Northwest Territories
Cumulative Impact Monitoring Program
Final Report Submission Form 2019/2020

1) Project Information	
NWT CIMP #	**192**
Project Title	A multidisciplinary investigation of recovery in Yellowknife area lakes from 50 years of arsenic pollution: What are the factors inhibiting recovery and the biological consequences?
Project length (years of CIMP funding)	**3**
Date Submitted	**August 21, 2020**
Author(s) & their Organizations: (add rows as appropriate)	Mike Palmer, Aurora Research Institute William Lines, Yellowknives Dene First Nation John Chételat, Environment Canada Murray Richardson, Carleton University Heather Jamieson, Queen's University Maikel Rosabal, Université de Québec à Montréal Marc Amyot, Université de Montréal
Contact Information Include mailing address, email, telephone and website	Mike Palmer, Aurora Research Institute 5004-54th St Yellowknife, NT X1A 2R3
Type of Research	☒ Science ☐ TK
Valued Component Check all that apply. If 'other' please specify.	☐ Caribou ☒ Fish ☒ Water ☐ Other
Geographic Area/Region	☒ North/South Slave ☐ Dehcho ☐ Sahtu ☐ Gwich'in ☐ ISR ☐ Wek'èezhii
Project Keywords (at least 4)	Arsenic, antimony, Giant Mine, biological effects, lake recovery
Location In **decimal degrees (dd.mmm)** provide coordinates for the general study location; or if regional, provide 4 coordinates for the bounding box.	Four lakes near Yellowknife, NT, including: Lower Martin Lake (62.5104, -114.4203), Handle Lake (62.4916, -114.3964), Long Lake (62.4765,-114.4358), and Small Lake (62.5185, -113.8266).
Consent I acknowledge that the completed report will be posted for public access on the NWT Discovery Portal.	☒ I agree

2) Abstract

Clearly and concisely identify in 300 words or less, the purpose, methodology, results and conclusions of the project.

The primary objective of this project was to investigate the mobility and fate of arsenic (As) in a small watershed that was heavily impacted by legacy mining emissions from 1948-1999 to better understand the recovery of As impacted environments.

We sampled lake waters, sediment porewaters, and lake sediments across seasons in two consecutive years to explore As, iron (Fe), and sulfur (S) dynamics under ice in Lower Martin Lake, a shallow subarctic lake impacted by 60 years of As emissions. We also sampled the lake inlet and outlet regularly, as well as catchment runoff to build a mass balance model that will help us understand the timing and relative importance of As fluxes across the landscape. The mass balance model includes measurements of As fluxes between sediments and overlying water, in and out of the lake, and the terrestrial loading of As being washed in to the lake from the surrounding catchment. These initiatives highlighted the importance of understanding the influence of winter conditions on lake water quality, as large fluxes of As may be mobilized from sediments to overlying waters under ice. This information builds our understanding of the factors that are likely contributing to the delayed recovery of shallow lakes near historic mining roasters.

3) Introduction

This section should include the background, purpose, rationale and objectives of the project.

Recent research has highlighted a persisting environmental legacy from historical mining activities in the Yellowknife area, as local lake waters, lake sediments and soils continue to exhibit elevated arsenic concentrations nearly 60 years after the bulk of mining emissions were released (Fawcett et al. 2015; Palmer et al. 2015; Galloway et al. 2017). Elevated levels of arsenic are particularly evident in the lakes and landscape of the Baker Creek watershed, which are proximal and downwind of historical ore roasting operations at Giant Mine. It remains unclear why these water bodies are showing little sign of recovery from legacy pollution. A better understanding of the mobility and transport of arsenic in the Baker Creek watershed is needed to evaluate continued downstream loading to Baker Creek and Yellowknife Bay, which is a key component of the Giant Mine Remediation Plan. Further, little information exists on the toxicological consequences of arsenic exposure to food chains in local lakes, which are important for residents that continue to rely on freshwater resources, including fish, for subsistence and recreational uses.

The overarching objectives of this research were two-fold:

1) To investigate watershed and within-lake abiotic processes affecting the recovery of mine-impacted lakes in the Yellowknife area, including storage and release of arsenic from soils, seasonal dynamics of arsenic export in runoff, and fluxes of arsenic to and from lake sediments; and
2) To investigate the toxicological consequences of more than half a century of elevated contaminant levels on food chains in mine impacted lakes.

