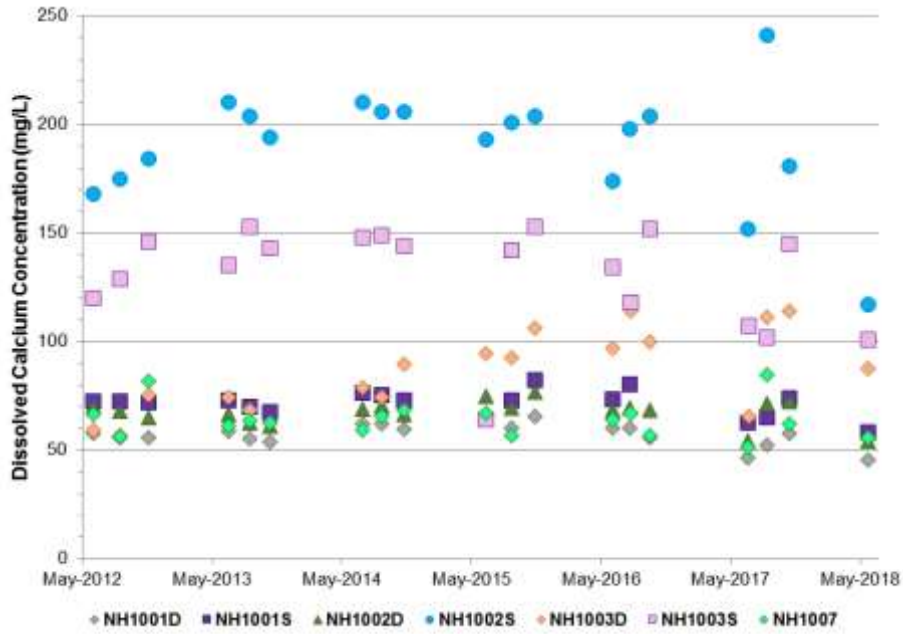**Figure 4-12:** Sulphate Concentrations in Groundwater at Key Well Locations

Figure 4-13: Dissolved Calcium Concentrations in Groundwater at Key Well Locations

Figure 4-14: Dissolved Magnesium Concentrations in Groundwater from Key Locations

Figure 4-15: Dissolved Arsenic Concentrations in Groundwater from Key Locations

Dissolved concentrations of nickel and cobalt reflect those observed for arsenic, with much higher values associated with NH10-07 on the order of 0.1 and 0.0005 mg/L, respectively, while those in other wells are typically below 0.01 and 0.001 mg/L respectively (**Figures 4-16 and 4-17**).
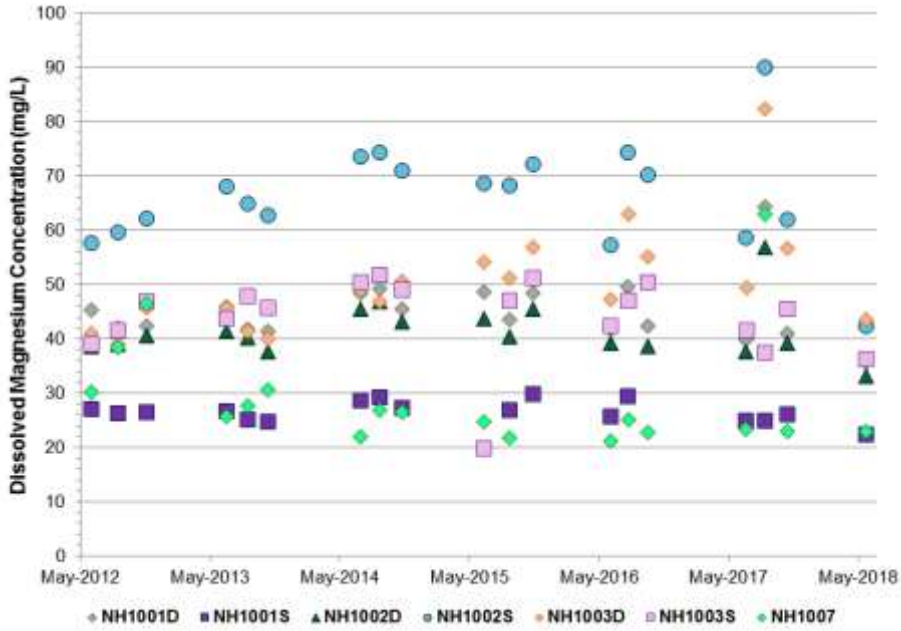

Figure 4-16: Dissolved Nickel Concentrations in Groundwater from Key Locations

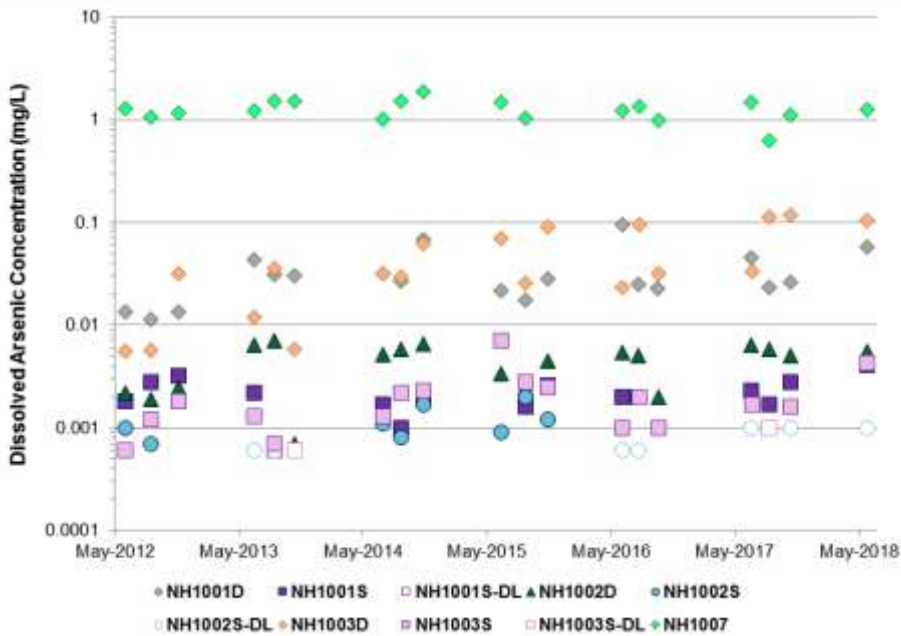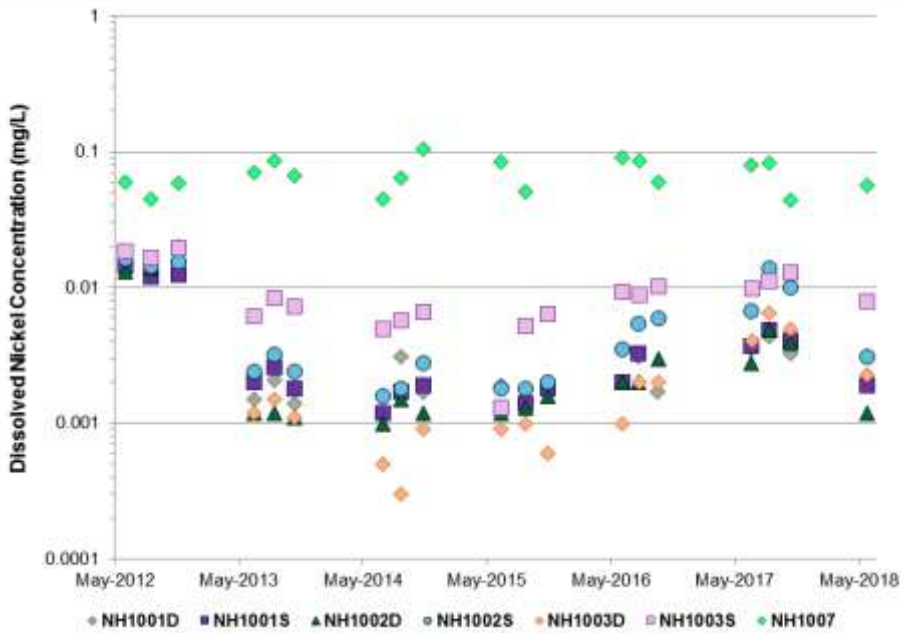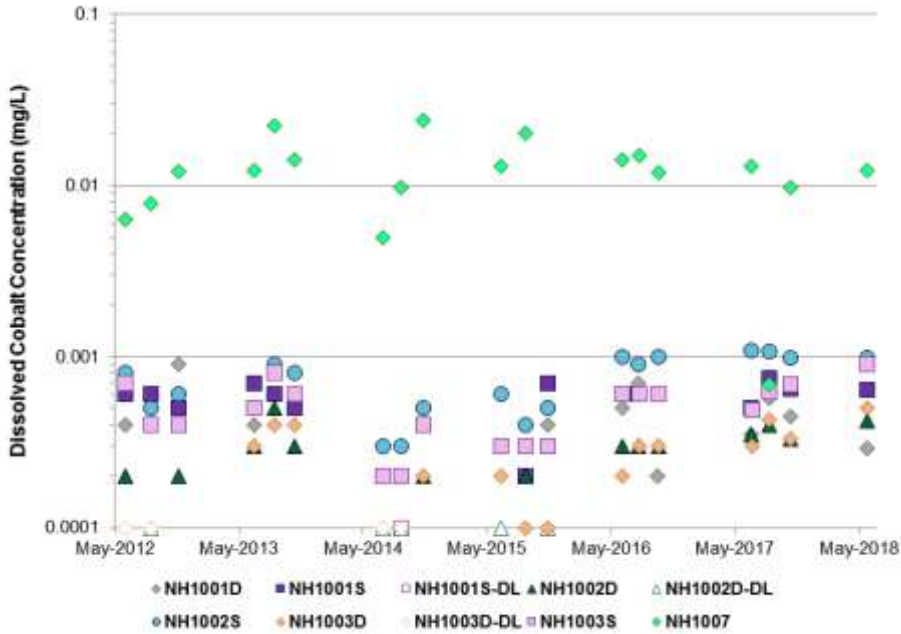**Figure 4-17:** Dissolved Cobalt Concentrations in Groundwater from Key Locations

