Synthesis Report for the Water Component, Canada-Alberta Joint Oil Sands Monitoring: Key Findings and Recommendations

1.1
Report Series

Oil Sands Monitoring Program Technical Report Series

Canada

Alberta

Synthesis Report for the Water Component, Canada-Alberta Joint Oil Sands Monitoring: Key Findings and Recommendations

Lead Authors: Joseph M. Culp[1], Ian G. Droppo[1] and Peter D. di Cenzo[1]

Contributing Authors: Alexa Alexander-Trusiak[1], Donald J. Baird[1], Greg Bickerton[1], Spyros Beltaos[1], Barrie Bonsal[1], Robert B. Brua[1], Patricia A. Chambers[1], Yonas Dibike[1], Nancy E. Glozier[1], Jane Kirk[1], Lucie Levesque[1], Mark McMaster[1], Derek Muir[1], Joanne Parrott[1], Daniel L. Peters[1], Kerry Pippy[1] and Jim W. Roy[1]

[1]Environment and Climate Change Canada

This publication can be found at: https://open.alberta.ca/publications/9781460140253

Recommended citation:
Culp, J. M., Droppo, I. G., di Cenzo, P. D., Alexander-Trusiak, A., Baird, D. J., Bickerton, G., Beltaos, S., Bonsal, B., Brua, R. B., Chambers, P. A., Dibike, Y., Glozier, N. E., Kirk, J., Levesque, L., McMaster, M., Muir, D., Parrott, J., Peters, D. L., Pippy, K. & J. W. Roy. 2018. Synthesis report for the water component, canada-alberta joint oil sands monitoring: key findings and recommendations. Oil Sands Monitoring Program Technical Report Series No. 1.1. 46 p.

Note that this report was updated in March 2019 to correct formatting issues to Figure 21 and 22 on pages 32 and 33.

June 2018
ISBN 978-1-4601-4025-3

Foreword

Since February 2012, the governments of Alberta and Canada have worked in partnership to implement an environmental monitoring program for the oil sands region. In December 2017 both governments renewed their commitment to working together with Indigenous communities in the region by the signing the *Alberta-Canada Memorandum of Understanding (MOU) Respecting Environmental Monitoring in the Oil Sands Region*. The MOU establishes the foundation for an adaptive and inclusive approach to program implementation ensuring that the program is responsive to emerging priorities, information, knowledge, and input from key stakeholders and Indigenous peoples in the region.

The Oil Sands Monitoring Program is designed to enhance the understanding of the state of the environment and cumulate environmental effects as a result of oil sands development in the region though monitoring and publically reporting on the status and trends of air, water, land and biodiversity. Its vision is to integrate Indigenous knowledge and wisdom with western science to design, interpret, assess, report and govern the program.

Canada and Alberta have provided leadership to strengthen program delivery, and ensure that necessary monitoring and scientific activities meet program commitments and objectives. The oil sands industry provides funding support for the program under the Oil Sands Environmental Regulation (Alberta Regulation 226/2013). Key findings and results from the program inform regional resource management decisions and importantly, are considered as an objective source of scientific interpretation of credible environmental data.

A mandated cornerstone of the program is the public reporting of data, status and trends of environmental impacts caused by development of oil sands resources. The Oil Sands Monitoring Program *Technical Report Series* provides an objective, and timely, evaluation and interpretation of monitoring data and information collected across environmental media of the program. This includes reporting and evaluation of emission/release sources, fate, effects and transport of contaminants, landscape disturbance and responses across theme areas including atmospheric, aquatic, biotic, wetlands, and community based monitoring.

Executive Summary

The design of the integrated Joint and Oil Sands Monitoring Program (JOSM) was based on the core principles identified by the Federal Oil Sands Advisory Panel (2010). These principles include designing and implementing the program so that it is holistic and comprehensive, scientifically rigorous, adaptive and robust, inclusive and collaborative and transparent and accessible. These core principles are reflected within all components of JOSM (Water, Air and Terrestrial Components), however, this synthesis report and the seven individual technical reports (study/themes) that follow, are specific to the Water Component. Further, it is important to note that these reports were necessarily restricted to the information and data delivered by March 2015 (end of the three-year implementation plan). Information and data acquired after March 2015 will be incorporated in future reports and primary publications. All current JOSM data can be found on the Information Portal: Canada-Alberta Oil Sands Environmental Monitoring (https://www.canada.ca/en/environment-climate-change/services/oil-sands-monitoring.html).

The Oil Sands (OS) Water Component's monitoring design is structured from an integration of the seven different study/themes which assess the physical/chemical and biological/ecological condition of the Lower Athabasca River (LAR), its tributaries and the extended geographical area (EGA - including the Peace Athabasca Delta). This integrated approach further provides for a causal assessment of ecological effects, which drives potential future changes to the monitoring program. The adaptive nature of the program also allows for appropriate adjustments to reflect new moni-toring questions and emerging issues of potential concern (e.g., climate change).

The JOSM Water Component retained some aspects of the pre-JOSM monitoring structure, while incorporating significant improvements as directed by the outcomes of the seven technical reports (study/themes). These enhancements included:

1. An improved integrated monitoring and assessment approach which informs on ecological health of the aquatic environment, and advances the scientific/process understanding of these systems;
2. Monitoring at more sites within rivers and with increased geographic coverage;
3. Increased sampling frequency to improve precision and accuracy;
4. Increased number of parameters to improve causal assessment of ecological effects (e.g., nutrients, contaminants, sediments, etc.); and
5. Improved analytical and field techniques (increased sensitivity) for assessment of a broad suite of compounds related to oil sands activities (e.g., metals, polycyclic aromatic compounds, and naphthenic acids).

The seven interconnected themes reflect a functional framework for the evaluation and monitoring of the contemporary state of aquatic health relative to potential environmental effects. Atmospheric Deposition (Kirk et al. 2018) provides insight into, and a sampling strategy for, the assessment of particulate deposition to the landscape via snow sampling and paleo-coring of lakes relative to the industrial areas of the Oil Sands. This contemporary and historical assessment of loadings to the terrestrial and aquatic environment has wide relevance to focused monitoring of water, wildlife, biodiversity and additional atmospheric investigations. The atmospheric deposition work is particularly relevant to the Water Quality Monitoring Program (Chambers et al. 2018; Glozier et al. 2018), as surface water washoff (i.e., storm and snowmelt) will influence the water quality and aquatic health of the tributaries, LAR and the EGA. This was particularly true during the freshet (snowmelt) periods when the majority of contaminant loads are transported within the rivers and delivered to downstream ecologically-relevant environments. As such, an increased frequency of sampling was recommended for this period at key river sites in the LAR and EGA. Further, the delivery and deposition of sediments and associated contaminants to lakes and rivers of the oil sands region will have concomitant effects on fish (McMaster et al. 2018) and benthic (Culp et al. 2018) community health (i.e., exposure concentrations). For water quantity, groundwater flows (Bickerton et al. 2018) were found to have their most significant effect during the ice covered winter months where they are important for maintaining ecological habitat. Numerical modelling (Droppo et al. 2018) has provided insight into the implication of extreme events and climate change (warming, more precipitation, less snow accumulation, earlier peak flows), with respect to flows and sediment/contaminant transport. Key areas of deposition are identified for the LAR and the modelling information can provide insight into frequency and locational change sampling (chemical and biological) as dictated by a change in flow/loads.

Causal assessment of ecological effects was undertaken by linking effects in tributary, mainstem and deltaic ecosystems to candidate causes, with consideration of the evidence supporting the importance of particular effect pathways. The observed biological effects for LAR tributaries included increased polycyclic aromatic compounds (PACs) in fish tissue and more tolerant invertebrate taxa that appear to be associated with contaminant exposure. The source of this exposure is, however, confounded by the presence of, and inability to differentiate between, oil sands operation activity (principally atmospheric deposition) and natural bitumen inputs (e.g., erosion) within the aquatic ecosystem. Ecological effects observed in the LAR mainstem below Fort McMurray included larger white sucker size, higher EROD activity in fish, higher benthic invertebrate abundance, an increased number of tolerant invertebrate taxa and decreased mussel condition. Causal pathways suggest these LAR ecological trends were associated mostly with nutrient enrichment from treated municipal sewage effluent from Fort McMurray. Contaminant exposure from sewage effluent, industrial operations, tailings pond seepage and natural exposure to bitumen may also contribute to these ecological trends, but focused investigation of cause field studies and experiments are required to separate the ecological effect of nutrients and contaminants. It is stressed that the identification of effects caused by contaminants derived from natural bitumen or industrial activity will remain limited until these natural and industrial-derived contaminants can be discriminated. Finally, wetland benthic macroinvertebrate assemblages in the Peace-Athabasca Delta (PAD) appear to be in a healthy state, exhibiting high biodiversity. Assessments indicated that nutrients, contaminants and sediments showed no adverse effects on benthic macro-invertebrates in the wetland deltas from the major potential sources of inputs (atmospheric, fluvial).

Following the three years of JOSM, a number of knowledge and/or data gaps as well as research needs were identified that could potentially improve the monitoring design. As JOSM was designed to be an adaptive monitoring program, it has a built-in flexibility that allows the program to evolve as new research validates a need for change. Such change may be reflected in a change in sample sites (inclusion of new sites or the suspension of existing sites until a threshold or trigger is identified), frequency of sampling, or a change to the parameter list (new or suspended parameter). Research may also drive a change in the monitoring program in terms of 1) methodology (field and/or analytical), 2) instrumentation (field and/or analytical), 3) ecological health assessment, 4) biogeochemical understanding, 5) numerical model advancement and projection, and/or 6) identification of new issues of interest.

The three years of JOSM resulted in numerous recommendations (stated in general above) and provided suggestions and options for improving the ability of the JOSM monitoring program to detect degradation in ecosystem health. The monitoring approach can be adapted through time to reduce measurement variability and link ecological change to the environmental cause. These recommendations provide options to improve monitoring based on interpretations of quantitative results from JOSM. For more detailed information on aquatic condition, ecological effects, research in support of monitoring and recommendations, readers are referred to the individual technical reports (study/themes).

Table of Contents

Page

List of Tables

List of Figures

1. Introduction

Public and scientific concern has been raised in Canada and internationally as to whether development of the Alberta oil sands (Fig. 1) has the potential to adversely affect the environmental health of the Lower Athabasca River (LAR) watershed and its downstream receiving ecosystems. Moreover, questions have been raised as to whether environmental monitoring of this development was sufficient to provide the necessary information to inform on environmental status and trends and the protection and preservation of the environment. Although previous monitoring programs and research activities have generated considerable information on the LAR system, there had been a lack of integration among these efforts, a situation identified in several independent science reviews and journal papers (e.g., Timoney and Lee 2009; Kelly et al. 2009, 2010; Giesy et al. 2010; Schindler 2010), as well as expert science panel reviews (e.g., Royal Society of Canada 2010; Federal Oil Sands Advisory Panel 2010; Alberta Water Monitoring Data Review Committee 2011; Alberta Environmental Monitoring Panel 2011).

Collectively, these reviews and assessments established that past monitoring efforts were diffuse and disparate and did not deliver data of sufficient quantity or quality to quantify the effects of oil sands development. Specifically, the previous monitoring efforts lacked rigour in statistical design (e.g., inadequate spatial coverage of sites and/or related sampling frequency), lacked clear objectives and hypothesis-driven analyses, and lacked ability to measure change cumulatively over space and/or time. In addition, oil sands monitoring of air, groundwater and surface water had not been integrated in a source, transport and fate construct.

To address the shortcomings identified in past monitoring efforts, in 2011, the Governments of Canada and Alberta developed the Joint Oil Sands Monitoring (JOSM) plan, drawing upon input on the scope and design solicited from key experts from federal, provincial and territorial departments/agencies, academia, and non-government organizations (NGO). It is noteworthy that, although widely criticized and in need of redesign, past monitoring activities had yielded data at some sites and during some time periods that were deemed critical to the optimal functioning of the new monitoring plan. A major goal of the new monitoring plan was to incorporate the sound components of existing monitoring and improve data collection activities to facilitate holistic assessment of contaminant sources, their transport and ultimate fate in the environment. Additionally, the plan aimed to provide risk-based assessments of impacts on environmental health and examinations of causal-effect relationships. Thus, an adaptive, integrated, multi-media monitoring and research program was developed to better understand, predict and report on the status and trends of water quality and quantity, the accumulated state of the environment, and on changes in ecosystem structure, function and health. Ultimately, the JOSM program aims to determine cumulative impacts of development on the LAR ecosystem.

The overall goal of the Joint Oil Sands Monitoring Plan (JOSM) (Environment Canada and Alberta Environment 2012) was to obtain scientifically credible information that would allow the accurate description of the baseline physical and chemical environmental conditions as well as ecosystem structure and function. This baseline will allow assessment of changes in ecosystem condition and determination of trends in space and time, high quality assessment of environmental impacts, and reporting on the State of Environment (SOE). Such an evaluation will also allow improved assessment of environmental and human health risk, support and feedback for modelling, management, and policy development, and should provide for meaningful stakeholder input.

1a. Joint Oil Sands Monitoring (JOSM) Plan

Following recommendations made in the Federal Oil Sands Advisory Panel report (Federal Oil Sands Advisory Panel 2010) and in response to the above concerns, the Governments of Canada and Alberta jointly developed a series of five technical plans for integrated monitoring in the Alberta oil sands region. These plans, including specific JOSM monitoring questions, were developed with solicited and unsolicited input provided by experts from federal, provincial and territorial departments/agencies, academia, First Nations and Metis, and NGOs. The five plans released in 2011 include:

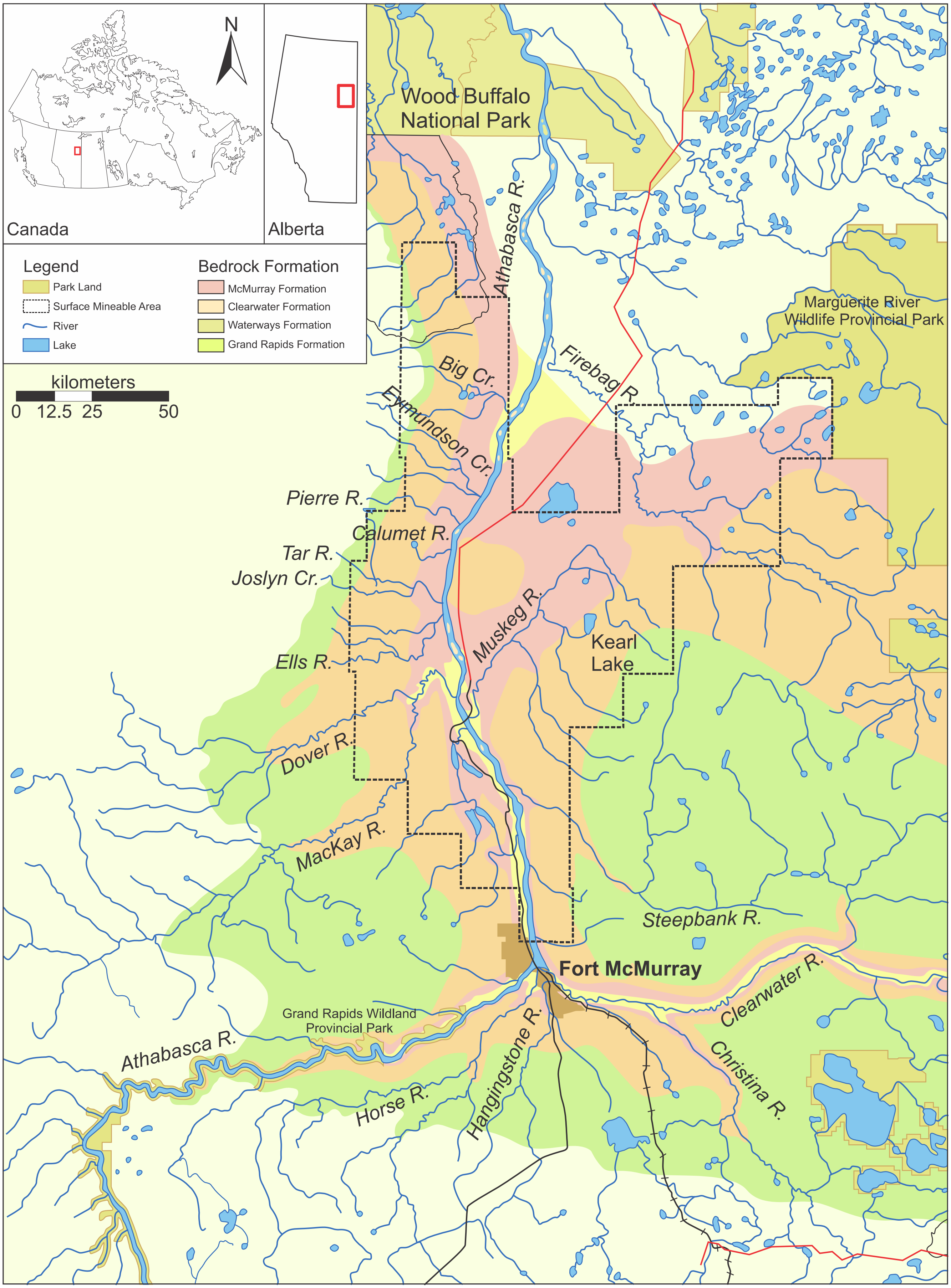

Figure 1. Location of the Lower Athabasca surface minable Oil Sands area in NE Alberta, Canada, along with the bedrock geology expressed at the land surface, and the Lower Athabasca River and its tributaries.

1. *Lower Athabasca Water Quality Monitoring Program – Phase 1. (Environment Canada and Alberta Environment 2011a);*

2. *Integrated Monitoring Plan for the Oil Sands – Expanded Geographic Extent for water Quality and Quantity, Aquatic Bio diversity and effects, and Acid Sensitive Lake Component (Environment Canada and Alberta Environment 2011b);*

3. *Integrated Monitoring Plan for the Oil Sands – Air Quality Component (Environment Canada and Alberta Environment 2011c);*

4. *Integrated Monitoring Plan for the Oil Sands – Terrestrial Biodiversity Component (Environment Canada and Alberta Environment 2011d); and*

5. *An Integrated Oil Sands Environment Monitoring Plan (Environment Canada and Alberta Environment 2011e).*

In 2012, the Joint Canada-Alberta Implementation Plan for Oil Sands Monitoring (hereafter referred to as "The Implementation Plan"), guided by the above five technical plans, was developed and phased in over a 3-year period (2012/13-2014/15) (Environment Canada and Alberta Environment 2012). To facilitate this implementation, the series of five plans were integrated into three component areas: Water, Atmosphere, and Terrestrial (Fig. 2). Each of these components was guided by the specific JOSM monitoring questions which are interconnected within and among components. The rational for the JOSM questions are articulated in the technical plans (Environment Canada and Alberta Environment (2011a, b, c, d, e) and in the thematic technical reports summarized within this synthesis report.

1b. Water Data Synthesis Report

This data syntheses report is specific to the Water Component and focuses on key issues as they relate to water quality and quantity, modelling, benthic and fish health within the LAR and receiving water bodies. Text Box 1 highlights the over-arching questions that focus the thematic technical reports and this synthesis report towards an improved monitoring design. The aim of the revised water monitoring design was to facilitate the necessary modification to enhance our ability to characterize the state of the environment in the oil sands area and improve our predictive abilities for future environmental condition. The expanded water program increased site-specific, reach-specific and regional-scale information. This allowed for a systematic and comprehensive quantification, assessment and modelling of contaminant sources, transport, loadings, fate, and effect on ecosystem health. Wherever possible, monitoring activities were co-located to allow for integrated ecological assessment.

The Water Component synthesis report integrates information obtained from the seven study themes and long-term monitoring activities during the implementation phase of JOSM (fiscal years 2012/13-2014/15) (Text Box 2) and focusses on the physical-chemical (water quality and quantity) and ecological condition (fish and benthic health) with respect to ecosystem health impacts (Fig. 3). An integrative cross-theme approach within the Water Component allows for local/regional assessment of potential ecological effects on a variety of end-points, and for assessment of the overall environment. The report encompasses the physical and chemical condition of the aquatic ecosystems followed by the biological/ecological condition (Sections 2 and 3 respectively); both cover the full geographical extent of JOSM. Section 4 integrates the primary findings of the seven themes to provide a causal assessment of ecological effects. Possible effects based on known sources and candidate proximal causes are expressed and rated for their strength of evidence. With such a large monitoring program, it is not surprising that after the implementation phase of JOSM there are a number of research needs identified that could further improve the monitoring design. These needs are provided in Section 5 and point to strategies to improve knowledge and/or data gaps in the monitoring program. Finally, Section 6 summarizes the substantive recommendations for an ongoing, adaptive monitoring program to improve the ability of the program to detect and assess environmental change and possible ecological effects.