The key research questions for this project include:

1) What are the current processes that are loading and removing arsenic from Yellowknife area lakes and how does this influence lake recovery?
    a) Continued loading: how much arsenic continues to be derived from watershed sources, i.e. catchment soils, inflow from upstream lakes, and fluxes between contaminated lake sediments and overlying surface waters?
    b) Export processes: how much arsenic is exported downstream from the lake via lake outflow or retained in the lake through sedimentation processes?
    c) How do these processes vary seasonally, and what are the most important seasons for transport?
2) How do lake water conditions affect the diffusion of legacy arsenic from sediments and its speciation in the water column?
    a) How does oxygen at the sediment-water interface and temperature affect the diffusion of arsenic from contaminated lake sediments?
    b) How do sunlight and water chemistry affect the speciation of inorganic arsenic in the water column?

3) How is legacy arsenic accumulating in food chains of mine impacted lakes?
   a) What is the speciation of arsenic accumulating in fish and their invertebrate prey?
   b) What tissues are the main stores of arsenic and metals in fish?
4) Are fish showing signs of toxicity at the subcellular level?

4) Methods

This section should clearly identify the study area, and methods used to collect and analyze the data.

Study area:

The research for this project was focused on four lakes near Yellowknife, NT, including: Lower Martin Lake, Handle Lake, Long Lake, and Small Lake (Fig. 1).

Fig. 1. Location of field sites visited during project investigations.

Methods:

We used a combination of methods to better understand the fluxes and fate of arsenic in the watershed of Lower Martin Lake, including:

- continuous monitoring of lake physical parameters (dissolved oxygen, temperature, conductivity);
- bi-weekly water chemistry sampling within the lake, and at the lake inlet and outlet;
- sediment porewater and sediment sampling during the open-water and ice-covered seasons;
- measurement of surface runoff and chemistry in a small terrestrial subcatchment;
- measurement of precipitation chemistry

We also sampled invertebrates and fish from each of the lakes to assess the toxicological effects of legacy mining emissions on aquatic organisms.

5) Results and Discussion

In this section, the results of the project must be provided. Appropriate values for all statistical tests, if applicable, must be reported. Figures and tables should be included where appropriate. It must also be *clearly articulated how the results of this project advance the understanding of cumulative impacts in the NWT.*

Project component 1: Mobility and fluxes of arsenic in a small subarctic watershed

Results from this part of the project demonstrated that there was substantial seasonal variation in the concentration of As in small shallow lakes in the region. Concentrations of As increased substantially under ice in lakes less than 4 m deep (Fig. 2) and these differences corresponded with large increases in iron and manganese. Detailed sampling over the course of two years in Lower Martin Lake elucidated some of the processes controlling these large winter increases and demonstrated that lake sediments are a significant source of As to the overlying water column during winter (Fig. 3). The influence of large winter fluxes of As to overlying water, however, was dependent on the winter hydrology of the lake. In low water years when the lake was hydrologically disconnected from the surrounding watershed, anoxia developed through the water column, which promoted the release of As to overlying water (see winter 2017 in Fig. 3). In high water years, when oxygenated water enters the lake, overlying water concentrations of As were lower due to the precipitation and settling of As on particulate Fe minerals.

