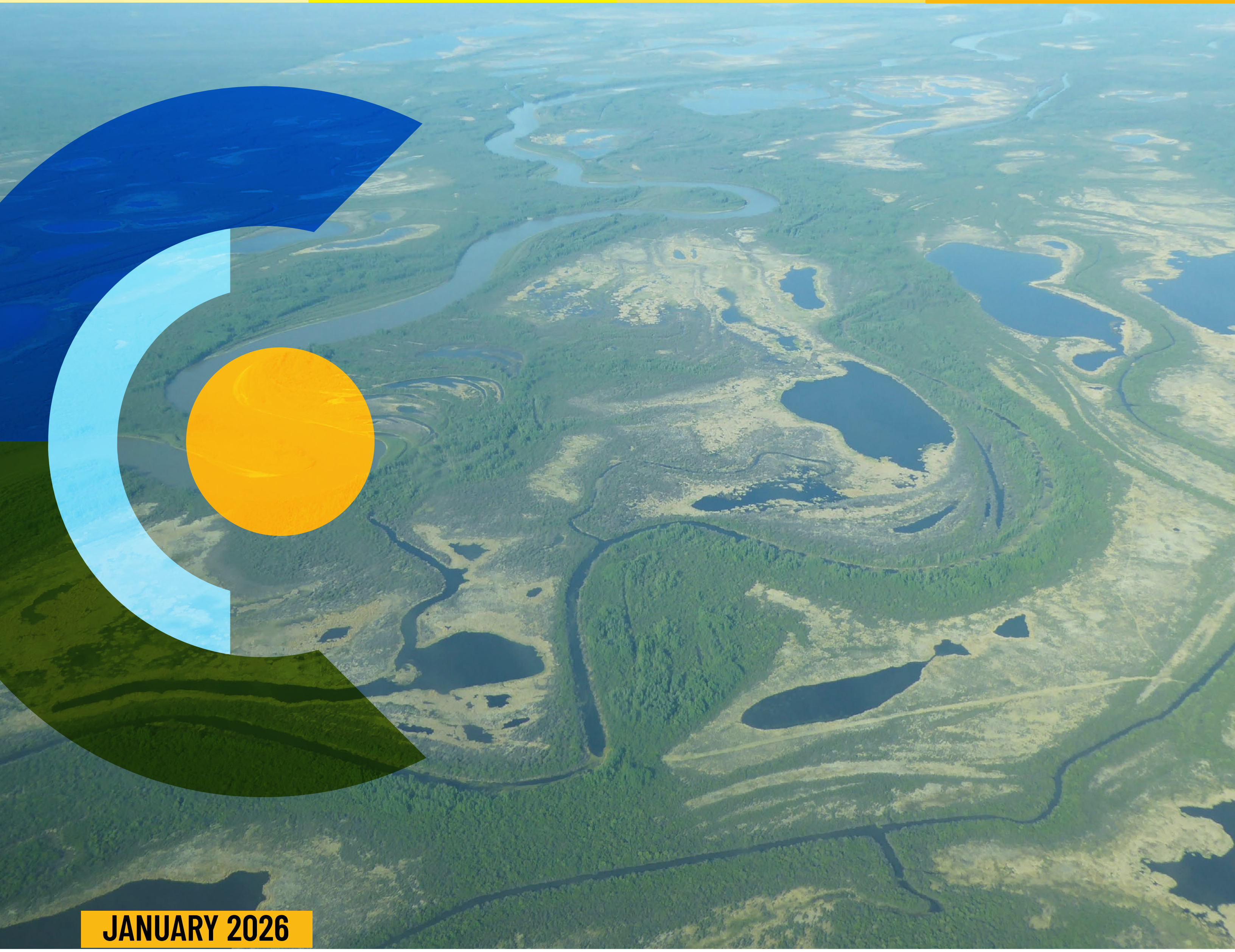

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Safeguarding the Peace-Athabasca Delta: Recommendations for a Lake Monitoring Program to Inform Policy

Waterloo Climate Institute Policy Brief

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ABSTRACT

International, federal and Indigenous governance bodies have issued urgent calls to implement long-term monitoring of lakes at the Peace-Athabasca Delta (PAD), the world's largest freshwater boreal delta, to safeguard its freshwater resources from threats posed by major energy projects and climate change, and to inform stewardship decisions. Drawing on knowledge gained from 7 years of research, we offer action-oriented solutions to address key challenges that have long impeded establishment of an effective, sustainable lake monitoring program. We acknowledge that decisions to implement a lake monitoring program must be made with input from many stakeholders and rightsholders, and they must be informed by multiple knowledge systems, including the deep place-based knowledge of Indigenous communities whose lives are intricately connected to the land and waters of the Delta. Here we offer insights from our Western-science-based research to propose methods and approaches that generate information capable of detecting aquatic ecosystem degradation, identifying the probable cause(s), and evaluating the effectiveness of stewardship decisions. The latter includes assessing the success of installing weirs in the Delta to raise lake levels and using strategic water releases from the W.A.C. Bennett Dam to trigger ice-jam flooding – remediations that are currently under consideration by the federal Action Plan for Wood Buffalo National Park (WBNP) to mitigate the decline of freshwater availability in the Delta that has occurred in recent decades.

Keywords: Lake monitoring; Environmental degradation; Multiple stressors; Peace-Athabasca Delta; Wood Buffalo National Park World Heritage Site.

KEY MESSAGES:

- The Peace-Athabasca Delta (PAD) is recognized as a Ramsar Wetland of International Importance for its ecological and cultural significance, and it is a major contributor to the UNESCO World Heritage status of Wood Buffalo National Park (WBNP).
- International, federal and Indigenous governance bodies have issued urgent calls for effective and sustainable lake monitoring of freshwater availability and contaminant deposition that may be caused by major energy projects (hydroelectric dams, oil sands mines) and climate change.
- Key challenges to designing an effective and sustainable lake monitoring program include: **1)** The Delta's vast size, hydrological complexity and difficult-to-access lakes pose formidable obstacles to monitoring across informative scales of space and time, and **2)** The methods must be informative, sustainable and able to track changes in freshwater availability and contaminant deposition, and the cause(s).
- We present solutions to these challenges based on 7 years of multi-faceted research at 60 lakes. The new knowledge is now available to inform the design and implementation of a Delta-wide monitoring program capable of safeguarding lakes potentially threatened by multiple stressors, identifying the probable cause(s) and evaluating the effectiveness of stewardship decisions, including those under consideration by the federal Action Plan for WBNP.

