Lower Athabasca Region

Status of Management Response for Environmental Management Frameworks, as of October 2018

Environment and Parks, Government of Alberta

October 2020

Lower Athabasca Region Status of Management Response for Environmental Management Framework, as of October 2018

Any comments or questions on the content of this report, as well as general inquiries on management framework development and implementation, may be directed to:

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Executive Summary

Air Quality

As part of the Integrated Resource Management System, this report outlines the status of the Government of Alberta's management response to crossings of air quality and surface water quality triggers from 2012 to 2017 in the Lower Athabasca Region. It fulfills commitments made to Albertans in the Lower Athabasca Region Air Quality Management Framework for Nitrogen Dioxide (NO_2) and Sulphur Dioxide (SO_2) and the Lower Athabasca Region Surface Water Quality Management Framework for the Lower Athabasca River. Since 2012, no limits have been exceeded for air quality under the framework. This means that air quality objectives identified in the Lower Athabasca Regional Plan are being met.

In 2017, 17 air monitoring stations measuring nitrogen dioxide (NO_2) and 21 stations measuring sulphur dioxide (SO_2) were considered. Janvier and Surmont stations were newly added to reporting in 2017. Buffalo Viewpoint, Fort Hills and Waskow ohci Pimatisiwin stations did not meet data completeness criteria for inclusion in the 2017 report. Key results from 2017 include:

- No limits were exceeded for air quality indicators.
- Lower Camp station exceeded the trigger for Level 4 for the upper range of ambient concentrations of SO_2.
- Mildred Lake and Mannix stations exceeded the Level 3 trigger for upper range of ambient concentrations of SO_2.
- Fort McKay –Bertha Ganter, Buffalo Viewpoint, Firebag, Fort McKay South, Muskeg River and Wapasu stations exceeded the trigger for Level 2 for the upper range of ambient concentrations of SO_2.
- Shell Muskeg River station exceeded the trigger for level 2 for both annual average and upper range concentrations of NO_2.
- Fort McKay –Bertha Ganter, Fort McKay South, Fort McKay-Athabasca Valley and Horizon stations exceeded the trigger for Level 2 for the upper range of ambient concentrations of NO_2.
- An investigation into SO_2 trigger crossings occurred in 2017 and the report is currently under review.

As a response to trigger crossings in previous years, a number of management activities have already been undertaken:

- Actions initiated by Syncrude as part of their Emissions Reduction Program have effectively lowered total SO_2 emission scenarios of Syncrude operations.
- An improved trend assessment methodology has been developed and is under review by Alberta Environment and Parks; this includes the creation of a tool for the flexible application of this methodology in a user-friendly environment.
- Non-point source emissions in the Lower Athabasca Region (LAR) have been reported on by the Clean Air Strategic Alliance.
- Recommended improvements to the monitoring network program that came out of a third party review are currently under consideration by AEP.
- In response to trigger crossings at Lower Camp station, a detailed investigation of SO_2 was initiated for the Athabasca Oil Sands Region improve understanding of current emissions and to identify local and potential distant sources of ambient SO_2 in the region.

In 2017, the following detailed investigations are recommended for understanding both NO_2 and SO_2 in the Lower Athabasca:

- Collect existing information to assess the contribution of stacks (all height levels) and transportation (on- road vehicles) to NO_2 levels within the Athabasca Oil Sands Region.
- Collect new information to assess the contribution of flaring to SO_2 levels at Lower Camp station.
- Determine if SO_2 is emitted by coke piles during smouldering or burning and the potential of coke piles to contribute to SO_2 levels at Lower Camp station.

Surface Water Quality

Since 2012, no limits have been exceeded for surface water quality under the framework. This means that surface water quality objectives identified in the Lower Athabasca Regional Plan are being met.

- Indicators compiled from 2017 water quality data were compared to framework triggers and limits. Five water quality indicators crossed a trigger. No water quality limits have been exceeded since the framework was implemented.
- Trigger crossings included 3 mean triggers (Lithium D, Uranium D, Potassium (K^+)) and 2 peak triggers (Lithium D, Uranium D).
- Preliminary assessments were undertaken using trend analyses completed with and without accounting for river flow. The slope and significance of trends measured the degree of change. Trends not explained by flow result in an investigation.
- Chloride did not exceed its trigger in 2017. However, an upward trend was identified in flow-adjusted values. Thus, a preliminary assessment was completed that resulted in a new investigation.
- All existing investigations were continued for the following parameters: dissolved iron, potassium, sulphate, total nitrogen, dissolved lithium, and dissolved uranium. Trends in each were confirmed by repeating preliminary assessments using updated datasets.
- A map of monitoring stations and contributing areas outlines the current scope of investigations. Herein, a contributing area refers to a sub-catchment area that drain to a monitoring station but not to stations upstream of it. Details of investigative analysis are to be compiled into a technical report.

Alberta Environment and Parks (AEP) will post updates to the status of the management response and supporting documents on the Ministry website.

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1.0 Introduction to Air Quality

Under the Lower Athabasca Regional Plan (GoA, 2012), a management response is initiated when the Minister of Environment and Parks determines that an indicator trigger or limit, as identified in the Lower Athabasca Region Air Quality Management Framework (LAR AQMF; Alberta Environment and Sustainable Resource Development [AESRD] 2012a) has been exceeded.

Alberta Environment and Parks (AEP) is the lead coordinator in undertaking the management response and works with other government branches and regulators (e.g. Alberta Energy Regulator) and external parties as required to implement the identified management actions.

A full description of the management system can be found in the LAR AQMF. The management response is a seven step process that is undertaken, in full or in part, when an ambient air quality trigger is crossed or a limit is exceeded.

Part of the management response is determining the need for management action. Presently, nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) are reported annually through the State of Ambient Environmental Condition report. When a new condition report becomes available, the previous management response is evaluated for its effectiveness and updated based on new information.

The management response for air quality considers a variety of factors including but not limited to the type and location of the monitoring station, averaging time (i.e. hourly, 24-hour or annual) and the ambient air quality trigger or limit that was exceeded. In addition, the management response can also include investigation into the cause of a trigger crossing or limit exceedance, notification of the responsible sources and affected First Nations, Métis communities and stakeholders and the identification of management actions to prevent a re-occurrence.

The LAR AQMF, the state of ambient environmental condition, and the status of air quality and management response reports can be found on the Environment and Parks website (www.alberta.ca/lower-athabasca-regional-planning.aspx).

2.0 Summary of Ambient Levels Assigned

Environment and Parks conducts an annual assessment of ambient air quality data gathered from continuous ambient air monitoring stations in the Lower Athabasca region. Data are downloaded from Alberta's ambient air quality data warehouse and checked for accuracy and completeness. Once the data have been verified, the air quality metrics are used to assess ambient conditions relative to triggers and limits. Verification and preliminary assessment are reported in the 2017 Status of Air Quality, Lower Athabasca Region, Alberta (Alberta Environment and Parks [AEP] 2019).

In 2017, 17 air monitoring stations measuring nitrogen dioxide (NO_2) and 21 stations measuring sulphur dioxide (SO_2) were considered. Janvier and Surmont stations were included in the ambient condition report for the first time in 2017. Buffalo Viewpoint station started measuring NO_2 in August, 2017 and did not fulfill the data completeness criteria for consideration in this report. Similarly, Fort Hills station measuring NO_2 and SO_2 and Waskow ohci Pimatisiwin station measuring SO_2 became operational in summer of 2017 but were not considered in this year's report because they did not meet completeness criteria. In 2017, no rare or natural circumstances were identified as potential contributors to trigger crossings.

2.1 Verification and Preliminary Assessment

2.1.1 Nitrogen Dioxide (NO_2)

Previous reports indicate that most NO_2 emission sources (>90%) in the LAR are a combination of point-source (e.g. stacks) and non-point source (e.g. mine fleets) emissions. Elevated levels of NO_2 were recorded during the colder months under stable meteorological conditions when releases did not have an opportunity to disperse. Most of the NO_2 stations in the LAR are in management Level 2 (Liu et al. 2015 and AEP 2018).

ANNUAL AVERAGE OF NO_2 CONCENTRATIONS

In 2017, the annual average concentrations of NO_2 within the Lower Athabasca Region remained at Level 1 for all stations except for Muskeg River station (Figure 1). Muskeg River station has remained at Level 2 for last six years. Ongoing monitoring will continue to ensure they do not trend upwards but no specific investigations are warranted at this time, given that no increases in NO_2 are being observed at the Muskeg River station.

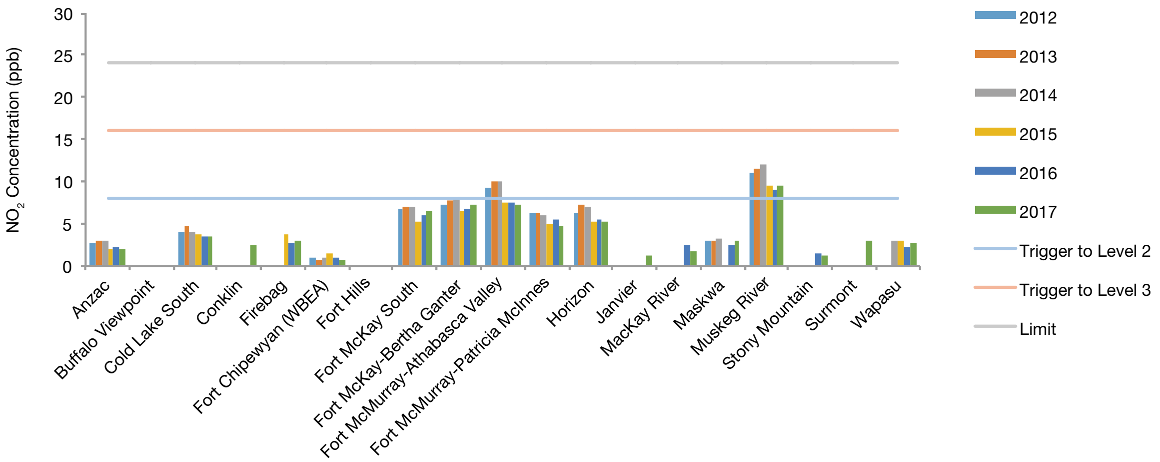


Figure 1. Annual average of the Hourly Data for Nitrogen Dioxide for 2012-2017 in the Lower Athabasca Region.

THE UPPER RANGE OF HOURLY NO_2 CONCENTRATIONS

The upper range of ambient concentrations of NO_2 exceeded the trigger to Level 2 at Fort McKay –Bertha Ganter, Fort McKay South, and Fort McKay Athabasca Valley stations for the first time. In 2016, the upper range value at the Horizon station dropped to Level 1 but increased again to a Level 2 in 2017 (Figure 2). Level 2 trigger crossings at these four stations warrant further investigation.