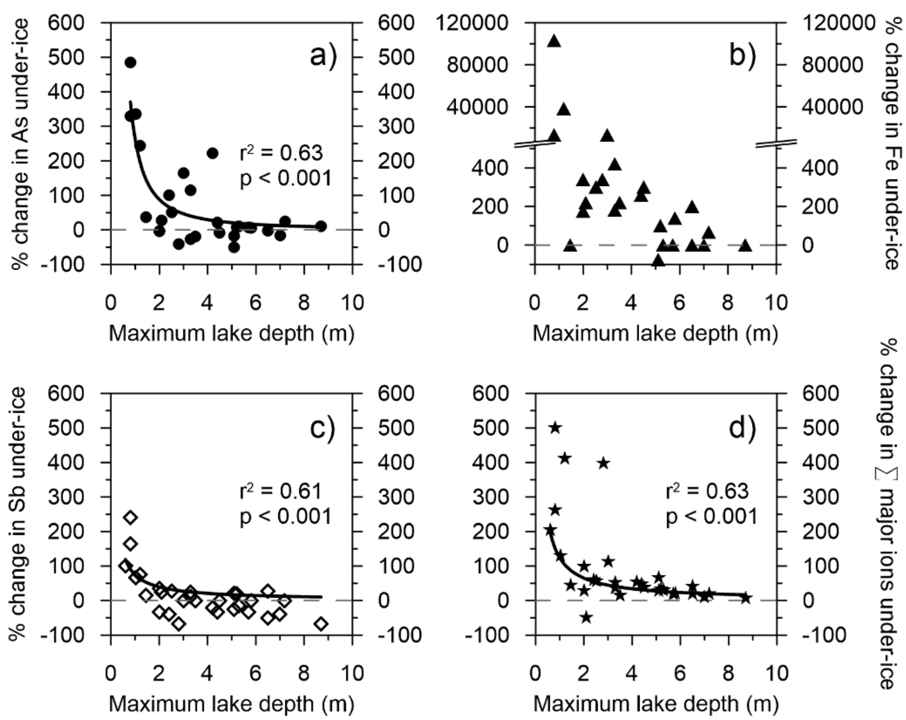

***Fig. 2**. Relationships between seasonal change in surface water concentrations of elements (as the percent change in water chemistry between fall and late winter) and maximum lake depth in 31 lakes within 30 km of Yellowknife, including: a) As; b) Fe; c) Sb; and d) sum of major ions. Only lakes with maximum depth < 10 m were included. All metal(loid) and ion data refer to the filtered fraction (< 0.45 µm) in surface waters. From Palmer et al. (2019).*