5 PHASE 2 – IN SITU TREATMENT OF THE NIGHT HAWK LAKE MINE OPEN PIT WATER

The bathymetric survey showed that the water volume in the NHLM open pit is approximately 98,000 m^3. On average, water quality monitoring results exhibit measured arsenic concentrations of 0.7 mg/L. Phase 1 testing indicated that a 20:1 molar ratio of iron to arsenic (Fe:As) would result in treated arsenic concentrations of 0.05 mg/L or less and as such, was the target ratio selected for dosing of the pit water. Therefore, about 1,000 kg of iron, was required to dose the entire pit. This represented about 6 totes of commercially available Ferric Sulphate solution (50% w/w) that contained 1350 kg of solution at 12.25 % iron (Fe) or about 165 kg of Fe each or 990 kg total.

5.1 Pumping, Dosing and Application of Ferric Sulphate

The field trial was designed to include circulation of about 10% of the pit water volume. The concept was to pump the minimum volume that allows mixing of the Ferric Sulphate with pit water by dispersing the reagent with the pit water over a large area of the water surface. This was accomplished by use of two water cannons stationed around the perimeter of the pit.

Ten percent of the pit water volume is ~10,000 m^3. A pump with a capacity of 1000 US gallons per minute (US gpm) or 227 m^3/hour was capable of pumping 10,000 m^3 in 44 hours or less than 5 days at 10 hours pumping per day. Portable trash pumps that are trailer mounted were used. Two pumps with a capacity of 500 US gpm were run simultaneously, each with a water cannon. Water was pumped from the pit, the ferric sulphate solution was connected to the inlet side of the pump hose and water was delivered to the cannons.

The ferric sulphate was initially pumped with a peristaltic pump to a T connector at the inlet side of each pump with a planned flow rate of 70 L per hour (1.15 L/minute) so that the spray water had an iron concentration of 89 mg/L. During the operation, the peristaltic pumps were found to have inadequate capacity to deliver the ferric sulphate and therefore the tubing to the pump was connected directly to the ferric sulphate totes and pinch clamps were used to regulate the flow rates.

Several photos have been provided below for reference (**Figures 5-1 to 5-5**).

Figure 5-1: Spray Application showing Totes of Ferric Sulphate at Right, Pump and Water Cannon

Figure 5-2: Throw of Spray Looking East

Figure 5-3: Water Cannon on West Side of Pit, Looking West

Figure 5-4: Near Completion of Application After Snowfall, Looking West.

Figure 5-5: Post Treatment Water Sampling Required Breaking
up the Thin Ice Layer for Access to Sample Locations.

5.2 Pit Water Chemistry

Two stations were established to monitor pit water chemistry prior to and after ferric sulphate addition. These stations, NHP1 and NHP2 are shown in **Figure 5-6**.

The pH, dissolved oxygen (DO), temperature and specific conductance were measured in the pit water profile to a maximum depth of 22 m, before and after ferric sulphate addition. Results are summarized in **Figure 5-7**. The pre-treatment profiles were measured in July 2018 and immediately before treatment on 06 November 2018. Post-treatment profiles were measured immediately after addition of the ferric sulphate on 12 November 2018.

The results show that the pH was typically in the range of 7.5 to 8.5 and overall values were slightly lower after treatment than before. The oxygen saturation values varied between about 100% near the water surface to less than 10% at depths greater than 16 m with very little difference before and after treatment. The temperature of the water varied between 4 and 5° prior to treatment and 3 to 5° after treatment with near surface temperatures higher than those at depth. In July 2018, the specific conductance values were in the range of 375 to 450 µS/cm with the minimum values at a depth of about 8 m and higher values near surface and at depth. The specific conductance values in November were in the range of 450 to 575 µS/cm, exhibiting lower values near the surface with abrupt increases at a depth of about 12 m below surface. The specific conductance values were slightly higher after treatment than before. The specific conductance profiles in November suggest that there may be a density layering at a depth below 12 m from surface with higher TDS water in the bottom layer.

Figure 5-6: Locations of Pit Water Monitoring Stations.

Total and dissolved arsenic concentrations at 3 depths within the pit were compared for the sampling event immediately prior to treatment and 3 sampling events after treatment and are summarized in **Figure 5-8**. Concentrations are shown on a log scale to more clearly distinguish the low range of values after treatment. Pretreatment concentrations of dissolved and total arsenic were on the order of 0.7 mg/L near the surface. Pretreatment samples exhibited slightly lower dissolved concentrations at depth relative to total concentrations. Immediately post-treatment, November 2018, the total arsenic concentration at the surface at NHP1 decreased to 0.01 mg/L and the dissolved concentration was less than 0.002 mg/L. Mid-depth samples for the same sampling event were approximately 0.03 and 0.01 mg/L for the total and dissolved arsenic concentrations, respectively. Arsenic concentrations at depth remained close to the initial concentrations prior to treatment. Arsenic concentrations in subsequent sampling events, post-treatment, exhibited similar trends with depth showing the lowest concentrations near the surface and the highest concentrations at depth. One exception was noted, the February 2019 results at NHP2 exhibited arsenic concentrations on the order of 0.02 mg/L near the bottom of the pit, in contrast to all other deep samples which remained relatively close to the initial concentrations prior to treatment.

Concentrations of iron were also examined in detail to understand the behavior and fate of iron added as ferric sulphate. Results for iron are summarized in **Figure 5-8**. Pre-treatment concentrations were typically less than 0.2 mg/L for both total and dissolved iron. Post-treatment,

total iron concentrations were as high as 2.0 mg/L in surface waters and increased marginally with depth, though it is noted that the total iron concentration at surface for NHP2 was unchanged from the pre-treatment sample. Total iron concentrations decreased with subsequent sampling events exhibiting values similar to pretreatment conditions at the shallow and mid depths by February 2019. Post-treatment dissolved iron concentrations also increased to values of about 2 mg/L in surface waters at NHP2 and were also elevated relative to the pre-treatment condition in bottom waters. The dissolved concentrations of iron increased between the November 2018 samples and the January 2019 samples at all depths and were similar among depths. By February 2019, dissolved iron concentrations decreased to near pre-treatment levels, similar to the total iron concentrations. These results suggest that while there was a perturbation in iron concentrations in the pit water as a result of the addition of the ferric sulphate, near pre-treatment concentrations of dissolved and total iron reestablished within 3 months of treatment.

Results for total nickel concentrations in the pit water are summarized in **Figure 5-9.** Pretreatment nickel concentrations ranged between 0.05 and 0.06 mg/L with lower concentrations in the surface sample. Post treatment nickel concentrations were essentially unchanged from these values and no reduction in nickel levels is attributable to the ferric sulphate dosing.

Results for total cobalt concentrations are summarized in **Figure 5-10.** Previous investigations have shown that concentrations of cobalt can also be reduced by the addition of ferric sulphate (AMEC, 2017). Results from this work show that prior to treatment, cobalt concentrations ranged from 0.001 to 0.004 mg/L with lower concentrations at the surface sample than at depth. After treatment, concentrations of cobalt near the surface decreased slightly while those at depth remain similar to pre-treatment values. Therefore and based on available data, there do not appear to be substantial differences in total concentrations of cobalt prior to and after ferric sulphate addition.

The addition of ferric sulphate to water releases acidity as the ferric iron consumes hydroxide from solution and precipitates as a ferric oxy-hydroxide solid. The "stored" acidity in the ferric sulphate plus the small amount of sulphuric acid used in the ferric sulphate solution can therefore lower pH or reduce alkalinity in the water being treated. Results for alkalinity pre- and post-treatment are summarized in **Figure 5-11.** Total alkalinity values prior to treatment ranged from 150 to 200 mg/L as $CaCO_3$ with lower concentrations at surface than at depth. Alkalinity remained high after treatment but were more variable and ranged from about 70 mg/L to 220 mg/L, again with lower concentrations at surface than at depth.