It is important to note again that this synthesis and the seven study-theme reports, upon which it is based, were necessarily restricted to the

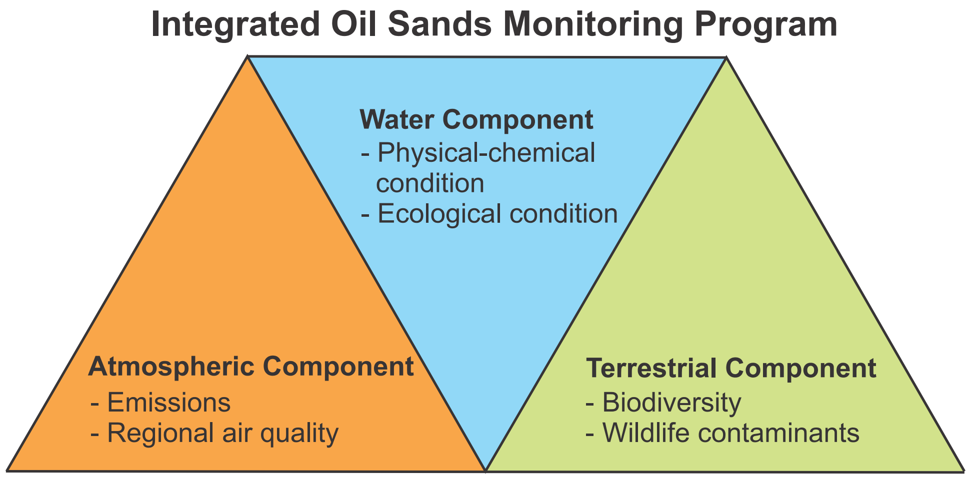

Figure 2. Scientific and information connectivity within the Integrated Oil Sands Monitoring Program (adapted from Environment Canada and Alberta Environment, 2011a).

TEXT BOX 1

Over-Arching JOSM Questions

- *What is the historical and current state of water quality in regions of the Lower Athabasca basin, including key downstream receiving environments?*
- *What is the direct atmospheric deposition of the identified contaminant species of concern to the surface of the Athabasca River and its tributaries, and to the landscape in the Lower Athabasca Region?*
- *What are the biological and ecological impacts of oil sands contaminants and operations on ecosystem health?*
- *What is the historical and current state of invertebrate community structure and function in the Lower Athabasca mainstem, tributaries, and key downstream environments?*
- *What is the historical and current state of fish population health in the Lower Athabasca mainstem, tributaries, and key downstream environments?*

information and data delivered by March 2015. Information and data acquired after March 2015 will be incorporated in future reports and primary publications. Finally, it is important to emphasize that this synthesis focused strictly on the Water Component. Atmospheric and Terrestrial Component syntheses reports will be forthcoming.

TEXT BOX 2

OSM Tech.Ser. 1.1: Overall Synthesis Report

Water Component Study Themes

OSM Tech.Ser. 1.2: Atmospheric Deposition

OSM Tech.Ser. 1.3: Water Quality – Tributaries

OSM Tech.Ser. 1.4: Water Quality – Mainstem and EGA

OSM Tech.Ser. 1.5: Groundwater Quality/Quantity

OSM Tech.Ser. 1.6: Water Quality/ Quantity Modelling

OSM Tech.Ser. 1.7: Benthic Invertebrates

OSM Tech.Ser. 1.8: Fish Health

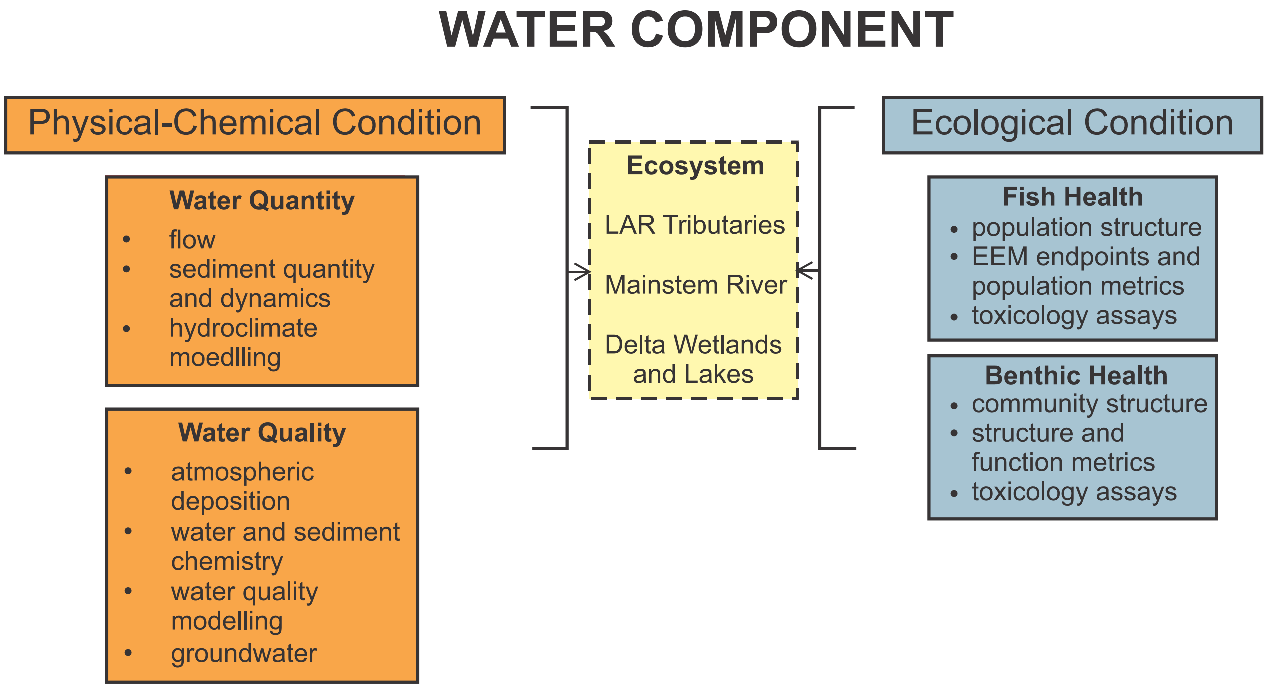

Figure 3. Linkages of ecosystem health to the physical-chemical and ecological condition of the aquatic environment under JOSM.

2. Summary of Physical and Chemical Condition of Aquatic Ecosystems

The physical (water quantity) and chemical (water quality) condition of the aquatic ecosystems in the Oil Sands region is driven by both natural processes (e.g., atmospheric deposition, runoff, erosion, groundwater flow) and human activities (e.g., contaminant inputs deposited on land, snow-cover or water; alterations to natural water flow). Data evaluation from five themes (Atmospheric Deposition; Tributary Water Quality; Mainstem and Extended Geographical Area Water Quality; Near-surface Groundwater Quantity/Quality; and Climate, Hydrology, Sediment Modelling) was undertaken in order to ascertain the past, present and projected future physical/chemical conditions of the aquatic ecosystem. These themes are linked together in an integrated framework (Fig. 4) and provide: an evaluation of the contemporary state of the aquatic health relative to potential environmental effects associated with both natural processes and human activities; a benchmark for determining if important changes have occurred since earlier assessments; and a modelling approach to allow for projections of water quality/quantity.

2a. Atmospheric Deposition (OSM Tech. Ser. 1.2)

This theme (Kirk et al. 2018) uses snowpack measurements and dated lake sediment cores to assess spatial and temporal trends in atmospheric contaminant deposition. Snowpack measurements are utilized because they represent a temporally integrated measure of wet and dry atmospheric deposition from various sources (e.g., emissions, wind-blown dust) spanning the period between first snowfall to sampling immediately prior to spring melt. In the absence of pre-development monitoring for this region, high resolution dated lake sediment cores were used to assess the natural range in contaminant deposition to this region and to obtain a historical perspective of contaminant loadings. The principal JOSM questions addressed were:

- *What is the aerial deposition to the landscape (including lakes) in the Athabasca River Basin from Fort McMurray to the Athabasca delta?*
- *How does the aerial deposition to the landscape affect water quality in the tributaries and mainstem?*

Results of the snowpack program demonstrate that a variety of contaminants [polycyclic aromatic compounds (PACs), metals, total mercury (THg), methyl mercury (MeHg)] and a variety of other constituents of interest [total suspended solids (TSS), total phosphorous (TP), particulate organic carbon (POC), and particulate organic nitrogen (PON)] are deposited via wet and dry deposition to the oil sands region. These results suggest that, at snowmelt (spring freshet), a complex mixture of chemicals enters aquatic

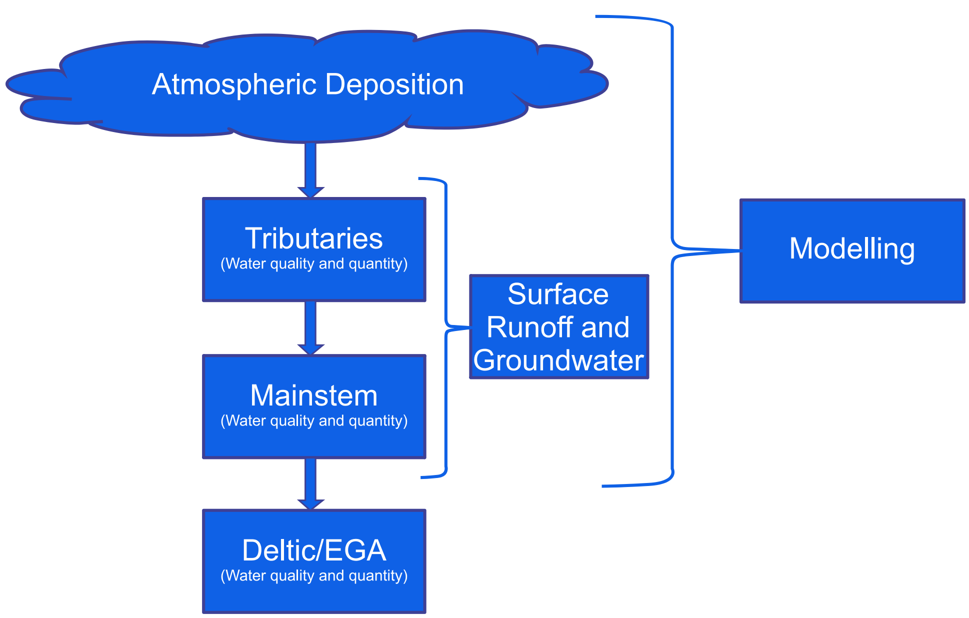

Figure 4. Flowchart illustrating the logical flow of data interpretation and discussion for physical and chemical assessment under JOSM.

ecosystems that could impact biological communities of the oil sands region. A large proportion of the contaminants measured in snowpacks located in close proximity to the major developments were particle-bound, which may affect transport and fate in aquatic and terrestrial ecosystems. Deposition of PACs in the oil sands region in winter 2012-2014 was highest near the major development area with areas of maximum deposition covering parts of the Athabasca, Steepbank and Muskeg river basins (Fig. 5). Contaminant deposition decreased rapidly with distance from the major development and was found to be close to background levels beyond 50-75 km. Interpolated snowpack loadings were used to estimate atmospheric contaminant loads to the region within 50 km of the major development area. Interpolated snowpack loadings were compared to the National Pollutant Release Inventory (NPRI) emission estimates and results suggest that unreported elements, such as fugitive dusts (e.g., mining, tailings, on/off roads, etc.), may be important contributors to contaminant deposition in the Athabasca oil sands region.

Analysis of dated lake sediment cores collected from lakes located 10-200 km from the major oil sands developments showed that atmospheric deposition of PACs (Fig. 6) and inorganic contaminants, primarily Vanadium (V), have increased since oil sands development began in this region in the 1960s, with impacts most pronounced in lakes <50 km from the major development. Examination of diagnostic PAC ratios demonstrated that recent (post-2000) sediment horizons showed evidence of greater petrogenic influence than those from before oil sands development began (pre-1960s). Canadian Council of Ministers of the Environment (CCME) Interim Sediment Quality Guidelines (ISQGs) were exceeded for seven PAHs in one lake located close to mining and upgrading operations. Comparison of metals concentrations in lake sediments to the CCME sediment quality guidelines demonstrated that the Interim Sediment Quality Guidelines (ISQG) were exceeded for Arsenic (As) (in two lakes), Cadmium (Cd) (in five lakes), Mercury (Hg) (in two lakes), and Zinc (Zn) (in three lakes) of the 28 lakes studied. CCME Probable Effects Level (PEL) guidelines, which are higher than ISQG guidelines, were exceeded for As in only two sediment intervals in two study lakes. Results from principal component analysis (PCA) analyses suggest that regional bedrock (i.e., McMurray and Waterways formations, Birch Mountains) is the primary determinant of the broad geochemical composition of lake sediments.

Reconstructions of within-lake primary production (expressed as algal Chlorophyll *a*) were generated using visible near-infrared spectroscopy (VNIRS). Modern primary production rates are greater than background values at all 23 sites analyzed, regardless of proximity to industry. Significant ($p<0.05$) positive correlations were found between mean annual and seasonal air temperatures and VNIRS-Chl *a* z-scores in all lake sediment cores, suggesting that climate warming is a driver of increased aquatic primary production in the oil sands region. An assessment of *Cladocera* fossil remains in five study lakes showed shifts in composition of cladoceran assemblages between 1960 and 1970. In addition, Daphniids increased as a percentage of the cladoceran assemblage between the mid-1900s and modern times at all sites, suggesting that the sentinel zooplankton Daphnia has not yet been negatively impacted by decades of high atmospheric PACs and metals deposition. The findings of changes in lake primary productivity and Cladocera fossil remains over the past ~100 years suggest that oil sands lake ecosystems have entered new ecological states distinct from those of previous centuries.

Atmospheric deposition is clearly a vector of contaminants to the land and water surfaces of the Oil Sands region and the EGA. The degree to which this particulate material is delivered to the water courses is at this point still unclear and will require additional sampling and modelling. The delivery of atmospheric particulate matter to the river will depend on a number of factors which may vary from year to year, including: rate of snow melt, rate of ground thaw [frozen ground surface (semi-impervious) or not frozen (pervious)], basin slope topography, vegetation layers, distance of surface runoff to nearest connecting channel, to name a few. Clearly more research and modelling are required to determine: (1) the proportion of atmospheric deposition that is incorporated into the soil matrix due to infiltration and entrapment processes versus the proportion that enters aquatic ecosystems; and (2) the relative contributions of contaminants deposited via atmospheric deposition versus contaminants entering the rivers via natural processes of channel/bank erosion to river contaminant concentrations and loads.

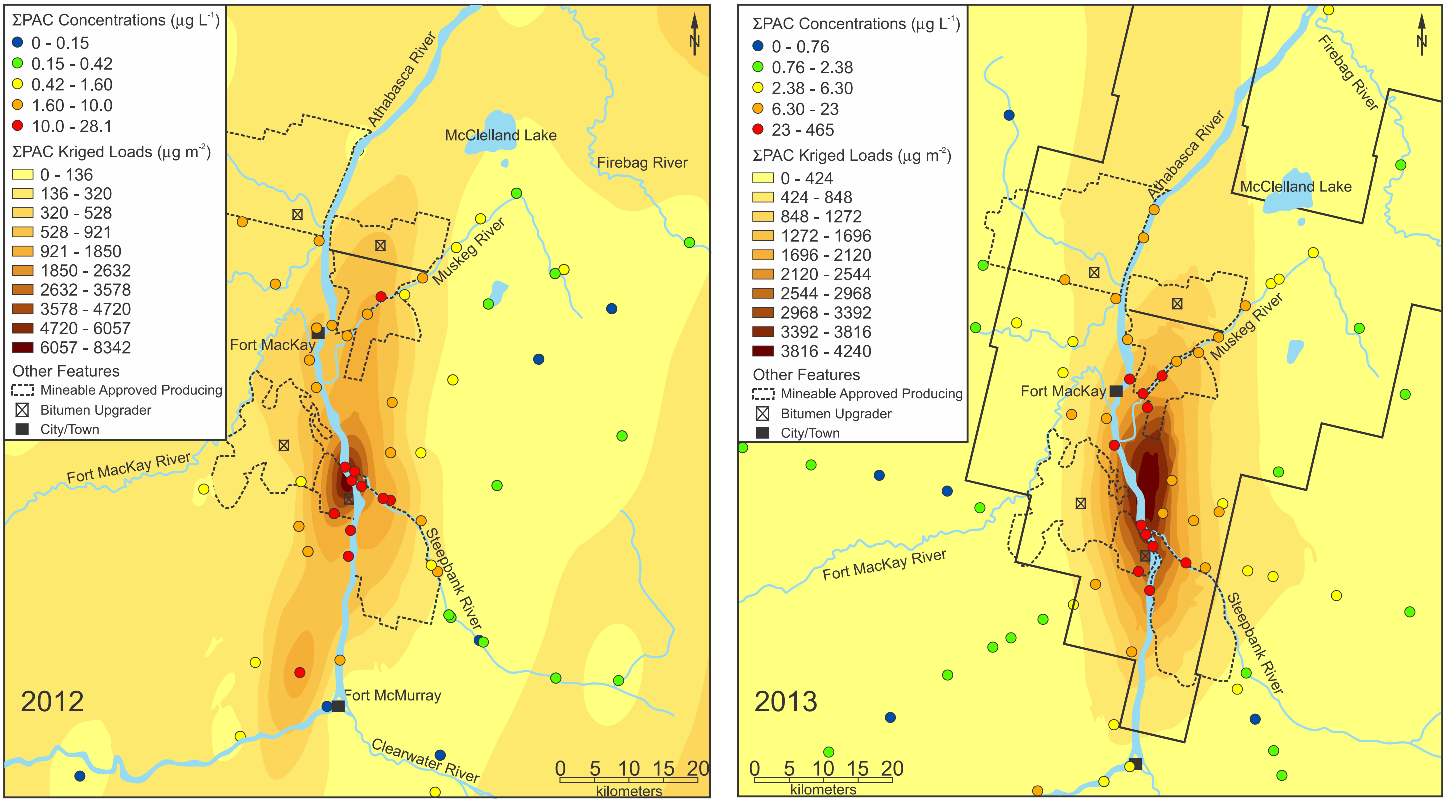

Figure 5. Deposition of ∑PACs to the Athabasca Oil Sands region in winters 2012 and 2013. Interpolated ∑PACs loads (ng m^{-2}) produced using ArcGIS Geostatistical Analyst software are overlain by measured concentrations (μg L^{-1}) at each site.

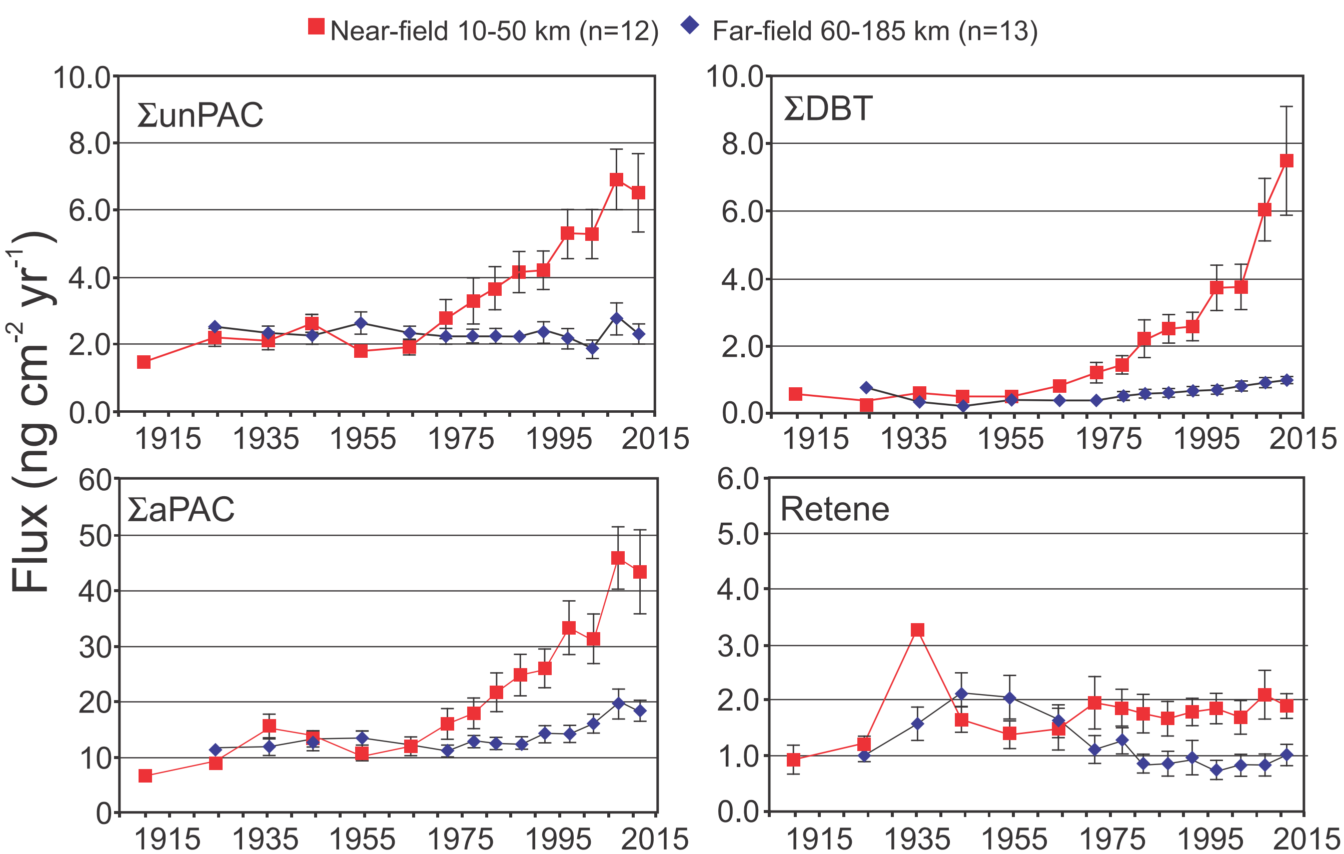

Figure 6. Decadally averaged fluxes for the sum of unsubstituted (parent) PACs (ΣunPAC), alkylated PAC (ΣaPAC) and Dibenzothiophene (ΣDBT) in lake sediment cores from near-field and far-field lakes. Results show an increasing trend following industrial development principally within the near-field lakes.