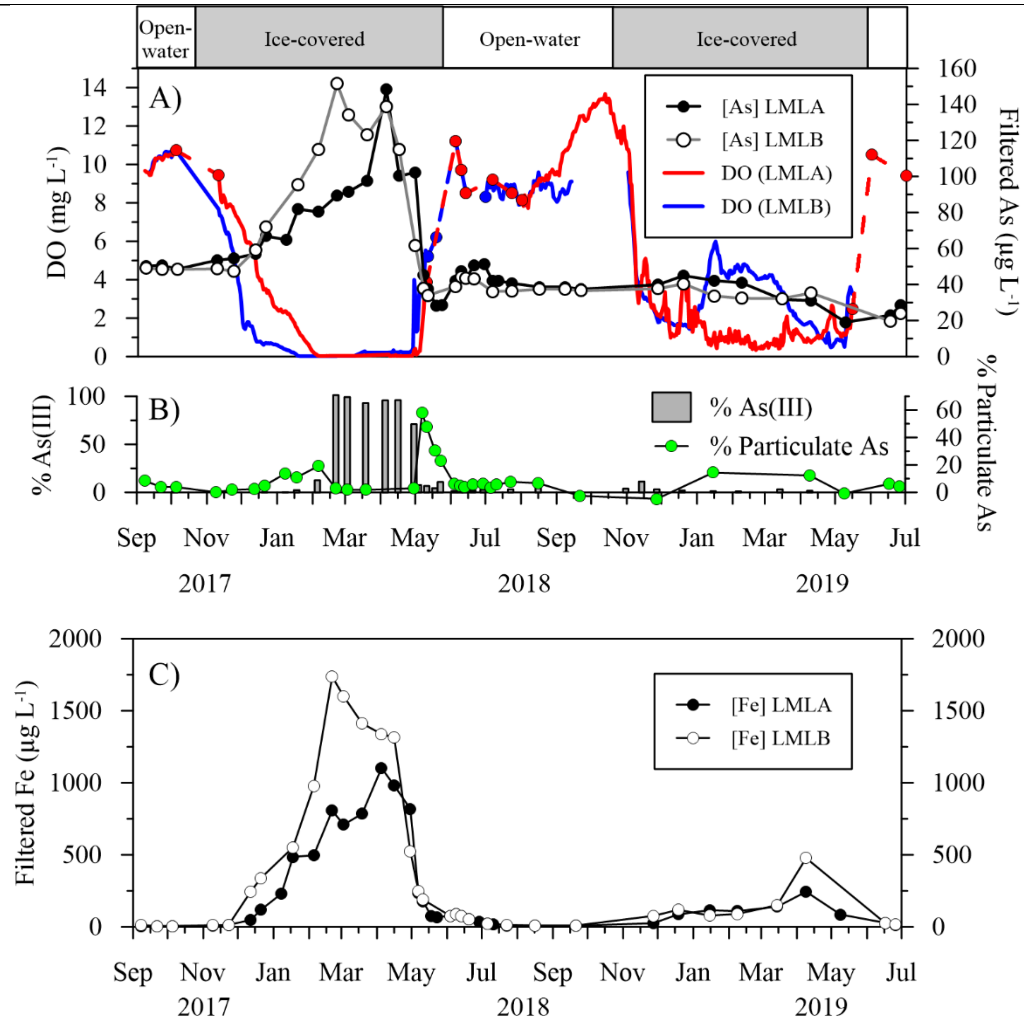

Fig. 3 *Time-series of A) total filtered As and dissolved oxygen; and C) total filtered Fe at two locations in Lower Martin Lake, September 2017 to July 2019. Water concentrations represent the depth-integrated mean of 3-4 sampling intervals within the water column. Dissolved oxygen was measured continuously 1m above the sediment boundary, except for the periods represented by red and blue circles connected with dashed lines, which indicate discrete measurements and interpolated DO levels between measurements. The middle panel B) represents the proportion of total inorganic As as As(III) at the mid-water column sampling depth and the proportion of total As in the particulate fraction at LMLA. Results of full water column As speciation analyses are presented in Fig. 4. From Palmer et al. (2020).*

Project component 2: Toxicological effects on invertebrates and fish:

- Our ecotoxicological studies are focused on amphipods (*Hyalella azteca*) and liver cells of Northern pike (NP, *Esox lucius*) and Lake whitefish (WF, *Coregonus clupeaformis*) collected from various aquatic ecosystems located in the Yellowknife area (Fig.1).

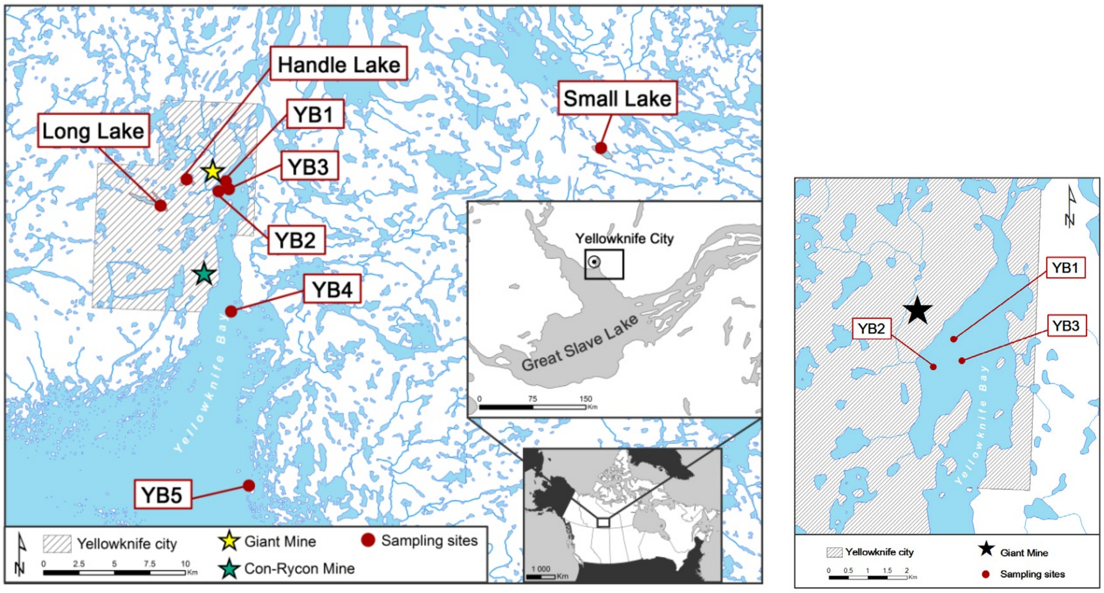

Figure 4. Sampling sites for invertebrates and fish in the Yellowknife area

Invertebrates:

- Metal concentrations in *Hyalella azteca* collected from Yellowknife Bay (5 sampling sites) and Lakes (Long, Handle and Small Lakes) showed markedly spatial differences where metals associated with mining activities (As, Sb) generally decreased in the following order: YK Bay sites > Handle and Long Lake > Small Lake (Fig. 2). We also reported concentrations of some metals belonging to rare earth element group (La, Ce, Y, Nd)