INTRODUCTION

A LAKE MONITORING PROGRAM IS URGENTLY NEEDED AT THE PEACE-ATHABASCA DELTA

Effective and sustainable monitoring of lakes across the Peace-Athabasca Delta (PAD) is urgently needed. Athabasca Chipewyan First Nation (ACFN), Mikisew Cree First Nation (MCFN), and Fort Chipewyan Métis Nation (FCMN) have long relied on the Delta's intricate waterways and the resources provided by its vast array of ecosystems to sustain their cultural identities, traditions and ways of life (Timoney 2013; Vannini and Vannini 2019; WSSS 2021). This expansive (~6000 km^2) floodplain lies downstream of major petroleum and hydroelectric energy projects and other stressors in the watershed (e.g., conventional oil and gas, pulp mills, effluent and runoff from industries and municipalities, etc.). Potential environmental consequences from these developments are further compounded by changes in climate, including at the alpine headwater areas of the Peace and Athabasca rivers in the Rocky Mountains, which threaten to alter critical water supplies to much of northwestern Canada (Wolfe et al. 2012; Bonsal et al. 2020; Lamontagne et al. 2021). Collectively, these factors introduce multiple potential stressors to the Delta's thousands of vulnerable, shallow lakes. Without effective and sustainable long-term monitoring, cumulative effects of stressors and the causes will remain difficult to identify.

The Delta is recognized as a Ramsar Wetland of International Importance and contributes to Wood Buffalo National Park's (WBNP) designation as one of Canada's 22 UNESCO World Heritage Sites. Despite protections afforded by these designations, MCFN has petitioned for WBNP (which contains 80% of the Delta) to be included on UNESCO's List of 'World Heritage in Danger' due, in part, to inadequate monitoring for detecting degradation of the Delta's aquatic ecosystems that may have occurred because of upstream industrial developments (MCFN 2014). Ensuing investigations have issued urgent calls to implement a long-term lake monitoring program at the Delta capable of detecting changes to freshwater availability and contaminant deposition and the cause(s), and to evaluate the effectiveness of stewardship decisions (MCFN 2016; WHC/IUCN 2017, 2023; IEC 2018; WBNP 2019).

BACKGROUND/RELEVANT FACTS

- **Late 1960s:** Commercial oil sands production begins in 1967 along the Lower Athabasca River. Hydroelectric regulation of Peace River flow commences in 1968 with operation of the W.A.C. Bennett Dam.
- **Early 1970s:** The Peace-Athabasca Delta (PAD) Project Group issues the first formal recommendation for long-term monitoring at the Peace-Athabasca Delta to track degradation of the Delta's lakes and determine the cause(s) (PADPG 1972).
- **1990s:** The PAD Technical Studies (PADTS 1996) and Northern River Basins Study (NRBS 1996) reiterate the need for long-term monitoring to: "*provide a better understanding of ecosystem function, provide baselines against which changes in the health of the delta can be detected and measured, and permit evaluation of the success of restoration efforts*" (PADTS 1996).
- **1997:** The Regional Aquatics Monitoring Program (RAMP) is established to understand the potential effects of oil sands development on aquatic ecosystems, then is replaced by the Joint Canada–Alberta Oil Sands Monitoring (JOSM) program in 2012 and Oil Sands Monitoring (OSM) in 2015. They focus on the Lower Athabasca River watershed and include a few river sites and flood-prone lakes in the Delta.
- **2008:** Indigenous-led community-based monitoring programs begin in the PAD to assess for environmental changes that impair safe access and use of traditional lands and food sources, as per Section 35 (Aboriginal and Treaty Rights) of the Constitution Act 1982 (Maclean et al. 2021). These programs sample mainly boat-accessible sites at rivers and river-connected lakes. In partnership with WBNP, several upland lakes are monitored in winter for muskrat abundance and water depth.
- **2014:** Mikisew Cree First Nation formally petitions that UNESCO inscribe WBNP on the List of 'World Heritage In Danger', in part because "*provincial and federal monitoring of the effects of upstream activities and climate change on WBNP and the PAD has been wholly inadequate*" (MCFN 2014, p. 34).
- **2016-2017:** In September 2016, a joint Reactive Monitoring Mission led by the World Heritage Committee and International Union for Conservation of Nature formally assesses the state of conservation of the Park and the potential threats to its Outstanding Universal Value. The Mission's report concludes that Canada should be given a single opportunity under the World Heritage Convention to promptly develop a structured and adequately funded response addressing all 17 of their recommendations (WHC/IUCN 2017). Among the recommendations is to: "*Expand the scope of monitoring and project assessments to*

encompass possible individual and cumulative impacts on the Outstanding Universal Value of the property and in particular the PAD" (WHC/IUCN 2017, p. 4).

- **2019:** Canada releases a federal Action Plan for WBNP and commits $87 million to ensure its successful implementation (WBNP 2019).
- **2022-2023:** In August 2022, a second joint Reactive Monitoring Mission reassesses the conservation status of WBNP, reviews progress on recommendations from the first joint Mission, evaluates the implementation of the federal Action Plan, concludes that inscription on the List of 'World Heritage In Danger' is not warranted at this time, and recommends ongoing monitoring and a follow-up Mission in 2026 (WHC/IUCN 2023).
- **2024:** Canada provides an update to WHC and IUCN on the conservation of WBNP and the progress in responding to recommendations from the 2022 Mission and implementation of the federal Action Plan (State Party of Canada 2024).
- **2025:** The Oil Sands Mine Water Steering Committee issues recommendations for Alberta and Canada regarding standards for releasing treated oil sands mine wastewater into the Athabasca River (OSMWSC 2025), reigniting concern for environmental degradation of the Delta (Meyer 2025).
- **2026:** WHC and IUCN will reassess progress and decide whether to downgrade WBNP's conservation status to 'World Heritage In Danger'.

KEY CHALLENGES AND PROPOSED SOLUTIONS

Based on 25 years of research in the Delta by the senior authors, which culminated in the 7-year-long study to inform monitoring approaches (reported in Neary et al. 2024), we have identified key challenges that have impeded the implementation of an effective, sustainable Delta-wide lake monitoring program and we offer solutions.

With critical support from Parks Canada Agency and local Community Based Monitoring (CBM) programs, 21 seasonal (spring, summer, fall) sampling campaigns were conducted at 60 well-dispersed lakes across the Delta from 2015 to 2021 (Figure 1). To track changes in hydrology and water quality, water samples were collected seasonally for measurement of water isotope composition and water chemistry, and continuous water-level measurements were recorded using depth loggers. In two of the years, we measured metal concentrations in surface sediments to determine if oil sands development and other industrial activities have contaminated waterbodies.

Beyond generating a rich dataset, the study provided insights into the most critical logistical, methodological and design challenges that must be addressed before establishing a Delta-wide lake monitoring program. Below, we highlight the key challenges and propose practical solutions to support decision makers, stakeholders and rightsholders, and to UNESCO committee members who will soon determine whether Wood Buffalo National Park's (WBNP) status should be downgraded to 'World Heritage In Danger'.