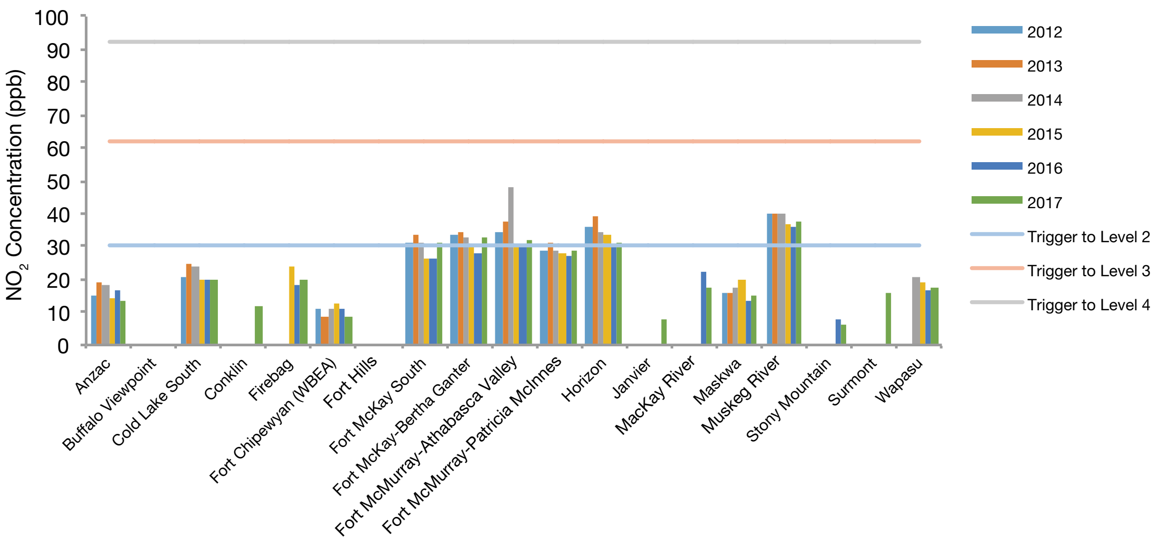


Figure 2. Upper range of the Hourly Data for Nitrogen Dioxide for 2012-2017 in Lower Athabasca Region

2.1.2 Sulphur Dioxide (SO_2)

The Joint Oil Sands Monitoring Emissions report (ECCC and AEP 2016) indicates that industrial point sources in the Athabasca Oil Sands Region (AOSR) are major contributors of SO_2 in that area. Despite a reduction in total SO_2 emissions in the region, a number of trigger crossings were identified at air monitoring stations nearer to the oil processing facilities in 2017.

ANNUAL AVERAGE OF SO_2 CONCENTRATIONS

In 2017, the annual average ambient concentrations at all air monitoring stations remained at or below the trigger to Level 2 (i.e. were in Level 1; 3 ppb) (Figure 3). Lower Camp station reported an annual average SO_2 concentration of 3 ppb, placing this station at the trigger between Levels 1 and 2; however, Lower Camp has been assigned to Level 1 because the AQMF rounds to the nearest whole number and the measured annual average concentration for Lower Camp is 2.73 ppb. No specific investigations assessing annual average SO_2 concentrations are warranted at this time.

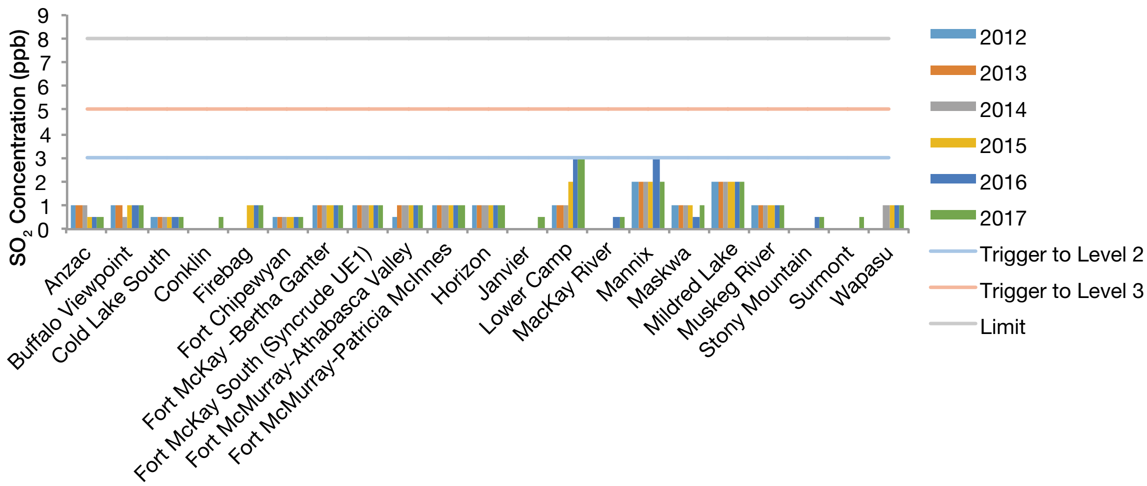


Figure 3. Annual average of the hourly data* for Sulphur Dioxide for 2012-2017 in Lower Athabasca Region.

*Sites with annual averages that round to zero are shown as 0.5 ppb to distinguish them from sites that did not meet completeness requirements.

UPPER RANGE OF HOURLY SO_2 CONCENTRATIONS

The upper range of ambient concentrations of SO_2 was in Level 2 at six stations (Buffalo Viewpoint, Firebag, Fort McKay –Bertha Ganter, Fort McKay South, Muskeg River and Wapasu). Three stations in 2017 (Fort McKay–Bertha Ganter, Fort McKay South, Muskeg River) have been in Level 2 since reporting began in 2012. Mannix and Mildred Lake stations continue to be in Level 3 and Lower Camp station is in Level 4 for the second consecutive year (Figure 4). The number of stations in levels 2, 3, or 4 in 2017 justify more detailed investigation into the sources of hourly SO_2 emissions.

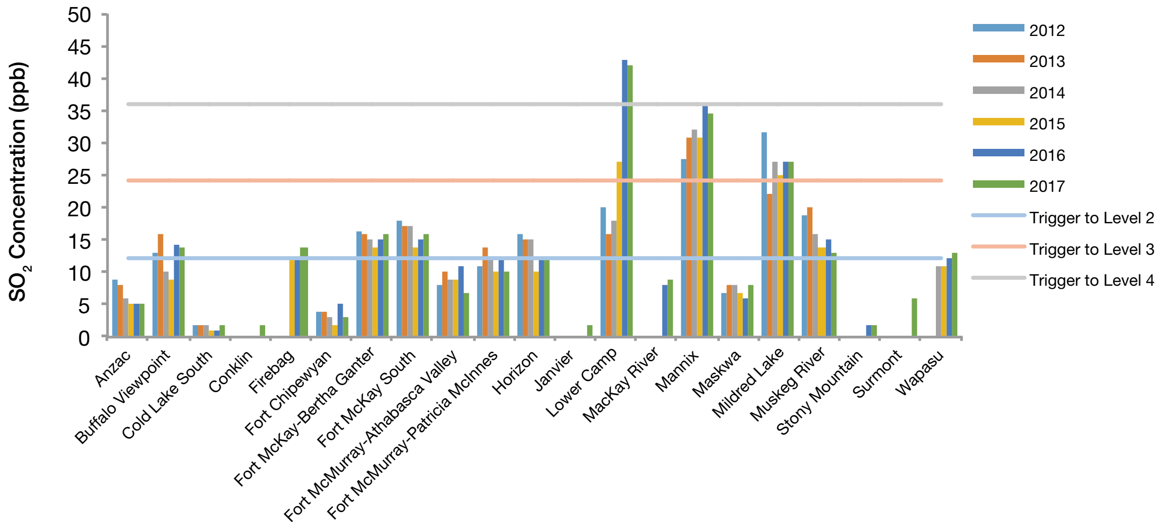


Figure 4. Upper range of the 99th percentile hourly data for Sulphur Dioxide for 2012-2017 in Lower Athabasca Region

2.2 Minister's Determination

The Minister's Determination confirmed that no annual average limits were exceeded for any air quality indicators for January 1 to December 31, 2017 in the Lower Athabasca Region, or since the implementation of the framework. However, crossing of air quality triggers occurred at several monitoring stations, resulting in the assignment of air quality levels described in the 2017 Status of Air Quality, Lower Athabasca Region, Alberta (Table 1).

In 2017:

- At Lower Camp station, the trigger for Level 4 for the upper range of ambient concentrations of SO_2 was crossed for a second time (2016, 2017);
- Mildred Lake and Mannix stations have consistently crossed the Level 3 trigger for the upper range of ambient concentrations of SO_2 since 2012;
- The upper range of ambient concentrations of SO_2 exceeded the trigger to Level 2 at Firebag and Wapasu stations for the first time;
- Buffalo Viewpoint, Fort McKay –Bertha Ganter, Fort McKay South and Muskeg River stations remain at a Level 2 as in previous years;
- The upper range of ambient concentrations of NO_2 exceeded the trigger to Level 2 at Fort McKay –Bertha Ganter, Fort McKay South, Fort McKay Athabasca Valley, Horizon and Muskeg River stations.
- Muskeg River station exceeded the trigger to Level 2 for both the annual average and upper range concentrations of NO_2 since reporting started in 2012.

Table 1: Ambient levels assigned to air quality monitoring stations in the Lower Athabasca Region for 2012-2017 based on triggers and limits established in the framework.

Station Name	Nitrogen Dioxide (NO_2)												Sulphur Dioxide (SO_2)											
	Annual Average						Upper Range						Annual Average						Upper Range					
	2012	2013	2014	2015	2016	2017	2012	2013	2014	2015	2016	2017	2012	2013	2014	2015	2016	2017	2012	2013	2014	2015	2016	2017
Anzac	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
**Buffalo Viewpoint					-							-	1	1	1	1	1	-	2	2	1	1	2	2
Cold Lake South	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Conklin[1]					-	1					-	1					-	1					-	1
Firebag				1	1	1				1	1	1				1	1	1				1	1	2
Fort Chipewyan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
*Fort Hills						-						-						-						-
Fort McKay - Bertha Ganter	1	1	1	1	1	1	2	2	2	1	1	2	1	1	1	1	1	1	2	2	2	2	2	2
Fort McKay South	1	1	1	1	1	1	2	2	2	1	1	2	1	1	1	1	1	1	2	2	2	2	2	2
Fort McMurray – Athabasca Valley	2	2	2	1	1	1	2	2	2	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1
Fort McMurray - Patricia McInnes	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1
Horizon	1	1	1	1	1	1	2	2	2	2	1	2	1	1	1	1	1	1	2	2	2	1	1	1
Janvier						1						1						1						1
Lower Camp													1	1	1	1	1	1	2	2	2	3	4	4
MacKay River					1	1					1	1					1	1					1	1
Mannix													1	1	1	1	1	1	3	3	3	3	3	3
Maskwa	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mildred Lake													1	1	1	1	1	1	3	2	3	3	3	3
Muskeg River	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	2	2	2	2	2	2
Stony Mountain					1	1					1	1					1	1					1	1
Surmont						1						1						1						1
Wapasu			1	1	1	1			1	1	1	1			1	1	1	1			1	1	1	2
Waskow ohchi Pimatisiwin*																								-

* Fort Hills and Waskow ohci Pimatisiwin were operational in 2017 but did not meet the criteria of 75 percent data completeness in order to be included in reporting and analysis.