Results for sulphate concentrations in the pit water pre- and post-treatment are summarized in Figure 5-12. The addition of ferric sulphate for the treatment of arsenic resulted in an increase in the sulphate concentrations as expected. Sulphate concentrations prior to treatment were in the range of 100 to 120 mg/L and after treatment were on the order of 130 to 170 mg/L.

Overall, the addition of ferric sulphate to the pit resulted in an effective removal of arsenic from the mid and upper depths of the pit water and substantial removal of nickel as well. There were no adverse effects on water quality parameters as a result of the in-pit treatment.

The treatment using surface application of ferric sulphate did not appreciably reduce arsenic concentrations in the deeper zone of the pit, below about 10 m from surface as of February 2019. It was also noted that there is a contrast in the total dissolved solids that may represent a chemocline with slightly denser water in the bottom layer below 12 m than in the lower TDS water in the upper layer that were observed prior to and after application of the ferric sulphate in November 2018. Additional monitoring will determine if the pit will completely mix during 2019 and effectively treat the bottom-most layers as well.

The presence of a chemocline with higher TDS in the bottom layer may be playing a role in the maintenance of higher arsenic concentrations near the bottom of the pit compared to those at mid-and shallow depths. It is also evident that the bottom layer is anoxic and therefore may be subject to the reducing potential of organics that have accumulated in the bottom of the pit. Reduction of ferric iron in the form of ferric oxyhydroxides by the decomposition of organic matter could result in the release of arsenic and dissolution of iron in the ferrous (Fe^{2+}) form. However, results for dissolved iron in the February 2019 sampling event suggest that, if ferrous iron is present, it does not occur in substantial concentrations. Further monitoring and follow-up will be required to determine the cause of the higher arsenic concentrations in the deeper zones of the pit.

Phase 2 of this study suggests the effective treatment of arsenic in the upper 10 m representing 70% of the total pit water volume, and provides a positive effect that can be used for the management of water in most pits in temperate climates that have a natural outlet for flow from the pit. The outflow will represent pit water near the surface and the effective treatment of that water by removing arsenic can allow for release to the environment at the concentrations observed after this treatment trial. Therefore, the more elevated concentrations of arsenic at depth are not necessarily problematic for in-pit treatment but are recommended for follow up investigations in order to confirm the effectiveness of the treatment and the potential for diffusion or mixing of these higher concentrations upwards within the water column.
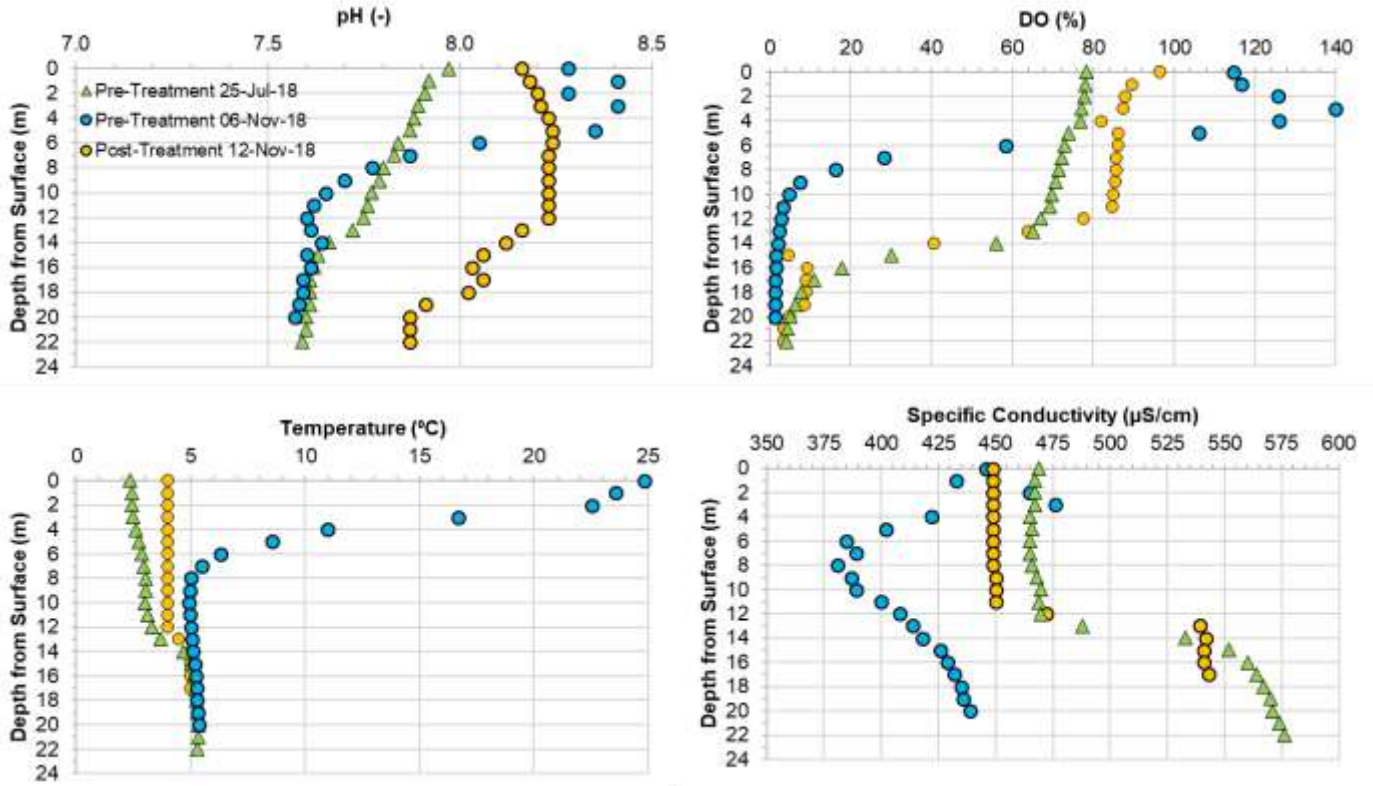
Figure 5-7: Profiles for pH, Dissolved Oxygen Saturation, Temperature and Specific Conductivity, Pre- and Post-Treatment.
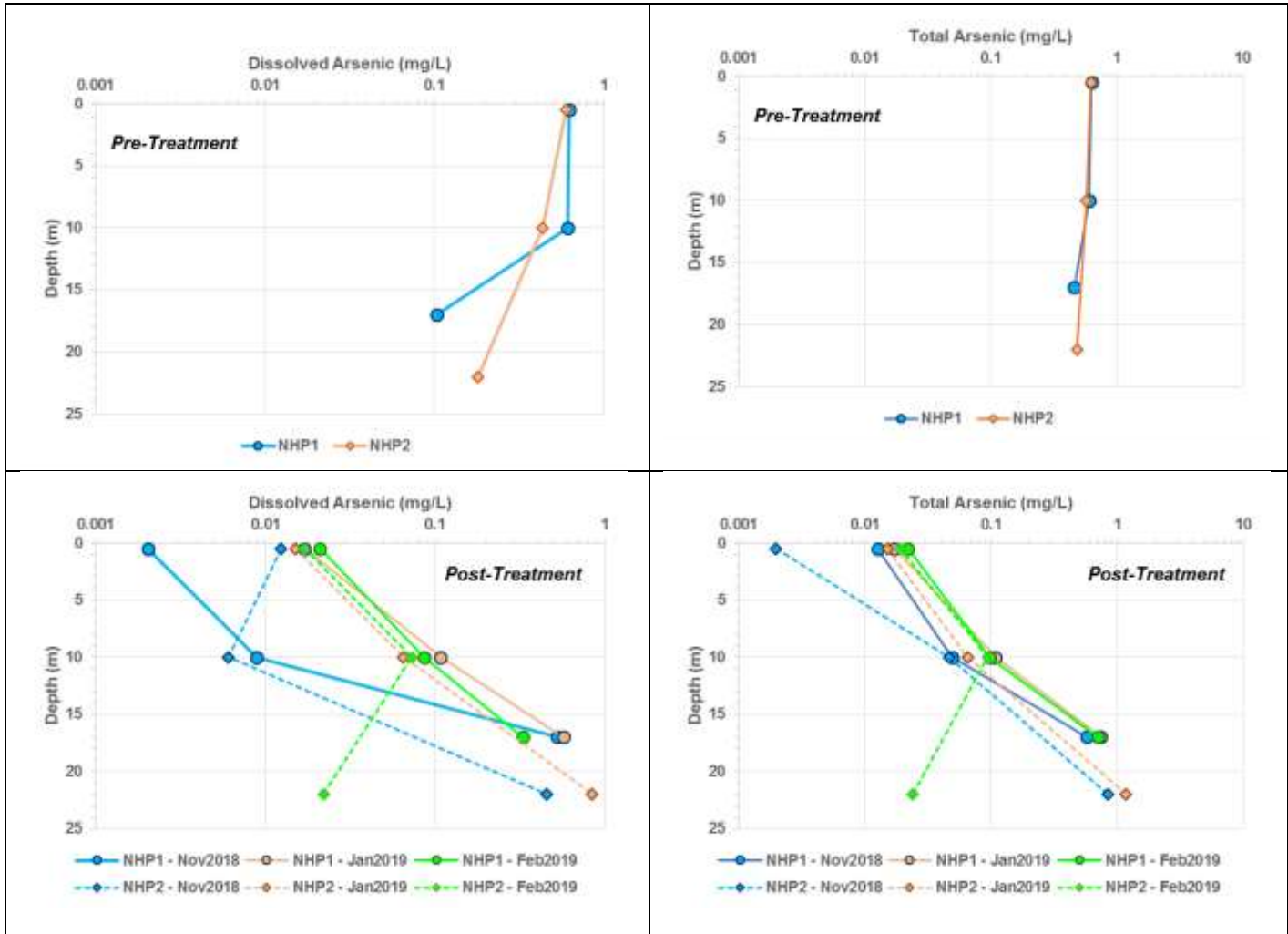
Figure 5-8: Dissolved and Total Arsenic Concentrations with Depth, Pre- and Post-Treatment.