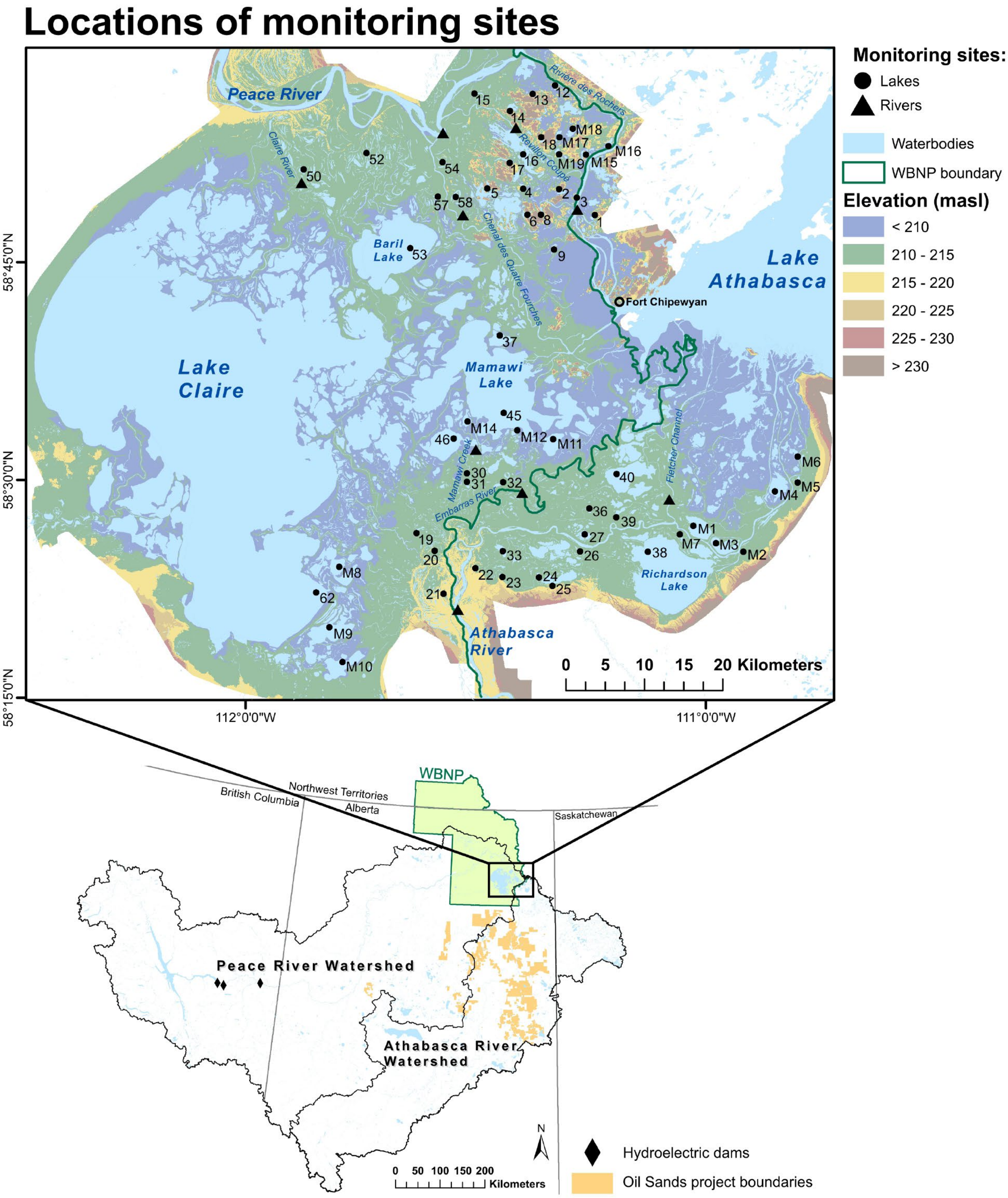


Figure 1. The upper map shows the locations of 60 lakes and 9 river sites sampled in the Peace-Athabasca Delta from 2015-2021. The river sites are used to characterize the water isotope composition and chemistry of floodwaters that may influence values measured in the lakes when flooded. The lower map shows the location of key industrial operations, including upstream hydroelectric dams on the Peace River and oil sands mining boundaries. Figure reproduced from Neary et al. (2024).

CHALLENGE #1: The Delta's vast size, hydrological complexity and difficult-to-access lakes pose formidable obstacles to monitoring across informative scales of space and time.

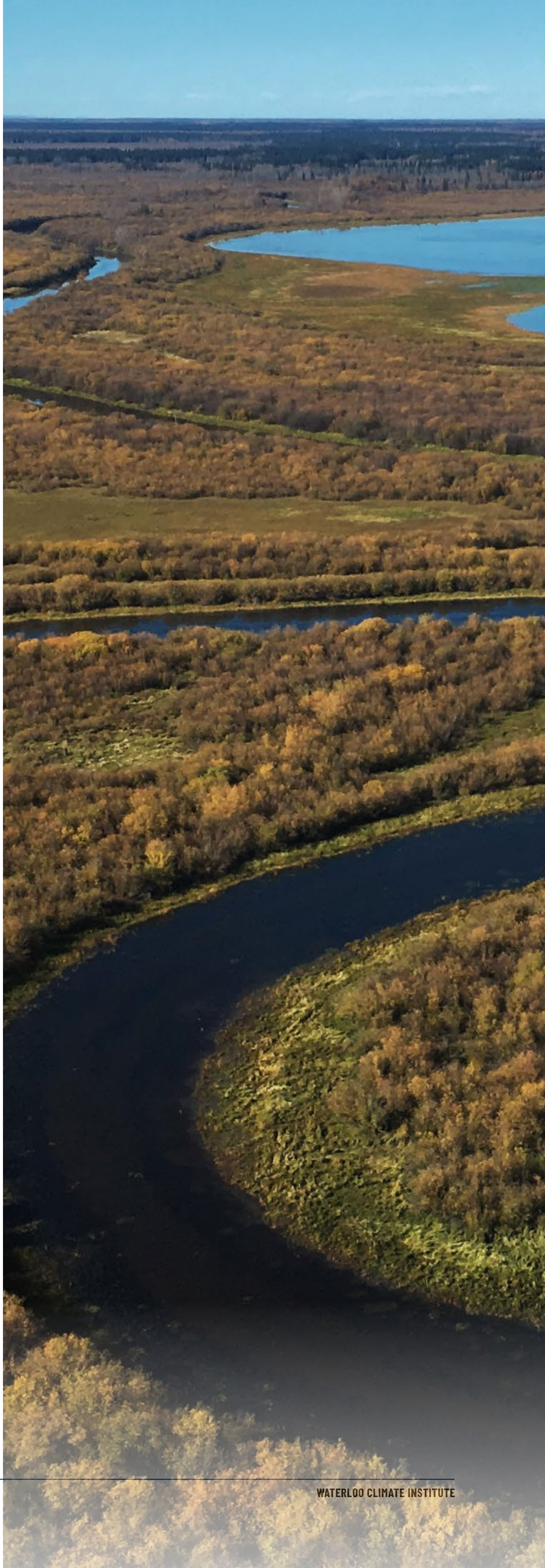
The hydrological processes that control lake water balances vary immensely across the vast, remote, dynamic and complex Delta (Timoney 2013, 2024; Neary et al. 2021, 2024). Open-drainage lakes occupy the lowest elevations, where they receive continuous through-flow of river water. Their water levels vary with river flow and evaporation has minor influence on their water balance. At the other end of the hydrological gradient, closed-drainage lakes occupy the highest terrain and receive input of floodwater only during infrequent ice-jam flood events. Their water levels respond mainly to changes in snow, rain and evaporation, and they are the most prone to drying up. Between these end members are restricted-drainage lakes which receive frequent input of floodwaters, including in summer when river flow is high. Effective long-term monitoring should include representation of lakes in all three categories, which is not easy to achieve because restricted- and closed-drainage lakes are difficult to access.