** Buffalo Viewpoint station started measuring NO_2 August 2017. Therefore, the station did not meet the completeness criteria of at least 75 percent data completeness for NO_2

[Shaded cell with diagonal line] Parameter was not measured at this location and period.

3.0 Status of Management Response

The management response is a set of steps that is taken, in full or in part, when an ambient air quality trigger or limit is exceeded. The management response undertaken is determined based on the trigger exceeded, issue being addressed, and the management intent associated with each trigger or limit exceeded. A full description of the management system is found in the LAR AQMF (AESRD 2012a). The status of the management response is reported on a yearly basis and may be supported by supplementary technical reports.

In circumstances where a station exceeds a trigger and is assigned management actions one year, then falls to a lower level the following year, management actions are still carried out but may be adjusted in response to that change in status.

3.1 Investigation Results

The purpose of the investigation stage is to determine the likely factors influencing the performance of an indicator and to inform decisions about management actions. The scale of the investigation depends on the management level as well as the complexity of the issue identified. Input from the public, Indigenous Peoples, industry, non-governmental groups, government at multiple levels and regulatory agencies may contribute to understanding regional issues and exploring options to address the ambient concentrations. Analysis of ambient concentrations, trends, and the identification of potential emission sources leading to elevated ambient concentrations are ongoing. A summary of the work in progress is described in Table 4.

3.1.1 Nitrogen Dioxide (NO_2)

In 2017, the upper range of hourly NO_2 concentrations was in Level 2 at the Fort McKay –Bertha Ganter, Fort McKay South, Fort McKay Athabasca Valley, and Horizon stations. NO_2 emissions from mine fleets and stacks that might contribute strongly at stations nearer to industrial sites (Bertha Ganter, Fort McKay South and Horizon) and from non-industry transportations at community station (e.g Fort McMurray Bertha Ganter) are not well characterized in current emission inventories (Liu et al. 2015).

Davies and Person (2012) and ECCC and AEP (2016) reports have also noted a gap in reporting requirements for NOx (reported as NO_2) emissions. Specifically, National Pollutant Release Inventory (NPRI) does not require reporting from stacks less than 50 meters in height, though these stacks may contribute significantly to total emissions. Analysis of the hourly emissions data suggests peaks in the number of elevated NO_2 events occurred at different times of the day at different stations and may be due to the relative importance of various emission sources.

Effective January 1, 2019, under the Air Monitoring Directive, Chapter 9, *Environmental Protection and Enhancement Act* (EPEA)-approved facilities will report on emission sources of NO_2 and SO_2 for all stacks regardless of height (AEP 2016a). In 2020, AEP will assess the reported emissions to determine if they can sufficiently explain NO_2 monitoring results or if further work will be required to find out NO_2 contributions from non-EPEA approved facilities in LAR.

3.1.2 Sulphur Dioxide (SO_2)

Based on recommendations from the 2015 and 2016 AQMF Management Response reports, a detailed SO_2 investigation has been started. Current projects include an investigation into ambient SO_2 levels and sources in the Athabasca Oil Sands region, including SO_2 emission inventory for 2010-2016, episode analysis for hourly SO_2 trigger crossings, determination of SO_2 source driven trigger crossings at air monitoring stations and influence of any potential local and distant emission sources, transboundary flows and exceptional events. The results of this work will give a better understanding of current SO_2 emissions sources and its ambient level in the oil sands region.

In 2017, the upper range of hourly SO_2 concentrations was in Level 2 or higher at nine stations. Of note are the Mannix and Mildred Lake stations at a level 3 and Lower Camp Station at a level 4. Mildred Lake station is located 3-4 km east of the main sulphur recovery stack at the Syncrude Upgrader and Mannix station is located 3-4 km south of the main sulphur recovery stack at the Suncor Upgrader. Lower Camp station, which is at Level 4 for the upper range of SO_2, is geographically located within the valley (elevation 235 m) between Syncrude and Suncor facilities (Figure 5). The proximity of these stations to major industrial sources (Syncrude and Suncor) likely explains the higher SO_2 concentrations recorded when compared to the other stations.

LARP CALPUFF (AEP 2009) and CEMA (Morris et al. 2012) studies showed that 99% of SO_2 emissions in Lower Athabasca Region originate from stacks (Liu et al. 2015). Emissions from specific point source (stacks) occur due to unplanned outages, boiler operational time, emergency flaring, process gas and continuous flaring time. In 2017, Syncrude Mildred Lake and Suncor Millennium emitted 28,442 and 12,684 tonnes of SO_2 emissions, representing 65% and 29% of total SO_2 emissions in the LAR, respectively (Table 2). Horizon station (Level 1) and Firebag station (Level 2) are located close to the CNRL upgrader and Firebag facility respectively and account for much smaller percentages of the total–reported SO_2 emissions in the LAR (Table 2). All other stations that are at a Level 2 are located near or within the mineable oilsands area (Figure 5).

Despite the significant reductions of SO_2 emissions from Syncrude (Syncrude Sulphur Emission Reduction Project, SERP), the assigned management level at Lower Camp station increased after 2014 (Table 2 and Figure 4); the causes of this increase are currently unknown. However, active oil sands mines, main processing plants and large coke deposits are located in the vicinity of Lower Camp station. Ambient SO_2 concentrations at Lower Camp Station may be influenced by contributions from flaring, local meteorology influences, and emissions from coke piles if they are releasing SO_2. More investigation needs to be done to determine if any of these are factors in determining Lower Camp SO_2 levels.

Table 2: Facility-specific annual total (all stack sources) SO_2 emissions (tonnes/year) in Alberta Oil Sands Region from 2012-2017.

Facility	2012	2013	2014	2015	2016	2017
Suncor Millennium	18,536 (20%)	14,102 (17%)	16,675 (37%)	12,634 (29%)	12,948 (34%)	12,684 (29%)
Suncor Firebag	308 (0.33%)	326 (0.40%)	262 (0.58%)	197 (0.45%)	263 (0.69%)	196 (0.45%)
Syncrude Mildred Lake	72,275 (77%)	62,339 (77%)	25,428 (56%)	27,947 (64%)	22,457 (59%)	28,442 (65%)
CNRL Horizon	2,418 (2.60%)	4,069 (5%)	2,993 (6.60%)	3,035 (6.90%)	2,748 (7.20%)	2,420 (5.50%)
Total	93,537	80,836	45,358	43,814	38,417	43,743

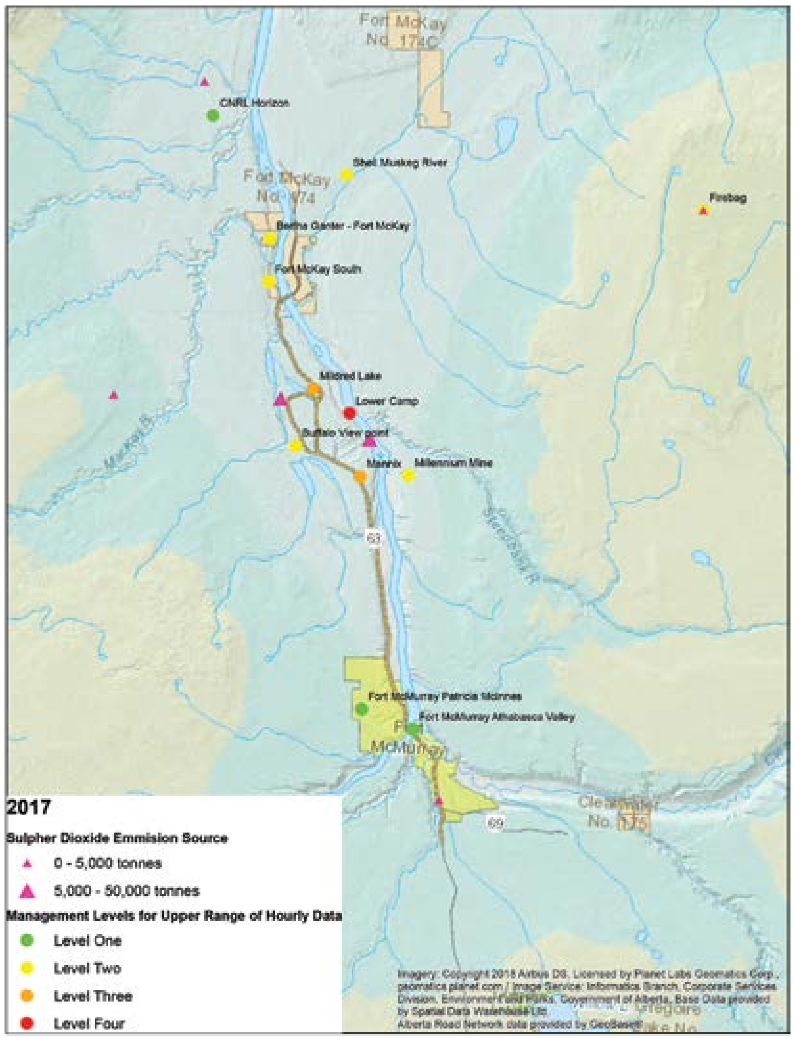


Figure 5. Major SO_2 emission sources in LAR and air monitoring station locations in 2017.

Proposed Next Steps of the Investigation

To improve understanding of the SO_2 trigger crossings in the region, specifically at Lower Camp station, AEP has proposed three new investigations in 2017 (Table 3). The oversight and delivery of these tasks are detailed below:

1. **Investigating the possible influence of industry flaring on the concentration of SO_2 (upper range) at Lower Camp and other neighbouring stations**

SO_2 emissions from flaring stacks can be more than one order of magnitude larger than SO_2 emitted under normal operating conditions and are a focus of future assessments (ECCC and AEP 2016). If hydrogen sulphide (H_2S) is included in the waste gas stream, nearly all of the hydrogen sulphide is converted to sulphur dioxide (SO_2) and emitted into ambient air during flaring (AER 2015).

Contributions of SO_2 flaring remain a significant portion of total emissions in this region as it is shown in annual emission reports of these four facilities (Table 2). A next step is to understand if SO_2 contributions due to flaring and venting are trending upward and if this is related to upper range of hourly SO_2 concentrations at air monitoring stations in LAR.

2. **Investigating fugitive emissions from petroleum coke as a potential contributing factor to ambient level of SO_2 in the Lower Athabasca Region**

A recent fire incident (Alberta Environmental and Dangerous Goods Emergencies Incident Number 340937) at the Mildred Lake petroleum coke pile (Suncor site) occurred at a time and with a wind direction that suggests possible connection to elevated SO_2 at the Mildred Lake and Lower Camp stations. Petroleum coke contains 6-7% sulphur in the Oil Sands Region (Suncor 2018) and is commonly stored on site, including within ~1 km of the Lower Camp station. It is possible that, if temperatures are high enough as a result of smouldering or fire, the sulphur within the petroleum coke piles may be released as SO_2. Additional data will be collected to determine if petroleum coke piles influence SO_2 concentrations at Lower Camp station.

