



# Challenges and Benefits of Approaches Used to Integrate Regional Monitoring Programs

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Although challenging to develop and operate, some degree of integrated monitoring is often necessary, especially at regional scales, to address the complex questions of environmental management and regulation. The concept of integration is well-understood, but its practice across programs and studies can be diverse suggesting a broader examination of the existing general approaches is needed. From the literature, we suggest integration of monitoring can occur across three study components: interpretation, analysis, and design. Design can be further subdivided into partial and full integration. Respectively combining information, data, and designs, we further define these types of integration and describe their general benefits and challenges, such as strength of inference. We further use the Oil Sands Monitoring program in northern Alberta as an example to clarify the practices common among integrated monitoring programs. The goal of the discussion paper is to familiarize readers with the diverse practices of integrated monitoring to further clarify the various configurations used to achieve the wider goals of a program.

**Keywords:** environmental monitoring, integrated monitoring, oil sands, regional monitoring program, environmental management

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## INTRODUCTION

Human activities influence the environment in many ways and monitoring over time is intended to provide timely, clear, systematic information on their status (Yoccoz et al., 2001). While needed to inform the larger strategic goals of reducing, eliminating, or controlling the impacts of those activities, multiple approaches are available for measuring environmental attributes and assessing status. However, monitoring may not always be straightforward and may not always provide widely-accepted and certain evidence showing the presence of impacts (leading to effective interventions), or their absence (and reassurance of safety; Munkittrick et al., 2019). For example, monitoring programs must often translate high-level management questions, such as “Are there effects?” into focused and testable scientific hypotheses which may not wholly reflect the original objectives. Monitoring must also contend with other challenges. Risk tolerances among stakeholders may vary and “safe”, or acceptable conditions may not be objectively characterized. There can also be unknown long-term consequences of low levels of environmental change (Soulé, 1985; Biber, 2011; Addison et al., 2016; Suter, 2016), obscure or unknown exposure of organisms (Tetreault et al., 2020), and various interactions of both anthropogenic and natural environmental stressors (Gieswein et al., 2017; Arciszewski et al., 2018).

The well-known challenges of monitoring have motivated the further development of approaches and tools (e.g., Lindenmayer and Likens, 2010). One common solution to improve the utility of information provided by a monitoring program is expanding its spatial, temporal, and technical scope (Dowdeswell et al., 2010; Gosselin et al., 2010; Lott and Jones, 2010; AEMP, 2011). However, as these scopes increase, new challenges can emerge. While it may be desirable, monitoring at regional scales (such as those larger than  $10^3$  km<sup>2</sup>) can extend across different biomes (Hunsaker et al., 1990) and can incorporate the influence of multiple human activities and multiple stakeholders with diverse values. Regional monitoring initiatives may also cover areas comprised of multiple political jurisdictions with different environmental regional planning objectives and legal requirements, such as monitoring programs examining status and trends, environmental effects monitoring, compliance monitoring, cumulative effects assessment, pre-development baseline studies, and research programs.

Further solutions are often suggested and implemented to overcome the challenges of monitoring programs with wide temporal, spatial, and technical scopes. Most notable among them are the repeated calls for integration (e.g., Dowdeswell et al., 2010; Liu et al., 2012; Hopke et al., 2016). Integration of programs is seen as a solution to enhance efficiency and efficacy of programs (Lindenmayer and Likens 2010; Liu et al., 2012; Norton et al., 2014; Cooke and Hilton 2015; Arciszewski et al., 2017b), to provide increased sensitivity to surprises (Munn, 1988), and to foster scientific contributions to environmental management (Thackeray and Hampton, 2020).