Additional complexity arises because there are two main rivers that variably influence lake levels and lake water balance (Remmer et al. 2020a,b; Neary et al. 2021, 2024). The undammed Athabasca River flows through the southern portion of the Delta after traversing the Alberta Oil Sands Region (AOSR) where mining and processing activities may increase supplies of substances of concern. As a result, most of the attention is on the risk of pollution from the Athabasca River, especially since legislation may soon allow operators to discharge treated mine wastewater directly into this river (Alberta EPA 2024; OSMWSC 2025). Of note, floodwaters from the Athabasca River do not spread out evenly across the Delta. Rather, they tend to be influenced by the Embarras Breakthrough, a natural event in 1982 that re-directs river flow towards central areas of the Delta and away from low-lying south-eastern areas at the terminus of the Athabasca River (Wolfe et al. 2008; Kay et al. 2019). The Peace River flows along the northern margin and regulates the rate of outflow from the Delta when flow is sufficiently high to overcome resistance from weirs installed in 1976. Peace River flow has been regulated for hydroelectricity production since 1968, and concerns center on the possibility that operation of the W.A.C. Bennett Dam has reduced ice-jam flooding and caused closed- and restricted-drainage lakes to dry up (Beltaos 2018; Wolfe et al. 2020). The concern has increased with operation of the Site C Dam in 2025. Differences in the flow regimes of the two rivers will likely elicit different responses of lakes to climate change in the southern Athabasca sector of the Delta versus the northern Peace sector, as demonstrated for the past several decades (Kay et al. 2024).

PROPOSED SOLUTION #1: Monitor a representative suite of lakes to capture the broad hydrological gradients and generate information reflective of the entire Delta.

Because of the Delta's vast size, two influential rivers, and broad hydrological gradients, a substantial number of lakes and rivers must be monitored to detect when and where changes occur, determine the potential cause(s), and inform stewardship decisions and actions. Thus, selection of sites for monitoring must include lakes in all three hydrological categories (open-, restricted- and closed-drainage) and span both the Athabasca and Peace sectors of the Delta. There are only three open-drainage lakes, which occupy southern (Richardson Lake) and central (Lake Claire, Mamawi Lake) areas of the Delta (Figure 1). They are fed mainly by the Athabasca River, and monitoring is recommended at all of them to capture variation in influence of river flow and for early detection of contamination from upstream industrial activities. Restricted- and closed-drainage lakes are abundant in both sectors, but their responses to climate change and major energy projects can be expected to differ, because closed-drainage lakes are the most responsive to changes in the ice-jam flood regime whereas restricted-drainage lakes are more vulnerable to contamination from oil sands mining and other industrialization.

Our 7 years of research have established a rich database from 60 lakes that capture the broad gradients and hydrological complexity of the Delta (Figure 1).



CHALLENGE #2: Monitoring methods must be informative, sustainable and able to track changes in freshwater availability and contaminant deposition, and their cause(s).

Prominent methodological challenges have long impeded effective monitoring of freshwater availability and contaminant deposition in the Delta. Numerous hydrological processes can influence lake water balances over varying scales of space and time, including ice-jam and open-water flooding, snowmelt and rainfall, and evaporation. The net outcome of these processes, at any given time, can be considered a measure of freshwater availability across the Delta, and discerning which hydrological processes are most influential is key to identify the cause(s) of change. Thus, the methods employed require nimbleness and sensitivity to the varying effects of these hydrological processes on lake water balances.

The foundation of effective sediment quality monitoring requires knowledge of reference conditions before oil sands development and other industrialization began to characterize natural variation and accurately detect contamination from human activities. Indeed, calls for improved characterization of reference conditions occurred more than a decade ago (e.g., Dowdeswell et al. 2010).

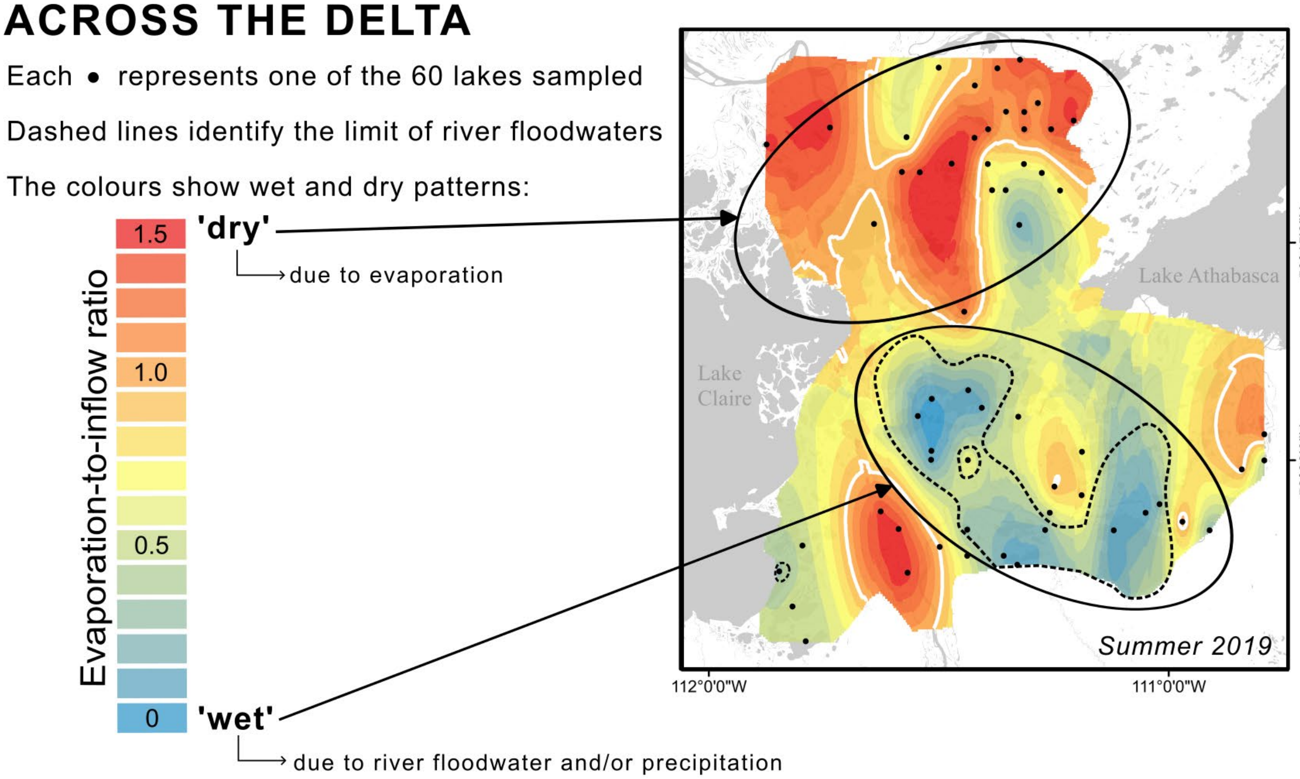
As summarized below, our research has developed and applied approaches that overcome these methodological challenges, and which can readily be implemented for ongoing monitoring in the Delta.