2b. Tributary Water Quality (OSM Tech. Ser. 1.3 and 1.5)

The uncertainty in ascertaining whether oil sands development activities pose a threat to aquatic ecosystem health required an assessment of current tributary monitoring activities and the development of an improved more informative water quality monitoring program. In this regard, the tributary monitoring program focused on the following five key questions identified within JOSM:

- *What is the current state of the water quality of lower Athabasca River tributaries?*
- *What is the distribution of contaminants in surface water along tributaries to the lower Athabasca River?*
- *Are toxic substances, such as mercury or PACs, increasing or decreasing and what is their rate of change?*
- *Are the substances added to the rivers by natural and man-made discharges likely to cause deterioration of the water quality?*
- *What is the relative importance of both inputs?*

The monitoring program measured approximately 150 water chemistry constituents. While the complete data set will be evaluated, for the purposes of the theme report (Chambers et al. 2018) and for this synthesis report, only water quality parameters that are typically associated with oil sands development (As, Hg, Se, V and PACs) are discussed. Where appropriate, a mass-balance approach was used to quantify and compare water chemistry among sites and over time, thus permitting assessment of sources, fate, and loadings of contaminants in the lower Athabasca tributaries. Included within this theme is the influence of groundwater on tributary conditions (Bickerton et al. 2018), as groundwater clearly affects both tributary flow and water quality. In this regard, the groundwater program focused on the following key question identified within JOSM;

- *What is the relative importance and contribution of groundwater quality and quantity to surface waters?*

It was evident that the original number of tributary water quality sampling sites and the frequency of sampling were inadequate to provide adequate information on (1) the frequency of exceeding water quality guidelines or (2) changes in water quality, both temporally and spatially, along a tributary as a result of natural processes and mining activity. As such, under JOSM, the number of sites sampled and the sampling frequency (particularly at high flows) increased substantially. Prior to JOSM, 43 tributary sites were monitored with, at most, monthly sample collection whereas under JOSM, 62 sites were monitored, 14 sites with high frequency (daily or alternate days during snowmelt and thereafter decreasing) and 48 sites monitored monthly, seasonally or annually. This effort resulted in approximately 2800 samples collected during JOSM, each of which was analyzed for a full suite of water quality parameters.

Of the 46 contaminants (metals, metalloids, selenium) and 52 PACs analyzed by Environment and Climate Change Canada, 24 have Guidelines for the Protection of Aquatic Life (Canadian Council of Ministers of the Environment – CCME). Exceedances of guidelines are not uncommon in many river systems within and outside of the Oil Sands region and, in general, are associated with high flow events when suspended solids and contaminant loads are the greatest. Only a few parameters in the oil sands region were classified with frequent exceedances (i.e., >10% of samples for total aluminum (Al), total copper (Cu), total iron (Fe) and TSS). Several parameters only occasionally exceeded guidelines: <5% of samples for total cadmium (Cd), total chromium (Cr), total silver (Ag), total zinc (Zn), total arsenic (As) and total selenium(Se). All measurements of total Hg were below the CCME guideline. Only pyrene from the PACs showed occasional exceedances for established guidelines (Chambers et al. 2018).

Seasonal variation for the majority of parameters within the Athabasca tributaries can be strong and is often highly reflective of the hydrological regime (i.e., highest concentrations during snowmelt periods or rain events as seen with total PACs and total mercury in the Steepbank River in 2012; Fig. 7). A slight variation to this general pattern is seen for MeHg which showed increasing concentrations with increasing flow during spring but was greatest during the mid-to-late summer months when MeHg production is principally controlled by microbial pathways.

Groundwater contributions to surface water also showed temporal variations relative to total river flows. Although only assessed in detail on a portion of the MacKay River (i.e., 125 km), groundwater contributions during low flow conditions of autumn were estimated to be between 2 and 10%. However, during under-ice conditions, groundwater contributions may be as high as 35% (Bickerton et al. 2018). It is likely that the other main tributaries of the lower Athabasca will provide similar results but this would need to be assessed. During open water periods, the relatively small contributions of groundwater are unlikely to have a major influence on the water quality parameters; however, more research/monitoring will be required. The significant contributions of groundwater during winter under ice flows will likely be important in the maintenance of thermal regimes favourable to biota and in the preservation of aquatic habitat during under ice periods. The MacKay River study may provide a reference condition for comparison of groundwater contributions if assessments of progressive impacts of development on groundwater discharge are required.

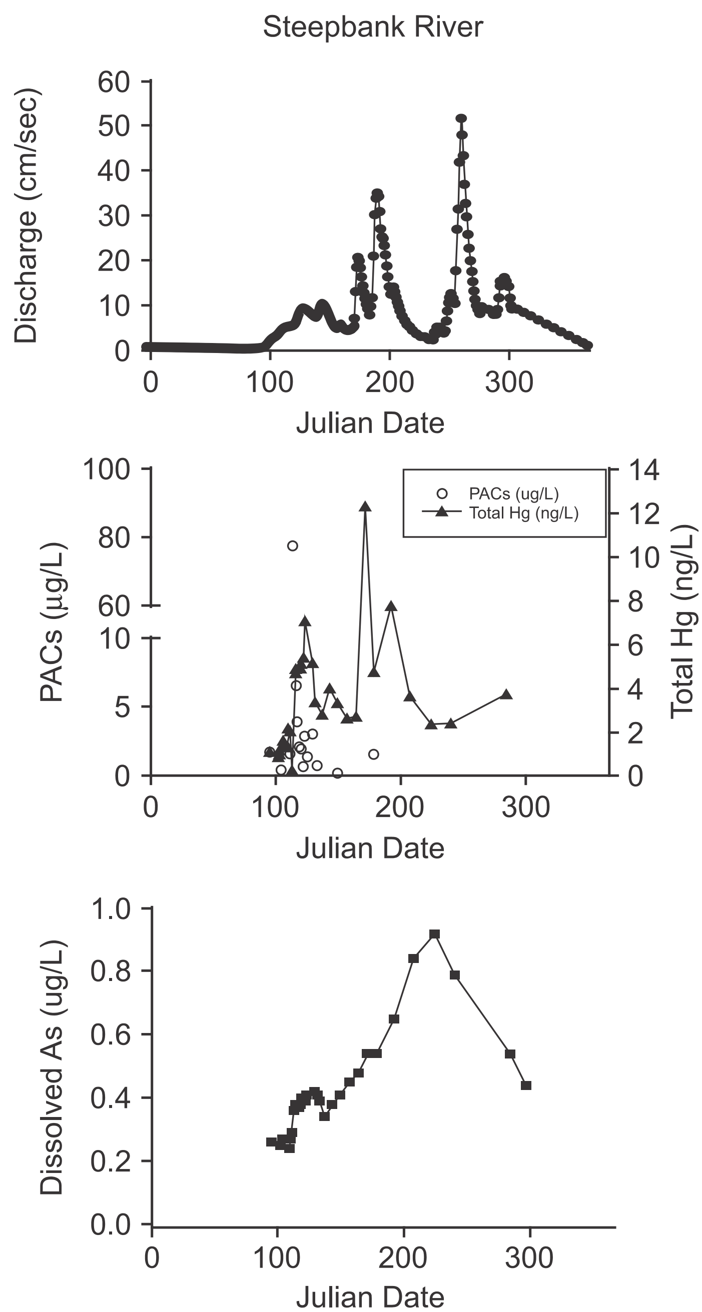

Figure 7. Discharge and concentrations of total PACs, total mercury and dissolved arsenic in the Steepbank River during 2012.

Spatial variation of parameters within tributaries generally showed a pattern of increasing concentrations and loads between samples collected upstream of development versus those collected downstream of development (near mouth of tributary – but above back water effects). Analysis of historical data (1972-2010) showed no discernible change in concentrations and loads of total V, dissolved Se and dissolved As when sampled above versus below the McMurray formation prior to development. However, following development, concentrations and loads were often greater downstream of development compared to measurements from reference sites (Fig. 8). This historical analysis is suggestive of a possible influence of Oil Sands development on these parameter concentrations and loads, with concentrations being highest during the land clearing phase of development due to overburden disturbance.

2c. Mainstem and EGA Water Quality (OSM Tech. Ser. 1.4)

Tributaries and associated groundwater of the LAR contribute less than 20% of the Athabasca mainstem flow volume, and is therefore greatly diluted by upstream sources (based on hydrometric data at Fort McMurray and Embarrass just upstream of the Delta). Clearly, there is a strong dilution of tributary, and particularly groundwater, inputs by the large volume of water delivered to the Lower Athabasca River from upstream sources. Nonetheless, monitoring on

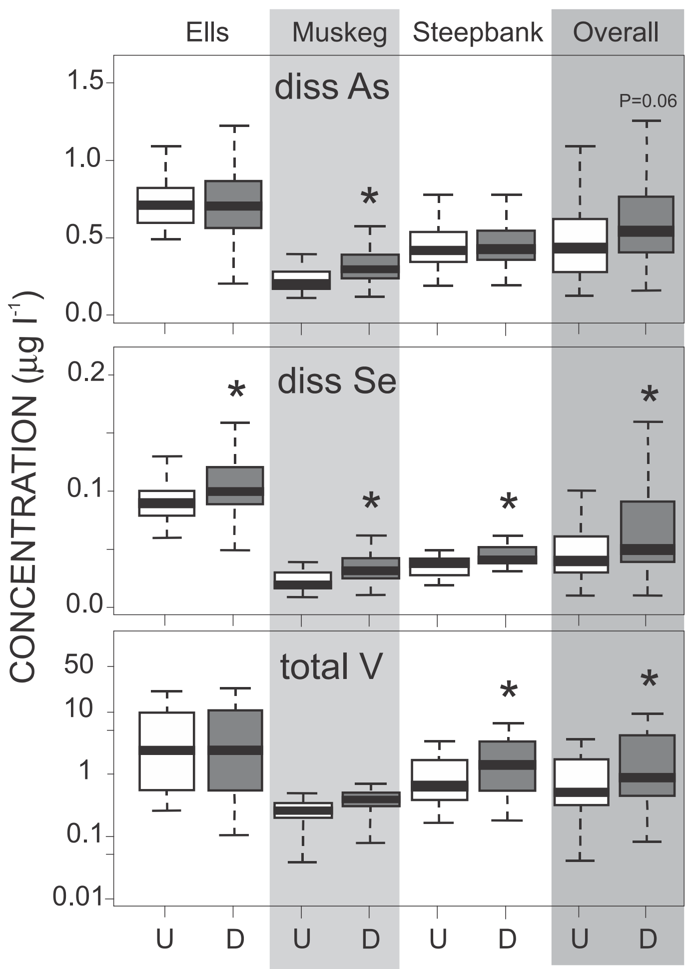

Figure 8. Mean annual (2012-2014) concentrations of dissolved arsenic (diss As), dissolved selenium (diss Se) and total vanadium (total V) at upstream (U) and downstream (D) sites on three Athabasca River tributaries (Ells, Muskeg, Steepbank). Significant differences (P<0.05) are identified (*) between upstream and downstream sites on the same river (Ells, Muskeg or Steepbank) or the three rivers overall.

the Athabasca mainstem (quality and quantity) has been occurring since the 1970s to provide water quality data to assess temporal and spatial variations and loadings to the Athabasca Delta.

Building upon the existing monitoring, JOSM was designed to provide improved information (via more frequent measurements, at more locations, and for a greater number of water quality parameters) for the LAR, and for the Expanded Geographical Area (EGA) comprising the Peace River, Slave River, and tributaries of the Peace-Athabasca Delta. The enhanced monitoring information allows the following five key JOSM questions to be addressed:

- *What is the current state of the water quality?*
- *What is the distribution of contaminants in surface water?*
- *Are the substances added to the rivers by natural and man-made discharges likely to cause deterioration of the water quality?*

In order to address the JOSM questions, the water quality program within the LAR and the EGA was specifically designed to: (1) accurately determine the mass, or load, of water quality constituents transported from the upstream boundary of the LAR to Lake Athabasca and the expanded geographical area (downstream receiving environments including the Peace-Athabasca Delta); and (2) allow for status and trends assessments in water quality at key sites.

Similar to the LAR tributaries, data collection sites and sampling times in the LAR and EGA prior to JOSM were sparse and generally only occurred during open water seasons. The JOSM mainstem water quality monitoring program expanded the historical program by augmenting with additional sites and increasing sampling frequency to span the entire calendar year. Thus, spatial representation increased with 15 additional sites added to the existing six historical sites (all with enhanced frequency and parameter numbers); in all, 1300 water quality samples were collected from 2011-2015 and analyzed for Appendix B parameters (Environment Canada and Alberta Environment 2011a), the result being a nearly five-fold increase in samples for the LAR and EGA.

As stated for the tributary water quality theme (Chambers et al. 2018), exceedances of guidelines are not uncommon in many river systems with the majority occurring with high flow events when bed erosion, suspended solids and contaminant loads are the greatest. From the large number of samples and analysis, the relative percentage of exceedances of guidelines were calculated for the LAR and EGA combined, although it was observed that the percentages were similar for the LAR and the EGA. Of the water quality parameters with guidelines, 19 showed no exceedances in any samples throughout the LAR and EGA (alkalinity, pH, two nitrogen nutrients, five total metals, MeHg and nine organics). In general, the remaining parameters had excursion rates of less than 20% with the exception of total iron, aluminum and copper (94-98%, 75-78% and 36-46% respectively). Exceedances of guidelines of major earth elements such as iron and aluminum are not uncommon in rivers due to seasonal and event-based changes in discharge (e.g., spring freshet and storm events) and should not be viewed as an alarming issue.

Many chemical constituents show consistent seasonal change in concentration that are caused either by dilution during high flows (in the case of dissolved constituents) or by entrainment of particulate matter also during high flows (in the case of particulate constituents). Thus, in the LAR mainstem, dissolved constituents typically exhibited a pattern inverse to the hydrograph, with minimum concentrations occurring during high discharge periods and maximum concentrations occurring in low flow, under ice. Conversely, constituents associated with high suspended sediment loads generally had higher concentrations during high flow spring/summer periods. These results will be of significance to the benthic (Culp et al. 2018) and fish health (McMaster et al. 2018) themes and are implemented within their assessments.

In addition to seasonal patterns, strong inter-annual patterns in water quality were established at the downstream site in the LAR (M9). Historically (1989-1999), TP concentrations were increasing at the LAR downstream site; however, with an improved Fort McMurray sewage treatment plant, TP concentrations have levelled off over the last 15 years (although still higher than values measured near the start of the historic record). Some dissolved and total metal levels, however, are continuing to increase which will require the continuation of long term monitoring to ascertain if this is a global pattern for rivers of this region.

While Appendix B of the Phase 1 document (Environment Canada and Alberta Environment 2011a) included many parameters, only TP, DOC, total mercury, methyl mercury and metals (As, Se, V and B) have, at present, been assessed for spatial variation in the LAR (work is continuing on many of the other parameters). In the LAR mainstem, water quality constituents typically increased from upstream to downstream of Fort McMurray, likely as a result of municipal sewage discharge, and influence from the Clearwater River, but thereafter were relatively consistent until the Peace Athabasca Delta (PAD). PACs (as measured by Semi-Permeable Membrane Devices—SPMDs) were highest in the sites within the oil sands minable area. As water transited through the PAD and connected with the EGA tributaries and the Peace River, concentrations generally dropped due largely to dilution by the large volume of water entering from the Peace River but also to biological processing of nutrients (specifically dissolved nutrient forms) in the productive PAD wetland system.

While not a specific component of the core mainstem water quality monitoring program, there was a clear need specified within JOSM to assess if groundwater was seeping from industrial installations or reclamation areas. This was expressed under the key JOSM question; –

- *Is there groundwater seepage from tailings ponds and/or other oil sands industrial operations entering the surface water system?*

To address this question an intensive groundwater sampling program was conducted along the west side of the Athabasca River below Suncor Pond 1 (reclaimed tailings pond) (Bickerton et al. 2018). While there are indications of Oil Sands Process Water (OSPW) entering groundwater and reaching the near-shore bed sediments of the Athabasca River beside Pond 1, there is no broad-scale (i.e., covering 100s of m) risk posed to aquatic life from groundwater discharging compared to other nearby areas. The groundwater program also provided a "toolbox" (2-tier suite of chemical analysis) of methods for determination of OSPW present within groundwater which will prove useful for future monitoring actions should thresholds for water quality or biological health (i.e., benthic or fish) be surpassed and thus trigger effects monitoring.

2d. Regional Hydro-climatic and Sediment Modelling (OSM Tech. Ser. 1.6)

The broad objective of this aspect of JOSM was to provide critical knowledge about, and improved predictive modelling capability for, water availability and sediment/contaminant transport in the LAR (Droppo et al. 2018). Such an understanding will be essential for guiding future strategic sampling within other research/monitoring initiatives investigating the ecological effect of any deposited material and to provide loadings to the Athabasca Delta. In this regard the modelling activities focused on the following four key questions identified within JOSM:

- *What is the historical, current and projected-future spatial and temporal variability of water flow and sediment transport into and through the lower Athabasca River (LAR) and from tributaries?*
- *What are the water and sediment budgets for the LAR and tributaries, considering upstream source regions?*
- *What are the effects of various oil sands development activities on the spatial and temporal variability of water and sediment yields from the LAR tributaries to the Athabasca River?*
- *Based on improved physically-based knowledge and modelling capability, what have been the conditions and changes in the environment that have created current state of flow and sediment conditions on the Athabasca River system, and what are the projected possible outcomes of future development?*

Water availability within the Lower Athabasca River is largely dependent on the alpine snowmelt-fed headwaters, which is strongly affected by climate variability and change. Hence, atmospheric and full-basin hydrologic modelling studies were initiated to evaluate how the magnitude and seasonality of flow in the region was affected by various climatic drivers. Historical

(1900-2011) hydro-climatic variability assessments suggest that over the entire Athabasca River basin, there was considerable year to year and inter-decadal variability in water availability (as indicated by a standardized precipitation evapotranspiration index (SPEI)), with a suggestion of increased variability since approximately 1990. With regard to future projections, several climate model runs reveal a change toward increasing occurrence of drier, warmer conditions, however, there was considerable variability among the projections (with some scenarios indicating wetter conditions; see Fig. 9). Even though the exact direction (wetter/drier) and magnitude is uncertain, most models revealed considerable inter-annual and inter-decadal hydro-climatic variability with the periodic occurrence of dry and wet extremes continue into the future.

A process-based and distributed hydrologic model of the Athabasca watershed was setup and applied to investigate the effect of various projected climate change scenarios on water availability (streamflow) at many hydrometric stations along the Athabasca River and its tributaries. Overall, climate scenario simulations indicate the following results:

- *a projected increase in the annual and seasonal precipitation and air temperature for the full Athabasca River basin, however, summer precipitation projections have both positive and negative values;*
- *projected increases in mean annual flow resulting from increases in spring and winter flows with a higher rate of increase for a high greenhouse gas emissions scenario compared to that of a moderate one. These increases in spring and winter flows and the associated increases in annual flows were most significant in the upper reach (mountainous area) of the Athabasca River. Specifically, the scenarios predict;*
  a. an overall shift in the flow regime to an earlier start of the spring freshet and an associated decrease in summer stream flow; and
  b. application of the currently preferred water-management rules for industrial withdrawal from the LAR under future climate scenarios indicate possible future improvement in system performance and a reduction in storage requirements resulting from the projected increases in winter and spring flows.

Using further hydrologic modelling coupled with different land-cover scenarios (intensity of development), a comparison of the relative influence of climate and land-cover changes on hydrologic responses was also carried out for the Muskeg River Basin. Results indicate that the projected spring flows exhibit different responses to climate and land-cover changes; that is, decreasing flow with respect to land-cover changes (due to modifications of evapotranspiration) and increasing flow under projected climate conditions (due to wetter and warmer conditions). Sensitivity analysis suggests that in the near future, land-cover change may play a much larger role than climate change in affecting the Muskeg River Basin hydrologic regime, except that of spring runoff (this is likely to be reflective of other developed tributaries in the oil sands region as well).

For the LAR an integrated deterministic numerical modelling framework was developed and implemented to study the spatial and temporal variations of river hydrodynamics, water quality and sediments/chemical transport. The framework was based on a combination of 1-dimensional and 2-dimensional hydrodynamics, sediment transport and water quality models externally coupled with a 1-dimensional river ice process model to account for the cold season effects.