While integration is popular and can be beneficial, it is often a strategic and conceptual objective (e.g., Bagstad et al., 2013; Dubé et al., 2013; Noble 2015; Arciszewski et al., 2017b; Cronmiller and Noble, 2018b) may refer to diverse practices. Integration can refer to multiple, but related actions including the combination of approaches (Burton et al., 2002a; Ankley et al., 2010), of several related measurements within a given study (Löfgren et al., 2011; Scrimgeour et al., 2013; Vethaak et al., 2017), or of measuring and modeling (Haeberli et al., 2007). Integration can also refer to the combination of information and data from a variety of spatial and temporal scales using techniques such as Weight-of-Evidence and development of causal criteria (Lowell et al., 2000; Cash et al., 2003). Finally, integration may also refer to the combination of multiple studies, including multiple field studies, or laboratory and field studies (Wolska et al., 2007; Barra et al., 2020), parallel and mutually supporting monitoring and research (Wrona and Cash 1996; Bunn et al., 2010), or monitoring based on tiers and triggers (Arciszewski and Munkittrick, 2015; Somers et al., 2018).

While all examples above satisfy the conceptual demands of integration, the diversity of its practices may not be recognized when initial recommendations for a program's direction and objectives are made. This can be especially problematic if the conceptual and initial vision for an integrated program is also not explicitly and practically defined. In this discussion paper, our specific goal is to propose a framework to organize the types of integrated monitoring programs and describe the practical methods currently used to combine information, data, and designs. We also discuss their benefits and the potential

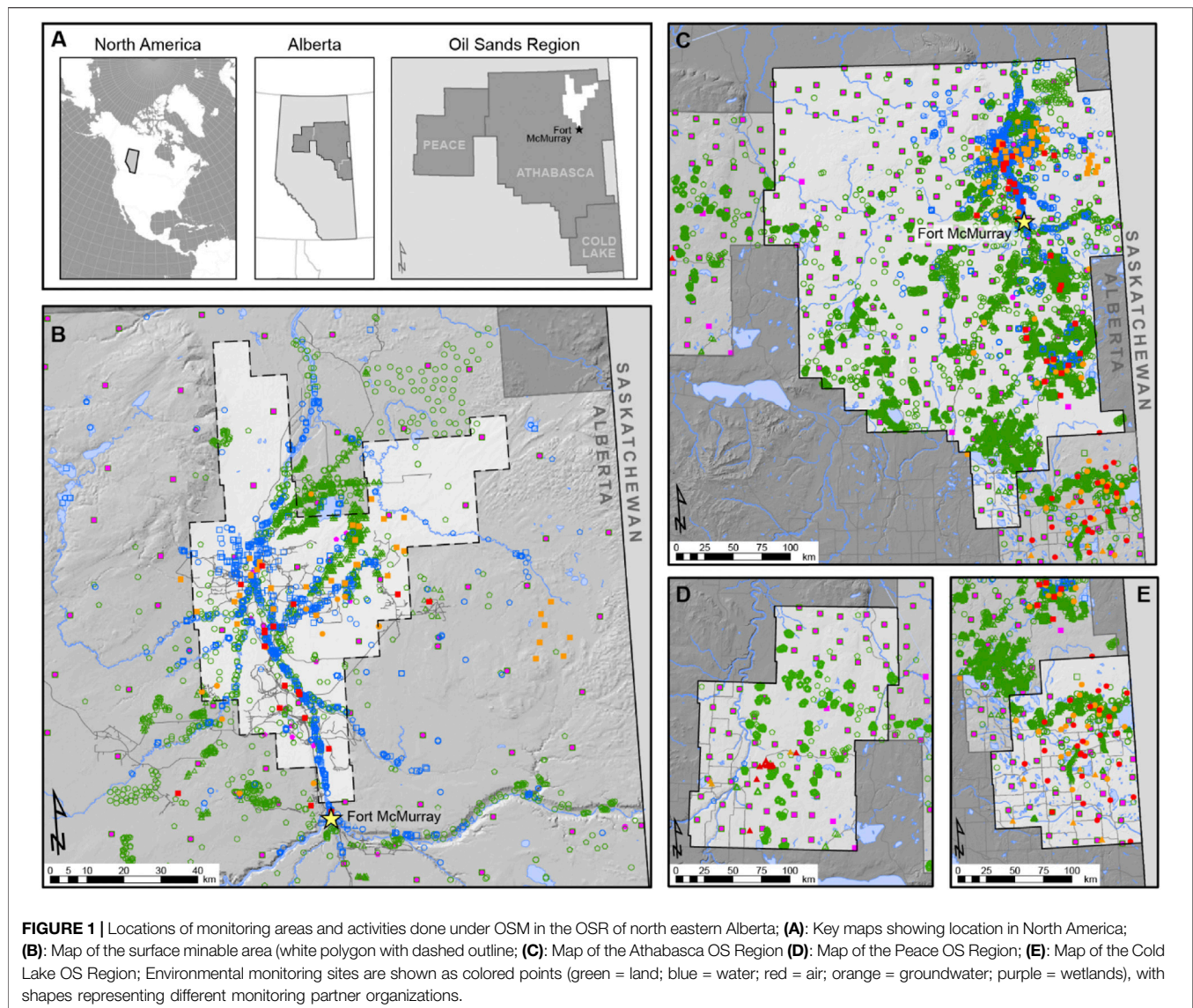
challenges with each approach and frame these practices using the Oil Sands Monitoring (OSM) program; a multi-year, multi-indicator, multi-theme, multi-million dollar program in northern Alberta. Finally, we conclude with a general discussion of how to overcome the challenges of different forms of integration and how they can occur simultaneously within a large regional monitoring program. Our general goal with this discussion is to clarify the various practices of integration and provide a common language for use among participants of large regional monitoring programs.