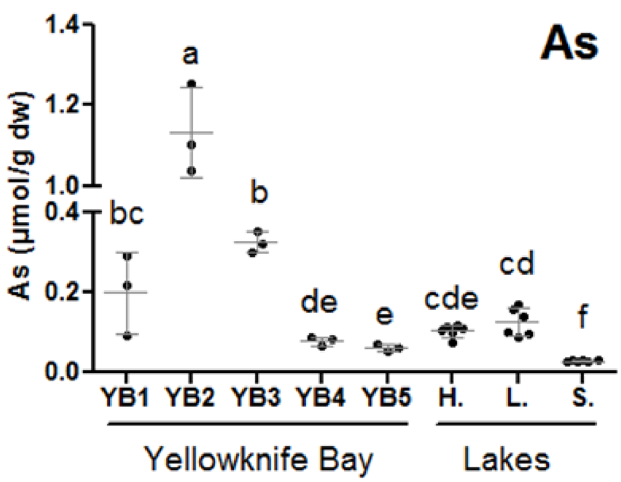

Figure 5. Concentration means (± SD; in umol /g dw; n = 5-8) for As in Hyalella Azteca collected from Yellowknife Bay (YB1-YB5) and from Handle (H), Long (L), and Small (S) Lakes. Different letters indicate significant differences (P<0.05).

- Contrasting bioaccumulation gradients (ratio between the most and the least contaminated organism) were observed for the metals studied (Zn: 3.4, Pb: 14; Ce: 6253, Nd: 6455).

- We carried out experiments to determine the ratio between metal adsorbed and metal internalized in amphipods collected from Long Lake. Our results indicated that metals studied are less adsorbed than internalized (Fig. 3). The ratios of adsorbed metal (%) varied from 6% (Cd) to 49% (Sb).

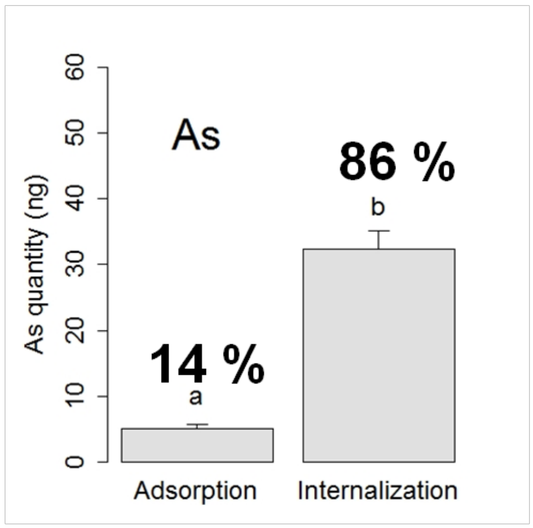

Figure 6. Distribution of quantity mean for As ± SD, in ng, n = 3) between metal adsorbed and metal internalized in Hyalella Azteca collected from Long Lake.

- Our depuration experiments showed that metal concentrations in amphipods after 48 hours of depuration were lower than those obtained in amphipods without evacuation (0 hours), but these differences were not significant.

Vertebrates:

- In liver cells of Northern pike (NP; *Esox lucius*) and Lake whitefish (WF; *Coregonus clupeaformis*), total metal concentrations also showed contrasting differences among sample sites. Fish from Long Lake (As) and Yellowknife Bay sites (Sb, Cd, La, and Ce) are more contaminated than those collected from Small Lake (which was the site furthest from legacy mining sources).

- Relevant bioaccumulation gradients were also observed for both fish species for La (WF: 84), Ce (WF: 84), Cd (NP: 54) and Sb (WF: 39). In general, WF liver was consistently more contaminated (e.g., As, Sb, La et Ce) than hepatic cells of NP.

- Analyzes of trace elements at the subcellular level after the application of an optimized protocol in each of these aquatic organisms are in progress and we expect that the results will provide valuable information on the metal-handling strategies used by these organisms to cope with these contaminants.