The sediment and chemical transport simulations generally showed that the concentration of chemical constituents in the bed sediment is the major factor in determining the state and variation of their concentration in the water column. The floodplain, back channels, and islands were found to be the major areas for deposition of sediment and associated chemical constituents while high flows periods transported the majority of sediment and chemical constituents in the LAR (Fig. 10). Dissolved oxygen, and nutrient modelling suggest temporal fluctuations especially during summer periods with substantial differences in levels between the main channel and flood plains. During ice cover conditions water levels are increased and dissolved oxygen decreases, however, sediment and chemical

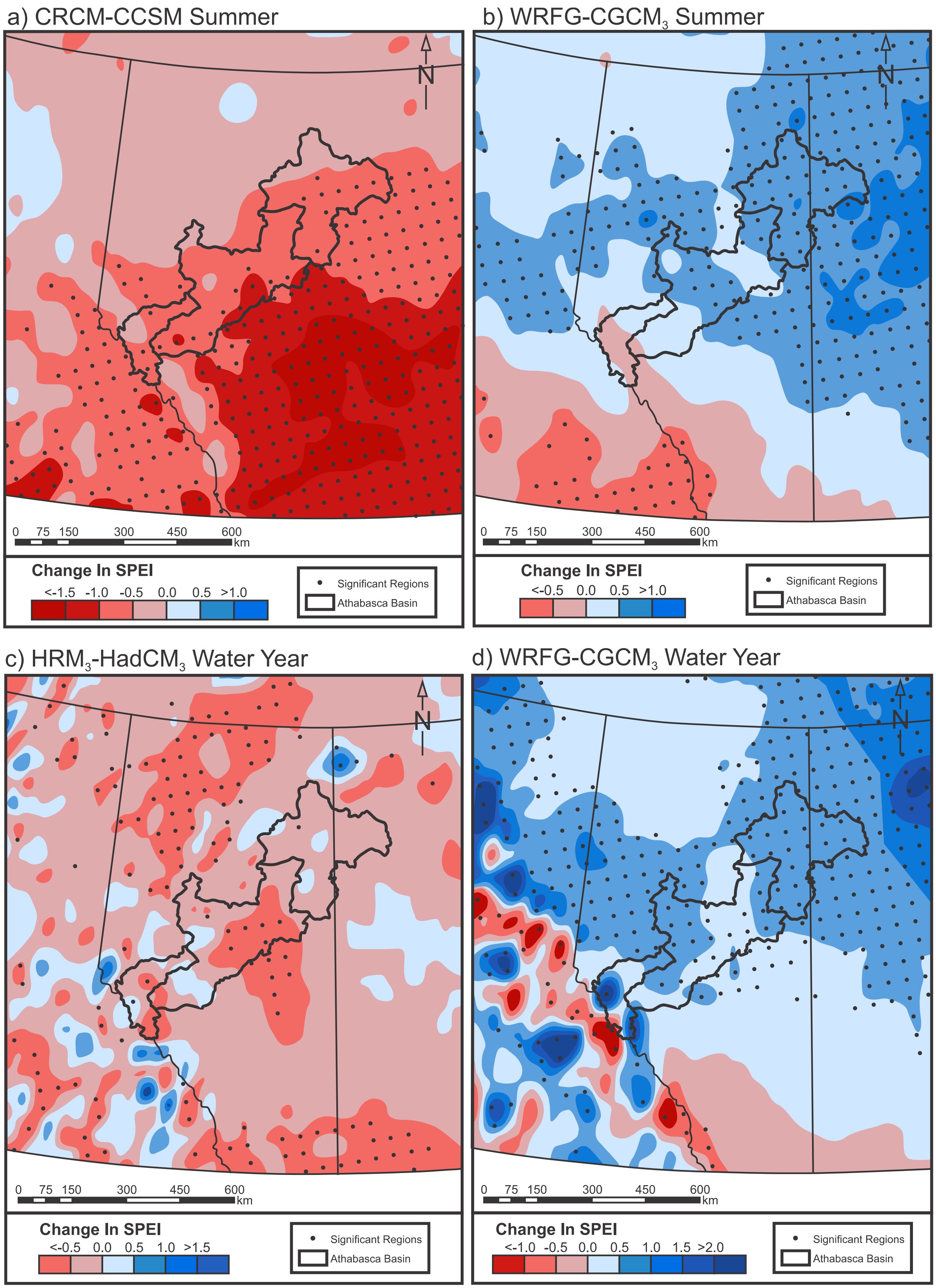

Figure 9. Projected future (2041-2070) SPEI changes over the Athabasca River basin from selected Regional Climate Models (see full report for details) during summer (Jun-Jul-Aug) a) CRCM-CCSM; b) WRFG-CGCM3; and the water year (Oct to Sep) c) HRM3-HadCM3; and d) WRFG-CGCM3. Negative changes are indicative of drier, warmer conditions and positive changes signify wetter, cooler conditions. Black dots signify grids with significant changes at the 0.05 significance level.

transport are less significant at this time of year. Such information proved useful for interpretation of data with the fish and benthic themes (Culp et al. 2018; McMaster et al. 2018).

Hypothetical increased chemical inflow scenarios from tributaries (using JOSM data for selected metals and PACs – see Droppo et al. 2018) were also modelled and suggest a gradual decrease in the effect of tributary inflow contribution to the mainstem water column concentration with distance downstream of the confluences due to dilution and mixing. Further, scenario-based studies to assess the impacts of projected climate, and associated changes in the hydrologic regimes showed projected increases in the mean monthly water level and suspended sediment concentration for most seasons.

The McMurray Formation sediments (bitumen) were found to be poorly flocculated and of a hydrophobic nature (Fig. 11). Hydraulic modelling for the Ells and Steepbank Rivers suggest that these characteristics promote poor setting (relative to non-bitumen containing particles) and the possibility for long range transport. However, the process of sediment entrapment within the cobble bed river which forms large areas of most LAR tributary's riverbeds was found to be the principal form of sediment and contaminant removal from the water column (i.e., sediment is forced through the pores of the bed and are trapped until flows are sufficient to mobilize the bed). This information is of key importance to the fish and benthic themes (Culp et al. 2018; McMaster et al. 2018).

While under-ice flow, sediment and contaminant transport were assessed as above, the models were unable to account for the highly dynamic processes and bed disturbances that occur during ice breakup with subsequent changes to sediment and contaminant dynamics. Using a reach of rapids above Fort McMurray (within the McMurray Formation), 2013 and 2014 comprehensive field data collection programs during the ice breakup resulted in detailed documentations of the spatial and temporal variation of the water level within the study reach of the LAR. Assessments indicate that ice-jam releases and the ensuing energy waves in the water generated by the rapid release of an ice-jam (referred to as Javes) generate extreme erosive forces and suspended sediment concentrations (Fig. 12). This period typically generates the highest TSS loads for the year with subsequent possible downstream effects on aquatic health. The findings of this study demonstrate the important role played by breakup processes and will serve as calibration/validation data sets for future addition of ice breakup modelling routines that will be a key process in hydrodynamic models for sediment/contaminant transport projections.

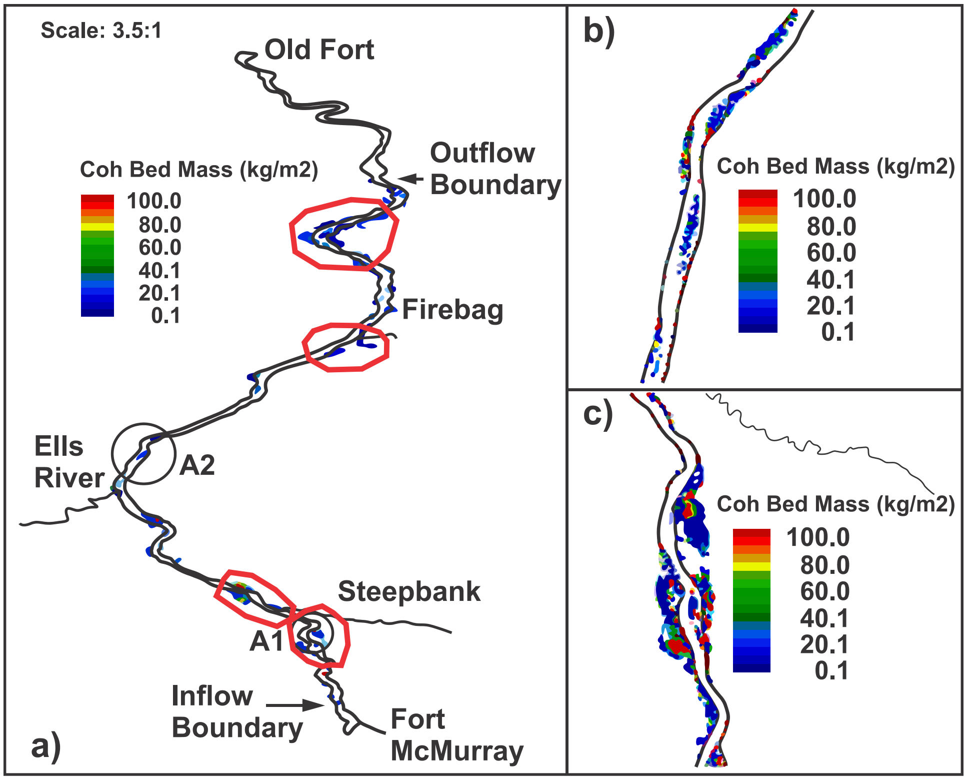

Figure 10. a) Plan view of the 2-dimentional model domain within the lower Athabasca River below Fort McMurray and showing simulated depositional areas for cohesive bed mass (major areas of deposition are circled in red). b) Deposited cohesive (Coh) bed sediment at A2. c) Deposited cohesive bed sediment at A1. Results shown are for the end of the case scenario.

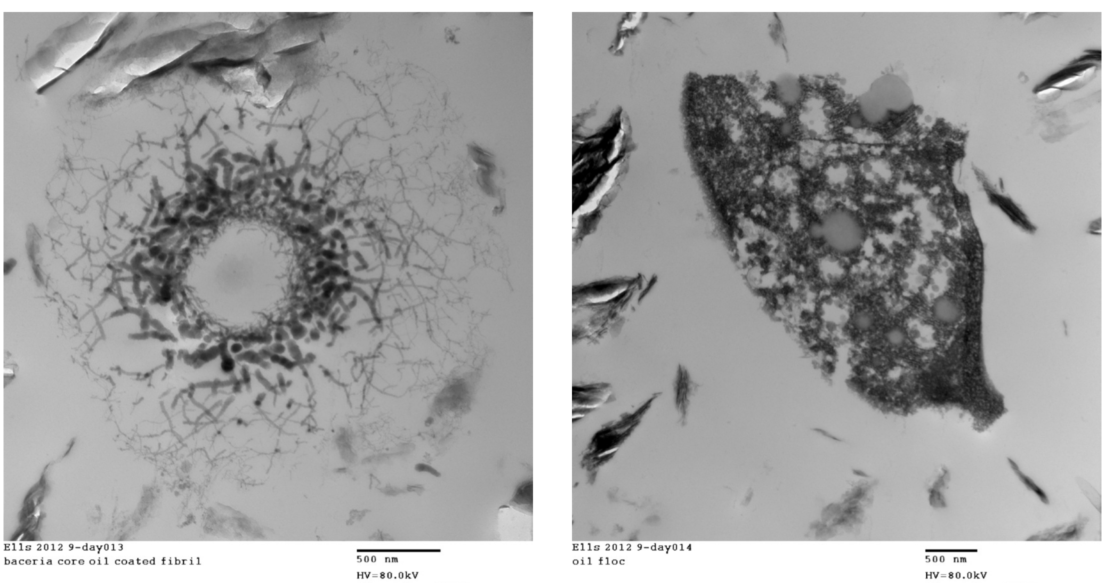

Figure 11. Two micrographs showing an Ells River bacterial cell with external fibrils coated by bitumen (left) and a principally inorganic small particle (floc) containing bitumen (right). Bitumen containing sediment will result in a hydrophobic property which will influence transport within the rivers.

Figure 12. Extreme suspended sediment concentration is visually evident during the early phase of the ice run just up-river of the Fort McMurray water treatment plant, April 27, 2014. Photo was taken by time-lapse camera installed on the left (North) river bank and looking across and slightly downstream. The water surface is exposed in the lower left portion of the image.

3. Summary of Biological/Ecological Condition of Aquatic Ecosystems

JOSM investigations for benthos and fish in the LAR tributary, mainstem, deltaic and extended geographical ecosystems were undertaken to evaluate the efficacy of monitoring designs to answer bioassessment questions identified in the Phase 2 Integrated Monitoring Plan for the Oil Sands (Environment Canada and Alberta Environment 2011b). This bioassessment evaluates the contemporary state of aquatic ecosystem health in relation to potential environmental effects, determines if important change has occurred since earlier assessments, and describes associations among the biological and the physical-chemical environment. Required adjustments in the proposed monitoring approach are suggested with the aim of producing a more robust assessment of long-term aquatic health status and trends.

The principal bioassessment questions of the JOSM Benthos and Fish themes include:

- *What is the current status of benthic assemblages and fish populations in these ecosystems?*
- *Are there existing differences in benthic assemblages and fish populations among reference and potentially impacted sites?*
- *Are there significant changes in benthic assemblages and fish populations since historical studies?*
- *Do predictive relationships exist that link system drivers (including development stress) to benthic assemblage and fish responses?*
- *Is there evidence of cumulative effects of development on benthic assemblages and fish populations in the Lower Athabasca River and/or in its tributaries?*
- *What additional data are required to assess current and future developments?*
- *What are contaminant levels in fish?*
- *What are the important aquatic routes of exposure and potential effects in organisms?*

3a. Lower Athabasca Tributaries

Benthic Macroinvertebrates (OS Tech. Ser. 1.7)

Previous evaluations of biomonitoring programs undertaken in the LAR tributaries recommend the development of a reference model to provide the baseline against which test sites could be evaluated (Ayles et al. 2004; Dillon et al. 2011; Main 2011). These reviews also identified the need to develop standardized sampling protocols and to focus the sampling design on more clearly defined habitats. Further, modification of study designs must aim to reduce variability by determining relevant spatial and habitat scales for sampling. The JOSM study of LAR tributaries considered these recommendations and, where possible, incorporated them into the study design and sampling approaches of the Phase 2 Integrated Monitoring Plan for the Oil Sands (Environment Canada and Alberta Environment 2011b).

Bioassessment questions related to the ecological condition of tributary benthos were aimed at developing new monitoring approaches (Fig. 13) and improving understanding of the potential effects of development on benthic macroinvertebrate assemblages of the LAR tributaries (Culp et al. 2018). Benthic invertebrate investigations categorized tributaries as outside of the oil sands region, inside the natural deposit with minimal industrial footprint, and inside the natural deposit with increasing industrial footprint. The sampling design included Reference Condition Approach model development, Before-After-Control-Impact designs, and gradient designs within individual streams. Sampling method comparison and calibration was necessary to align historical sampling (e.g., Hess sampler) with contemporary Canadian Aquatic Biomonitoring Network (CABIN) protocols (time-limited kick net). In addition, an in situ caging approach using the invertebrate, *Hyalella azteca* (a freshwater amphipod crustacean), was conducted at a subset of the benthic macroinvertebrate monitoring sites representative of the three exposure categories. As *Hyalella* survival and growth responds to a number of diverse chemical mixtures (PACs, metals, pesticides, pulp mill effluents, municipal wastewater effluents), the objective was to evaluate this approach for detecting effects of environmental exposure at locations within the natural bitumen deposits as well as sites with surrounding industrial activity.

The JOSM benthic program increased tributary sampling effort by five-fold with the addition of

Figure 13. Examples of sampling methodology used in the tributaries of the Lower Athabasca River benthic biomonitoring study: a) collection of kick net sampling for benthic invertebrates – here different mesh sizes are used to aid comparison of historical and contemporary samples; b) estimation of bank height as part of the Canadian Aquatic Biomonitoring Network (CABIN) procedures; 3c) collection of algal periphyton on hard substrate using the "scalpel-scraping" technique; and 3d) measurement of wetted width of sampling reach.

over 85 new sites. This improvement enhanced the ability to characterize benthic macroinvertebrate assemblages in both reference and exposure sites. Benthic assemblages in LAR tributaries generally exhibited good ecological condition with high abundance of intolerant Ephemeroptera (mayfly), Plecoptera (stonefly) and Trichoptera (caddisfly) (EPT) taxa among the sites. There was no significant difference between reference sites that were located outside of the oil sands region compared to those within the natural deposit. In contrast, benthic assemblages in areas with an increased industrial footprint were divergent from reference sites (e.g., lower EPT abundance), a trend that may be indicative of mild environmental stress. Further investigation is required to determine whether there is a causal relationship between exposure to environmental stressors and altered assemblage composition as definitive statements on this linkage are not yet possible. For example, observations of lower proportions of sensitive EPT taxa at test sites in the Steepbank and Ells rivers were associated with higher land disturbance and increases in total PAC concentration. The short-term, single species bioassays with caged *Hyalella* did not detect any differences in survival or body size at the sites where changes were shown at the benthic community level. A comparison of sampling methods using taxonomic composition as the measurement variable revealed that the kick sampling method led to a greater separation among sites; thus, ongoing assessments should employ the kick net sampling approach to increase measurement precision and accuracy.

Fish Health (OS Tech. Ser. 1.8)

JOSM studies of fish health (McMaster et al. 2018) for tributaries of the LAR mainstem were undertaken to develop a comprehensive and robust monitoring program based on existing Environmental Effects Monitoring (EEM) methods for Pulp and Paper and Metal Mining industries. The fish program focused on fish health endpoints in select sentinel species as differences in growth, reproduction, condition and survival put fish at risk. Knowing this level of risk is important for managing aquatic ecosystems and can be detected earlier than changes in fish communities. A primary objective was to develop health baselines for sentinel species, primarily the slimy sculpin (*Cottus cognatus*), and use this information to determine the potential for oil sands development to affect overall fish health. The fish health assessment asked whether there are effects of development on wild fish and, when effects were observed, the following questions were posed: 1) Are effects similar to those for invertebrates? 2) Are the response patterns of fish species of the mainstem LAR similar to one another? 3) Are contaminants in fish exhibiting similar patterns? 4) Can these changes be linked to indicators of exposure and, ultimately, what is causing the effects in wild fish? Toxicological analyses were also completed on fathead minnows (*Pimephales promelas*) to examine the potential importance of different exposure pathways on fish health, and to contribute baseline data for future site-specific comparisons.

Slimy sculpin were sensitive biological indicators as shown by consistent changes in fish health between reference and exposure sites within the oil sands deposit (Fig. 14). The recorded endpoint changes included increases in liver size with corresponding induction of EROD activity for fish collected at exposure sites. The EROD fish biomarker indicates exposure to planar halogenated and polycyclic aromatic hydrocarbon compounds, such as PACs. EROD induction in slimy sculpin was associated with reductions in energy invested in reproductive development as represented by lower gonadal development. These downstream responses are indicative of exposure to inducing compounds as EROD activity followed a very similar pattern to PAC body burden. Moreover, assessment of sediment toxicity suggests that sediments are the source of the elevated PACs in the water column. Although differences among sites were observed in the condition of male and female fish, these changes were not clearly associated with a known environmental gradient. The JOSM results will aid comparison to historical fish health studies conducted on the Steepbank River when a smaller portion of the watershed was affected by oil sands development (Tetreault et al., 2003). Additional years of data collection are required on other tributaries to the LAR before current status of fish health in those tributaries can be determined with sufficient levels of confidence.