3. **Analysis of micro-meteorology in the valley area that may influence SO_2 hourly concentrations at Lower Camp station**

Valley breezes are formed by the daily difference of the thermo effects between peaks and valleys. Due to the location of Lower Camp station along the Athabasca river, there is a strong possibility that valley breezes that are formed during the daytime that pass through this valley cause SO_2 peaks at this station. Receptor modeling could be used to analyze 5-minute or shorter time-span SO_2 concentrations with meteorological data (wind speed, wind direction) from nearby sources for better understanding of the upper range of hourly values at this station location.

Table 3. Status of Identified Investigation Tasks

Investigation Task	Status
Collecting additional information on industry flaring to determine its possible influence on the SO_2 upper level measurements at Lower Camp and neighbouring stations.	Proposed
Collecting information to determine if petroleum coke piles are emitting SO_2 and thus contributing to the overall results.	Proposed
Analysis of micro-meteorology in the valley area that may influence SO_2 hourly concentrations at Lower Camp station.	Proposed

3.2 Identification of Management Actions

Achieving the air quality objectives identified within the Lower Athabasca Regional Plan requires a proactive and future-based approach. Management actions support, rather than replace existing policies and regulations. These actions range from policy or regulatory initiatives to reduce emissions, to voluntary actions, and raising awareness and education on air quality.

Management actions may include activities that contribute to the gathering of baseline information, improving scientific understanding and knowledge, learning from other jurisdictions and identifying initiatives that are already committed to or underway that can lead to air quality management. Management actions, and their impacts often require longer time periods to take effect and are commonly dependent on collaborative efforts to be successful.

No new management actions have been identified to respond to SO_2 trigger crossings in 2017 because additional investigation is required to understand where SO_2 emissions can be targeted to influence air quality results (see Section 3.1). Ongoing initiatives that are being developed or are in place to reduce emissions in the region are detailed in Section 3.3 based on responses to trigger crossings prior to 2017.

As part of the commitment to stakeholder engagement under the Lower Athabasca Regional Plan, AEP began formal engagement in 2017 and have held two multi-stakeholder workshops to share information on the proposed management response and solicit input on additional management response options.

3.3 Oversight and Delivery of Management Actions

Investigations of SO_2 emission in Athabasca Oil Sands Region

To establish a better understanding of current emissions and to identify local and potential distant sources of ambient SO_2 in the Athabasca Oil Sands Region, a detailed investigation was initiated based on the recommendations from the 2015-16 management response. Information from this investigation will contribute to the SO_2 emission inventory for 2010-2016 for the Athabasca Oil Sands Region while identifying contributors to SO_2 source-driven trigger crossings. Review of the investigation report is expected to be complete by end of March 2019 and the results will be used to inform future management actions.

Wind and dispersion modeling

The project has not been undertaken to date due to limited budget and time. This project is intended for understanding the micro-meteorological influence at the valley area and finding relationships between SO_2 emission sources and hourly peaks at air monitoring stations nearer to emission sources.

Develop Improved Trend Assessment Methodology

The 2012 management response report recommended developing a tool suitable for calculating both short-term and long-term trends in SO_2 and NO_2 concentrations in the Lower Athabasca Region Tool development was undertaken by the Environmental Monitoring and Science Division (EMSD) of Alberta Environment and Parks (AEP) and is undergoing implementation trials for subsequent release.

Assess and Improve Monitoring Network

This project was initiated to improve understanding of emitted pollutants and their transport, transformation and deposition in the Athabasca Oil Sands Region. A third party report has been submitted and is currently under review by EMSD.

Table 4. Status of the delivery of investigation tasks including ongoing initiatives as of September 2018

Investigation Tasks	Lead	Status	Notes
Investigation of SO_2 level and sources in Athabasca Oil Sands region: • Compile a detailed SO_2 emissions inventory in the oil sands region for 2012-2016 • Episode analysis of hourly SO_2 at lower camp and neighbouring stations. • Trajectory analysis of SO_2 hourly concentrations at Lower Camp station.	AEP Operations	Complete	Report under review by AEP - Operations Division. The results of this report will give a better understanding of source of SO_2 emissions and its relative contributions to ambient conditions.
Wind and dispersion modeling	AEP Operations	Proposed in 2016.	Not started because lack of resources. Proposed in 2017
Develop improved trend assessment methodology	AEP EMSD	Underway	Under review by AEP – Environmental Monitoring and Science Division. Expected completion - December 2018. This tool will be used for verifying possible emission trends at Wood Buffalo Environmental Association stations.
Assess and improve monitoring network	AEP Policy	Ongoing	Under review by AEP – Environmental Monitoring and Science Division. Expected completion - the end of the March 2019. The actual report will be available early in the 2019-20 fiscal year.

4.0 Air Quality Next Steps

Environment and Parks will continue to oversee the delivery of previously identified management actions while initiating investigations required to help us understand NO_2 and SO_2 trigger crossings, particularly at the stations triggering into Level 3 and above. AEP Operations Division will continue to work closely with EMSD on proposed and outstanding investigation tasks (see Section 3.1.2). AEP will also work with specific stakeholders and Indigenous Peoples to inform the investigation and management actions stages of the management response and to assist in improving the current environmental management system for point and non-point source emissions. Progress updates on the work outlined in this report will be communicated to the public in the 2018 Status of the Management Response report.

5.0 Introduction to Surface Water Quality

This report provides a summary of the 2018 management response to surface water quality in the Athabasca River at 'Old Fort'. Herein, the Surface Water Quality Management Framework for the Lower Athabasca Region (AESRD 2012b) is referred to as "the framework".

The framework requires a management response if a trigger or limit is exceeded. In addition, undesirable trends in the concentrations of water quality variables can also result in a response. Each year the response is re-evaluated and updated as new information becomes available or work is completed. A full description of the management system can be found in the framework (AESRD 2012b).

The intent of this report is to summarize the current management responses. A management response consists of up to six steps, undertaken as needed (AESRD 2012b). Initial steps include verification and preliminary assessment. Verification identifies whether or not a trigger or limit has been exceeded. Preliminary assessment determines if an investigation is needed. Verification and preliminary assessments are complete for all trigger crossings to date. Details of the preliminary assessments conducted in response to trigger crossings are included in this report.

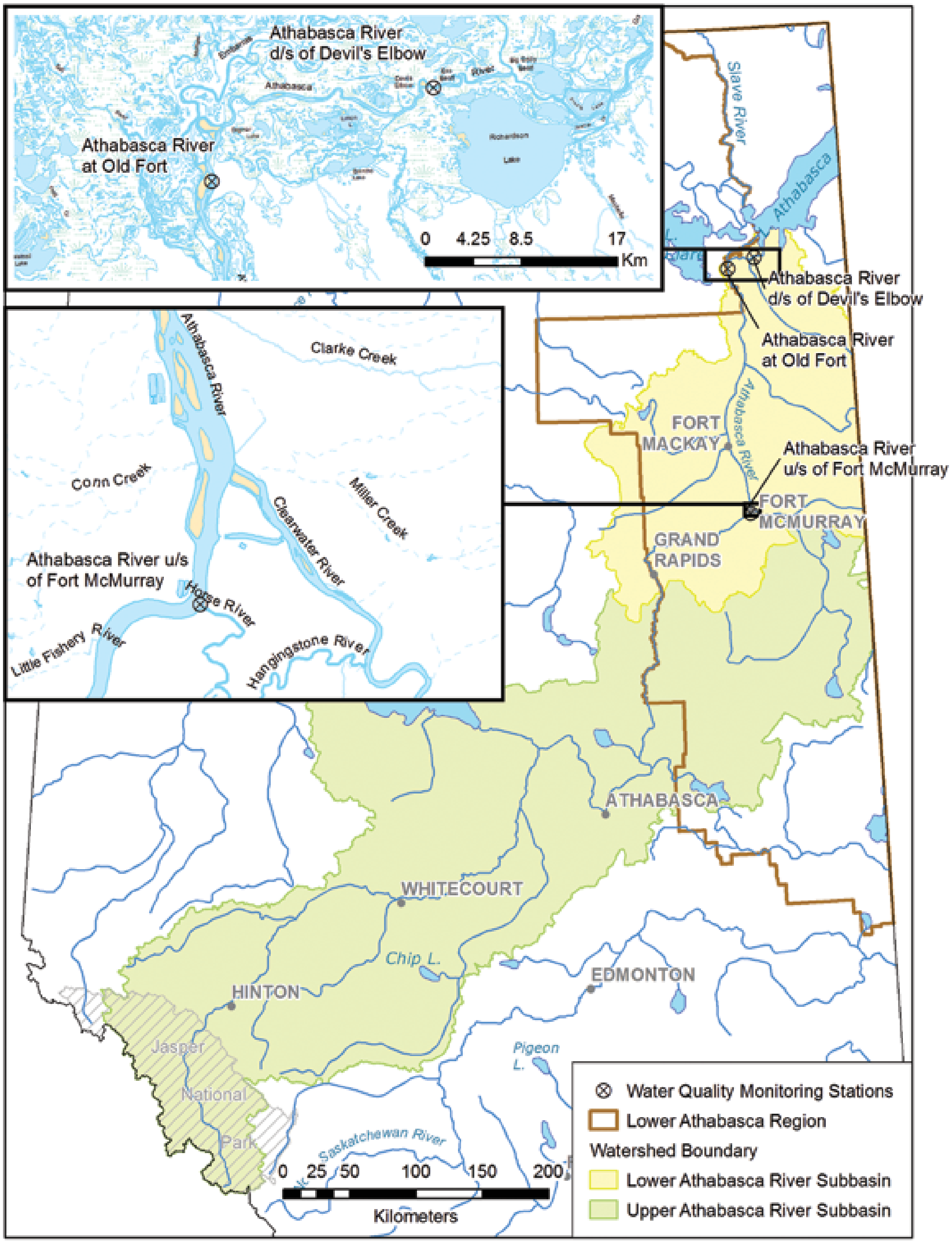
The third step in a management response is investigation. The intent of an investigation is to identify possible causes for changes in water quality. The goal is to generate enough detail to enable the implementation of effective mitigation. Thus, investigations can span multiple years and begin with a broad geographical scope. Investigations employ approaches that narrow the range of possible sources. In keeping with the intent of this document, the area and monitoring stations under investigation are outlined below. More details on investigative progress will be reported in supporting documents.

Steps beyond investigations are premature for the current response. Investigations need to reveal what sources to mitigate before a strategy is developed or implemented (step 4). This also precludes evaluating their effectiveness (step 5). Communicating progress (step 6) already occurs through this and other reports.

Environment and Parks is the lead coordinator in undertaking the management response and will work with other government organizations (e.g. Alberta Energy Regulator) and external parties as required.

5.1 Monitoring of the regulatory site

Triggers and limits identified in the framework apply at a site referred to as 'Old Fort'. 'Old Fort' is located along the mainstem of the Athabasca River within the Peace-Athabasca Delta. The sites that make up 'Old Fort' are upstream of Lake Athabasca and downstream of all oil sands development (Figure 6). 'Old Fort' refers to a combination of two monitoring sites: Old Fort and Devil's Elbow. The Devil's Elbow site is approximately 20 km downstream of Old Fort, past the confluence of the Richardson River.