## OIL SANDS MONITORING

The Oil Sands Region (OSR) of northeastern Alberta covers a surface area of 142,200 km<sup>2</sup> containing three deposits of bitumen, together comprising the third largest known reserve of hydrocarbons in the world (Figure 1). Where the bitumen is within ~75 m of the surface, it is extracted through conventional truck and shovel mining. Where the reserves are deeper, *in situ* methods, often using steam-assisted gravity drainage (SAGD), liquefy the bitumen in the reservoir and transport it to the surface. The extraction of bitumen occurs throughout the region. Within the 4,800 km<sup>2</sup> minable region north of Fort McMurray, roughly 1,264 km<sup>2</sup> is disturbed (ABMI, 2018). As of 2018, ~22,252 km<sup>2</sup> of the total OSR is physically disturbed (ABMI, 2018), but this is most intense within the Athabasca Oil Sands (sub) region. While physically located in northern Alberta, gases and particles emitted to the atmosphere can be deposited in downwind areas outside the OSR, including northern Saskatchewan (Makar et al., 2018). The activity is also the subject of intense local, national, and global environmental concern and scrutiny (e.g., Miall, 2013).

Regional monitoring initiatives have been common in northern Alberta. Historically, there were many monitoring programs examining potential changes in the ambient environment surrounding oil sands development, including regional cooperative programs, industry-driven programs, industry-funded programs, provincial and federal monitoring programs, and joint government initiatives (Figure 2). However, in 2009 and 2010 independent research showing the accumulation of contaminants of concern in snow near mines was published (Kelly et al., 2009; Kelly et al., 2010). This work highlighted gaps in monitoring and initiated reviews of the existing regional programs (e.g., Dowdeswell et al., 2010; AEMP, 2011). The reviews of monitoring consistently identified the need to achieve a more fully integrated monitoring system in the OSR (e.g., Gosselin et al., 2010; Lott and Jones, 2010). For example, the lack of data compatibility, including lack of consistency in chemical measurements and biological indicators, truncated sampling schedules, incompatible analytical methods, and fragmented data sets have affected the attempts at integrated interpretation and analyses conducted prior to 2012 (Gosselin et al., 2010).