PROPOSED SOLUTION #2: Use easy-to-obtain samples and well-established measurements that provide high information content for detecting changes in freshwater availability and contaminant deposition, and the cause(s).

Rapid collection of water samples, and use of depth loggers, to evaluate changes in freshwater availability by industrial activities and climate change: Our research demonstrates the value and insights provided by rapid collection of small samples of water (30 ml) during three seasonal surveys (spring, summer, fall) per year and measuring the water isotope composition to track hydrological processes affecting lakes over space and time. This includes ability to determine the main input water sources (snow, rain, river floodwater), generate flood maps, and quantify the importance of evaporation on lake water balances (Remmer et al. 2020a,b; Neary et al. 2024). These samples require no pre-treatment or special handling before analysis, which may be attractive to monitoring programs because this minimizes costs for training of staff and for storing and transporting the samples. Measurements of water isotope composition are inexpensive and can be used to compute evaporation-to-inflow (E/I) ratios, which provide accessible information about the status of each lake's water balance. For example, E/I ratios greater than 1.0 occur when water loss by evaporation exceeds inflow, which identifies water-level drawdown. Samples collected in spring inform about the influence of snowmelt and ice-jam flooding, which are critical sources that sustain water levels during summer. Samples collected in summer and fall inform about the influence of rainfall, open-water season flooding and evaporation. Depth loggers installed in spring and retrieved in fall provide continuous, high resolution (e.g., hourly) complementary measurements of water-level change that identify the influence of short-lived events (e.g., river flooding, snowmelt runoff, intense rainfall) and the amount of drawdown (Neary et al. 2021, 2024; Imran et al. 2025).

Maps are highly effective for communicating large amounts of complex, often technical, information in a form that is readily interpretable by a range of audiences. A key example from our research is the display of E/I ratios as maps (or 'isoscapes'), which show variation over space and time in lake water balances (Figure 2). One isoscape is generated for each seasonal sampling campaign and provides a snapshot of variation in freshwater availability across the Delta. Many of them reveal marked spatial variation, including 'hotspots' where lakes are drawing down by evaporation (these are the orange and red areas in Figure 2 where E/I ratios exceed 1.0) and areas where inflow exceeds evaporation because lakes received recent input of floodwaters (the blue areas in Figure 2 within black dotted lines where E/I ratios are below 0.5). The spatial variation is particularly apparent in summer of 2019 when unusually high Athabasca River flow caused extensive open-water flooding in the central portion of the southern Athabasca sector, while arid weather caused E/I ratios to exceed 1.0 in the northern Peace sector and non-flooded portions of the Athabasca sector. In contrast, isoscapes for all three seasons in 2020 and 2021 display consistently low E/I ratios due to substantial input of river floodwater, snowmelt and rainfall. Indeed, compilation of isoscapes from all 21 sampling campaigns reveals increasing areas with blue hues, which demonstrates a marked rise of freshwater availability between 2015 and 2021.

WATER ISOTOPES TRACK FRESHWATER AVAILABILITY ACROSS THE DELTA



Each map below shows variation in freshwater availability across the Delta in spring, summer and fall of 2015-2021

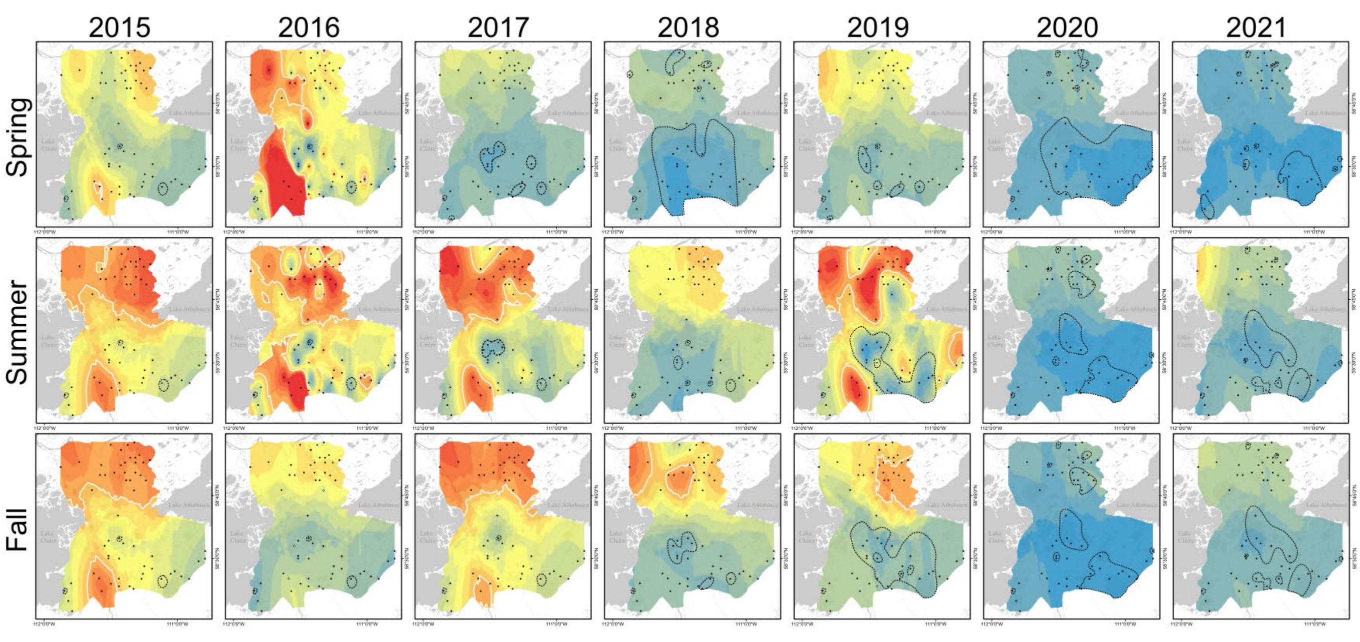


Figure 2. Maps (isoscapes) depicting the distribution of lake evaporation-to-inflow (E/I) ratios across the Peace-Athabasca Delta from 2015–2021, with warm colors indicating relatively high evaporation and cool colors indicating relatively high inflow from snowmelt, river floodwater and rainfall. Figure modified from Neary et al. (2024).