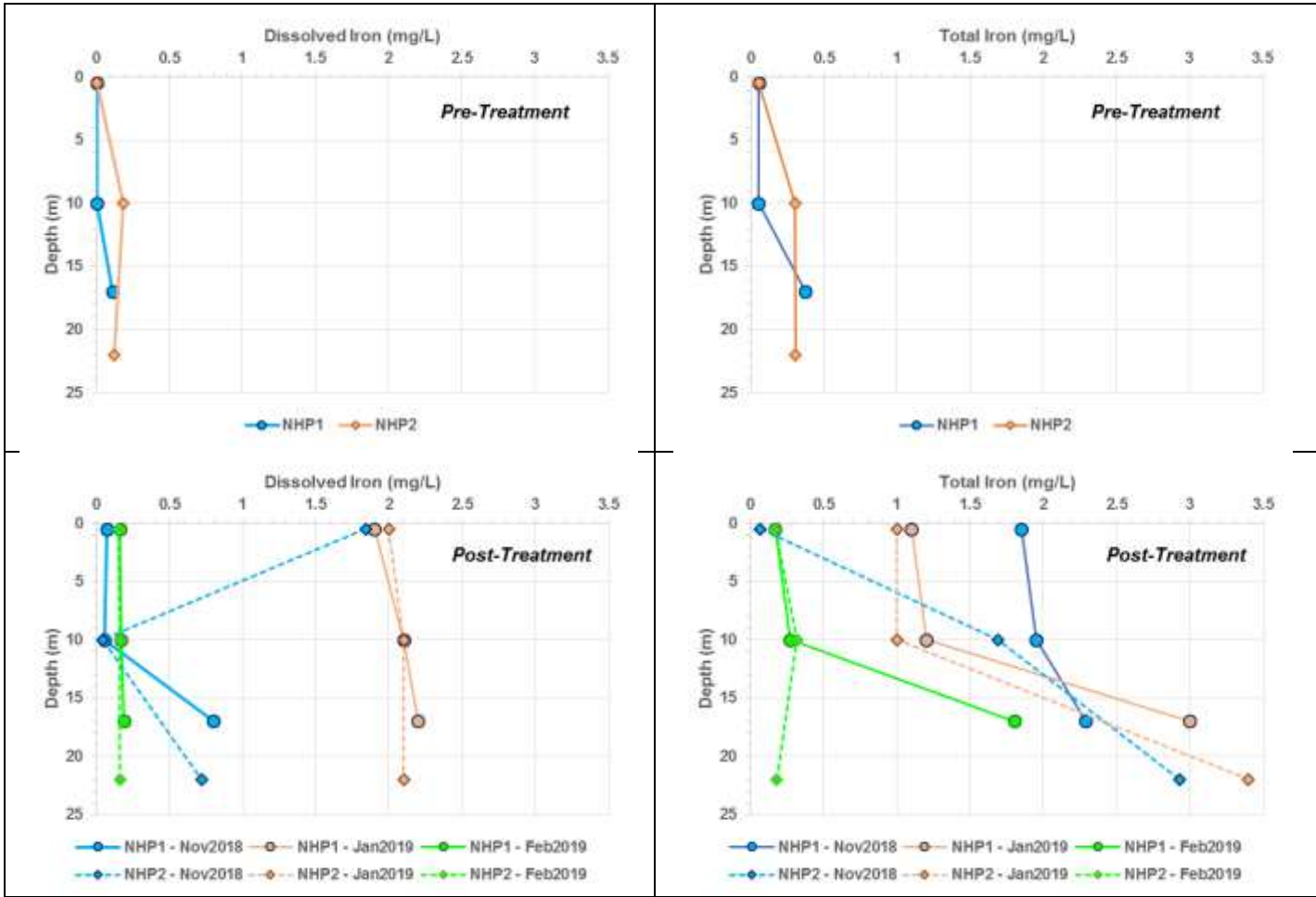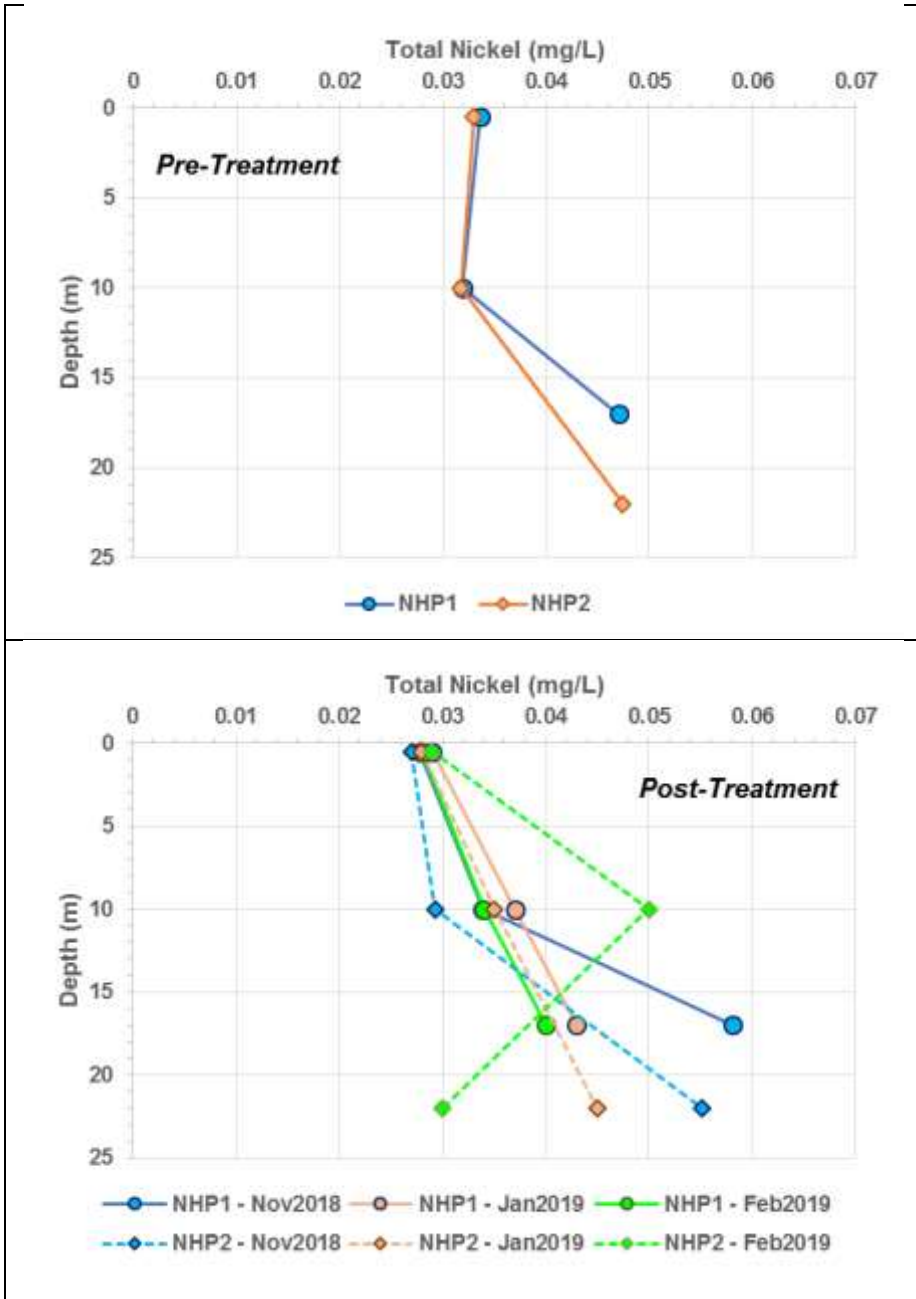**Figure 5-9:** Dissolved and Total Iron Concentrations with Depth, Pre- and Post-Treatment.