Project component 3: Photooxidation of arsenic in remote and mine-impacted northern freshwaters

- We conducted short-term laboratory photochemical experiments using natural waters from remote thaw ponds and lakes from the High Arctic and lakes from a mining region near Yellowknife. As(III) added to the samples was rapidly photooxidized into the less toxic, less mobile As(V) in all samples, whereas very low dark oxidation was observed (See figure below). This photooxidation was influenced by organic matter and controlled by UV radiation. Short-lived radicals were involved. Samples unamended with As(III) but naturally containing it yielded higher oxidation rates. Further studies are warranted to determine the biogeochemical significance of this oxidative process in the changing North.

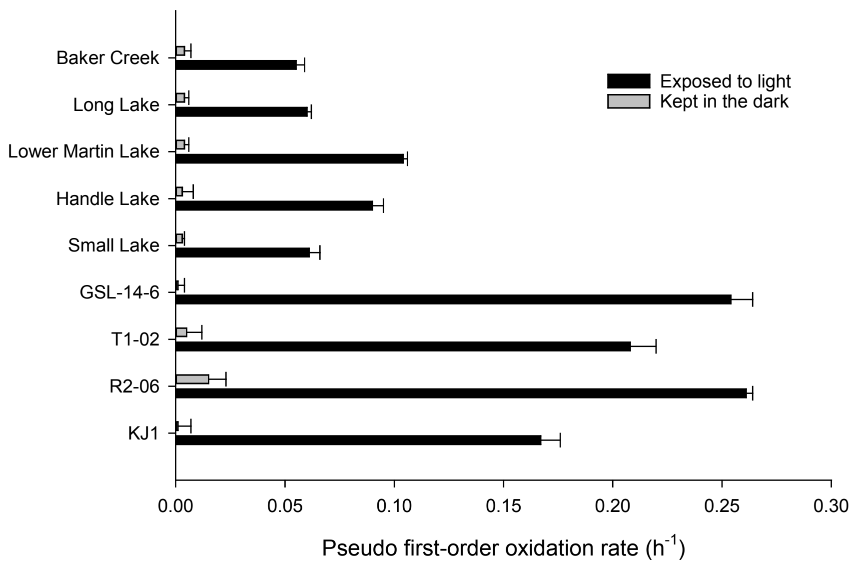

Fig. 7. Experimental oxidation rates (As(III) to As(V)) for water samples collected in lakes and ponds across the subarctic. These data show rapid oxidation of As(III) to As(V) in the presence of UV light. Oxidation rates were much slower when samples were kept in the dark.

6) Resource Management Implications

In this section, describe how the results will apply to northerners, particularly environmental regulators, Aboriginal organizations, and community members. (3-5 bullets)

- We developed a high-frequency water quality dataset for Lower Martin Lake, which is the last lake before Baker Creek enters the Giant Mine property. These data were shared with the Giant Mine Remediation Team (GMRT) to support the Baker Creek water quality model that was developed for the site.
- We developed a mechanistic understanding of processes affecting water quality in Lower Martin Lake. This has given regulators and the GMRT the tools to better predict downstream loading of As and other metals in Baker Creek.
- Our findings on the role of winter conditions on annual lake water quality has highlighted the

importance of this understudied part of the year on the recovery of mining impacted lakes. This information is applicable for shallow lakes across the region and is relevant for future projects beyond the mine lease boundary of Giant.

- The information from this study has been provided to the Office of the Chief Public Health Officer and has been integrated into the public health advisory re: arsenic in local lakes.

7) Project Linkages

Please state how NWT decision-makers and communities engaged in the project. Identify any new linkages that have emerged during the project and the value of those new linkages. E.g. A new decision-maker has been identified that can use the data or results. Include a list of dates and times of meetings and presentations with communities and/or decision-makers. Include a description of who attended the meetings. (Suggest 2 paragraphs)

This project has strengthened relationships between the research team and several decision makers in the NWT. Specifically, we have worked closely with the Office of the Chief Public Health Officer to integrate the results of this project into ongoing work related to understanding public health risks to As exposure in the region. We have also strengthened our relationship with the Giant Mine Remediation Team and water quality data from this study was shared with the GMRT (July 13, 2020) for use in the water quality model for the Giant Mine site.