Information as depicted is subject to change, therefore the Government of Alberta assumes no responsibility for discrepancies at time of use.
Base Data provided by Spatial Data Warehouse Ltd. © 2014 Government of Alberta

Figure 6: Map of the Athabasca River Basin and Lower Athabasca Region surface water quality monitoring stations

Historically, surface water samples were collected at the Old Fort site during the open water season and from the Devil's Elbow site in winter. In 2017, all samples used herein were collected from Old Fort only. Figure 7 depicts the location that each sample was collected from. Where possible, the source of observations (i.e. Old Fort or Devil's Elbow) are indicated in subsequent figures.

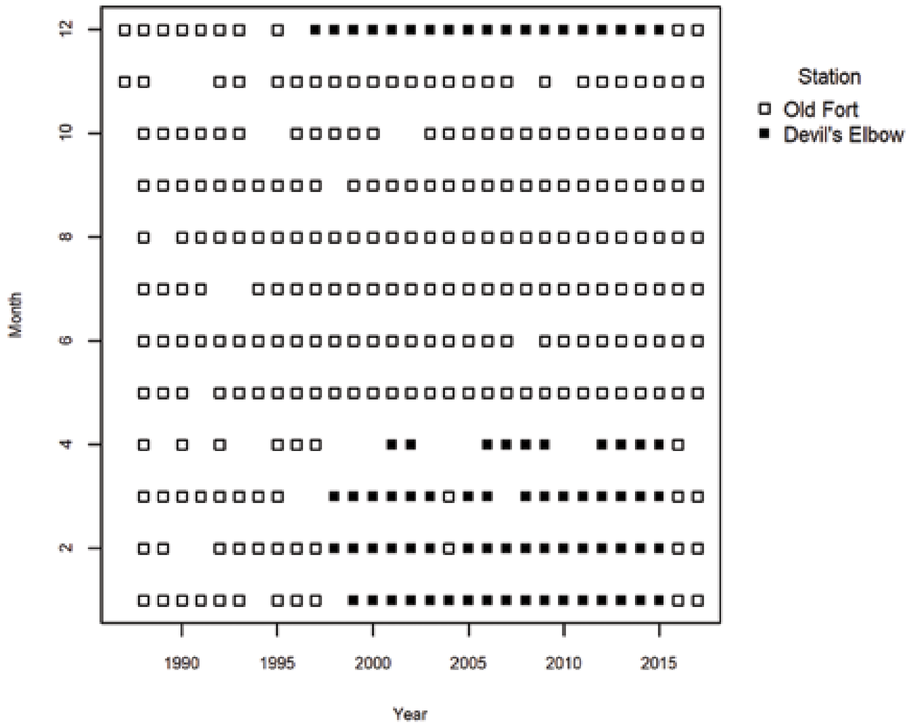


Figure 7: Locations of monthly sampling at Old Fort and Devil's Elbow sites (collectively 'Old Fort'). Blank spaces indicate that samples were not taken.

6.0 Summary of Trigger Crossings and Status of Management Response

This report is the fifth Status of Management Response Report for the Lower Athabasca Region. Previous reports can be found at the following url: http://aep.alberta.ca/land/programs-and-services/land-and-resource-planning/regional-planning/lower-athabasca/default.aspx.

To date, sampled concentrations of surface water quality indicators in the Lower Athabasca have not exceeded any limits. Trigger crossings have occurred each year since the framework was implemented in 2012. Table 5 summarizes mean and peak trigger crossings with an ongoing response.

Table 5: History of mean (M) and peak (P) trigger crossings for which current management response steps are being undertaken.

Parameter	2012	2013	2014	2015	2016	2017	Status of Management Response when last reported	Status of Management Response as of October, 2018
Potassium			M			M	Under investigation	Continued investigation
Sulphate			M	M	P		Under investigation	Continued investigation
Iron (dissolved)		M					Under investigation	Continued investigation
Nitrogen (total)	M	M					Under investigation	Continued investigation
Uranium (dissolved)	M/P	M/P	P	M/P	M/P	M/P	Under investigation	Continued investigation
Lithium (dissolved)	P				M/P	M/P	Under investigation	Continued investigation
Chloride							Standard regulatory practices	Initiated investigation

Despite no occurrence of a trigger crossing, a management response for chloride has been initiated this year. Analysis of regional data revealed an undesirable trend in chloride, leading to its inclusion in the suite of variables subject to preliminary assessment. Dissolved uranium consistently crossed triggers in the past, and has again in 2017. Dissolved lithium also crossed both mean and peak triggers for the second consecutive year. As of this report, there are 7 parameters under investigation. More details about past trigger crossings are available in the reports listed in Table 6.

Table 6: Primary sources for historical management response information

Year of exceedance	Report
2012	Status of Management Response Report: Air and Surface Water Quality as of March 2014
2013	Status of Management Response Report: Air and Surface Water Quality as of May 2015
2014	Status of Management Response Report: Air and Surface Water Quality as of May 2015
2015	Status of Management Response Report: Air and Surface Water Quality as of December 2016
2016	Status of Management Response Report: Air and Surface Water Quality as of October 2017

7.0 Status of Management Response

The following section describes actions taken since the previous management response report as a result of ongoing management response work or as a result of trigger crossings that occurred in 2017.

7.1 Verification

Verification is completed each year as new data become available. Indicators are tallied and compared to triggers provided in the framework. This tests whether recent values differ from historical norms. Significant results are referred to as trigger crossings. Details can be found in annual Status of the Ambient Environment reports. When a trigger crossing occurs the parameter advances to a preliminary assessment.

7.2 Preliminary Assessment

Preliminary Assessments evaluate the need to investigate the cause of an exceedance or trigger crossing. An investigation is often warranted if an undesirable trend has been observed. However, flow-driven trends are likely borne from changes in climate or hydrology, which cannot be addressed through the land use management approaches that may be used as mitigation in this framework. The absence of a trend suggests that the issue resulting in a trigger crossing was likely transient or due to variability within an otherwise stable state. Therefore investigations are usually only implemented when trends are present and not explained by flow.

Preliminary assessments test if statistical trends in concentration are present over time and also if statistical trends are caused by temporal changes in river discharge. By comparing past water quality and streamflow, an expected concentration can be calculated for the rate of flow. Flow-adjusted concentration values are obtained by subtracting the model predicted concentration values from the field measured sample concentrations. Both flow-adjusted and unadjusted measurements are analyzed. Flow correction models are developed and verified using methods described in appendix A.

In 2017, only chloride was subject to preliminary assessment. The remaining water quality variables for which indicators identified trigger crossings were already under investigation and updated results are found in section 7.4 of this report.

7.2.1 Chloride

The limit for chloride within the Lower Athabasca Regional Surface Water Quality Management Framework is set at 100 mg/L, with a peak trigger of 45 mg/L. In 2017, no occurrences were above the limit or the peak trigger. The maximum value observed in 2017 was 31 mg/L which is 0.689 times the peak trigger value and 0.31 times the limit. The 2017 measurements were all within the range of values observed prior to 2010 (which is analogous to the defined historical period) and during the interim period between 2010 and 2017. The dataset for chloride analyzed for the trend analysis herein spanned from 1987 through 2017.

The trend analysis for chloride revealed a decreasing statistical trend in the unadjusted concentration that was not statistically significant at 'Old Fort' (Figure 8). In contrast, flow-adjusted chloride concentrations revealed a significant increasing statistical trend.

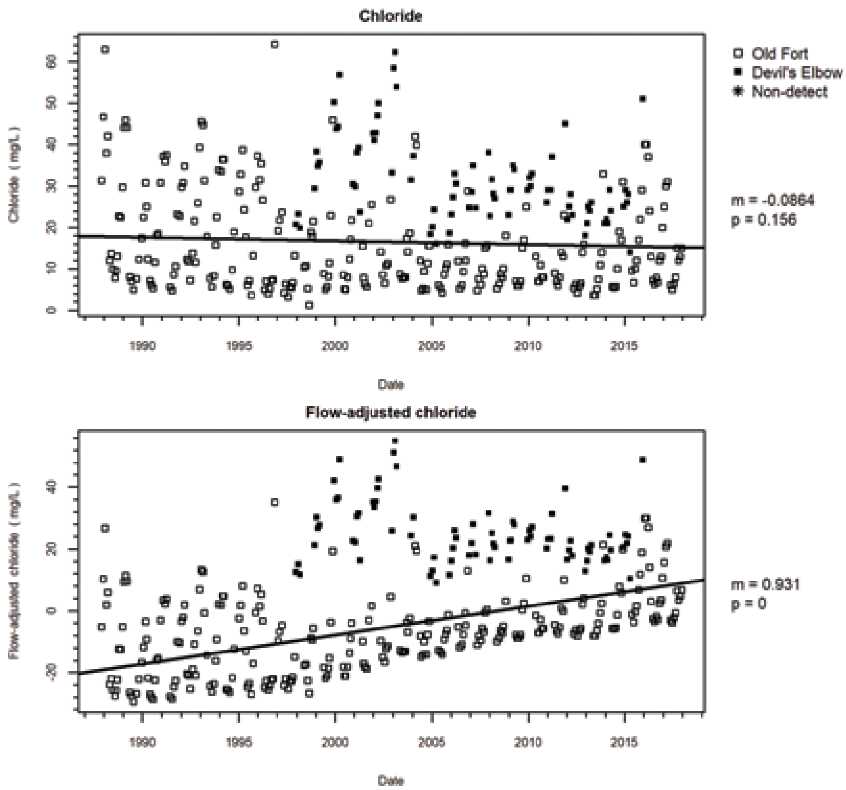


Figure 8: Time series plots of unadjusted concentrations (top) and flow-adjusted concentrations (bottom) of chloride from the Athabasca River at 'Old Fort'. Trend lines represent Akritas-Theil-Sen line.

The trend in chloride was seemingly obscured by changes in flow. While no significant trajectory in concentrations could be discerned from unadjusted measurements, trends indicated that concentrations were increasing at a rate of 0.931 mg/L per year relative to flow. Thus, chloride will proceed to the investigation phase.

7.3 Investigation Plan

The purpose of an investigation is to identify sources that degrade surface water quality. Knowing where and at what times of year changes are occurring can offer clues about potential causes. Existing surface water quality monitoring site data is evaluated to ensure that the data is useable despite any data gaps, periods of limited data collection, cessation or interruption of data collection, or changes in the monitoring location. Where necessary, data from close-by substations are pooled to compile a sufficient dataset.

Where enough data is available, investigations will employ a seasonal Kendall (SK) analysis (Hirsch et al. 1982; Hirsch & Slack 1984). SK analysis assesses trends in concentration within each month of the year. This will tell us what times of year trends are developing. Alignment in the trajectory and timing of trends observed at a site with those observed downstream would indicate that a source is likely contributing from within or upstream of the drainage area associated with that reach of river. Knowing the location and/or timing of changes in water quality will help to refine and prioritize geographic areas for source-tracking and narrow the range of prospective causes of change.

Where data gaps are too large to perform statistical trend analyses, two sample tests will be used to compare sampled concentrations before and after the gaps. In contrast to SK, two sample tests will not be able to discern temporal patterns or rates of change (slope in statistical trend). Interpreting two sample test results involve a number of assumptions and caveats. However, these tests will provide a general direction of trajectories in water quality at those sites.