Several years of consistent, systematic measurements are needed to detect directional trends and cycles in lake water balance, and to identify the probable cause(s). For instance, display of average E/I ratios for the 60 lakes during 7 years (2015-2021) of seasonal sampling and their comparison to an index that characterizes climate variation in western Canada (the Oceanic Niño Index (ONI) of the El Niño Southern Oscillation (ENSO)) offers insights into the primary drivers of change in freshwater availability in the Delta (Figure 3). This climate index displays strikingly common patterns with the modelled trendline of average E/I ratios for lakes across the Delta. During 2015 and 2016, scarce freshwater availability (average E/I ratios near and above 1.0) aligns with strongly positive values of the climate index when an El Niño phase produced warm winters, thin snowpacks, and strong moisture deficits in western Canada. Extensive wildfires occurred in the region in 2016 (e.g., wildfire at Fort McMurray), which was then the globally hottest year on record. During 2017-2019, the climate index was near-neutral, and it corresponds with moderate freshwater availability (average E/I ratios near 0.5 and consistently below 1.0). A marked shift to strongly negative values of the climate index occurred after 2019, which denotes onset of a 3-year La Niña phase (2020-2022) that generated cool winters, thick snowpacks, and unusually high summer precipitation. Correspondingly, freshwater became abundant (average E/I ratios are below 0.3) across the Delta due to widespread flooding, above average precipitation and higher humidity. At this time, water levels in open-drainage lakes rose to the second highest elevation of the 94-year-long record.

When the 7 years of data are expressed as time-series of maps and trendlines, it is evident that freshwater availability in the Delta during this interval is strongly influenced by broad-scale climate patterns – knowledge that should help to inform decisions at UNESCO regarding their evaluation of a change to WBNP's World Heritage status.

FRESHWATER AVAILABILITY ACROSS THE DELTA RESPONDS TO SHIFTS IN CLIMATE

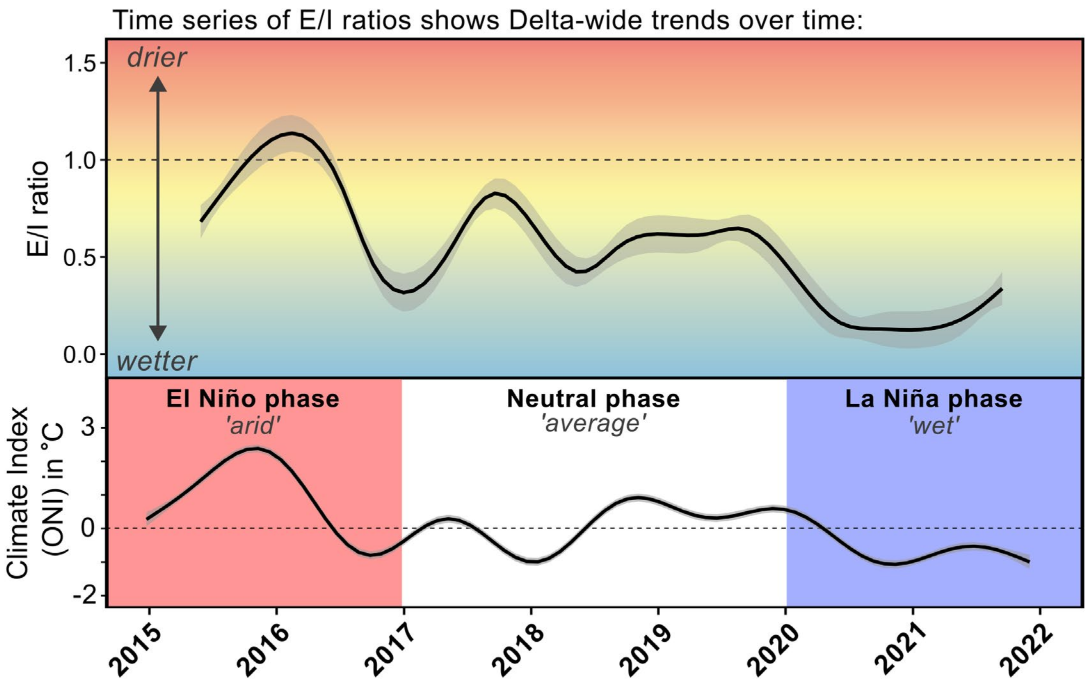
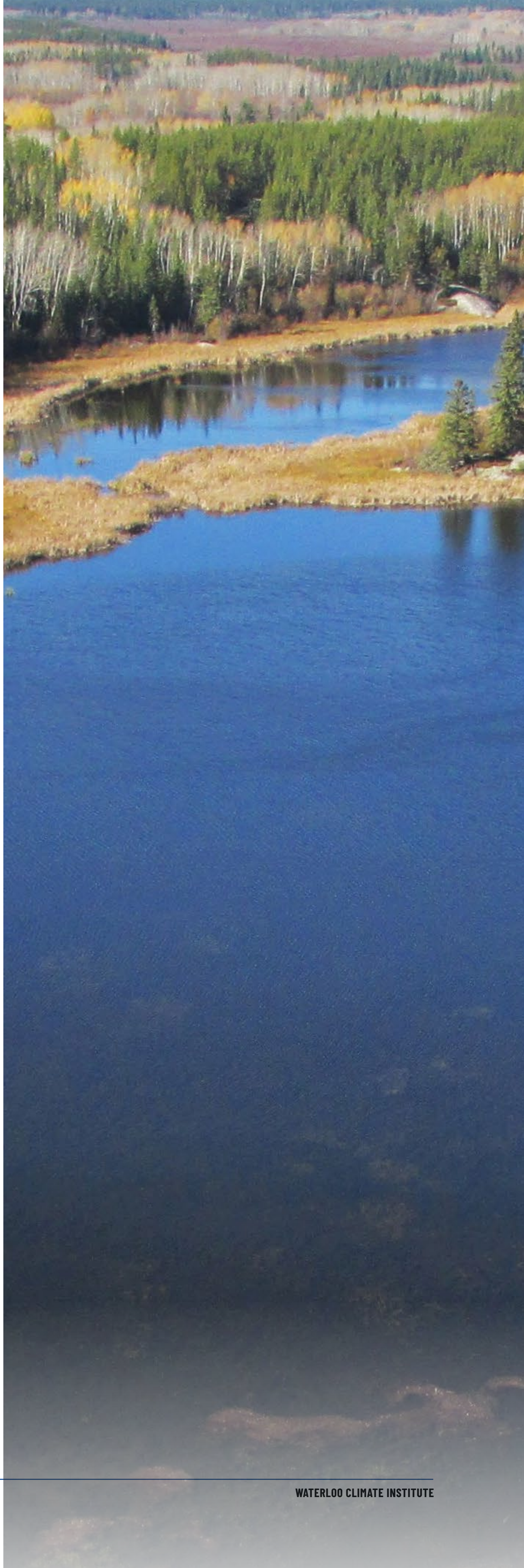