Controlled exposures of fathead minnows to natural oil sands sediment from two river sites (Steepbank River and Ells River lower sites) demonstrated decreased embryo-larval fish survival. Early-life exposure to PACs was associated with some non-lethal deformities and changes to social behaviour in the fathead minnow, but the most significant impact was poor egg production as adults. In addition, laboratory exposure of fathead minnow larvae to melted snow from sites near to mines and industrial

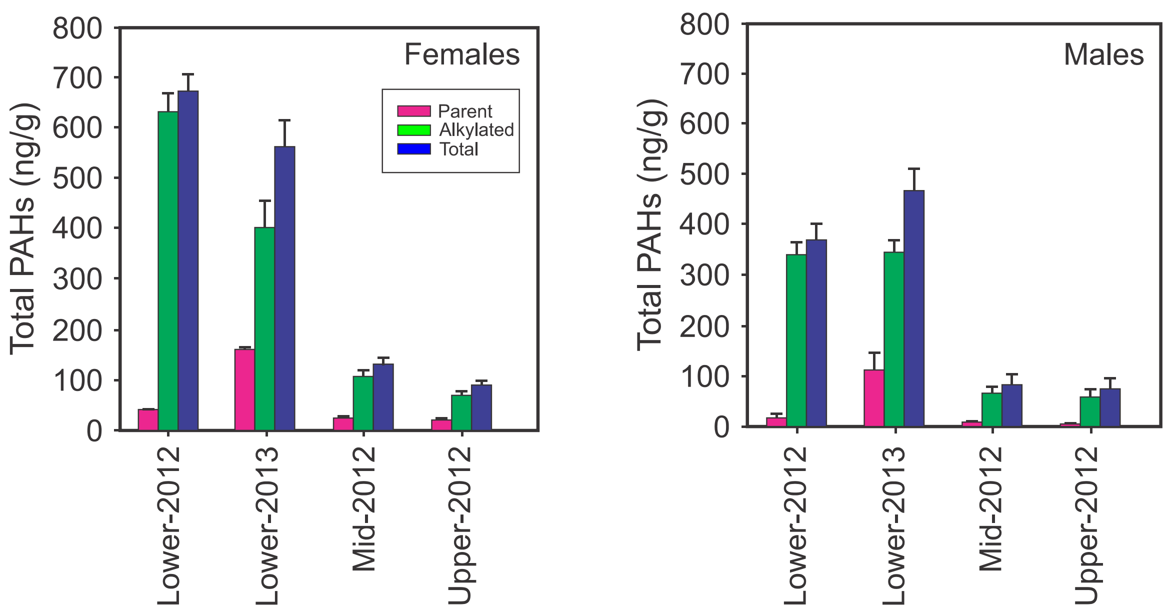

Figure 14. Polycyclic aromatic hydrocompounds (PAHs) levels in slimy sculpin collected from the Steepbank River during the fall of 2012-13. Sites represent the Steepbank lower site (lower and RAMP lower – same site), Steepbank mid site (MC Mid), Steepbank upper site (MC Upper) and a site further upstream (RAMP Upper). Values represent the mean ± S.E. Parent PAHs – pink; Alkylated PAHs – green; total PAHs – blue.

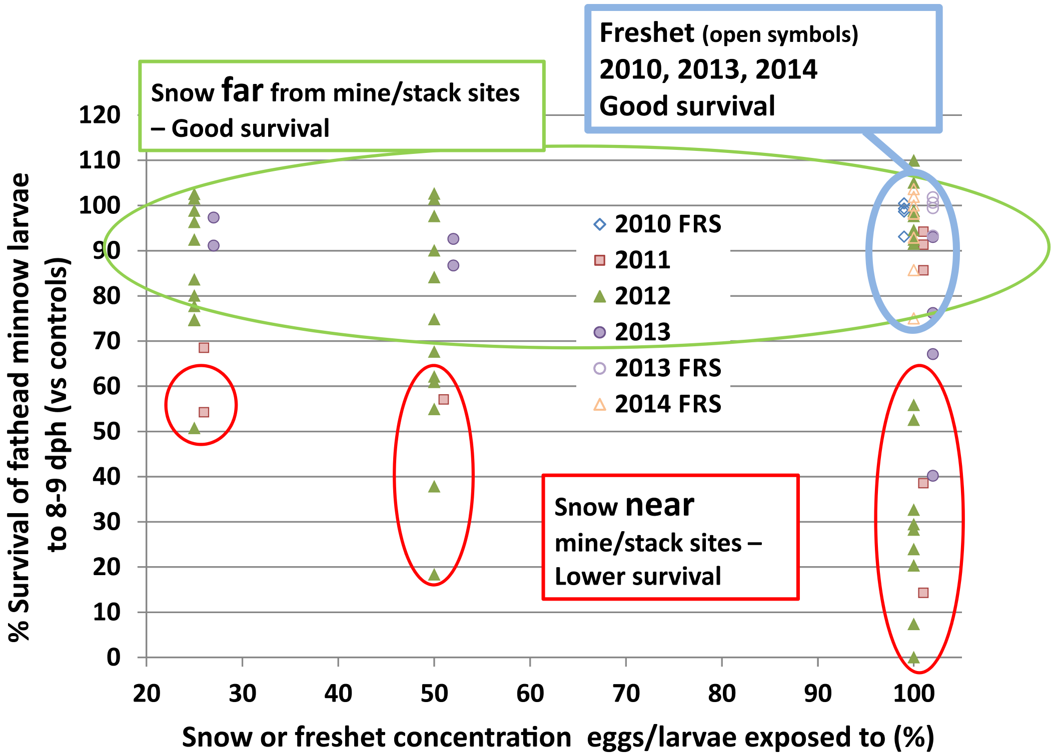

Figure 15. Fathead minnow (*Pimephales promelas*) embryo-larval survival after exposure to melted snow or freshet (FRS) water collected from the Athabasca, Ells, and Steepbank rivers. Exposures were to 25, 50, and 100 % melted snow or 100 % freshet. Some points are shifted slightly to allow overlapping data points to be seen. Different coloured symbols show various snow and freshet sampling years from 2010-2014.

stacks decreased larval fish survival (Fig. 15). However, exposure to freshet water from either location did not impact survival, which suggests that dilution may be sufficient to limit impacts to fish. Snow far from mines and stacks contained lower contaminant levels and exposure to this meltwater did not affect larval fish survival in the lab. Continuous exposure of resident fish to sediment within the oil sands deposit appears to be required for the increased expression of EROD activity at these sites.

Sufficient data were obtained through the JOSM program to assess the spatial and temporal variability of several endpoints, and to develop reference baselines that can be used to separate variability caused by exposure to oil sands compounds from variability linked to natural environmental changes. Using a minimum three years of data (more was available from the Steepbank River), mean values for condition, gonado- and liver somatic indices were calculated for slimy sculpin by sex. From these data, the upper and lower limits of the critical effect sizes (CES) and +2 SD (standard deviation) of the mean of endpoints were calculated. The CES for condition was +10% of the mean, while CES values for the gonado- and liver somatic indices were +25% of the mean (Environment Canada, 2012). All CES thresholds were derived using Steepbank River Upper reference sites data from 2010-2013 in order to reflect the contemporary reference state. Although some endpoints were outside of the pre-determined CES, this portion of the fish program (Steepbank River) has been shifted to the long-term monitoring plan with the next confirmation sampling period to occur in 2016.

3b. Lower Athabasca Mainstem

Benthic Assemblage (OSM Tech. Ser. 1.7)

The benthic mainstem sub-theme examined the efficacy of the Phase 2 technical plan (Environment Canada and Alberta Environment 2011b) and focused on developing a robust benthic monitoring approach for the LAR mainstem (Culp et al. 2018). Key objectives were to establish an appropriate sampling approach for this large river, and to determine which habitat should be sampled in the bioassessment program. Development of such a program was complicated due to the Athabasca River's large width, depth, and flow. Previous efforts to monitor the mainstem included limited sampling of the depositional habitat using Ekman grabs or the erosional habitat using Neill/Hess or Surber samplers, both of which proved insufficient methods to assess impacts. Samples for this program were collected in cobble and sand habitats from reference areas upstream of oil sands development, sites within the oil sands formation but above active mining, sites in the active mining extraction area, and sites downstream of mining activity. In addition, an in situ caging approach using a freshwater mussel (*Anodonta grandis simpsoniana*) was undertaken at LAR mainstem sites above and below oil sands mining activity. Besides providing insights that could improve the design of future monitoring approaches, the work also assessed the ecological condition of the LAR mainstem in relation to the physical-chemical environment.

Between September 2011 and September 2014, Environment Canada established 21 new sampling sites (11 for cobble and 10 for sand habitats) along 11 reaches in standardised benthic habitats (Fig. 16). During the three-year study, more than 300 benthic samples were collected and processed at sites M0 to M9 and 278 taxa belonging to more than 80 families of invertebrates were identified. The substantial increase in data collection produced by the JOSM mainstem benthic sub-theme will improve the ability to detect biological change related to human development.

The benthic assemblages of the LAR mainstem largely exhibited good ecological condition with intolerant EPT taxa found in large abundances at all sampling sites. However, the middle reaches of the study area that are exposed to municipal sewage effluent (MSE) from Fort McMurray and oil sands development show increased relative abundance of tolerant taxa. Moreover, far-field sites considerably downstream of the development shifted back towards reference communities upstream of the disturbance such that there is a decrease in relative abundance of tolerant taxa, similar to the reference site (Fig. 17). OS-exposed mussels were also less able to cope with stress tests and, compared to reference sites, mussel condition was lower at sites downstream of the MSE and oil sands development area.

These longitudinal patterns in ecological condition may be an indicator of mild environmental stress between sites M3 to M7C that is related to the combined effects of nutrient and contaminant stressor exposure. Although the observed difference in middle reach benthic communities was associated with trends in Chlorophyll *a*, POC, and V, definitive statements on the linkage of environmental drivers to this ecological change are not yet possible. Future assessments should focus on examining associations between the longitudinal benthic pattern and key supporting variables (e.g., nutrients, PACs, V). Future monitoring designs need to include sediment chemistry and SPMD deployments as these appear to measure critical environmental variables that are associated with patterns of benthic assemblage.

Analyses to date indicate that benthic assemblages in cobble habitat provide better resolution for detecting ecological change between M0 to M9 than sampling effort in sand habitat. Ongoing monitoring of benthic assemblages using kick net approaches in cobble reaches of the LAR mainstem are required to detect change associated with human activities. Relative to contemporary macroinvertebrate assemblages, historical assemblages were comprised of more tolerant taxa (e.g., chironomids). Although this potentially suggests a reduced ecological condition in the LAR mainstem at that time, this trend is most likely an artifact of the earlier studies locating sampling in shallower, nearshore habitats comprised of substrates with large amounts of fine sediments. These nearshore environments would be less suitable for intolerant invertebrates such as the EPT. In summary, this work has developed a robust mainstem sampling program that will be reproducible, and also provides an initial assessment of the potential effects of human development on the benthic assemblages of the LAR mainstem.

Fish Health (OSM Tech. Ser. 1.8)

This investigation aimed to develop a comprehensive, robust fish health monitoring program for the LAR mainstem by adapting methods developed for Canada's EEM program (McMaster et al. 2018). Challenges to designing and implementing fish health monitoring were in part related to multiple human developments and the remoteness of this large, northern river ecosystem. Issues such as seasonality of fish dis-

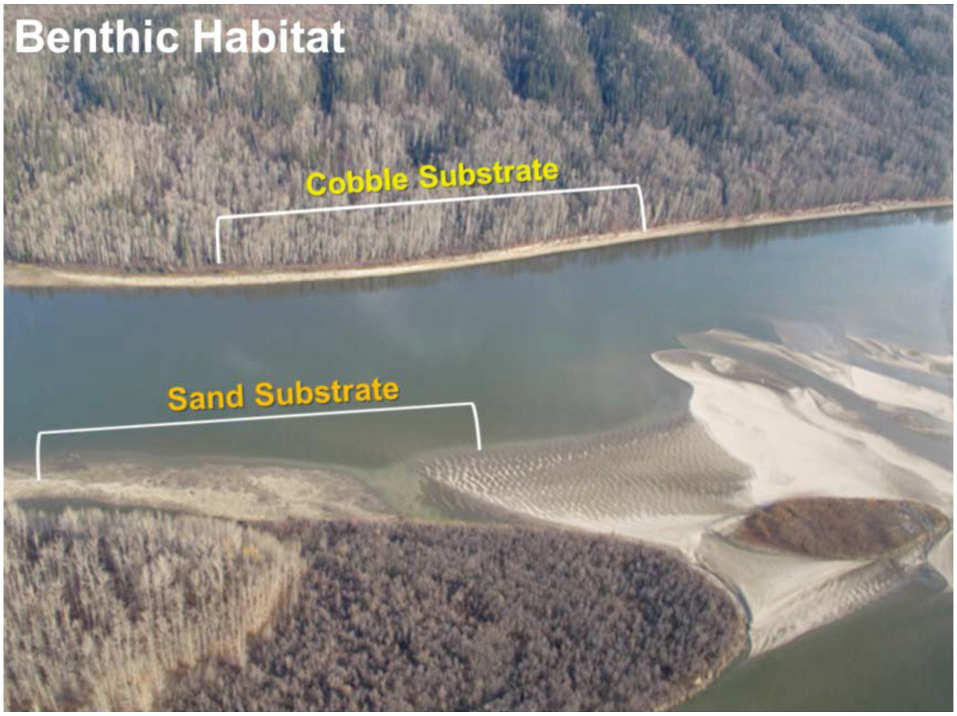

Figure 16. Benthic habitat in the Lower Athabasca River as shown by aerial photograph of the main channel showing representative habitat of cobble (east bank) and sand (west bank) substrate.

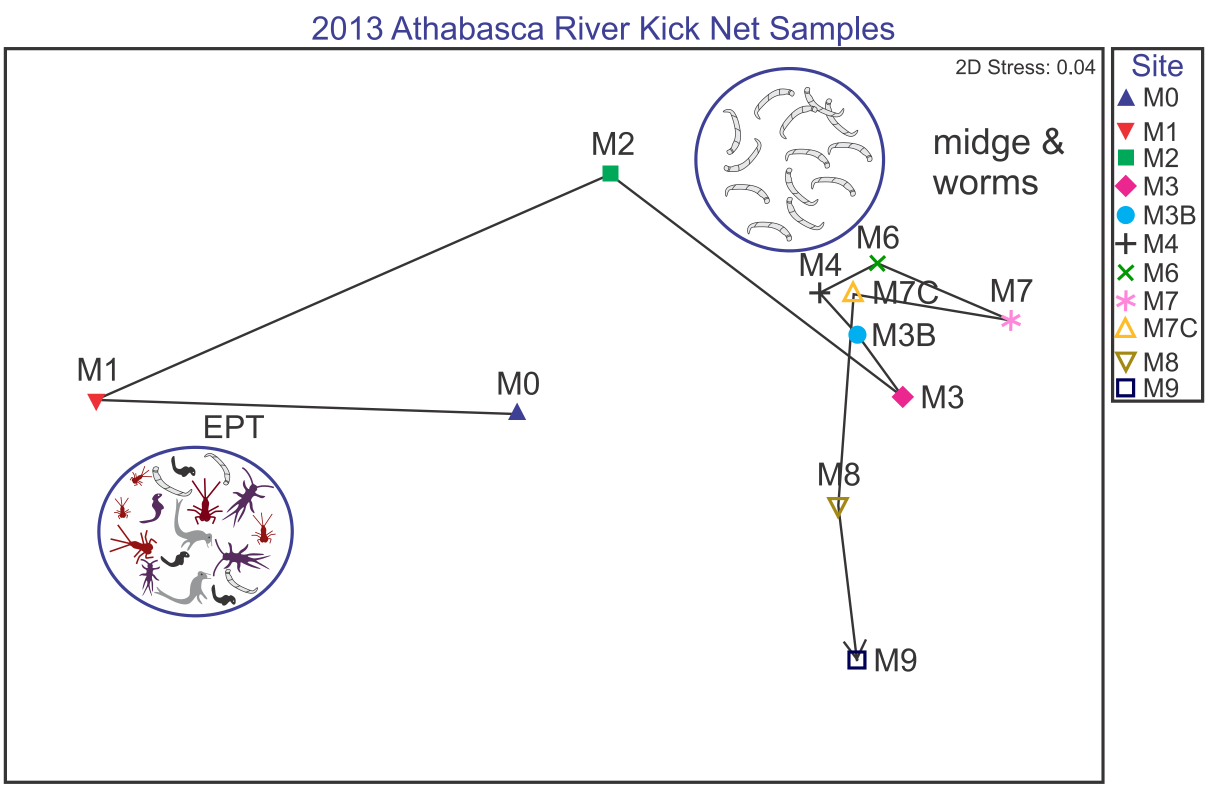

Figure 17. Path ordination diagram (nonmetric multidimensional scaling) of the averaged benthic macroinvertebrate community composition for 11 sites collected in September 2013 along the Lower Athabasca River. Composition changes from taxa associated with reference sites (EPT; Ephemeroptera, Plecoptera, Trichoptera) to pollution tolerant forms in mid-reaches in the area of development. Downstream sites considerably downstream of the development shifted back towards reference communities upstream of the disturbance.

tribution (e.g., migratory species), low species richness (fewer fish available for capture), high flow events, changes in river habitat within the study area, and limited access for electrofishing (Fig. 18) resulting in difficulties in sampling all stretches of the river. Previous fish health sampling on the LAR mainstem was limited to EEM studies assessing pulp and paper mill discharges and by Program of Energy Research and Development (PERD) studies in the late 1990's. Thus, the JOSM investigations targeted the development of baseline fish health across the watershed as recommended in the Phase 2 Plan (Environment Canada and Alberta Environment 2011b) and Canada-Alberta Implementation Plan (Environment Canada, 2012). The main objective was to address key questions related to the health of fish populations including evaluating growth, reproduction and survival, the presence of abnormalities and contaminants in fish. Critical effect sizes developed through the EEM programs and decision thresholds for ecological effects endpoints were adopted. This information provides the materials needed for cumulative effects assessment and for the comparison of contemporary and historical fish health.

Sampling locations included reference sites inside and outside the oil sands deposit that were upstream of development; sites were also established downstream of development within the deposit. Two sentinel fish species were identified, namely white sucker (*Catostomus commersonii*) and trout perch (*Percopsis omiscomaycus*). The large-bodied white sucker is a benthic feeder, which provide linkages to the invertebrate community bioassessment, and was sampled during the fall because it demonstrates high site fidelity in this season. Trout perch were also included as a sentinel species as this species has year-long site fidelity (i.e., low mobility) and its health should thereby more closely reflect local conditions. Fish were assessed for age, size at age, relative gonad size, condition, and relative liver size. Additional species were captured during the large bodied fish health assessments for the determination of contaminants in a harvested fish species; e.g., walleye (*Sander vitreus*).

White suckers were sensitive indicators of fish health in the LAR mainstem as consistent changes were documented in fish health downstream and within the oil sands deposit in 2011 to 2012. This pattern is indicative of nutrient enrichment as white sucker were older, longer, and heavier than reference fish, but had increased condition and increased levels of internal fat stores (Fig. 19). Similar to the tributary fish collections, white sucker within the deposit also demonstrate exposure to inducing compounds as EROD activity was higher within the deposit with some increases downstream of mining development. During the third year of baseline data collection, white sucker collected within the deposit more closely resembled those of upstream reference fish (Fig. 19). As conditions indicated improvements in fish health (approaching reference fish), the white sucker fish health program shifted into the long-term program with monitoring occurring on a three year basis with collections planned in 2016.

Although trout perch are less mobile than the white sucker, they were not consistently responsive to the various environmental conditions in the river. Results for both males and females did not demonstrate consistent alterations in fish health endpoints within sites and among years, indicating that exposure to oil sand deposits or development was not a major factor affecting trout perch health. Nevertheless, these data do provide a baseline for trout perch health that can be used to assess ecological change as development in the oil sands area progresses. The trout perch fish health program has also changed to the long-term monitoring plan with collections planned in 2018.

The fish biomarker, EROD activity, was a good indicator of exposure to PAC related compounds. White sucker livers of fish sampled within the deposit had significantly increased enzyme activity. Moreover, increased PAC levels in liver tissue and induction of enzyme activity was found downstream of development in both sexes. PAC levels were higher in male livers compared to female, a trend also observed for walleye. These results indicate that fish within the deposit are exposed to inducing compounds and that downstream of development appears to increase exposure to these compounds.

Within this theme, fish health baselines have been developed for the LAR mainstem. This information was used to define the normal range of endpoint values for sites by calculating a cumulative mean ± 2 SD. With an improved un-

Figure 18. Environment and Climate Change Canada staff undertaking an electrofishing survey to evaluate the health of reference fish populations on the Athabasca River upstream of the oil sands deposit.