8) Contribution to understanding

This section demonstrates the progress that has been made over the life of the project.
Part 1*: Check all boxes that apply* ***for the entire project life****, and provide a brief explanation in Part 2.*
Part 2: *Provide a brief description and explanation of each of the areas checked in Part 1. Use clear language that will be understandable by those who are not experts in the project area. Provide enough detail to give an understanding of the progress that was made and its significance. It should be clearly articulated how the project advances the understanding of cumulative impact monitoring in the NWT.*

Part 1

Monitoring and research conducted *during the project life* led to:		
New or enhanced knowledge in the field of study	☒	**1.**
New or enhanced knowledge of cumulative effects	☐	
Directly impacted a current decision-making process (1)	☐	
Could contribute to a future decision-making process	☒	2.
Development of a standardized monitoring protocol(s)	☐	
Adoption of standardized monitoring protocol(s) by decision-maker	☐	
Responded to a community concern	☒	3.

New or enhanced community capacity (2)	☐	
New or enhanced analytical tool	☒	4.
New or enhanced modeling capacity	☐	
Other (please specify, insert rows as required)	☐	

Part 2 - Must provide evidence that the project results have been directly used in a NWT environmental decision-making process between April 1, 2019 and March 31, 2020.

1. **New or enhanced knowledge in the field of study:** Information generated from this research has highlighted the importance of understanding the role of winter processes on the recovery of small shallow lakes impacted by legacy arsenic pollution. Early results have also highlighted the role of snowmelt processes on the oxidation and removal of As from the water column prior to freshet. This is an important concept, since this limits the downstream export of As.
2. **Could contribute to a future decision-making process:** Information from this project will help to inform the remediation of Giant Mine. Specifically, this project will provide important information on the upstream loading of arsenic to the mine site. Data from the project are currently being integrated in the Giant Mine water quality model.
3. **Responded to a community concern:** The impact of Giant Mine on local lakes has been a long-standing concern of the Yellowknives Dene First Nation and many residents in Yellowknife. This work led to a better understanding of how legacy deposited arsenic moves through the environment. Information generated from this study will also help to inform the public whether there are toxicological consequences of legacy pollution on the aquatic food chain.
4. **New or enhanced analytical tool:** We have refined a sediment incubation technique that can be used to measure the diffusive flux of elements from lake sediments to overlying lake waters. In addition, we are also optimizing/assessing a subcellular metal partitioning protocol for fish livers collected in the YK area using enzymatic biomarkers. Once the protocol is optimized, it will be used for incoming subcellular analyses.

9) Recommendations

In this section, provide recommendations regarding how the results of the project can be applied to advance the understanding of cumulative impacts in the NWT or how NWT CIMP can help to continue the transfer of this knowledge to NWT decision-makers and communities. Projects should clearly describe how the results and knowledge generated from the project could be used to make effective resource management decisions. Please explain the next steps to this project, if applicable.

- Results from this study show that lake sediments can be a substantial source of As, Fe, and Mn to surface waters. This can lead to much higher concentrations of these elements under ice and is likely contributing to the delayed recovery of shallow lakes in the region from legacy mining pollution.
- Future studies and regulatory sampling should consider the winter remobilization of As, Fe, and Mn in their design.

- Our results also show that shifting patterns in winter hydrology, due to climate change, can alter the connectivity between waterbodies, which may alter the mobility of As. The maintenance of oxygenated conditions under ice can suppress the release of As to overlying waters.
- Ongoing work for this project is being directed at understanding the remobilization of As and other contaminants from terrestrial to aquatic environments. This flux is poorly understood in the region, but may constitute an important contribution.
- Ongoing work continues on the subcellular partitioning of elements in fish species. This will help to support our understanding of the toxicological consequences of legacy mining on fish in the region.

10) Key Messages

Provide (in bullet form) the key messages and/or results of this project. Maximum of 5 bullets. These are high level summary points.

- Winter remobilization of As from lake sediments to overlying surface water leads to higher under ice concentrations of As in shallow lakes. This may be delaying recovery of shallow lakes in the region from legacy mining impacts.
- Changing winter hydrology can alter As cycling under ice. Increased connectivity and delivery of oxygen under ice can suppress the upward diffusion of As from contaminated sediments.
- Short-term experiments showed that As(III) in surface waters is rapidly oxidized to As(V) by sunlight.

11) Anticipated Publications

Please provide a list of anticipated publications related to the project. Include the title, the type of publication and the expected date of completion.

Palmer, M.J., Chételat, J., Jamieson, H., Richardson, M., and Amyot, M. 2020. Hydrologic control on winter dissolved oxygen mediates arsenic cycling in a small subarctic lake. Limnology and Oceanography.