Figure 5-10: Total Nickel Concentrations with Depth, Pre- and Post-Treatment
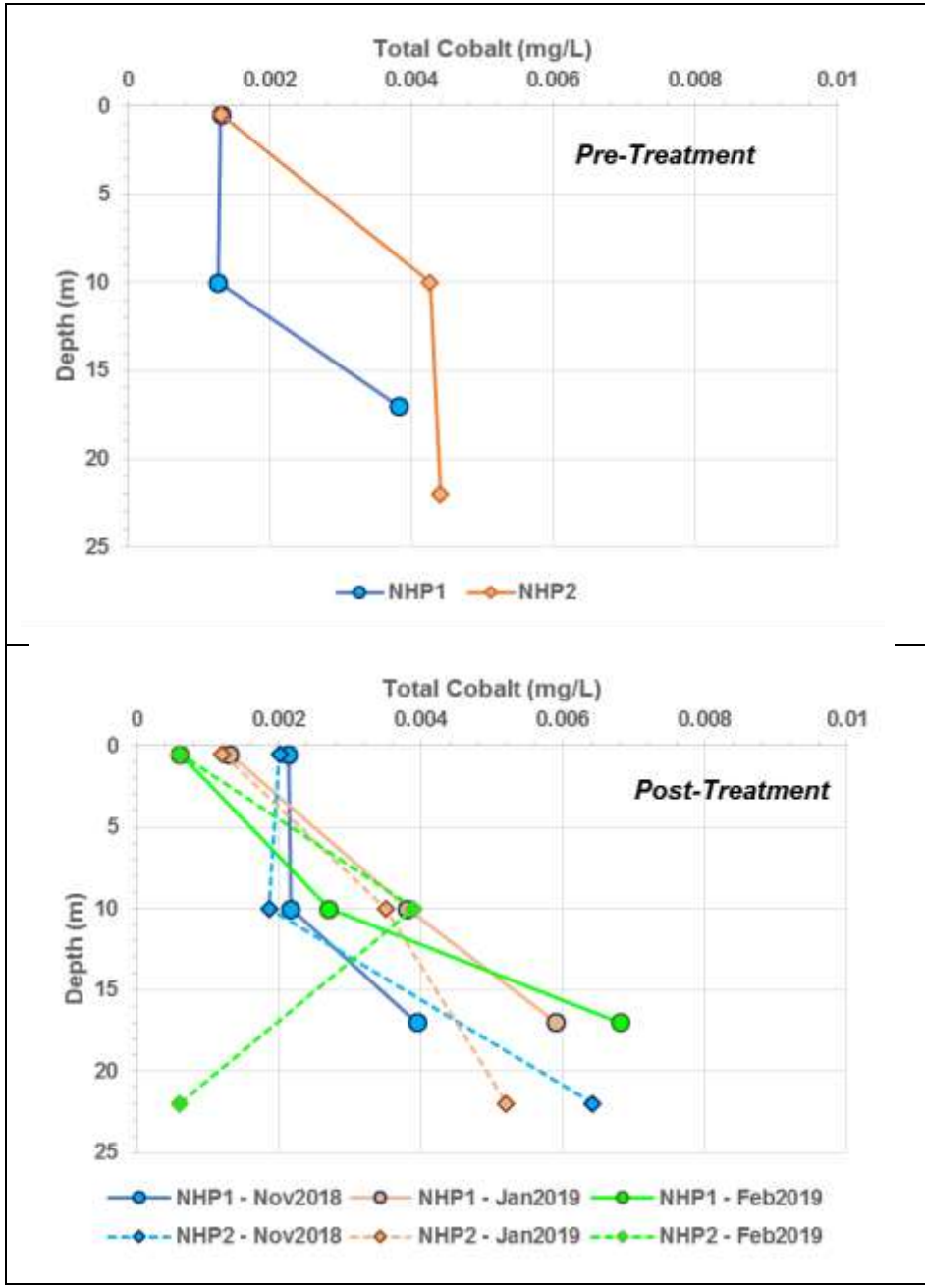
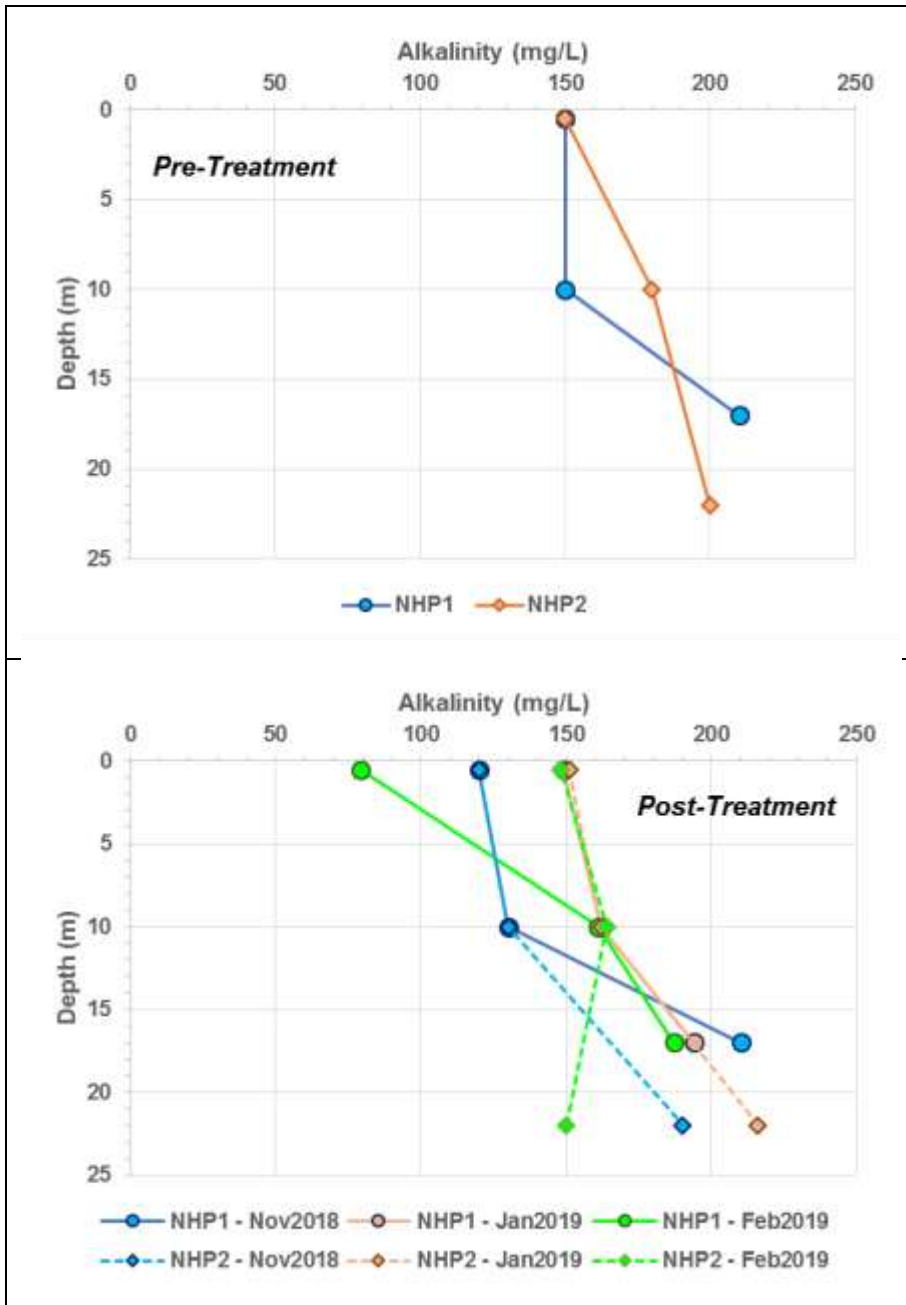**Figure 5-11:** Total Cobalt Concentrations with Depth, Pre- and Post-Treatment