Figure 3. Correspondence of trendlines for lake evaporation-to-inflow (E/I) ratios across the Peace-Athabasca Delta (upper graph) and a climate index (Oceanic Niño Index (ONI)) (lower graph) reveals strong influence of climate on freshwater availability. Figure modified from Neary et al. (2024).

Rapid collection of lake surface sediment samples to evaluate for contamination by industrial activities: Many substances of concern emitted by industrial activities do not dissolve readily in water and, instead, tend to bind to particles (Shotyk et al. 2021). Thus, they are much more abundant in sediment than water, which poses advantages for use of sediment quality analysis to determine if oil sands development and other industrial activities contaminate aquatic ecosystems in the Delta. As demonstrated by our study (Neary et al. 2024) and prior research (Kay et al. 2020; Owca et al. 2020), rapid collection of samples of recently deposited lake surface sediment and measurement of the concentration of select oil-sands-indicator-metals, such as vanadium which is relatively abundant in the mined bitumen and mine wastes, provides an effective methodology to screen for evidence of contamination. We can quantify the enrichment caused by industrial sources by comparing the concentrations in surface sediment versus sediment deposited before industrialization – a unique strength of this approach. To achieve this, our program has generated 'pre-disturbance baselines' for vanadium, and for several other metals and polycyclic aromatic compounds (a class of organic molecules) in lake sediment, based on analyses of sediment deposited before 1920 in lakes and riverbanks in the Delta (Hall et al. 2012; Wiklund et al. 2012, 2014; Owca et al. 2020; Kay et al. 2023; Neary et al. 2024).

An increase of concentrations relative to the pre-disturbance baseline can be expressed as an Enrichment Factor (EF), which is the concentration in a surface sediment sample divided by the average concentration in the pre-disturbance baseline samples. An EF of 1 identifies no increase, whereas an EF of 2, for example, indicates a doubling of the concentration. Thresholds and terminology presented in a comprehensive review (Birch 2017) provide internationally consistent thresholds for this informative metric that represent "minimal enrichment" (EF >1.5-3.0), "moderate enrichment" (EF>3.0-5.0), "considerable enrichment" (EF>5.0-10.0), and "severe enrichment" (EF>10.0).

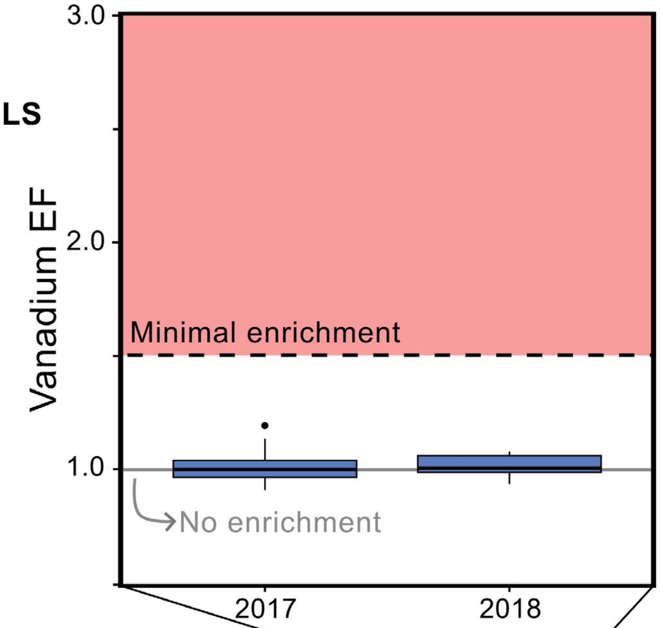
Our program has measured concentrations of a suite of metals in surface sediment collected from 60 lakes in the Delta in 2017, after several years without widespread flooding, and from 20 of the same lakes in 2018 soon after they were flooded by the Athabasca River (Owca et al. 2020). In these samples, the EFs for vanadium are consistently near 1.0 and well below the 1.5 threshold for "minimal enrichment", whether the lakes were recently flooded or not (top panel of Figure 4). This evidence indicates industrial activities have not increased concentrations of the oil-sands-indicator vanadium above natural concentrations that have long existed in the Athabasca River and the Delta. Should "minimal enrichment" of a cost-effective oil-sands-indicator metal be detected by a monitoring program in the future, we suggest this can trigger assessments for other substances of concern, such as polycyclic aromatic compounds, which are of great interest to stakeholders and rightsholders.



ENRICHMENT FACTOR CAN DETERMINE IF INDUSTRIAL ACTIVITIES HAVE INCREASED CONCENTRATIONS ABOVE NATURAL LEVELS

Boxplots show the range of vanadium Enrichment Factors for lake surface sediment collected in 2017 and 2018.

The dashed line at an EF of 1.5 identifies an internationally recognized threshold for "minimal enrichment" (Birch 2017).