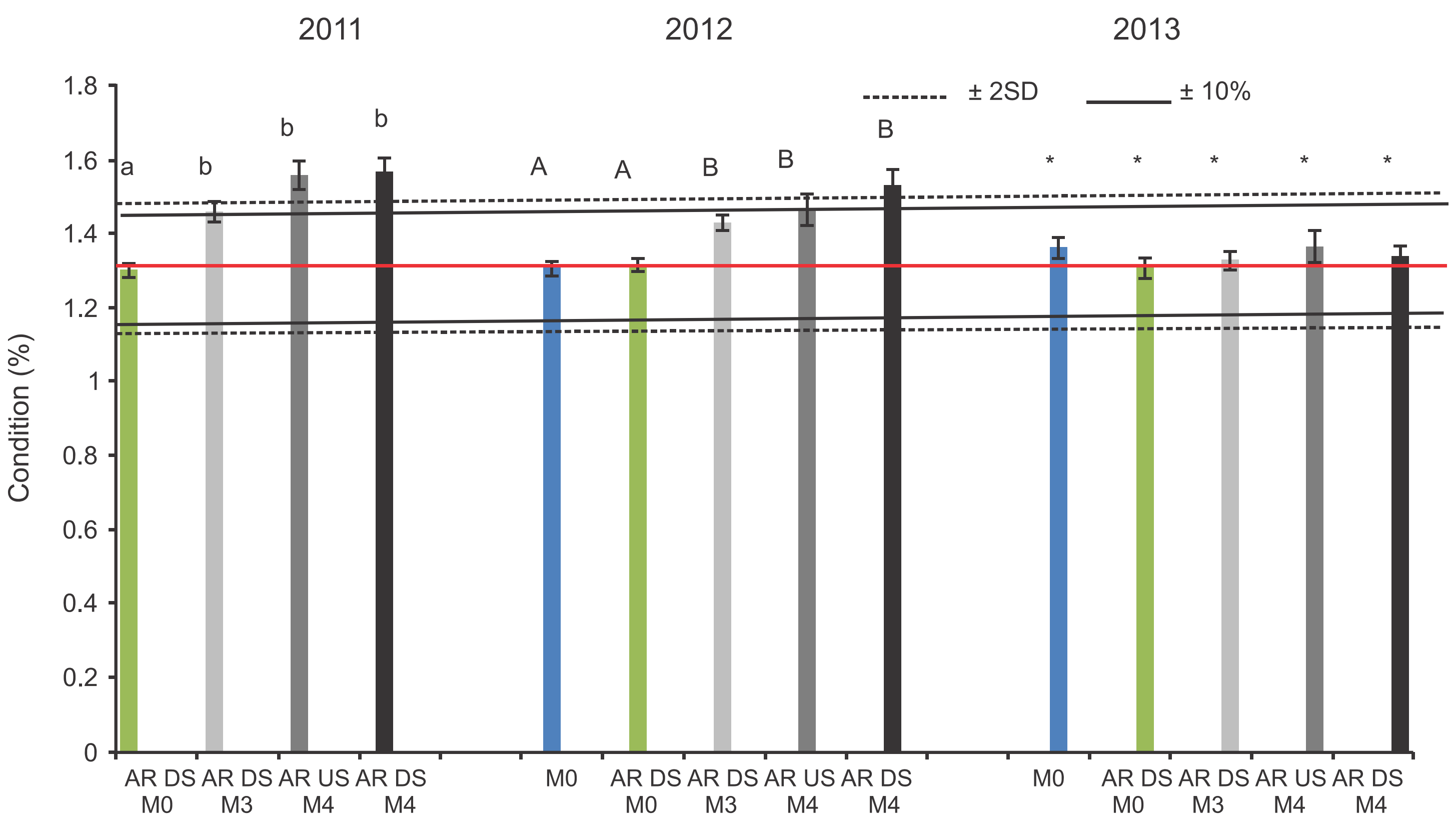

Figure 19. Male white sucker (*Catostomus commersonii*) body condition from sites collected on the Athabasca River (AR) in 2011-2013. Mean ± SE with the critical effects size of 10 percent and 2 SD of the reference site means indicated.

derstanding of reference site variability, this knowledge can be used to develop critical environmental thresholds of change, assess alterations in fish health and identify differences among sites. The work advances the ability to assess the cumulative effects of development on fish in the LAR mainstem by developing a consistent set of monitoring indicators, a series of adaptable monitoring thresholds for endpoints, and links the environmental drivers to the biological responses.

3c. Deltaic and Extended Geographic Area (EGA)

Benthic Macroinvertebrates (OSM Tech. Ser. 1.7)

The Deltaic and EGA work focused on determining baseline conditions for benthic invertebrate communities in wetland habitats (i.e., Slave River drainage; Peace, Athabasca and Birch deltas) (Culp et al. 2018). Previous work on these wetlands was limited and a Regional Aquatic Monitoring Program (RAMP) network was never established. In contrast, benthic macroinvertebrate monitoring sites had been established by RAMP on several LAR connecting channels (i.e., Embarras, Fletcher, Goose and Big Point). Thus, the key aim of the deltaic invertebrate work was to establish a monitoring network and methods to observe and detect ecological change in wetland habitats attributable to downstream effects of oil sands mining, with a particular focus on potential contaminant effects. Questions evaluated included those identified in the Phase 2 monitoring plan (Environment Canada and Alberta Environment 2011b) as outlined for the LAR mainstem and tributary invertebrate subthemes.

Wetland monitoring sites within the PAD represent a gradient in terms of potential exposure to oil sands contaminants. Two distinct exposure pathways were identified: (i) surface flow and associated sediment deposition from the Athabasca River; and (ii) atmospheric transport and deposition of emissions either in the form of snow, rain and/or dust particles. Wetland site selection was aligned, where possible, with historical and ongoing vegetation monitoring carried out by Parks Canada to assess long term ecological effects of oil sands contaminants.

Baseline biotic and abiotic environmental conditions were determined at each wetland monitoring site within the EGA. Local site hydrology and land surface connection to rivers were quantified, including the geospatial characteristics for interpretation (permanent, temporary or non-connections). Bioassessment involved undertaking a retrospective risk assessment of potential contaminant effects on delta benthic species and establishment of baseline levels of key oil sands contaminants in surface waters, sediments, and biota. This assessment compared seasonal versus annual sampling regimes, evaluated multiple years of baseline data to investigate 'within-' and 'between-site' variability in biotic composition, identified benthic invertebrate indicator taxa and derived cumulative effects metrics. Biological sampling focused on wadeable habitats at wetland margins dominated by emergent vegetation, including shallow inundated wet meadows. The standardised sampling method was based on the CABIN (Environment Canada, 2012) standard kick net (400µm mesh).

Delta wetland macroinvertebrate assemblages appear to be in a healthy state. They exhibit high biodiversity (93 taxa), strong seasonal and spatial variability of richness and composition, and to date there is no evidence of cumulative effects on deltaic ecosystems arising from oil sands activities. Athabasca and Peace delta communities have divergent community structure associated with different biogeographic origins and nutrient status. Tissue MeHg in dragonfly larvae shows seasonal changes in the PAD that suggests ongoing mercury methylation throughout the summer (Fig. 20). The deltas differ with respect to water chemistry. For example, the Whooping Crane Nesting Area (WCNA) has a much greater specific conductivity and lower total alkalinity than PAD sites, likely a result of the karst landscape of the WCNA. The Peace and WCNA sites demonstrate greater total nitrogen and lower TP than the PAD. For all parameters except TP, Peace delta sites show greater variation than Athabasca sites. These biotic and abiotic patterns will be confirmed as core sites numbers are expanded (i.e., full network established in 2016-17), thereby permitting improved determination of reference conditions, effect size criteria and associated statistical confidence to detect effects. As oil sands operations approach the EGA, wetland monitoring sites will be required in the eastern Athabasca delta as well as reference sites north of the PAD. Engagement of local stakeholders with the Peace-Athabasca Delta Environmental Monitoring Program (PADEMP) will be required during selection of monitoring sites.

This work established a robust sampling method for wetland invertebrates based on traditional taxonomic method, and augmentation of the approach with a trial of DNA-based identification provided added value by increasing taxonomic resolution and the overall number of taxa observed. Hydrological connectivity mediated by flooding in the PAD is affected by climate change and flow variability related to the operation of upstream hydroelectric facilities. Thus, improved understanding of hydrological drivers of change within the system is a key requirement to distinguish potential effects arising from any future oil sands contamination.

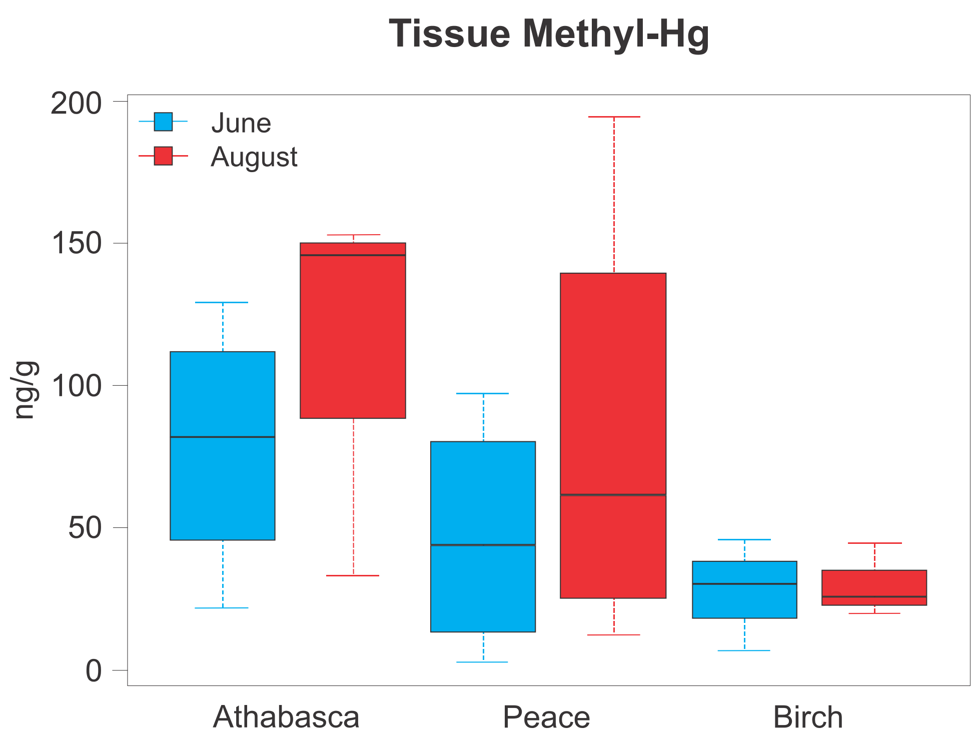

Figure 20. Boxplots of seasonal variation in methylmercury concentrations of dragonfly and damselfly tissues from sites in the Peace, Athabasca and Birch Deltas from material collected in June and August 2014.

4. Causal Assessment of Ecological Effects

Distinguishing among the ecological impacts of multiple stressors requires establishing causality links among effects and possible stressors. To aid this process for the JOSM Water Program, we adopted the ecological causality assessment method of Norton et al. (2015), which links ecological effects to candidate causes and considers the evidence supporting the importance of these effect pathways. Complicated environmental issues, such as those encompassed by the JOSM Water Program, require careful inference developed through a weight of evidence approach that ensures that all pertinent information is considered in order to determine which of the candidate causes are most strongly supported. Evidence is assessed based on its relevance, quality and strength, and can include a disparate mixture of information including site-specific observations, regional observations, modelling, laboratory tests, etc. (Norton et al. 2015). Additionally, the approach incorporates effect categories thereby avoiding the disadvantages of numeric systems that attempt to combine weights from very different types of evidence. The causal assessment models developed for the LAR ecosystems include effect pathway diagrams (Figs. 21 and 22) supported by Tables 1 and 2 that summarize evidence on the importance of each causal pathway. This material illustrates how ecological effect can be linked to the source stressor through candidate proximate causes with the strength of the relationship weighted according to the rating system described below.

Besides establishing important ecological effects, the JOSM Water Program also produced considerable new information on temporal and spatial trends in physical and chemical variables, which at present cannot be directly related to ecological effects. For example, flow regime affects sediment deposition and streambed habitat (Droppo et al. 2018), but the ecological effects of such changes are unknown for the LAR. Thus, physical-chemical changes in the LAR ecosystems that could be related to anthropogenic or natural sources (e.g., surface runoff rates), but not to ecological effects, are not included in Tables 1 and 2. As future monitoring programs acquire the additional information required for causal ecological assessments, there will be improved understanding of the interrelationships among the physical, chemical and biological variables.

An important aspect of the weight of evidence approach is to establish a formal method of assigning importance to causal pathways. Following Norton et al. (2015), evidence is weighed by recording a +, ++ or 0 to indicate the degree to which each pathway is supported as the cause of an observed ecological effect (Figs. 21 and 22). This weight of evidence approach can be linked to risk assessment frameworks for future monitoring through the probability assessment of environmental occurrence and impact (Fig. 23) and could identify where monitoring resources would best be allocated. The assignment of + (somewhat supports, Tier 2) is based on statistically significant field observations, ++ (strongly supports, Tier 1) indicates statistically significant field observations and strong spatial co-occurrence of stressor and effect, while 0 (Tier 3) indicates a pathway that has no effect (or shows ambiguous results). Pathways for which no supportive evidence exists are not included in Figs. 21 and 22. Such a weight of evidence approach can help guide future assessment as + and ++ level pathways would be the most likely linkages where more detailed investigation of cause through monitoring and research would yield information that could aid management and potential remedial action.

4a. Tributary Effects

The main tributary basins of the LAR represent a large area where atmospheric deposition and hydrological processes (e.g., overland flow, groundwater inputs and river routing) occur to varying degrees as influenced by climatic conditions. Clearly, the temporal variations in the candidate proximate causes of nutrients, contaminants, sediments and groundwater will vary throughout the year with rain storms, snow melt and duration of dry antecedent conditions (Table 1 and Fig. 21). Further, the magnitude and duration of bitumen exposure for fish and benthos increase with distance downstream as the water and sediments move into and through the natural McMurray Formation and into higher levels of industrial development (e.g., the Steepbank River). These tributaries will contribute to the ecological effects observed within the mainstem of the LAR (Table 2 and Fig. 22).

Table 1. Lower Athabasca Tributaries: Summary of causal assessment of ecological effects. Ratings are 0 (no support or ambiguous), + (some what supported) or ++ (strongly supported).

Ecological Effect (from upstream to downstream)	Source of Effect	Candidate Cause	Supporting Evidence	Rating
Fish Health • ↑ sculpin PAC in body tissue • ↑ EROD activity • ↓ survival in sediment toxicity tests (embryo-larvae) **Benthic Health** • ↑ tolerant taxa in lower stream reaches • change in community composition • ↓ mussel condition	Oil sands operation	Nutrient enrichment	Atmospheric deposition includes TP and PON but change in surface water nutrient concentrations were not observed within the industrial footprint[2,3].	0
		Contaminant exposure (surface water, groundwater and sediments)	In lower reaches downstream of increased area of land disturbance and in the zone of atmospheric deposition[2], fathead minnow survival was reduced in snow toxicity tests[7], sculpin showed increased liver EROD activity and increased PAC tissue levels[8], and benthos composition shifted to more pollution tolerant taxa[7]. Caged mussels showed decrease condition while sediment toxicity tests indicate decreased embryo-larval survival of fathead minnows[8]. No observed groundwater input from operations[5].	+
	Natural Bitumen	Nutrient enrichment	No change in total P and organic carbon attributable to McMurray formation[3,7].	0
		Contaminant exposure (surface water, groundwater and sediments)	Magnitude and duration of exposure for fish and benthos to bitumen-derived contaminants within water and sediment increases with distance downstream[7,8]. In the upper watershed sculpin liver EROD and PAC tissue levels[8], as well as benthic composition[7], were similar at reference sites outside and inside exposed McMurray Formation geology. In contrast, in lower stream reaches well within the exposed bitumen deposit sculpin show increased liver EROD activity and increased PAC tissue levels[8], and benthos composition changed to more pollution tolerant taxa[7]. Furthermore, caged mussels showed decrease condition while sediment toxicity tests show decreased embryo-larval[8]. Toxicity tests with Ells River groundwater showed reduced fathead minnow survival[8].	+
		Sediment input (habitat change)	Spatial co-occurrence in downstream reaches of more pollution-tolerant benthic taxa with increased deposited sediments (as indicated by numerical sediment modelling)[6,7].	+

Superscript numbers represent the technical report as listed in Text Box 2 of this synthesis report.

The effects observed in the downstream portions of tributaries of the LAR include, increased body tissue PAC for sculpin fish, higher EROD activity in fish, decreasing survival of embryo-larvae within sediment toxicity tests, an increased relative abundance of tolerant invertebrate taxa, changes to benthic community composition and a decrease in mussel condition. A summary of the likely candidate causes and evidence supporting causal pathways suggests that these ecological trends were possibly associated with contaminant exposure in surface water, groundwater and sediments. The source of this exposure is, however, confounded by the presence of, and inability to differentiate between, oil sands operation activity (principally atmospheric deposition) and natural bitumen inputs (e.g. erosion) within the tributaries (Fig. 21). Both

Table 2. Lower Athabasca Mainstem: Summary of causal assessment of ecological effects. Ratings are 0 (no support or ambiguous), + (some what supported) or ++ (strongly supported).

Ecological Effect (from upstream to downstream)	Source of Effect	Candidate Cause	Supporting Evidence	Rating
Fish Health • ↑ white sucker size • ↑ EROD activity **Benthic Health** • ↑ tolerant taxa • composition change • ↓ mussel condition	Municipal effluent discharge	Nutrient enrichment	Spatial co-occurrence between substantive nutrient increase below municipal effluent discharge and change in benthic composition[7], as well as increase in fish size, age, condition and fat stores[8]. Observed transition towards reference condition downstream at M9[7].	++
		Contaminant exposure	Increase in benthic tolerant taxa, decrease in mussel condition and higher EROD activity in fish downstream of municipal effluent discharge[7,8].	+
	Oil sands operation	Nutrient enrichment	Atmospheric deposition includes TP and PON but change in surface water nutrient concentrations were not observed within the industrial footprint[2,4].	0
		Contaminant exposure (surface water, groundwater and sediments)	In river reaches downstream of mining activity and in the zone of higher atmospheric deposition, fish show increased liver EROD activity and increased PAC levels in liver[8]. Intolerant invertebrates declined and higher stress levels were observed in mussels caged in these areas[7]. Lab toxicity tests indicate reduced fathead minnow survival in groundwater seepage[8].	+
	Natural Bitumen	Nutrient enrichment	No change in total P and organic carbon attributable to McMurray formation[4].	0
		Contaminant exposure (surface water, groundwater and sediments)	Decrease in benthic intolerant taxa and caged mussel condition, increased PAC levels in fish liver and muscle, and increased liver EROD activity in areas of exposed bitumen deposit. Toxicity tests with groundwater seepage show reduced fathead minnow survival.	+
		Sediment input (habitat change)	No observed ecological effects associated with sediment habitat change although numerical model output indicates deposition occurs in areas relevant to benthic and fish health.	0

Superscript numbers represent the technical report as listed in Text Box 2 of this synthesis report.

industrial operations and natural exposures to bitumen were therefore characterized as "somewhat supported" (+, Tier 2) as important causal pathways of effect (Table 1). In lower stream reaches, well within the exposed bitumen deposit and the zone of atmospheric deposition, sculpin showed increased liver EROD activity and increased PAC tissue levels, while benthos composition changed to more pollution tolerant taxa. Evidence of benthic habitat change in downstream reaches is also "somewhat supported" (+, Tier 2) by the co-occurrence of more pollution-tolerant benthic taxa with increasing deposition of sediment within the bed matrix (during low flows and as supported by numerical modelling - Droppo et al. 2018). Atmospheric nutrient inputs were not associated with change in surface water nutrient concentration or ecological effects. Differentiation of cause will only be possible once a discriminative test(s) is developed through further research and monitoring as to the source of contaminants.