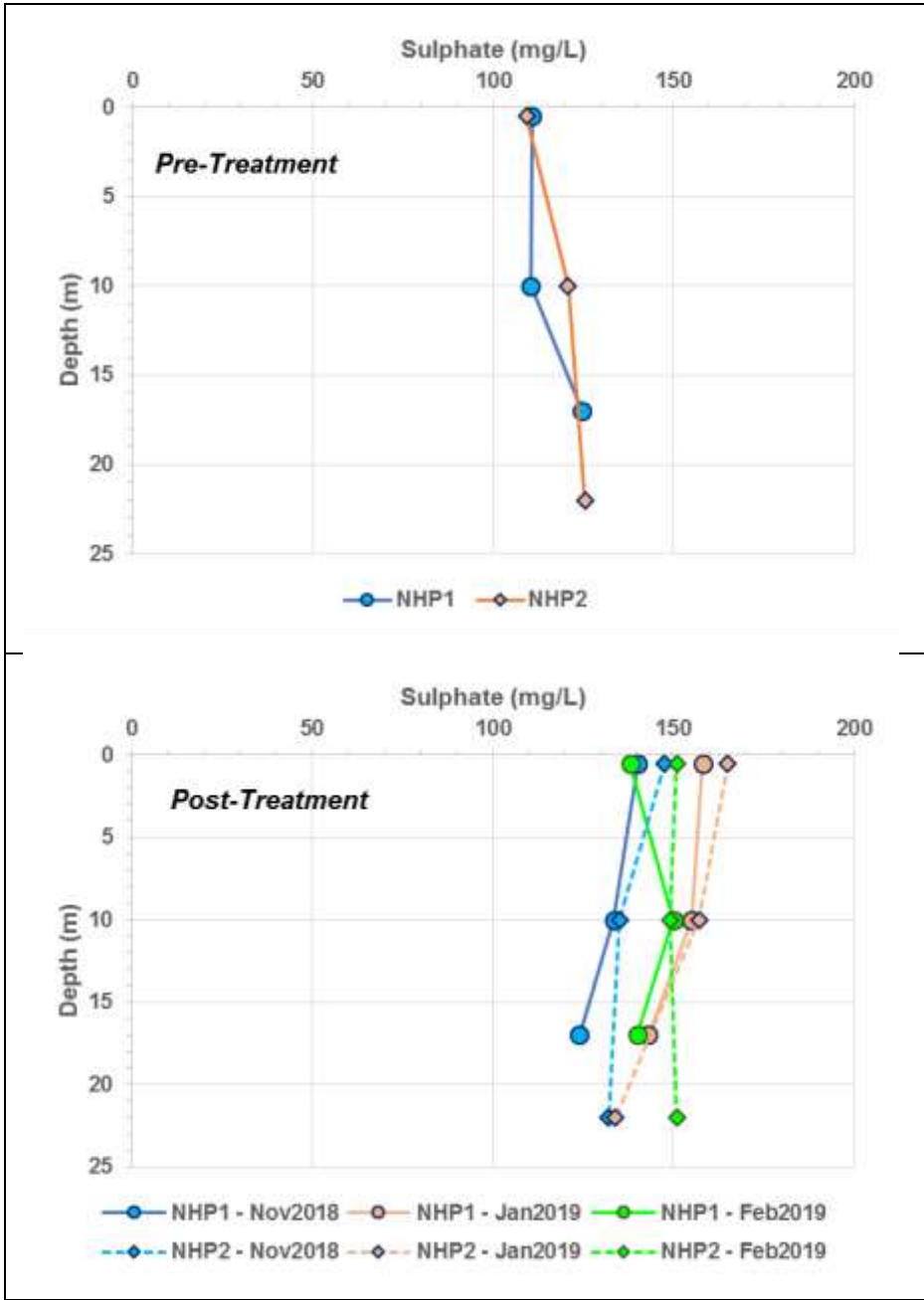**Figure 5-12:** Alkalinity Concentrations with Depth, Pre- and Post-Treatment

Figure 5-13: Sulphate Concentrations with Depth, Pre- and Post-Treatment

6 CONSIDERATIONS SURROUNDING THE APPLICATION OF IN SITU TREATMENT

To use in pit treatment as an alternative to active treatment it must provide the same risk reduction while remaining economically viable and competitive. The risk reduction is determined by setting a threshold at which treatment is initiated. As has been shown through the lab testing and the field scale application in the NHLM open pit, reaching the threshold through batch treatment is possible and the risk that the treatment itself will not succeed in reaching the threshold is low.

To predict the cost and economic viability of pit treatment, the frequency at which treatment will be needed must be known. The main driver of costs will be the interval at which treatment is needed. The frequency of treatment is based on three main variables: 1) the threshold at which treatment is initiated, 2) the mass loading rate of arsenic from all site aspects related to the pit water and 3) the volume of the pit water.

6.1 Water Quality Modelling in Support of the Field Trial

To better understand the ongoing contribution of constituent loadings and the required in-situ treatment frequency for the NHLM open pit, a site-wide loadings model was developed in MineMod™. A similar model was developed for a much larger scale open pit mine, using the Black Fox Mine (BFM), near Matheson, Ontario, east of the NHLM site, as an example, in order to compare requirements for in-situ treatment at that scale. A comparison of capital and operating expenditures has been provided for this example, in order to evaluate the application of in-situ treatment versus the installation of a water treatment plant.

A brief introduction to MineMod™ is provided below, as well as a summary of model predictions for both the NHLM and BFM sites.

EcoMetrix developed geochemical modeling software called MineMod™ (EcoMetrix, 2019a) that was used to create a site-wide loadings model for the NHLM and BFM sites (EcoMetrix, 2019b). MineMod™ is an interactive source term and water quality modelling and management tool to assess mine planning, operations, closure and reclamation scenarios. As shown in **Figure 6-1**, MineMod™ uses a windows interface to visually represent mine related objects including a base map or a satellite image. It presents objects in various layers that include the water bodies, catchment areas of interest and tailings and waste rock sources, etc.

Figure 6-1: Screenshot of the MineMod™ Model

Purpose-built aspects in MineMod™ provide model transparency and quality assurance by keeping physiochemical processes consistent for each mine aspect. The visual GIS based MineMod™ platform relates model and data components to geographical and site features and facilitates user experience and understanding. The platform promotes creativity and can quickly and economically compare the benefits of various operations and closure scenarios. Real time processing of scenarios has been shown to be conducive to round table meetings and regulator discussions/presentations.

The loadings model was used to predict concentrations of constituent of potential concern (COPC) within the pit(s), as well as within the downstream environment for both pre- and post-treatment conditions. The model integrates loadings from potential source areas and the Site water balance. The model represents a full mass and flow balance that includes chemical sources, surface water runoff and groundwater flow inputs, releases from sources to the surface water receiving environment as seepage flows within sub watersheds. Each of the mine-related constituent sources at the Site is unique and considered individually for purposes of the loadings assessment, as discussed in the sections below.

The main water balance features for the model are the surface areas, water flow connections, precipitation, evapotranspiration, surface areas of aspects, runoff from aspects, groundwater inflows or outflows, water storage volumes. These must be determined for each aspect and related to each other.

For an in-situ pit treatment model two main loads need to be considered:

1) The loads from the site (including contact water from the waste rock pile, surface flush of tailings, seepage from tailings process water, runoff contact waters). Assuming the site maintains neutral pH conditions, these loads are held constant over time. Depletion of COPCs in source materials should be checked but was not considered here.

2) Loads from initial flushing when the pit is flooded. These loads come from material that is either placed intentionally in the pit or rubble that was left behind during mining. The material is usually reactive and when flooded can release finite loads of constituents. However, once material in the pit, including pit walls are submerged loading rates are expected to cease.

The two different loads, a one-time initial flush and a continual load usually result in a spike in concentrations as the pit is filled and a gradual decline down to equilibrium concentrations which depend on the hydraulic residence time of the pit water as well as the specific loading rate to the pit water. If loading rates to the pit are small enough it is possible that only one batch treatment is sufficient. Conversely if loading rates are higher than the required frequency of treatment will increase and consequently, the relative benefit of in-pit treatment will diminish.

Two site wide models are detailed in the following sections to show how the interaction between the three main factors and the site physiochemical properties can result in very different conclusions regarding batch treatment. One model was completed for the NHLM open pit while the other is for the BFM open pit.

6.2 Night Hawk Lake Mine Open Pit

The NHLM model inputs were based on data from the closure plan (Goldcorp, 2012). It was assumed that all arsenic loadings that report to the pit originated from waste rock placed around the pit. Half of the waste rock pile was placed in the drainage area of the pit, and drainage from the other half reports directly to Night Hawk Lake. The runoff coefficient of the waste rock pile was set to 0.3 but all water was assumed to report to the pit.

The pit has a 1 ha area and since it is filled the runoff coefficient was set to 1. The volume was set to 97,858 m^3 based on a bathymetric survey. Initial conditions in the pit were set using monitoring data (i.e., 0.918 mg/L dissolved arsenic representing conditions in 2011).

Drainage area of the pit was determined from topographic maps and delineated to be 3 ha, including the WRP and pit. The runoff coefficient for the surrounding catchment area was set to 0.66. Only runoff was directed to the pit with other water infiltrating into shallow groundwater and reporting to Night Hawk Lake.

Initial concentrations in the pit water account for initial flushing that occurred during pit filling. There has been a gradual decrease in the arsenic concentrations in the pit from 2011 to 2018 (**Figure 6-2**). Two samples of weathered waste rock had undergone leach testing, results of which can be used to estimate contact water or porewater concentrations. Based on a 1 m flushing depth, a waste rock density of 1500 kg/m^3, and water content of 5% w/w; arsenic loading rates for the two samples were calculated to be approximately 0.02 mg (arsenic) / kg (waste rock) / week (mg/kg/wk) and 0.003 mg/kg/wk.