Since the last Status of Management Response Report, effort has focused on compiling information and data for ongoing investigations. Identifying appropriate sites with enough data has been the priority. For each of the selected sites, contributing drainage areas not contributing to upstream monitoring sites were delineated using basin scale digital elevation models at 100 meter resolution. The contributing drainage areas for each station are depicted in Figure 9.

Results of the trend and/or paired difference tests will be merged with maps of contributing areas to assess and prioritize finer scale investigation of sources. This information will be used to focus attention on identifying possible mitigative management options. Detailed results will be presented in a supporting technical report.

In section 7.4 below, the results of analyses to date are summarized. Each trend assessment therein has been performed on datasets updated to include observations from 2017.

7.4 Results of Management Response

7.4.1 Potassium

There is no limit for potassium in the framework. In 2017, 1 occurrence was above the peak trigger, which is set at 2.1 mg/L. The maximum value was 2.2 mg/L, which is 1.048 times the peak trigger value. The 2017 measurements were all within the range of values observed prior to 2010 (which is analogous to the defined historical period), and during the interim period between 2010 and 2017. The dataset for potassium analyzed for the trend analysis herein spanned from 1987 through 2017.

The slope of trends indicated that the concentration of potassium increased at a rate of 0.00819 mg/L per year over the period analyzed. Once variance in the data resulting from changes in flow (estimates) was accounted for the trends observed suggested that relative concentrations were increasing at a rate of 0.0329 mg/L per year.

The trend analysis for potassium revealed a statistically significant increasing trend in unadjusted concentration at 'Old Fort' (Figure 10). The trend was also significant when adjusted for flow. Thus, potassium will continue to be investigated.

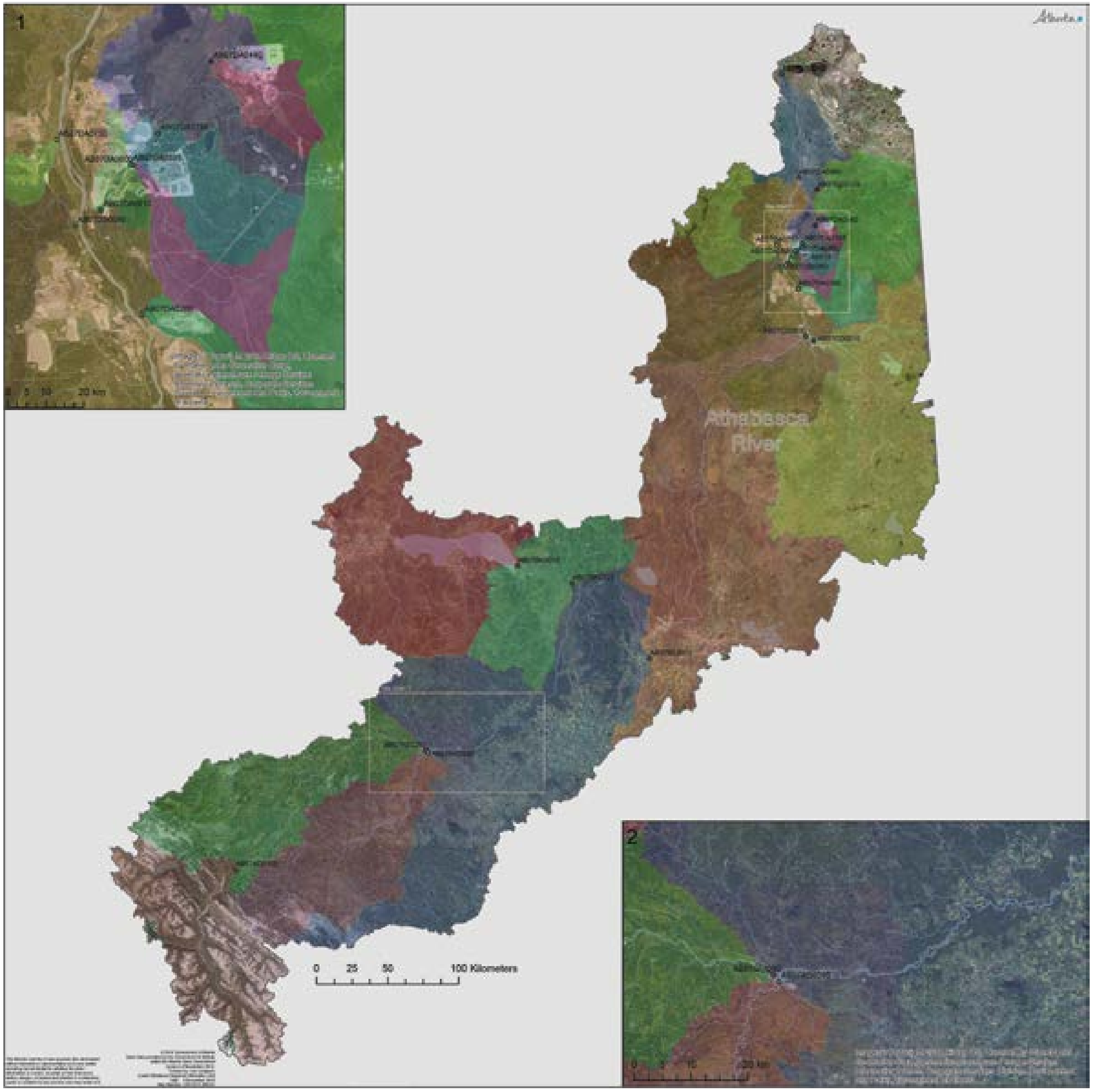


Figure 9: Map of the Athabasca River Basin surface water quality monitoring stations to be used in investigations and their contributing areas.

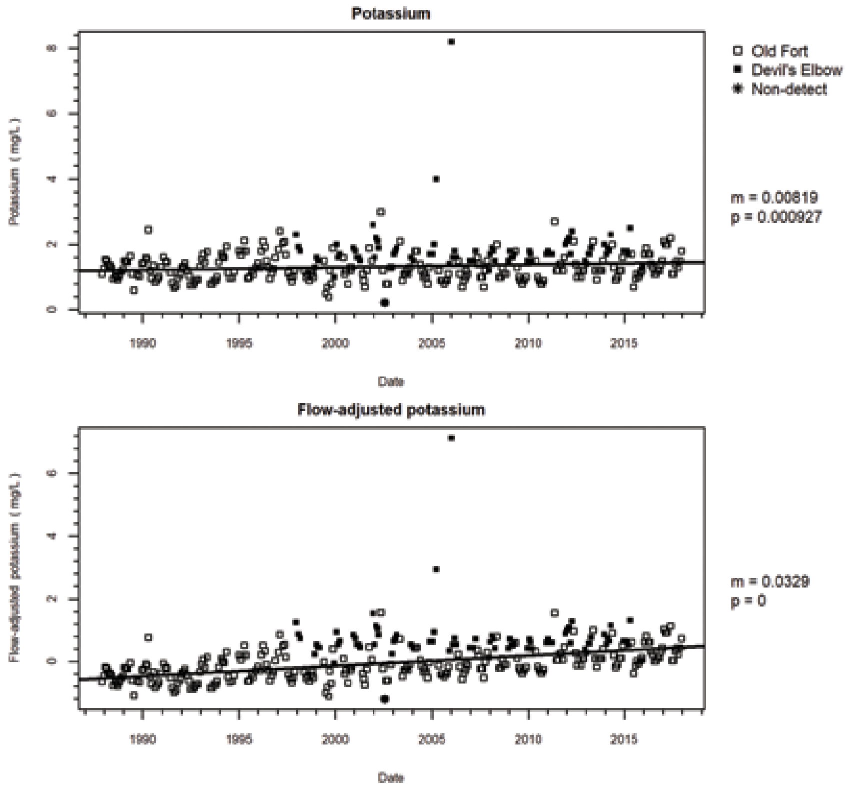


Figure 10: Time series plots of unadjusted concentrations (top) and flow-adjusted concentrations (bottom) of potassium from the Athabasca River at 'Old Fort'. Trend lines represent Akritas-Theil-Sen line.

7.4.2 Sulphate

The limit for sulphate within the framework is 500 mg/L. In 2017, no occurrences were above the limit and 2 occurrences were above the peak trigger, which is set at 41.4 mg/L. The maximum value observed in 2017 was 42 mg/L which is 1.014 times the peak trigger value and 0.084 times the limit. The 2017 measurements were all within the range of values observed prior to 2010 (which is analogous to the defined historical period), and during the interim period between 2010 and 2017. The dataset for sulphate analyzed for the trend analysis herein spanned from 1987 through 2017.

The slope of trends indicated that the concentration of sulphate increased at a rate of 0.269 mg/L per year over the period analyzed. Once variance in the data resulting from changes in flow (estimates) was accounted for the trends observed suggested that relative concentrations were increasing at a rate of 1.01 mg/L per year.

The trend analysis for sulphate revealed a statistically significant increasing trend in unadjusted concentration at 'Old Fort' (Figure 11). The trend was also significant when adjusted for flow. Thus, sulphate will continue to be investigated.

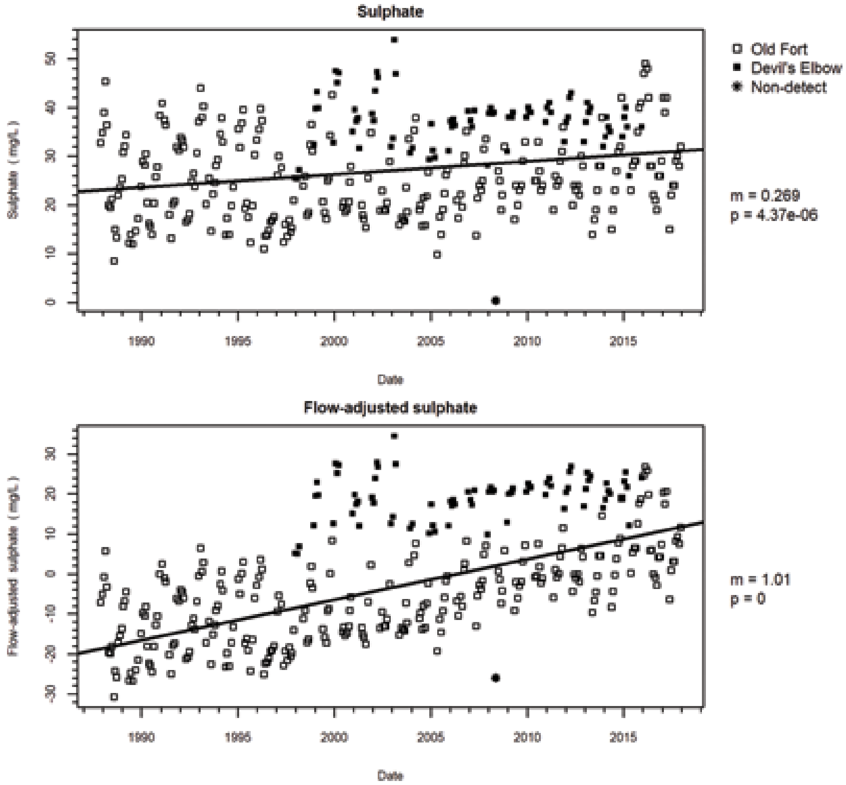


Figure 11: Time series plots of unadjusted concentrations (top) and flow-adjusted concentrations (bottom) of sulphate from the Athabasca River at 'Old Fort'.
Trend lines represent Akritas-Theil-Sen line.