4b. Lower Athabasca Mainstem Effects

Ecological effects observed in the LAR mainstem below Fort McMurray included larger white sucker size, higher EROD activity in fish, higher

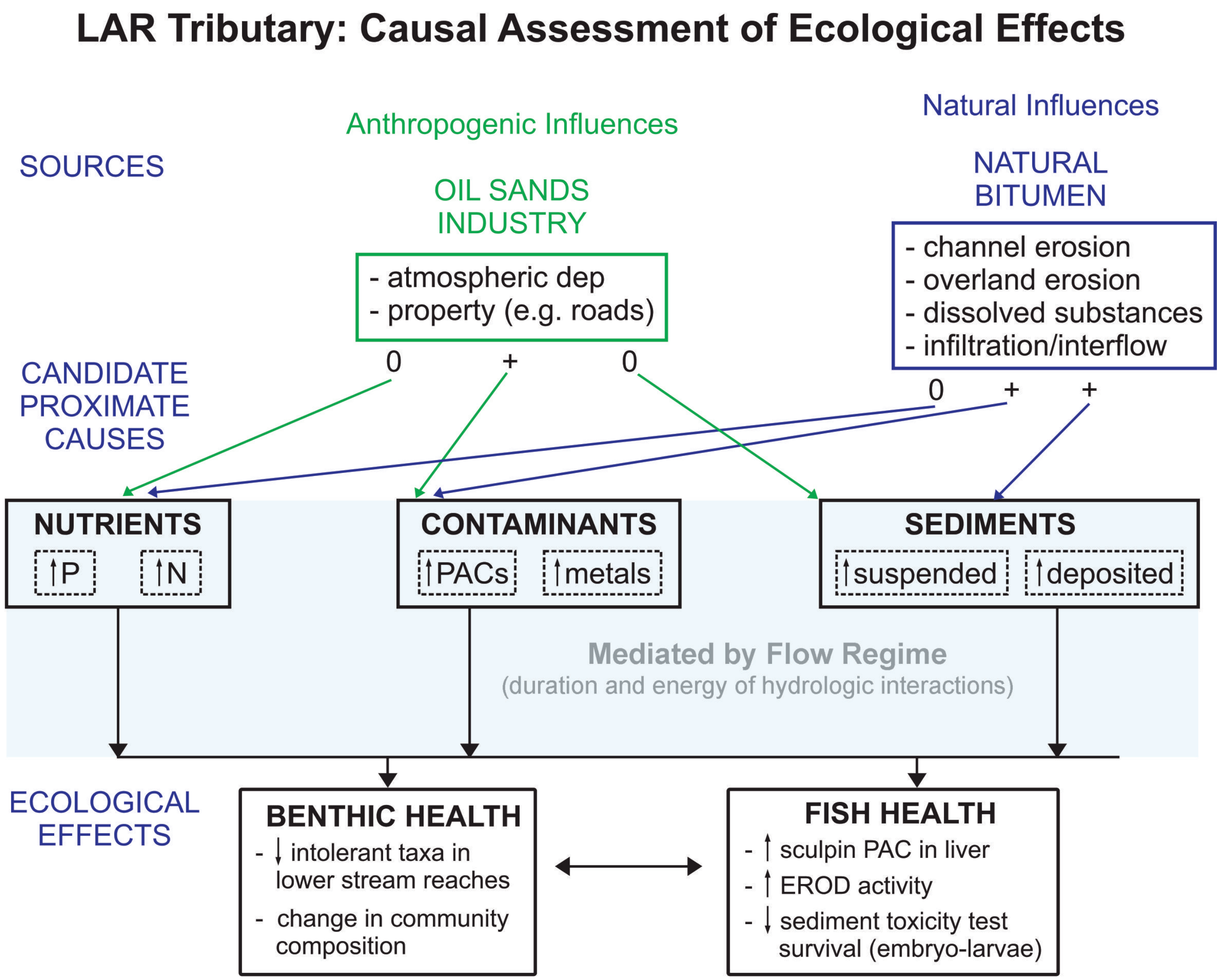

Figure 21. Lower Athabasca Tributaries: causal assessment of observed ecological effects showing linkages between sources of effects (industry and natural bitumen), candidate proximate causes (nutrient enrichment, contaminant exposure via surface water and sediments, habitat change from suspended and deposited sediment) and groundwater input (including contaminants).

benthic invertebrate abundance, an increased importance of tolerant invertebrate taxa and decreased mussel condition. A summary of the likely candidate causes and evidence supporting causal pathways suggests that these ecological trends were associated with nutrient enrichment and contaminant exposure (Fig. 22). Treated municipal sewage effluent (MSE) from Fort McMurray is “strongly supported” (++, Tier 1) as the cause of the increased biotic production in the LAR. This conclusion is reinforced by the spatial co-occurrence between the substantive nutrient increase below the MSE discharge and recorded changes in fish and benthos (Table 2). In contrast, isolating the source of contaminant exposure in the LAR was much more difficult as the MSE, industrial operations and natural exposure to bitumen were all “somewhat supported” (+, Tier 2) as important causal pathways of effect. For example, changes in biota, such as the increase in benthic tolerant taxa, a decrease in mussel condition and higher EROD activity in fish, were initially observed at M3 downstream of the MSE discharge. However, such ecological effects were also recorded in river reaches receiving higher atmospheric deposition of industrially derived toxic compounds where biota are simultaneously exposed to toxic compounds originating from erosion of natural bitumen. Because exposure to nutrients and contaminants is spatially confounded in the LAR, future monitoring effort should focus on investigating the cause of the ecological effects through field studies and experiments specifically designed to separate the ecological effect of nutrients and contaminants. However, the identification of effects caused by contaminants derived from natural bitumen or industrial activity will remain

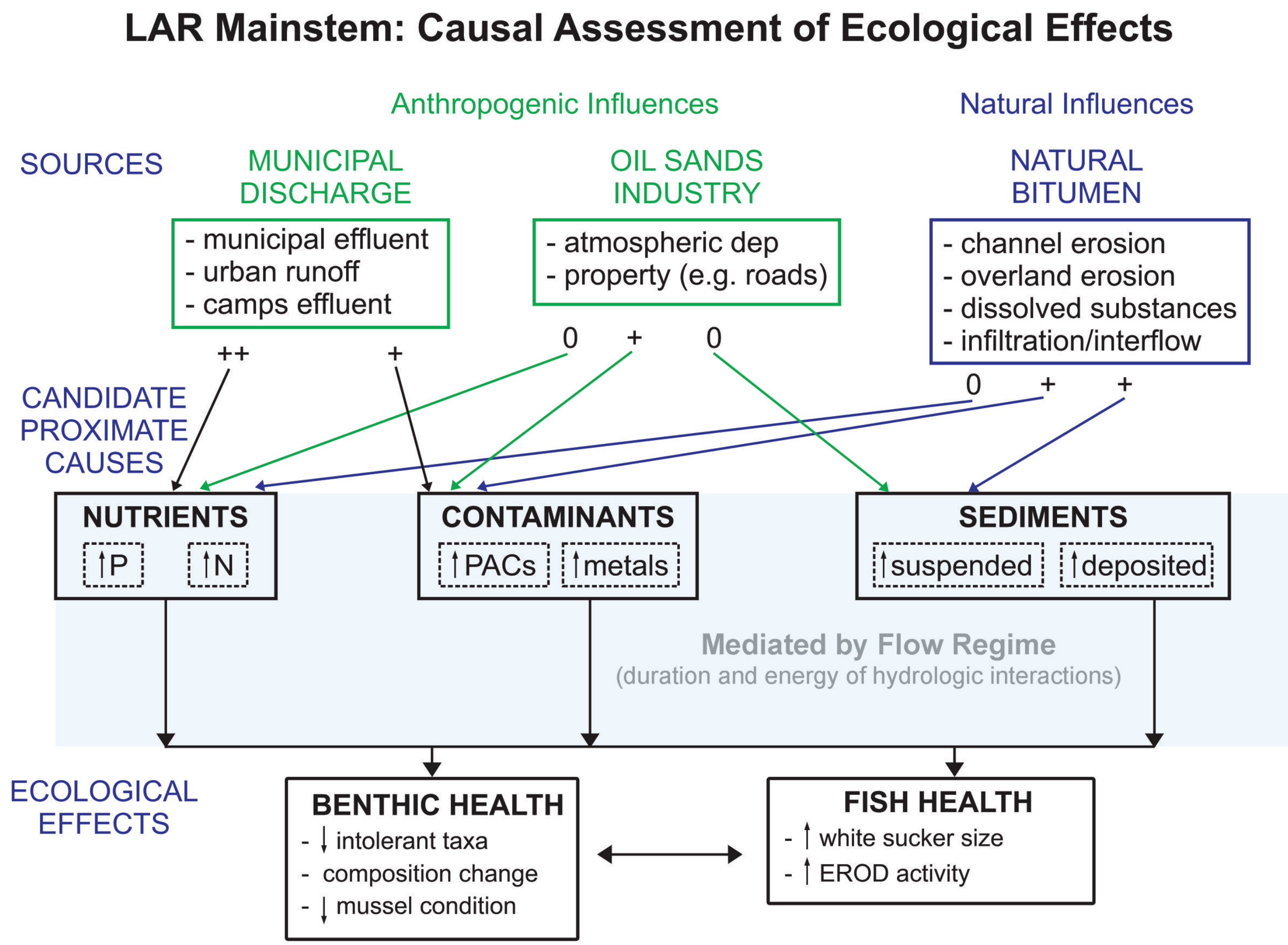

Figure 22. Lower Athabasca Mainstem: causal assessment of observed ecological effects showing linkages between sources of effects (industry and natural bitumen), candidate proximate causes (nutrient enrichment, contaminant exposure via surface water and sediments, habitat change from suspended and deposited sediment) and groundwater inputs (including contaminants).

limited until these natural and industrial-derived contaminants can be discriminated.

4c. Deltaic Wetland Effects

Overall, wetland benthic macroinvertebrate assemblages in the PAD appear to be in a healthy state, exhibiting high biodiversity. Assessments indicated that nutrients, contaminants and sediments showed no adverse effects on benthic macro-invertebrates in the wetland deltas from the major potential sources of inputs (atmospheric, fluvial). Although no guideline exceedances of nutrients and contaminants of interest were observed in the downstream receiving wetland environment thus far, it is notable that the analysis of data collected under this monitoring activity is still ongoing. Although the PAD currently shows no adverse effects the reader is referred to recommendations on research and monitoring needs to provide ongoing long-term assessment and detection of stressors that could lead to degradation of the ecological condition.

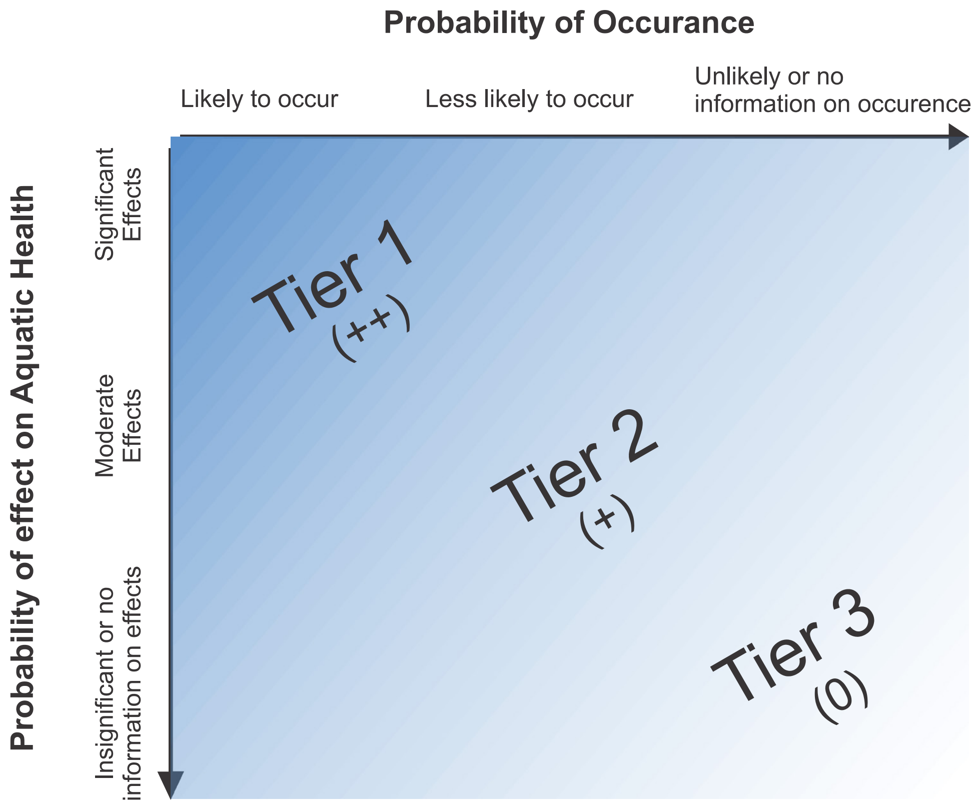

Figure 23. The weight of evidence approach for assigning importance to casual pathways can be linked to risk assessment frameworks by determining the probability (likelihood) of occurrence and impact, allowing for identification of where monitoring resources would be best allocated. The casual pathway assignment of ++ (strongly supports, Tier 1) indicates statistically significant field observations and strong spatial co-occurrence of stressor and effect, + (somewhat supports, Tier 2) is based on statistically significant field observations, while 0 (Tier 3) indicates a pathway that has no effect (or shows ambiguous results).

5. Research Needs to Support Monitoring

Following the three years of JOSM, a number of knowledge and/or data gaps as well as research needs were identified that could potentially improve the monitoring design. As JOSM was designed to be an adaptive monitoring program, it has a built-in flexibility that allows the program to evolve as new research validates a need for change. Such modification may be reflected in a change in sample sites (inclusion of new sites or the suspension of existing sites until a threshold or trigger is identified), frequency of sampling, or a change to the parameter list (new or suspended parameter). Research may also drive alteration of the monitoring program in terms of 1) methodology (field and/or analytical), 2) instrumentation (field and/or analytical), 3) ecological health assessment, 4) biogeochemical understanding, 5) numerical model advancement and projection, and/or 6) identification of new issues of interest.

Below are substantive suggestions for future research in the support of monitoring from the seven theme areas of the Water Component. These are divided into the physical-chemical condition and the ecological condition.

5a. Physical-Chemical Condition

Atmospheric Deposition

While significant information has been generated for the development of an atmospheric deposition monitoring program, limitations or knowledge gaps in the science became evident. Snow samples were consistently collected in accessible open areas, but clearly there is significant forest cover within the landscape of the Oil Sands region. As such it has been recommended that both open and under-canopy samples be collected to better understand the role of the forest in controlling contaminant deposition to the landscape. Further, there is a need to develop, in conjunction with the atmospheric, hydraulic and water quality themes, a numerical model and/or sampling program to assess the proportion of particulate material delivered to the surface by atmospheric deposition that actually enters the aquatic environment.

While loadings of atmospheric particulate deposition are temporally and spatially quantified, the actual proportional contributions from different sources remain unknown. It is suggested that a source material library from industries (e.g., emissions, road dust, truck emissions, petcoke) be collected and analyzed for various contaminants and markers to determine the relative importance of various sources to depositional loads to snowpacks and lake sediments.

Methyl mercury (MeHg) is an ecologically relevant parameter that can bioaccumulate within the food-chain, however, the biochemical processes that control its production/concentration is poorly understood, particularly as it relates to snowpacks. Thus, there is a need to explore the processes controlling MeHg in snowpacks (i.e., Is MeHg emitted from industrial processes or produced in situ?).

Water Quality

Given that there are many parameters (e.g., metals, PACs, nutrients) quantified within the water quality monitoring network, not all have been analyzed (historically and contemporarily) in order to establish regional reference concentrations. Clearly, this is work that will benefit the monitoring program and may result in cost savings if some parameters are not needed and removed. In addition, there are some parameters where CCME-type guidelines do not exist and may need to be developed, or where guidelines developed for other regions are not appropriate for use in the oil sands regions due to the presence of naturally occurring highly petrogenic bitumen deposits at or near the land surface. Furthermore, there is a need to continue the ongoing data analysis to establish regional fluxes of contaminants in tributaries to the Athabasca River in relation to mine development.

The atmospheric and hydrometric themes require additional quantitative comparisons between snowpack and runoff water loads as this will help to determine the extent to which contaminants in the snowpack are transported to proximate rivers and streams. This effort would tie into any modelling work suggested above for the atmospheric deposition theme. Further geospatial interpretation (GIS mapping/interpolation) of JOSM data would be helpful in spatial gradations and contaminant hot spot identification delineated by different land surface types (e.g., wetlands, forested vs. open landscapes, surficial geology, etc.).

As with atmospheric snow deposition (Section 2a) and benthic wetland environments (Section 3c), there is a need to understand inorganic mercury speciation, bioaccumulation, pathways and transformation mechanisms to MeHg. The link of MeHg production to the microbial community is not well understood and will likely vary between environments (e.g., wetlands vs. tributaries). Such spatial distribution could be tracked via an assessment of Hg stable isotopes concentrations and speciation. A multi-theme focused study on this important contaminant dynamic is suggested.

While tailings pond seepage has been shown to occur, but with no appreciable impact (Bickerton et al. 2018), there is still a need to assess local chronic ecological effects that may exist with exposure to prolonged seepage. This includes the need to continue existing research on refining current OSPW detection methodology to identify anthropogenic and natural chemical classes not present in natural background or OSPW. These methods have been applied to a limited number of tailings ponds and, given their known different biogeochemical makeups, other tailings ponds need to be assessed for OSPW reference composition of organic contaminants.

Water Quantity

While not a research need per se, the Water Survey of Canada (WSC) is responsible for the hydrometric data that supports the JOSM monitoring program. WSC is gradually taking over many of the former RAMP hydromet stations and making sure they meet WSC and international standards for data production. This is an ongoing process with the flow data being a key input variable for contaminant loading estimates and for the modelling of water quality and quantity, and sediment and contaminant transport.

Groundwater is known to contribute to river flow; however, in general its contribution is limited relative to surface water flows during open water within the LAR and its tributaries. In contrast, it may be more important during under-ice conditions where it likely sustains aquatic habitat (where the ice does not freeze to the bottom). The groundwater quantity work was limited to the MacKay River and the research (quantity, quality and habitat implications) should be expanded to other tributaries of the LAR. In this regard there is a need to determine the indirect groundwater contributions via lower-order tributaries and the implications this may have with land use change and ecological monitoring needs. This continued work will further allow for a refinement of methods for groundwater assessment.

Modelling (Water Quantity and Quality)

Water quantity and quality modelling is an ongoing, iterative process. The numerical models for the simulation of flow and the transport of sediments and contaminants transport in the LAR must be updated as new and up-to-date information and data become available. Model projections will gain accuracy as more data is used to provide temporal and spatial trend analysis. The models must also be updated with high resolution bathymetry and more spatially resolved bed sediment data (physical and chemical) as it becomes available. Further, the models have only been assessed for a small number of metals and PACs (long computational times required), and as such there are many more variables that need to be modelled for the LAR.

Projections to inform needed monitoring network design changes (location of sampling and frequency), and subsequent resource allocation, would benefit from applying the modelling framework under different scenarios (such as future climate and loading scenarios). This would also allow for the investigation of the future state of sediment and contaminant transport in the river and provide support in the sediment/chemical constituents monitoring effort.

As stated above, modelling the infiltration and overland transport of atmospherically derived contaminants from the terrestrial surface (during snow melt and/or rain events) to receiving water bodies is a key area of research that is required to link the Atmospheric and Water Components (an area currently lacking). While useful to measure contaminant loadings to the surface, it is of little use to aquatic health assessment if we do not know the actual load of atmospheric contamination to the aquatic environment. Included in this, is the need for physically-based modelling; process-driven research to provide algorithms to assess the movement of sediment and associated contaminants between and within terrestrial and aquatic environments.

A new and emerging area of research that will be of benefit to the monitoring program is the linking of hydrodynamic and transport models with biological and physical habitat simulation models. This will provide more assessment information that will inform on the cause/effect status of impairments on ecological health as discussed above in Section 3.

5b. Ecological Condition

Benthos

Research needs of the benthic monitoring programs in tributaries, Athabasca mainstem and the PAD include several common requirements related to contaminant source toxicity as well as specific needs for the individual programs. All benthic monitoring programs require the development of species sensitivity distributions for oil sands priority substances (identified in Appendix B; Environment Canada and Alberta Environment, 2011a), so that the hazardous concentration for 5% of the species (HC5) can be determined. Obtaining HC5 information through laboratory studies and data mining would aid the development of additional guideline information for the oil sands priority substances and provide a better understanding of potential sub-lethal toxicity effects of key contaminants to invertebrates. Additionally, all three monitoring programs should continue to explore, where possible, the application of EEM thresholds (e.g., critical effects size of 2 SD) to determine the possible effects of oil sands development. Specific needs for the mainstem benthic program include a focused study in the oil sands development region to investigate the observed changes of the benthic community that is associated with co-occurring nutrient enrichment and contaminant exposure (potential diagnostic approaches include field sampling, as well as field and mesocosm experiments). Tributary research needs include the development of techniques to transform historical benthic data collected with smaller kick-net mesh size (250 µm) so that this information can be compared with contemporary benthic composition obtained from sample nets with larger mesh (400 µm) currently being used (as per CABIN protocols). The Delta research needs to include the testing of wetland biomonitoring metrics developed under JOSM to confirm they respond to contaminant exposure. Consistent with the research requirements of the water quality and atmospheric snow deposition themes, there is a need to explore how MeHg transforms and biomagnifies. Finally, a thorough investigation of the relative toxicity of surface water, groundwater and sediments to invertebrates is required to determine which environmental components may be the cause of any observed changes in benthic community.

Fish

Research needs for fish monitoring in the tributaries, Athabasca mainstem and Delta include both common and specific requirements. All programs need additional guideline development for the oil sands priority substances and improved understanding of sub-lethal toxicity effects of key contaminants to fish and the comparative sensitivity of fish species. Comparisons of fish community and fish health investigations should be undertaken to compare and contrast the ability of these levels of ecological resolution to associate environmental change with biological endpoint variability. Such assessments should also focus on determining the statistical power required to detect biological effects (e.g., changes in different fish species) in order to establish environmental thresholds of good ecological condition. Further investigation of the effects of early-life exposure of fish to sediments is required along with the assessment of young-of-the-year abundance and body size at downstream reaches of the Steepbank and Ells rivers were sediment toxicity is highest. Mainstem studies need to determine the sampling frequency required to detect change in large-bodied fish and whether small-bodied fish results can be used to trigger large-bodied fish sampling. Moreover, a focused study should be initiated to attempt to determine the cause of lower Steepbank River fish having smaller gonads and larger livers. Finally, a program to assess delta fish community and fish health needs to be established.

6. Monitoring Recommendations

The following recommendations provide suggestions and options for improving the ability of the JOSM monitoring program to detect degradation in ecosystem quality and health as a result of anthropogenic activities. A basic assumption of all monitoring approaches is that they will be adapted through time to reduce measurement variability and link ecological change to the environmental cause as a more complete understanding of causal pathways. These recommendations are not meant to be prescriptive but rather represent options to improve monitoring based on interpretations of quantitative results from JOSM.