The average arsenic loading rate of 0.011 mg/kg/wk, as estimated from the results of leach tests, was first used in the model results in **Figure 6-3**. The modelled increase in arsenic concentrations in the pit suggest that the estimated loading rate was too high. The loading rate was then calibrated to a lower estimate of 0.003 mg/kg/wk and the results exhibit an increase rather than a decrease in arsenic concentrations in the pit water with time (**Figure 6-3**). The arsenic loading rate was then calibrated to a value of 0.001 mg/kg/wk to provide the best fit to the observed concentration trends in the pit water (**Figure 6-3**). The calibrated model was used to predict the effect of treating the pit and potential frequency of treatment required.
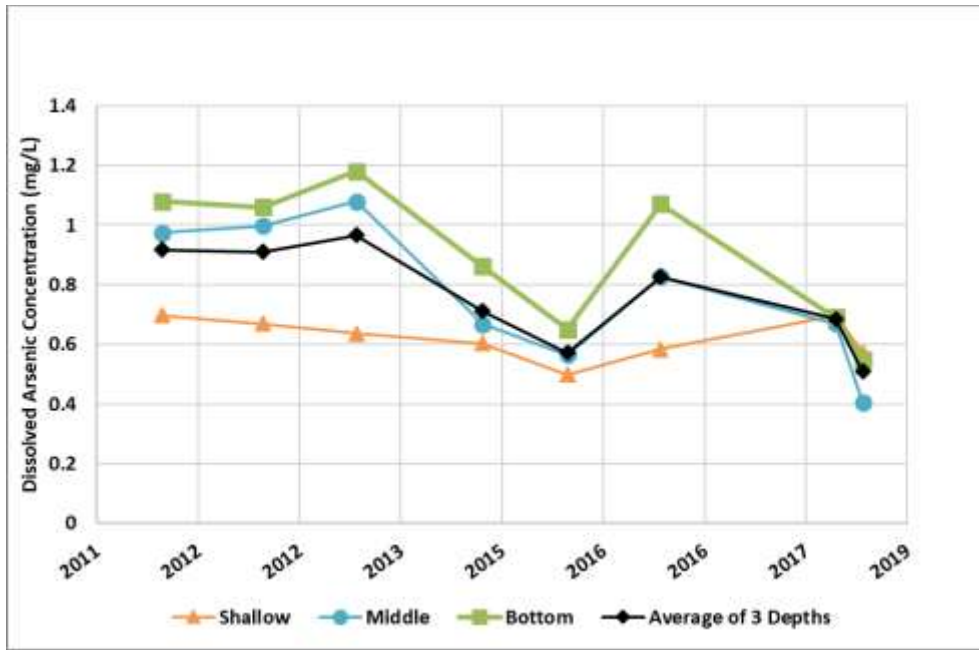
Figure 6-2: Dissolved Arsenic Concentrations in the NHLM Pit Water from 2011 to 2018 for Surface, Middle, Bottom Samples and Average Concentrations from the Three Depths.
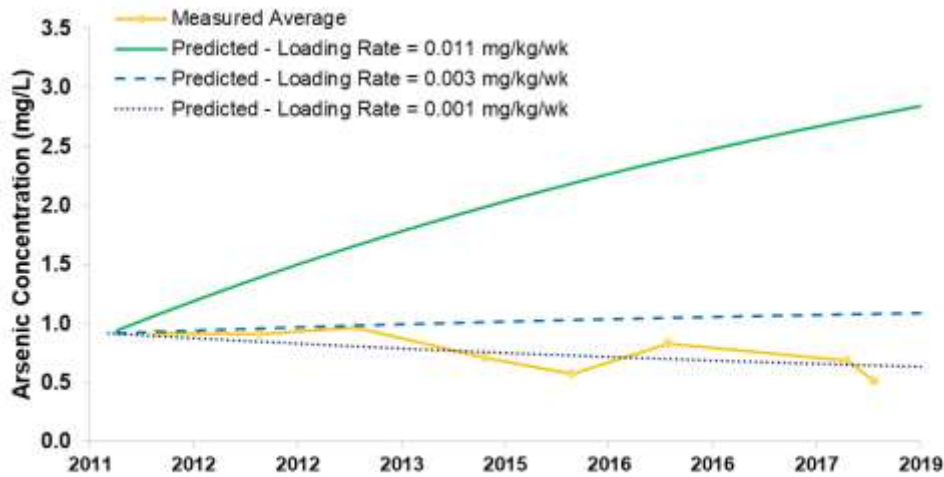

Figure 6-3: Modelled Dissolved Concentrations with Arsenic Loading Rates of 0.011, 0.03 and 0.001mg/kg/wk, Compared to Average of Measured Concentrations (2011 to 2018).

Without treatment model results suggest that the average concentration of arsenic would reach a steady state value of 0.4 mg/L (**Figure 6-4**). In order to achieve lower arsenic concentrations in the pit water, treatment will be required. The steady state arsenic concentration of 0.4 mg/L assumes that the arsenic loading rate will remain constant with time. After treating the pit water to a lower concentration, the ongoing loadings to the pit will cause the concentrations to increase toward 0.4 mg/L in time. Therefore, periodic in-pit treatment will be required to maintain the arsenic concentration in the pit below a threshold value that is less than 0.4 mg/L.

Different threshold scenarios were tested to show the difference in treatment frequency required. **Figure 6-4** shows that if a threshold concentration of 0.2 mg/L is selected as the maximum desirable arsenic concentration, the frequency of treatment would be every 7 years. However, if a threshold of 0.1 mg/L is selected, the resulting frequency of treatment is 2 years (**Figure 6-5**).

The projected short frequency of treatment for NHLM results from the small volume of water. Even though the arsenic loading rate is relatively small, it does not require much time to increase concentrations up to the threshold from the initial treatment concentration of 0.05 mg/L. This example shows how model results can be used to inform economically viable of in situ pit treatment.
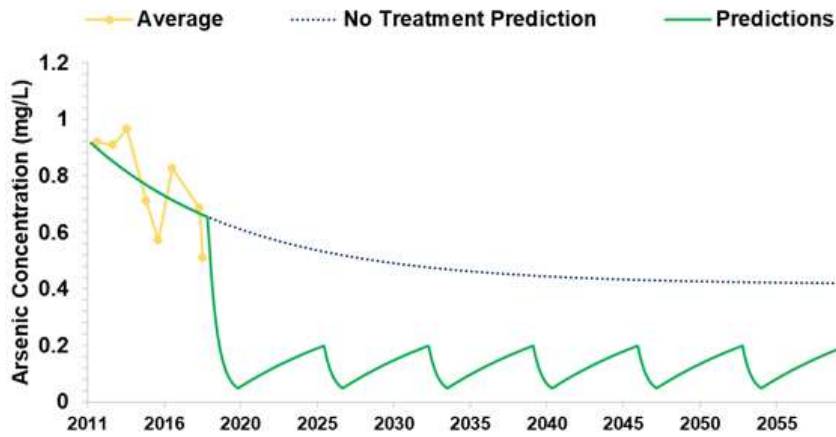

Figure 6-4: Modelled Arsenic Concentrations Without (Dotted Line) Treatment and With Periodic Batch Treatment (Solid Line) Assuming a Threshold Value of 0.2 mg/L.
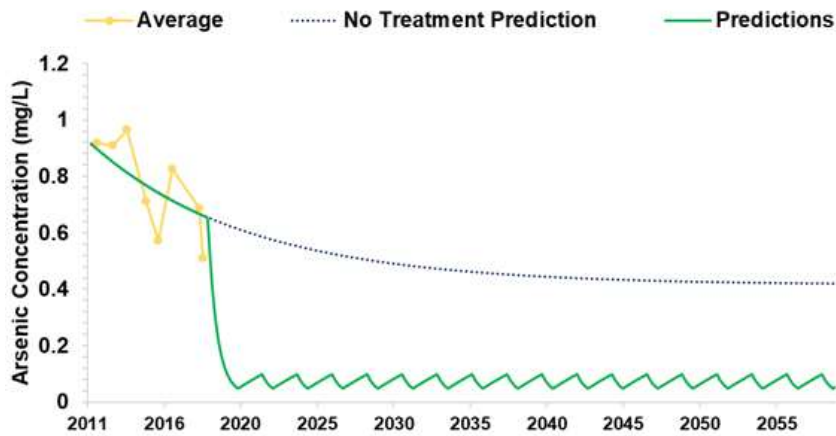
Figure 6-5: Modelled Arsenic Concentrations Without (Dotted Line) Treatment and With Periodic Batch Treatment (Solid Line) Assuming a Threshold Value of 0.1 mg/L.

6.3 Black Fox Mine

Drainage from one waste rock pile at BFM requires management prior to release to the environment as a result of arsenic concentrations. The closure plan includes a provision to collect waste rock drainage waters in the pit over a 20-year period. The quality of pit water was considered here in order to understand the potential need to treat or otherwise manage the water before the pit rises to the natural overflow elevation.