7.4.3 Dissolved iron

There is no limit for dissolved iron in the framework. In 2017, no occurrences were above the peak trigger, which is set at 372 µg/L. The maximum value was 296 µg/L, which is 0.796 times the peak trigger value. The 2017 measurements were all within the range of values observed prior to 2010 (which is analogous to the defined historical period), and during the interim period between 2010 and 2017. The dataset for dissolved iron analyzed for the trend analysis herein spanned from 1987 through 2017. There were 2 periods where data were missing in the time series for dissolved iron: 1994-1998, and 1998-1999. None of these data gaps exceeded a span equal to one third of the period of data collection; an approximate threshold suggested by Helsel and Hirsch (2002, pp. 349) for requiring the use of alternate methodologies for trend analyses. Thus, the trend analysis results will be considered as valid despite missingness in the dataset.

The slope of trends indicated that the concentration of dissolved iron increased at a rate of 1.1 µg/L per year over the period analyzed. Once variance in the data resulting from changes in flow (estimates) was accounted for the trends observed suggested that relative concentrations were increasing at a rate of 4.22 µg/L per year.

The trend analysis for dissolved iron revealed a statistically significant increasing trend in unadjusted concentration at 'Old Fort' (Figure 12). The trend was also significant when adjusted for flow. Thus, dissolved iron will continue to be investigated.

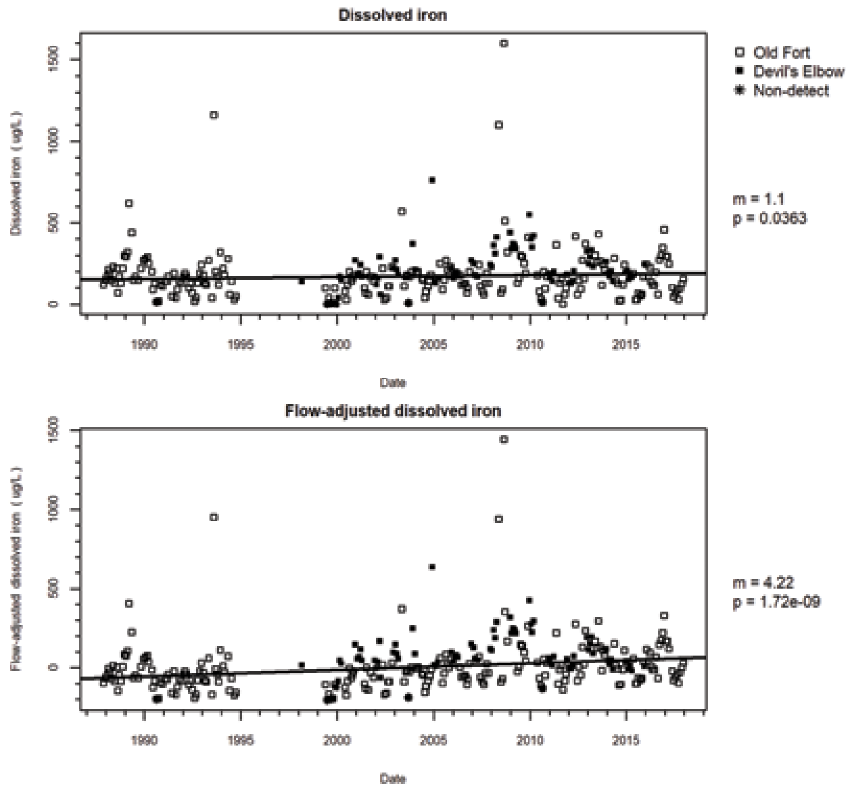


Figure 12: Time series plots of unadjusted concentrations (top) and flow-adjusted concentrations (bottom) of dissolved iron from the Athabasca River at 'Old Fort'. Trend lines represent Akritas-Theil-Sen line.

7.4.4 Total nitrogen

There is no limit for total nitrogen in the framework. In 2017, no occurrences were above the peak trigger, which is set at 1.041 mg/L. The maximum value was 0.87 mg/L, which is 0.8357 times the peak trigger value. The 2017 measurements were all within the range of values observed prior to 2010 (which is analogous to the defined historical period), and during the interim period between 2010 and 2017. The dataset for total nitrogen analyzed for the trend analysis herein spanned from 1987 through 2017.

The slope of trends indicated that the concentration of total nitrogen increased at a rate of 0.002931 mg/L per year over the period analyzed. Once variance in the data resulting from changes in flow (estimates) was accounted for the trends observed suggested that relative concentrations were increasing at a rate of 0.002556 mg/L per year.

The trend analysis for total nitrogen revealed a statistically significant increasing trend in unadjusted concentration at 'Old Fort' (Figure 13). The trend was also significant when adjusted for flow. Thus, total nitrogen will continue to be investigated.

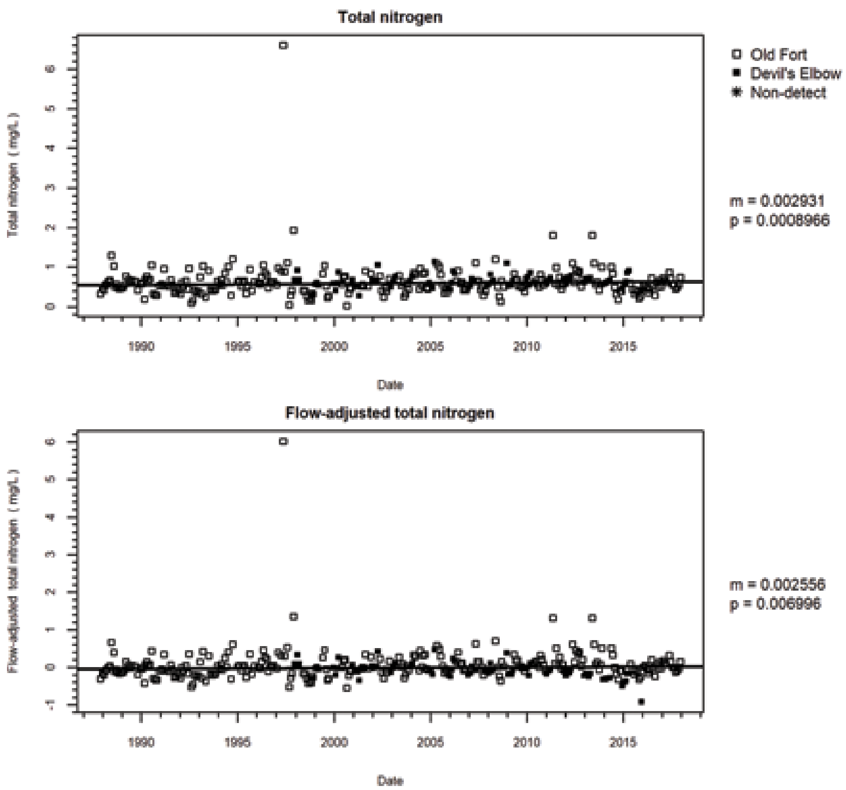


Figure 13: Time series plots of unadjusted concentrations (top) and flow-adjusted concentrations (bottom) of total nitrogen from the Athabasca River at 'Old Fort'. Trend lines represent Akritas-Theil-Sen line.

7.4.5 Dissolved uranium

The limit for dissolved uranium within the framework is 10 μg/L. In 2017, no occurrence was above the limit and 6 occurrences were above the peak trigger, which is set at 0.381 μg/L. The maximum value observed in 2017 was 0.46 μg/L which is 1.207 times the peak trigger value and 0.046 times the limit. The 2017 measurements were all within the range of values observed prior to 2010 (which is analogous to the defined historical period), and during the interim period between 2010 and 2017. The dataset for dissolved uranium analyzed for the trend analysis herein spanned from 1999 through 2017.

The slope of trends indicated that the concentration of dissolved uranium increased at a rate of 0.00531 μg/L per year over the period analyzed. Once variance in the data resulting from changes in flow (estimates) was accounted for the trends observed suggested that relative concentrations were increasing at a rate of 0.00766 μg/L per year.

The trend analysis for dissolved uranium revealed a statistically significant increasing trend in unadjusted concentration at 'Old Fort' (Figure 14). The trend was also significant when adjusted for flow. Thus, dissolved uranium will continue to be investigated.

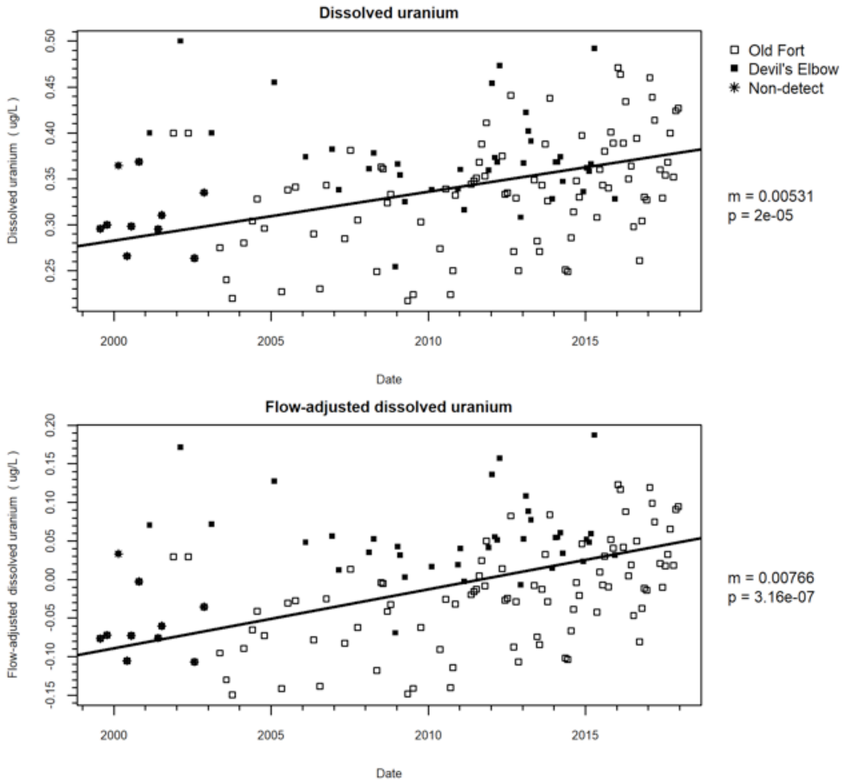


Figure 14: Time series plots of unadjusted concentrations (top) and flow-adjusted concentrations (bottom) of dissolved uranium from the Athabasca River at 'Old Fort'. Trend lines represent Akritas-Theil-Sen line.