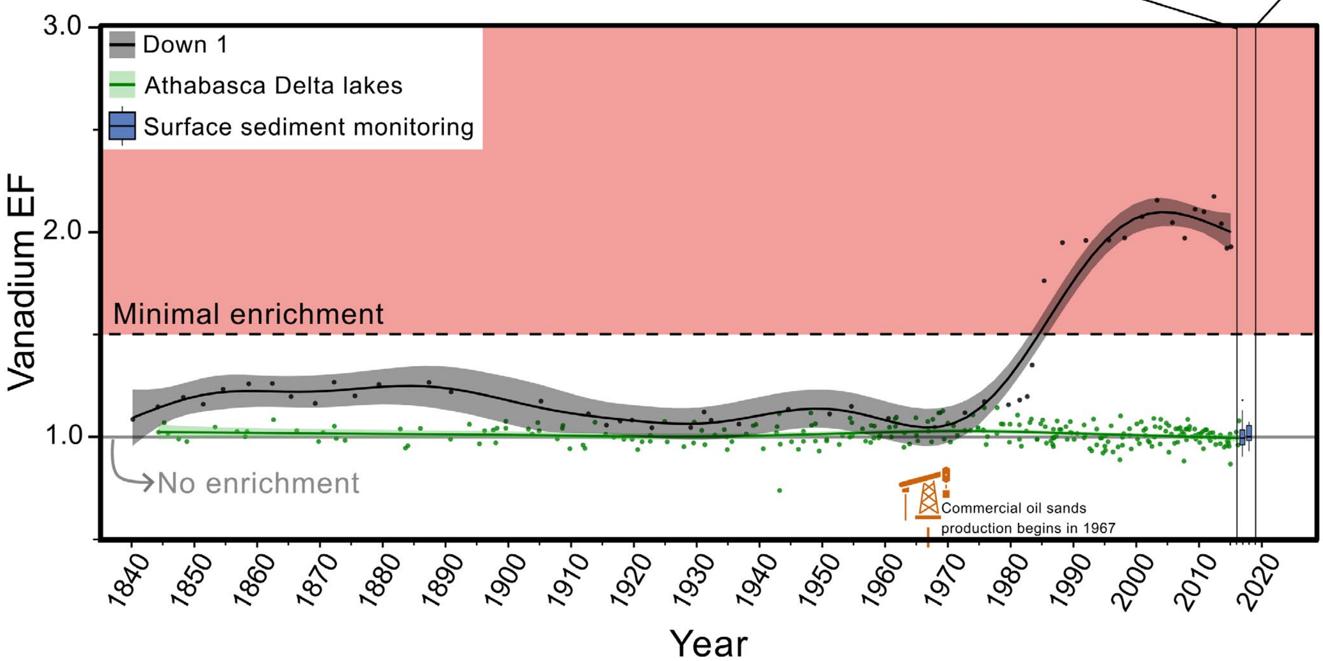


Figure 4. Upper panel: Boxplots showing the distribution of Enrichment Factors (EFs) for concentrations of the oil-sands-indicator metal vanadium in samples of surface sediment collected from 60 lakes in the Delta in 2017 (left boxplot) and from 20 of those lakes in 2018 shortly after they were inundated by Athabasca River floodwaters (right boxplot) relative to pre-disturbance (pre-1920) baseline concentrations. Bottom panel: Trendlines of vanadium Enrichment Factors for lakes near to (Down 1) and downstream (Athabasca Delta lakes) of Alberta oil sands mining operations. Surface sediment monitoring in 2017 and 2018 at lakes in the Athabasca sector of the Delta are shown as blue boxplots. Threshold for "minimal enrichment" (EF>1.5-3.0), identified by the horizontal, black-dashed lines and pink rectangles, is from Birch (2017). Data derived from Neary et al. (2024) and Klemt et al. (2020).

Inclusion of other contaminant data offer useful temporal and spatial perspectives. In the bottom panel of Figure 4, a trendline is shown for vanadium EFs in a sediment core from a flood-prone lake we named 'Down 1', located adjacent to the Athabasca River at the 'heart of oil sands development' (Klemt et al. 2020). The trendline remained near 1.0 between 1840 and early 1980s, indicating little to no enrichment when river levels were higher than at present and the lake was frequently flooded. After the mid-1980s, when Athabasca River levels dropped and the lake flooded infrequently, the EFs increased and exceeded 2.0. The "minimal enrichment" of vanadium documented after the mid-1980s at Down 1 is attributed to atmospheric deposition of industrial emissions as the river-derived pathway weakened. Detection of enrichment in sediment cores from this industry-proximal lake provides compelling evidence that measurement of metal concentrations in aquatic sediment and their comparison to pre-disturbance baselines as an Enrichment Factor can detect contamination by industrial emissions, when and where it occurs.

Similar expression of vanadium concentrations in sediment cores from several flood-prone lakes adjacent to the Athabasca River within the Delta reveals very consistent EFs close to 1.0 since the 1840s until present, and comparable to the range of values in the surface sediments collected in 2017 and 2018 from lakes within the Athabasca sector of the Delta (Kay et al. 2023). This provides robust evidence that industrial activities have not elevated concentrations of vanadium in lakes within the Delta.

CONCLUSION

More than 50 years ago, the Peace-Athabasca Delta (PAD) Project Group, a multijurisdictional environmental impact assessment of Peace River flow regulation, recommended initiation of a long-term monitoring program for the Delta's aquatic ecosystems (PADPG 1972). During the next two decades, periodic environmental reassessments reiterated this need (PADIC 1987; PADTS 1996) and, following UNESCO's Reactive Monitoring Mission in 2016 (WHC/IUCN 2017) in response to the Mikisew Cree First Nation petition (MCFN 2014), the Wood Buffalo National Park Action Plan has committed to implementing an "integrated PAD Research and Monitoring program … to detect cumulative effects on the PAD and generate information that informs land-use management and regulatory decision making" (WBNP 2019, p. 57). Unfortunately, implementation of an effective and sustainable Delta-wide lake monitoring program has remained elusive even as concern has grown over the potential for aquatic ecosystem degradation by hydroelectricity dams on the Peace River, oil sands development along the Athabasca River, and climate change.

The Delta's vast size, remoteness and hydrological complexity have created formidable challenges for establishing a lake monitoring program that encompasses its broad hydrological gradients. Here we have provided approaches and methods that are well-designed to overcome these challenges, and several years of data demonstrate their utility to serve as the foundation for ongoing monitoring. Continued collection of these data will be critical for 1) assessing change in freshwater availability and detecting pollution in the Delta, and their cause(s) and 2) informing upstream land- and water-use management decisions and policies, and evaluating their effectiveness. Regarding the latter, we are aware of the long-standing interest in strategic releases from the W.A.C. Bennett Dam to enhance ice-jam flooding of the Delta when meteorological and hydrological conditions are favourable for such an event. Indeed, this mitigation strategy is repeatedly cited in the Action Plan (WBNP 2019). But if a decision is made for this to occur, how would the success of a strategic water release be evaluated if informative data have not been routinely collected at lakes spanning the hydrological gradients in the Delta before and after the release? Similarly, if legislation is enacted that allows for treated oil sands mine wastewater to be discharged into the Athabasca River, how will we know whether this contaminates lakes in the Delta? Our recommended approaches and methods provide precisely the data that are needed to assess the effectiveness of these environmental stewardship decisions. We would welcome opportunity to discuss a collaborative approach to implement a Delta-wide lake monitoring program with interested partners (e.g., those who lead existing sampling programs in the region for Indigenous Nations and federal and provincial government agencies), with input from other rightsholders, stakeholders and decision makers on WBNP's World Heritage status.

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