Various sources of COPCs were considered and a water quality management model developed to calculate concentrations in the pit water after 20 years of filling.

6.3.1 Site Location

The Black Fox Mining Complex or ("BFMC" or "Site") is located approximately 10 km east of the town of Matheson on the south side of Hwy 101 (**Figure 6-7**). The BFMC comprises the operating BFM and the Froome and Grey Fox deposits that are located 1 km west and 3 km south, of the BFM, respectively
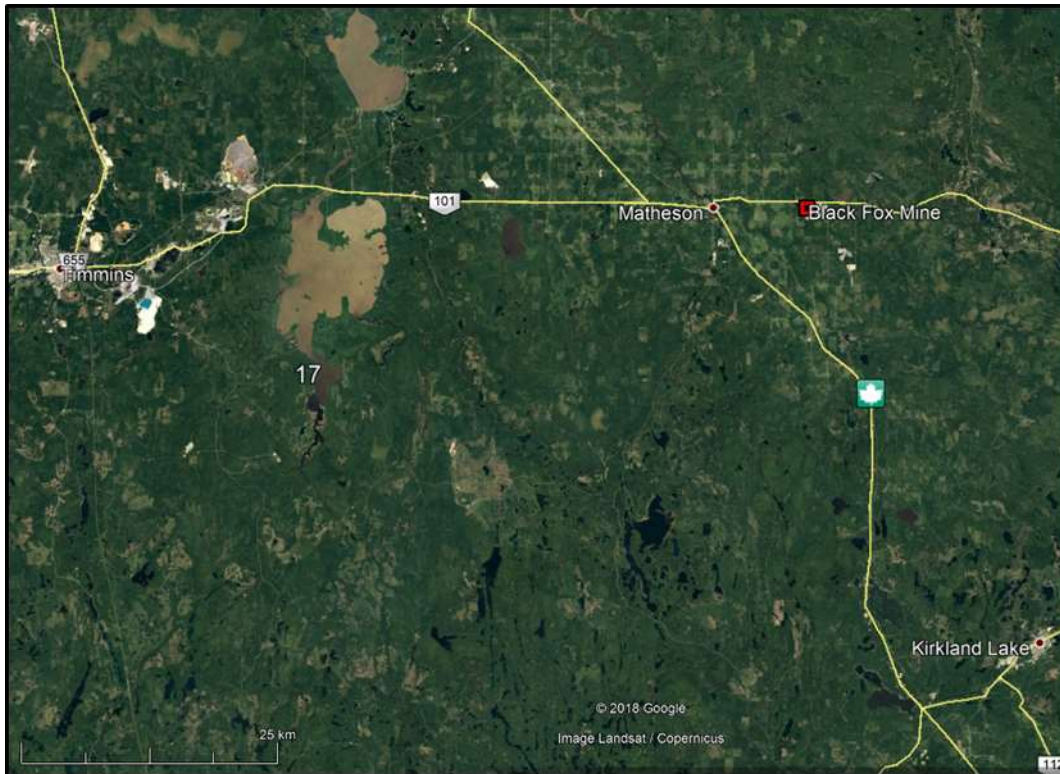

Figure 6-6: Location of the Black Fox Mine Site, near Matheson, Ontario

Key surface features of the BFM include an open pit (and associated underground workings), ore stockpile and crushing facilities, two waste rock piles, an overburden stockpile, water management infrastructure and an administrative area.

The open pit at the BFM was developed in three phases and has a surface area of approximately 550,000 m^2 and a depth of 200 m. Waste from the open pit operations was stored in one of two dedicated waste rock storage facilities – the Potentially Metal Leaching (PML) waste rock storage area and the non-PML waste rock storage area. In total, approximately 14 million tonnes of overburden and 58 million tonnes of waste rock, including approximately 15 million tonnes of non-PML and 43 million tonnes of PML waste rock, were excavated during the development of the pit.

Waste rock generated by current underground mining activities is used to backfill underground mine workings. Water collected from the underground workings and from on-site aspects are directed to the Mine Water Management System that includes chemical treatment with ferric sulphate, prior to being discharged to the Pike River.

6.3.2 Model Assumptions

The total void volume for the combined open pit and underground workings utilized to determine the open pit filling time was 25,500,000 m³.

The number of years to fill the pit was estimated by incorporating the planned rehabilitation of the west and eastern portions of the PML waste rock stockpile. Inflow rate to the pit was estimated to be approximately 1,100,000 m³, based on net precipitation directly into the pit, natural pit inflows and drainage diverted from the PML waste rock stockpile to the open pit. The time to fill the open pit with a void volume of 25.5 Mm³, is estimated to be about 23 years.

For purposes of this modelling exercise, diversion of PML waste rock stockpile drainage to the open pit was considered for a 20-year period. This time frame also allows sufficient time from a planning perspective to perform batch treatment of pit water, if necessary and/or to re-divert the PML waste rock stockpile drainage to a treatment plant.

During the 20 years of pit filling, the pit will receive water from natural inflow sources, including direct precipitation, local runoff and groundwater that will have background concentrations of COPCs that were assumed to represent effectively no loadings of COPCs to pit water. Drainage from the waste rock area that will be collected and pumped to the pit will contain COPCs as a result of leaching from the rock and therefore was accounted for in the prediction of concentrations of COPCs in the pit water. The residual rubble in the pit at the end of mining can be a potential source of COPCs to the pit water as it is submerged of during pit filling. This flushing of COPCs from rubble was also considered in the prediction of COPC concentrations during the predicted pit filling period.

6.3.3 Water Quality Predictions

Using the open pit to continually collect seepage from the PML waste rock stockpile, after the first batch treatment event, will result in ongoing arsenic loadings to the pit that will cause arsenic concentrations in the pit water to increase slowly with time. To ensure the protection of downstream water quality, total arsenic concentrations within the water filled pit are proposed to be maintained below the Ontario Aquatic Protection Value (APV) from MOE (2011) for arsenic of 0.15 mg/L. An arsenic concentration of 0.10 mg/L was therefore used as a threshold concentration that will trigger batch treatment via ferric sulphate.

Water quality management for the PML waste rock stockpile is expected to be required for more than 100 years and contingency to accommodate such management was considered (EcoMetrix, 2019b). The frequency of batch treatments was estimated at every 32 years for worst case or highest estimated loadings scenarios. Therefore, regular monitoring of pit water concentrations would provide adequate time to implement batch treatment.

6.3.4 Cost Considerations at Closure for the Black Fox Mine Example

Closure strategies for the BFM concerning water quality were centered on the requirement for long term management of drainage/seepage from the PML waste rock storage area. An internal conceptual trade-off study was undertaken that considered first order costs associated with treating drainage/seepage with ferric sulphate in a conventional treatment plant versus periodic in pit batch treatment.

With a conventional water treatment plant (WTP), drainage/seepage is treated over a 4 to 6-month period annually and discharged to the local receiving environment via pumping to an existing mine water outfall. With in-situ batch treatment, drainage/seepage from the rock pile is directed to the open pit upon cessation of operations and the pit allowed to fill with a passive drainage system. Concentrations of

arsenic and other constituents at depth will need to be considered in the context of potential groundwater interactions and transport.

The site water balance was used to estimate the open pit filling time, with the first batch treatment occurring prior to water levels rising to the passive overflow elevation. The frequency of periodic batch treatment episodes thereafter was determined with the aid of a site-wide constituent loadings model that used arsenic concentrations as the trigger for treatment.

The cost model associated with each water quality management option was run out for 160 years, the period required for discounted costs to become negligible, and a 3% discount rate was used to determine the net present value (NPV) costs. An analysis of first order Capital Expenditures (CAPEX) and Operating Expenditures (OPEX) for each strategy indicated that the batch treatment option costs were 3-4 times less than those of the conventional water treatment plant.

7 RECOMMENDATIONS

Upon completion of this work, several recommendations are made for future work in order to monitor the performance of the in-situ batch treatment and the resultant water quality within the NHLM pit.

7.1 Water Quality

Water quality within the NHLM pit will continue to be monitored in accordance with Newmont Goldcorp's existing monitoring program, in order to evaluate the water quality as it evolves with time. Samples will be collected from continuous profiles and include measurement of pH, specific conductivity, dissolved oxygen and temperature. Results of the monitoring will help to refine model predictions in terms of expected water quality and potential loadings to the pit, as well as to evaluate the expected treatment frequency. Ongoing assessment of water quality results will also help to determine if mixing and residual treatment occurs, or if relatively elevated concentrations will exist within the bottom most layer of the pit.

7.2 Stability of Treatment Solids

Treatment solids formed after addition of ferric sulphate appeared to be very stable in the time frame of the tests performed in Phase 1. A test program on the treatment solids should be performed in order to understand the longer-term stability as well as conditions that may reduce the chemical stability of the solids and release arsenic and other COPCs to the water column. Understanding geochemical conditions that may negatively affect the stability of the solids will provide guidance for managing open pits in which arsenic treatment has occurred

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