7.4.6 Dissolved lithium

There is no limit for dissolved lithium in the framework. In 2017, 3 occurrences were above the peak trigger, which is set at 9 µg/L. The maximum value was 10.7 µg/L, which is 1.189 times the peak trigger value. The 2017 measurements were all within the range of values observed prior to 2010 (which is analogous to the defined historical period), and during the interim period between 2010 and 2017. The dataset for dissolved lithium analyzed for the trend analysis herein spanned from 1999 through 2017.

The slope of trends indicated that the concentration of dissolved lithium increased at a rate of 0.0927 µg/L per year over the period analyzed. Once variance in the data resulting from changes in flow (estimates) was accounted for the trends observed suggested that relative concentrations were increasing at a rate of 0.255 µg/L per year.

The trend analysis for dissolved lithium revealed a statistically significant increasing trend in unadjusted concentration at 'Old Fort' (Figure 15). The trend was also significant when adjusted for flow. Thus, dissolved lithium will continue to be investigated.

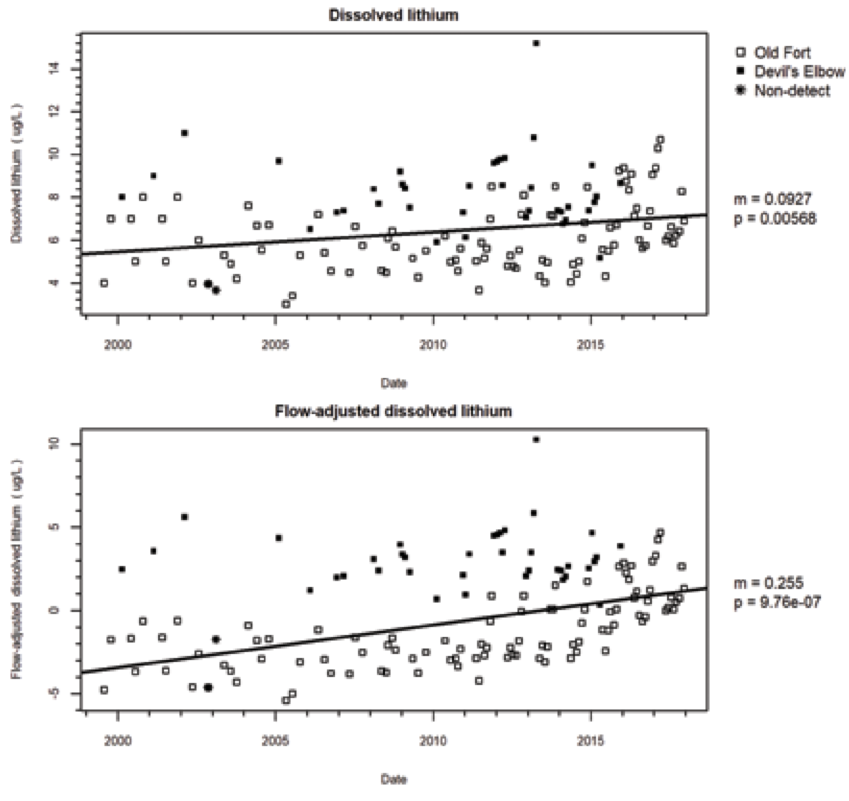


Figure 15: Time series plots of unadjusted concentrations (top) and flow-adjusted concentrations (bottom) of dissolved lithium from the Athabasca River at 'Old Fort'. Trend lines represent Akritas-Theil-Sen line.

7.5 Management Actions

Identifying contaminant sources is necessary to develop an effective mitigation strategy. Knowing the geography and timing of a problem is vital for source-tracking. Thus, the current management action is to prioritize potential source areas according to the methods described in the above sections for further refinement. Detailed results of these analyses will be communicated in forthcoming supporting technical documents. Future mitigation management actions will depend on information derived from investigations.

If sources are identified, available strategies for mitigative management action will be explored. Potential avenues for mitigation could include, but are not limited to: cooperative and/or voluntary development and implementation of mitigation measures, regional and sub-regional planning initiatives, developing targeted approvals requirements, public education campaigns, and where necessary, enforcement of compliance.

8.0 Next Steps

As of October, 2017 the status of the management response is as follows:

- An investigation into chloride has been initiated
- Investigations into the following parameters will continue:
  - dissolved iron
  - potassium
  - sulphate
  - total nitrogen
  - dissolved lithium
  - dissolved uranium

8.1 Indicators under Investigation

Dissolved iron, potassium, sulphate, total nitrogen, dissolved lithium, dissolved uranium, and chloride are currently under investigation. The next step in the investigations will focus on delineating the reaches where trajectories in water quality exist along the Athabasca River and its tributaries. Efforts to identify specific sources can then be focused on the sub-catchment areas most likely contributing to the trends observed downstream at the 'Old Fort' site.

Where possible, each of these parameters will undergo tests to identify trajectories in concentration at the monitoring stations listed in Table 7.

8.2 Indicators for which Management Response was Closed

There were no trigger crossings for which the management response was closed.

Table 7: List of monitoring stations relevant to investigations, their coordinates, and the waterbodies in which they are located.

Station Number	Water Body	Latitude	Longitude
AB07AE0360	Athabasca River	54.14889	115.7208
AB07CC0030	Athabasca River	56.72028	111.4056
AB07DA0980	Athabasca River	57.72361	111.3792
AB07BE0010	Athabasca River	54.72222	113.2861
AB07AD0100	Athabasca River	53.36750	117.7225
AB07DD0010	Athabasca River	58.38278	111.5178
AB07CD0210	Clearwater River	56.68871	111.3175
AB07DA0750	Ells River	57.30444	111.6758
AB07DC0100	Firebag River	57.64167	111.1750
AB07DA0600	Jackpine (Hartley) Creek	57.25944	111.4647
AB07BK0010	Lesser Slave River	55.30611	114.7597
AB07BK0125	Lesser Slave River	55.20667	114.1225
AB07DB0060	MacKay River	57.16833	111.6400
AB07AG0390	McLeod River	54.13611	115.6958
AB07DA2755	Muskeg Creek	57.30750	111.3892
AB07DA0440	Muskeg River	57.41667	111.2211
AB07DA0610	Muskeg River	57.19167	111.5681
AB07DA0595	Muskeg River	57.26389	111.4725
AB07DA0260	Steepbank River	57.02528	111.4603

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Appendices

Appendix A: Methods and rationale for performing flow-adjustment

Streamflow integrates the influences of weather and hydrological conditions in a basin. As such, streamflow measurements (and/or estimates) provide a way to constrain these influences when evaluating water quality measurements in time series. Flow-adjustment amplifies variability related to other factors by reducing the components of variance related to weather and hydrology. Thus, changes in the relationship between flow and concentration over time result from changes in export from the landscape (e.g. Smith et al., 1982).

For instance, as a thought experiment, imagine that water quantity and quality are monitored immediately upstream and downstream of a parcel of land that is relatively rich in potassium and that export of potassium increased with discharge. If that parcel remained unchanged from one year to the next but a greater volume of water moved through it one year, one would likely detect changes in both flow and concentration of potassium measured downstream to increase relative to the upstream measurements. The increase in potassium concentrations would be explained by flow rather than a change in landuse.

In contrast, imagine that the same parcel of land instead had years where similar volumes of water moved through it but that a disturbance occurred causing more potassium to be exported. One would expect the concentration of potassium to increase downstream while the flow remained unchanged. In this scenario the additional potassium measured downstream would not be explained by changes in flow. Thus, by accounting for flow one can begin to differentiate between anomalies caused by changes to the landscape and those caused by changes in the volume of water moving through it.

In another scenario, envision that the majority of potassium was emitted from a point source on the parcel discharging at a constant rate regardless of the volume of water moving through the landscape. Increases in flow through the landscape would dilute the concentrations measured downstream whereas decreases in flow would concentrate potassium in samples collected downstream relative to a normal year. Thus, depending on the source and speciation of the parameter analyzed, changes in flow may dilute, concentrate, or have no discernable effect (Hirsch et al., 1982).

While flow-adjustment is effective to amplify signals originating from upstream changes in land use (natural or otherwise), there are limitations to this approach. For instance, water quality measurements collected from rivers capture (some portion of) both suspended solids and dissolved constituents. Increasing flow provides additional energy that can entrain more solids in water causing increased concentrations. The flow regime and site characteristics influence the tendency for sediment to be eroded, transported, or deposited. Further, the solubility characteristics of each parameter may also differ. These considerations necessitate a unique calibration of the flow-concentration relationships for each parameter at each site. Calibrating flow-concentration relationships for time series analysis also requires consideration.

Streamflow influence was accounted for by undertaking flow-adjustment of the sampled water quality concentrations. Flow-adjustment values herein equals the residuals resulting from the subtraction of variance in concentrations as predicted from flow-concentration relationships from measurement values (Helsel & Hirsch 2002). The flow-concentration relationship was defined using the LOWESS method described by Cleveland (1979) as applied in R (R Core Team, 2017). The measured values prior to subtracting variability explained by flow were referred to as “unadjusted” values.

In some instances, the variability in the flow-adjusted concentrations (i.e. residuals) were unequal over time (aka heteroscedastic). In these instances, other factors or events may have occurred that influenced the concentration-flow relationships that may have compromised the reliability of the flow-adjustment. Where unequal variance in flow-adjusted time series was discovered and could not be corrected via data transformation (Box & Cox 1964; Fox & Weisberg 2011; R Core Team 2017), flow-adjustment models were assumed to be invalid and were not applied.

The validity of flow-adjustment models was assessed by applying Breusch-Pagan tests to time series regressions of flow-adjusted concentrations for each parameter, at each site (Breusch & Pagan 1979). From among the valid models, over- or under-fitting was avoided by selecting the maximum LOWESS span value (i.e. greatest smoothing) related to the output of pettitt tests applied to cumulative model residual variances, (Breusch-Pagan) Chi-squared-, and (Breusch & Pagan 1979) p-value outputs among the range of valid flow-adjustment models (Pettitt 1979; Pohlert 2018).

Appendix B: Methods and rationale for performing trend analysis

Trend analysis, with respect to the Framework, are tests performed using linear regression on a time series of water quality observations. In the trend analysis, the sampling dates were the independent variable and the measured concentrations (and flow-adjusted concentrations) were the dependent variables. The analysis determined if trends were not significant, increasing, or decreasing by calculating the magnitude and significance of regression line slopes.

If a trend in the sampled water quality concentration did not also occur in flow-adjusted values, the significance of a trend could be explained by the effects of changes in the volume of water flowing through the landscape rather than changes in the upstream landscape. Thus, the likelihood of finding another actionable explanation was considered to be low and that resources would be better spent exploring other issues. However, if a trend was detected in flow-adjusted concentrations, then other explanations were needed to account for the observed changes in condition.

The trend analyses herein were conducted using the cenken function within NADA package (Lee, 2017) within the R computing environment (R Core Team 2017). The slope and p-values represent the Akritas-Thiel-Sen nonparametric line estimates (Akritas et al. 1995; Helsel 2005) calculated from unadjusted and flow-adjusted values and dates converted to decimal format using the lubridate::date_decimal function (Grolemund & Wickham 2011).

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