6a. Tributaries

Physical-Chemical Condition

Snow pack atmospheric deposition to terrestrial and aquatic systems, groundwater contributions and water quality monitoring will be adjusted over time to improve the ability of the monitoring program to detect and assess changes in the aquatic environment. Improvements to the quantification of atmospheric deposition may be realized by having an annual snowpack sampling at a subset of the original sites located at varying distances from the major developments and in the Peace Athabasca Delta to track short-term temporal trends in contaminant deposition and changes in background conditions. The larger scale survey (n=~140 sites) at sites located across a grid-work patterns on the landscape should be carried out every ~2-3 years to allow for the determination of net spring-time contaminant loadings to the lower Athabasca River and its tributaries, and to examine changes in spatial depositional patterns as Oil Sands developments evolve (Kirk et al. 2018). Snowmelt is a key time of contaminant loading to tributaries and it is recommended that the water quality sampling frequency be increased to reflect this reality (daily sampling followed by a tapered off transition to a monthly sampling process). Further, monitoring of water quality and discharge, including both upstream and downstream of industry and the McMurray formation, should be maintained at theme co-located sites and on major tributaries (MacKay, Ells, Steepbank, Firebag, Muskeg). In addition, it is clear that analytical laboratories must analyze parameters with the same standard operating procedures (SOPs) (Chambers et al. 2018; Glozier et al. 2018). At the time of this report there were still some issues (principally for metals) that needed to be resolved to ensure consistent data reporting for comparative purposes.

As part of future shallow groundwater and surface water interaction investigations, detailed assessments on the particular groundwater conditions and interactions found in the major tributaries stated above should be integrated with surface water and ecological monitoring activities so that the effects (water quality, benthic and fish health) of groundwater can be separated from other influences. As the focus of groundwater work under JOSM was on the MacKay River, if development proceeds near the discharge areas identified in the Bickerton et al. 2018, it is recommended that groundwater monitoring be developed and established to appropriately monitor the groundwater discharge areas to ensure that in-stream flow needs and water quality are not adversely affected by changes in groundwater conditions.

To complement water quality and quantity assessments for both the tributaries and for the LAR itself (Section 6b below), it is recommended that hydro-climatic, hydraulic and sediment/contaminant transport models developed under JOSM be continuously updated as new data becomes available. This iterative process will increase the accuracy of model projections both for the current condition, and under future land-use and climate change scenarios. Further, modelling will inform on future instream flow needs (IFN), inform on potential adjustments to sampling sites and frequency for multiple monitoring themes given projected climatic and extreme event influences, and contribute to decision frameworks that may inform future triggers and thresholds (Droppo et al. 2018).

Ecological Condition

The benthos and fish monitoring programs for the tributaries will be adapted over time to improve the ability of the program to detect and assess environmental change. Improvement for benthic monitoring will include increasing the number of reference sites to better define the normal range of biological variability, to facilitate power analysis and the definition of critical effect size, and to allow for the application of Before-After-Con¬trol-Impact study designs to assess future developments. The fish health assessment program will apply the EEM approach and move to cyclical, long-term monitoring such that sampling will occur once per three-year period with additional monitoring undertaken if warranted from tiered assessment approaches and effect thresholds developed from the baseline data. Such data can be used to trigger additional sampling requirements or to initiate detailed investigation of cause studies as required. While it is recommended that in situ toxicity testing be discontinued, the sensitive fathead minnow embryo-larval laboratory tests developed and used in JOSM to assess water samples and sediments from oil sands areas can serve as a potential tool in focused studies. For example, lab exposures of fish could be used to investigate specific effects of contaminant sources observed in the field, to assess samples from areas of rivers where wild fish health or benthic communities are affected, and for the testing of end-pit lake waters prior to their potential regulated release back to local rivers.

6b. Lower Athabasca Mainstem

Physical-Chemical Condition

Water Quality monitoring and modelling within the Athabasca River is complicated as it is a highly mobile bed river with the thalweg shifting laterally over time. Cross-sectional variation assessment (Glozier et al. 2018) showed that representative water quality sampling is achieved with a thalweg sample (depth-integrated); hence, single vertical sampling at the thalweg is the recommended method for water sampling (with the exception of M3 where the left and right bank panels are also required in order to differentiate the upstream influence of the Fort McMurray municipal waste water treatment plant and Clearwater River confluence). Given the mobile nature of the bed, it is required that prior to each sampling period the location of the thalweg be determined. It is recommended that samples be collected every two weeks from all mainstem sites between mid-April and mid-August with monthly sampling occurring outside of this period. If environmental conditions permit, additional samples should be collected during ice-on and ice-off conditions.

Installation of water quality data sondes are recommended at key locations (above and below major tributary inflows, water intakes and outfalls, etc.) within the LAR to provide continuous high frequency information on standard WQ parameters (e.g., dissolved oxygen, pH, temperature, conductivity and turbidity). This information is an important complement to the existing monthly sampling and can capture event-based responses. It is also recommended that other remote autonomous water quality monitoring systems such as automated river platforms and instrumented lake buoys systems be considered at key locations. In addition passive time-integrated SPMDs are also recommended to allow for the determination of chronic effects of low level dissolved PAC exposure. Particulate bound PACs and other contaminants should also be sampled with time-integrated continuous flow centrifugation.

Ecological Condition

Monitoring of benthos and fish in the mainstem requires additional monitoring adjustments to further improve the programs. For benthic monitoring, future sampling must continue to include the critical environmental variables associated with SPMD deployment and sediment chemistry sampling, and reference sites must be added between M0 and M2 to improve characterization of the least disturbed environmental condition. Diagnosis of the relative importance of nutrients and contaminants as factors responsible for observed changes in invertebrate would be improved by the inclusion of in situ mussel caging studies and other novel sampling approaches (e.g., reciprocal transfer experiments) and analytical techniques (e.g., nuclear magnetic resonance spectroscopy, NMR). Similar to the monitoring approach for the tributaries, the fish monitoring program is now based on the EEM approach with sampling once every three years. Focused studies to determine the cause of observed ecological effects in fish will be aided by fish toxicity testing.

6c. Deltaic Wetlands

Ecological Condition

Future monitoring programs in the deltaic wetlands need to establish a robust program for fish that, where possible, is integrated with existing benthic sampling. In addition, the benthic program requires increased spatial coverage of delta wetland sampling sites with an aim to include areas of the Athabasca Delta outside Wood Buffalo National Park. DNA-based biomonitoring and analysis of sediment samples should also be implemented as operational mainstream techniques and include analysis of sediment samples. The continued development of benthic metrics suitable application to wetlands habitats metrics is needed to improve the ability to relate ecological change to contaminant exposures, and to distinguish such change from natural and human-driven shifts in hydrological regime, will hinge on the continued development of benthic metrics suitable application to wetlands habitats.

7. Summary

The Oil Sands Water Component's monitoring design is structured from an integration of the seven different study/themes which assess the physical/chemical and biological/ecological condition of the Lower Athabasca River, its tributaries and the extended geographical area (including the Peace Athabasca Delta). The seven interconnected themes reflect a functional framework for the evaluation and monitoring of the contemporary state of aquatic health relative to potential environmental effects. Atmospheric Deposition (Kirk et al. 2018) provides insight into, and a sampling strategy for, the assessment of particulate deposition to the landscape via snow sampling and paleo-coring of lakes relative to the industrial areas of the Oil Sands. This contemporary and historical assessment of loadings to the terrestrial and aquatic environment has wide relevance to the water, wildlife, biodiversity and additional atmospheric focused monitoring. The atmospheric deposition work is particularly relevant to the Water Quality Monitoring Program (Chambers et al. 2018; Glozier et al. 2018), as surface water washoff (i.e., storm and snow melt) will influence the water quality and aquatic health of the tributaries, the lower Athabasca River (LAR) and the EGA – (including the Peace Athabasca Delta and beyond). This was particularly true during the freshet (snowmelt) periods when the majority of contaminant loads are transported within the rivers and delivered to downstream ecologically relevant environments. As such, an increased frequency of sampling was recommended for this period at key river sites in the LAR and EGA. Further the delivery and deposition of sediments and associated contaminants to lakes and rivers of the oil sands region will have concomitant effects on the fish (McMaster et al. 2018) and benthic (Culp et al. 2018) community health (i.e., exposure concentrations). For water quantity, groundwater flows (Bickerton et al. 2018) were found to have their most significant effect during the ice-covered winter months where they are important for maintaining ecological habitat. Numerical modelling (Droppo et al. 2018) has provided insight into the implication of extreme events and climate change (warming, more precipitation, less snow accumulation, earlier peak flows), with respect to flows and sediment/contaminant transport. Key areas of deposition are identified for the LAR and the modelling information can provide insight into frequency and locational change sampling (chemical and biological) as dictated by a change in flow/loads. All current JOSM data can be found on the Information Portal: Canada-Alberta Oil Sands Environmental Monitoring.

(https://www.canada.ca/en/environment-climate-change/services/oil-sands-monitoring.html).

Causal assessment of ecological effects was undertaken by linking effects in tributary, mainstem and deltaic ecosystems to candidate causes, with consideration of the evidence supporting the importance of particular effect pathways. The observed biological effects for LAR tributaries included increased PAC in fish tissue and more tolerant invertebrate taxa and appear to be associated with contaminant exposure. The source of this exposure is, however, confounded by the presence of, and inability to differentiate between, oil sands operation activity (principally atmospheric deposition) and natural bitumen inputs (e.g., erosion) within the tributaries. Ecological effects observed in the LAR mainstem below Fort McMurray included larger white sucker size, higher EROD activity in fish, higher benthic invertebrate abundance, an increased number of tolerant invertebrate taxa and decreased mussel condition. Causal pathways suggest these LAR ecological trends were associated mostly with nutrient enrichment from treated municipal sewage effluent from Fort McMurray. Contaminant exposure from sewage effluent, industrial operations, tailings pond seepage and natural exposure to bitumen may also contribute to these ecological trends, but focused investigation of cause field studies and experiments are required to separate the ecological effect of nutrients and contaminants. It is stressed that the identification of effects caused by contaminants derived from natural bitumen or industrial activity will remain limited until these natural and industrial-derived contaminants can be discriminated. Finally, wetland benthic macroinvertebrate assemblages in the PAD appear to be in a healthy state, exhibiting high biodiversity. Assessments indicated that nutrients, contaminants and sediments showed no adverse effects on benthic macro-invertebrates in the wetland deltas from the major potential sources of inputs (atmospheric, fluvial).

Following the three years of JOSM, a number of knowledge and/or data gaps as well as research needs were identified that could potentially improve the monitoring design. As JOSM was designed to be an adaptive monitoring program, it has a built-in flexibility that allows the program to evolve as new research validates a need for change. Such change may be reflected in a change in sample sites (inclusion of new sites or the suspension of existing sites until a threshold or trigger is identified), frequency of sampling, or a change to the parameter list (new or suspended parameter). Research may also drive a change in the monitoring program in terms of 1) methodology (field and/or analytical), 2) instrumentation (field and/or analytical), 3) ecological health assessment, 4) biogeochemical understanding, 5) numerical model advancement and projection, and/or 6) identification of new issues of interest.

The three years of JOSM resulted in numerous recommendations (stated in general above) and provided suggestions and options for improving the ability of the JOSM monitoring program to detect degradation in ecosystem health. The monitoring approach can be adapted through time to reduce measurement variability and link ecological change to the environmental cause. These recommendations provide options to improve monitoring based on interpretations of quantitative results from JOSM. For more detailed information on aquatic condition, ecological effects, research in support of monitoring and recommendations, readers are referred to the individual technical reports (study/themes see Text Box 2 on page 4).

8. Acknowledgements

With seven Water Component study themes, there are too many contributors to list by name. However, we want to make a special thank you to a number of groups both within Environment and Climate Change Canada (ECCC) and Alberta Environment and Parks (AEP) for which their contributions were instrumental in the monitoring, interpretation and evaluation of results, reporting and production of the seven technical synthesis reports and this overall synthesis report. Firstly, we thank the Research Support group (Technical Operations and Engineering) of the Water Science and Technology Directorate of ECCC for providing excellent assistance with field work and logistics, and the Scientific Presentation and Design Support Services of ECCC in Burlington, Ontario, for their extensive work on the graphics and layout of all eight Oil Sands reports. We also thank the many individuals and teams within AEP for their integral assistance with field and laboratory work and for the provision of data, interpretations and reporting. Finally, we would like to thank the multitude of contributing individuals (including research scientists, technicians, students, contractors) from federal, provincial and territorial governments, academia, non-government organizations and stakeholders for their contributions to JOSM as a whole, and for their input into these reports.

9. References

Alberta Environmental Monitoring Panel (2011) A World Class Environmental Monitoring, Evaluation and Reporting System for Alberta. Prepared for the Government of Alberta, Minister of the Environment

Alberta Water Monitoring Data Review Committee (2011) Evaluation of Four Reports on Contamination of the Athabasca River by Oil Sands Operations. Prepared for the Government of Alberta, Minister of the Environment

Arciszewski TJ, Munkittrick KR (2015) Development of an adaptive monitoring framework for long-term programs: An example using indicators of fish health. Integrated Environmental Assessment and Management, 11(4):701-718

Anderson AM (1991) An overview of long-term zoobenthic monitoring in Alberta river (1983-1987). Alberta Environment, Environmental Quality Monitoring Branch, Environmental Assessment Division. Edmonton, Alberta, 115 pp

Arellano L et al (2014) Persistent organic pollutant accumulation in seasonal snow along an altitudinal gradient in the Tyrolean Alps. Environ Sci Pollut Res 21:12638-12650

Ayles GB, Dubé M, Rosenberg D (2004) Oil sands Regional Aquatic Monitoring Program (RAMP) Scientific Peer Review of the Five Year Report (1997-2001). Submitted to RAMP Steering Committee February 13, 2004.

Barton DR, Wallace RR (1980) Ecological Studies of the aquatic invertebrates of the Alberta Oil sands Environmental Research Program study area of northeastern Alberta. Alberta Oil Sands Environmental Research Program, Report AF 2.0.2, 216 pp

Bickerton G, Roy JW, Frank RA, Spoelstra J, Langston G, Grapentine L, Hewitt LM (2018) Assessments of Groundwater Influence on Select River Systems in the Oil Sands Region of Alberta. Oil Sands Monitoring Program Technical Report Series No. 1.5, 32 p. ISBN 978-1-4601-4029-1

Blanchard P et al (2005) Atmospheric Deposition of Toxic Substances to the Great Lakes: IADN Results through 2005. Environment Canada and the United States Environmental Protection Agency, 223 pp

Boerger H (1983) Distribution of macrobenthos in the Athabasca River near Fort McMurray. Final report for the Research Management Division by University of Calgary, Department of Biology, Report OF-53, 77 pp

Calow P, Petts GE (1994a) The Rivers Handbook: hydrological and ecological principles – Volume 1. Oxford, Blackwell Scientific Publications, ISBN 0-632-02832-7, 526 pp

Calow P, Petts GE (1994b) The Rivers Handbook: hydrological and ecological principles – Volume 2. Oxford, Blackwell Scientific Publications, ISBN 0-632-029854, 523 pp

Chambers PA, Alexander Trusiak A, Kirk J, Manzano C, Muir D, Cooke C, Hazewinkel R (2018) Surface Water Quality of Lower Athabasca River Tributaries. Oil Sands Monitoring Program Technical Report Series No. 1.3, 34 p. ISBN 978-1-4601-4027-7

Culp JM, Glozier NE, Baird DJ, Wrona FJ, Brua RB, Ritcey AL, Peters DL, Casey R, Choung CB, Curry CJ, Halliwell D, Keet E, Kilgour B, Kirk J, Lento J, Luiker E, Suzanne C (2018) Assessing Ecosystem Health in Benthic Macroinvertebrate Assemblages of the Athabasca River Mainstem, Tributaries and Peace-Athabasca Delta. Oil Sands Monitoring Program Technical Report Series No. 1.7, 82 p ISBN 978-1-4601-4031-4

Dillon PG, Dixon G, Driscoll C, Giesy J, Hurlburt S Nriagu J (2011) Water Quality Data Review Committee Final Report. Prepared for Government of Alberta, March 7, 2011. Available at http://environment.alberta.ca/03380.html

Droppo IG, Prowse T, Bonsal B, Dibike Y, Beltaos S, Krishnappan B, Eum H-ll, Kashyap S, Sakibaeinia A, Gupta A (2018) Regional Hydro-climatic and Sediment Modelling for the Lower Athabasca River Oil Sands Region. Oil Sands Monitoring Program Technical Report Series No. 1.6, 89 p ISBN 978-1-4601-4030-7

Dunne T, Leopold LB (1978) Water in Environmental Planning. WH Freeman, San Francisco, CA, USA, 818 pp.

Environment Canada (2012) Canadian Aquatic Biomonitoring Network Field Manual: Wadeable streams. Ottawa: Environment Canada.

Environment Canada and Alberta Environment (2011a) Wrona FJ, di Cenzo P (eds), Lower Athabasca Water Quality Monitoring Plan – Phase 1. Government of Canada

Environment Canada and Alberta Environment (2011b) Wrona FJ, di Cenzo P, Schaefer K (eds), Integrated Monitoring Plan for the Oil Sands – Expanded Geographic Extent for Water Quality and Quantity, Aquatic Biodiversity and effects, and Acid Sensitive Lake Component. Government of Canada

Environment Canada and Alberta Environment (2011c) Integrated Monitoring Plan for the Oil Sands – Air Quality Component, Government of Canada

Environment Canada and Alberta Environment (2011d) Integrated Monitoring Plan for the Oil Sands – Terrestrial Biodiversity Component. Government of Canada

Environment Canada and Alberta Environment (2011e) An Integrated Oil Sands Environment Monitoring Plan. Government of Canada

Environment Canada and Alberta Environment (2012) Joint Canada-Alberta Implementation Plan for Oil Sands Monitoring. Government of Canada

Federal Oil Sands Advisory Panel (2010) A Foundation for the Future: Building an Environmental Monitoring System for the Oil Sands. Prepared for the Government of Canada, Minister of the Environment

Giesy JP, Anderson JC, Wiseman SB (2010) Alberta oil sands development. Proc. Natl. Acad. Sci. USA 107: 951-952

Glozier NE, Pippy K, Levesque L, Ritcey A, Armstrong B, Tobin O, Cooke CA, Conly M, Dirk L, Epp C, Gue A, Hazewinkel R, Keet E, Lindeman D., Maines J, Syrgiannis J, Su M, Tumber V (2018) Surface Water Quality of the Athabasca, Peace and Slave Rivers and Riverine Waterbodies within the Peace-Athabasca Delta. Oil Sands Monitoring Program Technical Report Series No. 1.4, 64 p. ISBN 978-1-4601-4028-4

Hornberger GM, Wiberg PL, Raffensperger JP, D'Odorico P (2014) Elements of Physical Hydrology (2nd Edition). John Hopkins University Press, Baltimore, Maryland, USA, 378pp

Kelly EN, Schindler DW, Hodson PV, Short JW, Radmanovich R, Nielsen CC (2010) Oil sands development contributes elements toxic at low concentrations to the Athabasca River and its tributaries. Proc. Natl. Acad. Sci. USA 107:16178-16183

Kelly EN, Short JW, Schindler DW, Hodson PV, Ma M, Kwan AK, Fortin BL (2009) Oil sands development contributes polycyclic aromatic compounds to the Athabasca River and its tributaries. Proc. Natl. Acad. Sci. USA 106:22346–22351

Kirk J, Muir D, Manzano C, Cooke C, Wiklund J., Gleason A, Summers J, Smol J, Kurek J (2018) Atmospheric Deposition to the Athabasca Oil Sands Region using Snowpack Measurements and Dated Lake Sediment Cores. Oil Sands Monitoring Program Technical Report Series No. 1.2, 43 p. ISBN 978-1-4601-4026-0

Landers DH et al (2010) The Western Airborne Contaminant Assessment Project (WACAP): An interdisciplinary evaluation of the impacts of airborne contaminants in western US national parks. Environ Sci Technol 44:855-859

Main C (2011) 2010 Regional Aquatics Monitoring Program (RAMP) Scientific Review. Prepared for the RAMP Steering Commmitte, 160 pp.

McMaster M, Parrott J, Bartlett A, Gagne F, Evans M, Tetreault G, Keith H, Gee J (2018) Aquatic Ecosystem Health Assessment of the Athabasca River Mainstem and Tributaries using Fish Health and Fish and Invertebrate Toxicological Testing. Oil Sands Monitoring Program Technical Report Series No. 1.8, 76 p. ISBN 978-1-4601-4032-1

Norton SB, Cormier SM, Suter GW (2015) Ecological Causal Assessment. CRC Press, Boca Raton, Fl, USA, 248pp

Peters DL, Prowse TD, Marsh PM et al (2006) Persistence of Water Within Perched Basins of the Peace-Athabasca Delta, Northern Canada. Wetl Ecol Manag 14:221-243

Prowse TD, Beltaos S, Gardner JT et al (2006) Climate change, flow regulation and land-use effects on the hydrology of the Peace Athabasca Delta – Slave system; Findings from the Northern Rivers Ecosystem Initiative. Environ Monit Assess 113:167-97

Royal Society of Canada (2010) Environmental and Health Impacts of Canada's Oil Sands Industry. Royal Society of Canada Expert Panel Report, Ottawa, Ontario

Schindler DW (2010) Tar sands need solid science. Comment. Nature 468: 499-501

Tetreault GR, McMaster ME, Dixon DG , Parrott JL (2003) Using reproductive endpoints in small forage fish species to evaluate the effects of Athabasca Oil Sands activities. Environ Toxicol Chem 22(11): 2775-82

Timoney KP, Lee P (2009) Does the Alberta tar sands industry pollute? the scientific evidence. Open Conserv. Biol. J. 3: 65-81