Palmer, M.J., Chételat, J.C., Jamieson, H., Richardson, M., and Galloway, J. 2019. Seasonal variation of arsenic and antimony in surface waters of small subarctic lakes impacted by legacy mining pollution near Yellowknife, NT, Canada. Science of the Total Environment, 684: 326-339.

Palmer, M.J., Richardson, M., Chételat, J., Jamieson, H.E., Spence, C, Connon, R., Van Der Sluijs, J. (In prep). Arsenic mass balance model for a small watershed impacted by legacy mining pollution.

Rolland, A., Palmer, M., Chételat, J., Amyot, M., Rosabal, M. (In prep). Subcellular partitioning of trace metals (As, Ag, Cd, Sb, La, and Ce) in livers of Northern pike (*Esox lucius*) and Lake whitefish (*Coregonus clupeaformis*) from the mining-impacted Yellowknife area (NWT, Canada). Environmental Pollution.

Labrie, J., Palmer, M., Chételat, J., Amyot, M., Rosabal, M. (In prep). Subcellular accumulation of trace metals in amphipods from mine-impacted water bodies in Yellowknife region, Northwest Territories, Canada. Aquatic Toxicology.

Amyot M, Simon D, Chételat C, Palmer M, Ariya P, Laurion I. (In prep). Photooxidation of arsenic in remote and mine-impacted northern freshwaters.

12) Acknowledgements

If applicable.

We greatly appreciate logistical support from the NWT Geological Survey and Taiga Environmental Laboratory. Field support was provided through Environment and Natural Resources, GNWT, including from

Mike Palmer and Ryan Gregory. Additional field support was greatly appreciated from Dwayne Wohlgemuth, Ty Hamilton, Michael Gilday, Jack Panayi, and Jonathon Mackenzie. Judy Mah, Glen Hudy, Bruce Stuart, and Brad Koswan provided space and analysis at Taiga Lab and were critical to the success of the project.

13) Literature Cited

Final reports must provide appropriate citations.

Fawcett, S. E., H. E. Jamieson, D. K. Nordstrom, and R. B. McCleskey. 2015. Arsenic and antimony geochemistry of mine wastes, associated waters and sediments at the Giant Mine, Yellowknife, Northwest Territories, Canada. Appl. Geochemistry **62**: 3–17. doi:10.1016/j.apgeochem.2014.12.012

Galloway, J. M., G. T. Swindles, H. E. Jamieson, and others. 2017. Organic matter control on the distribution of arsenic in lake sediments impacted by ~ 65 years of gold ore processing in subarctic Canada. Sci. Total Environ. doi:10.1016/j.scitotenv.2017.10.048

Palmer, M. J., J. M. Galloway, H. E. Jamieson, R. T. Patterson, H. Falck, and S. V Kokelj. 2015. The concentration of arsenic in lake waters of the Yellowknife area. NWT Open File 2015-06. NWT Geological Survey. 29 pages.

14) Appendices

Attach Appendices as appropriate.

Pre-layout copies of two published papers are included as appendices (following copyright rules):

Palmer, M.J., Chételat, J., Jamieson, H., Richardson, M., and Amyot, M. 2020. Hydrologic control on winter dissolved oxygen mediates arsenic cycling in a small subarctic lake. Limnology and Oceanography.

Palmer, M.J., Chételat, J.C., Jamieson, H., Richardson, M., and Galloway, J. 2019. Seasonal variation of arsenic and antimony in surface waters of small subarctic lakes impacted by legacy mining pollution near Yellowknife, NT, Canada. Science of the Total Environment, 684: 326-339.

Email your submission to: NWTCIMP@gov.nt.ca

Final Report Submission Form Checklist

Completed final reports must be sent to NWT CIMP electronically and must be received on or before April 30. All information required for the evaluation of your project ***must*** *accompany the report, including all deliverables. NWT CIMP may request additional information after review of the report.*

A complete annual report should include:

- ✓ A complete final report form.
- ✓ A complete final budget.
- ✓ All deliverables as stated in the original proposal and subsequent annual reports (if not yet submitted to NWTCIMP). If not available, provide reason.
- ✓ Other supporting information *(if applicable)* such as site maps, photos, plans and specifications.

Contact Us!

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