In 2012 the existing programs were replaced by the Joint Oil Sands Monitoring Program (JOSM). JOSM was intended to be an integrated program (Environment Canada, 2011a) and was implemented in phases for each target medium (water, air,

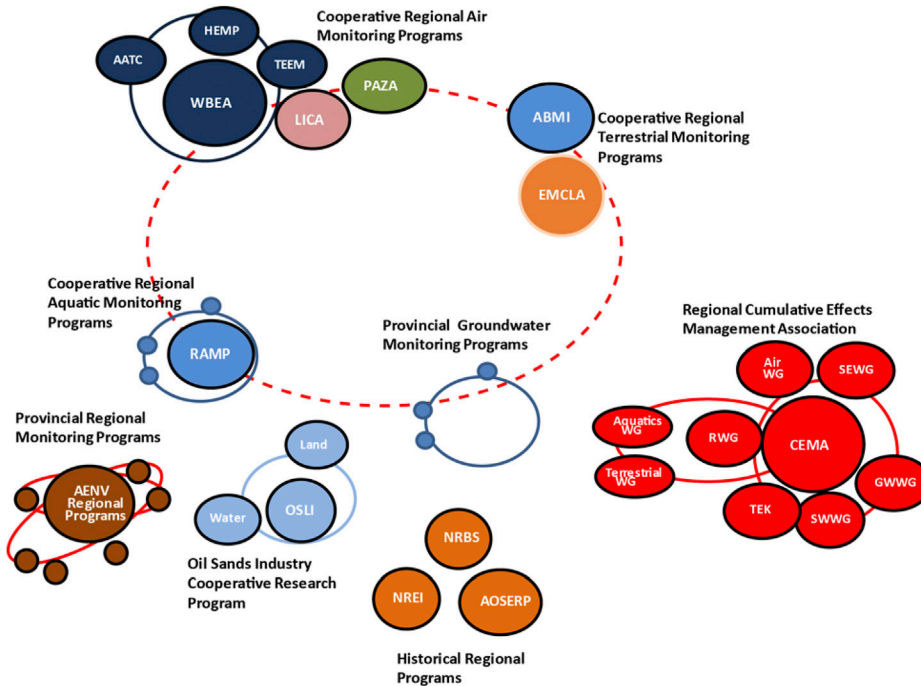


terrestrial). First the surface water program was released (Baird et al., 2011) followed later by separate program designs for terrestrial biodiversity (Environment Canada, 2011b), air (Environment Canada, 2011c), and an expanded geographical area (Wrona et al., 2011). In 2016, JOSM was rebranded as the OSM program (Dubé et al., 2018) after changes to administratively streamline and simultaneously broaden the governance of the program (Figure 3). OSM is currently administered and operated jointly by the Governments of Alberta and Canada and funded through a \$50 M per year industry levy. The total funding allocated for the OSM/JOSM program is now approaching \$500 M CAD.

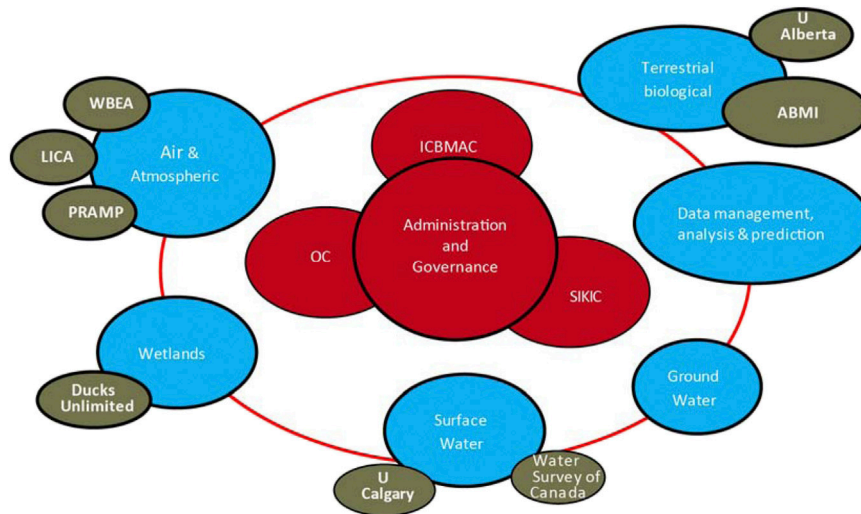
The technical scope of OSM is broad. It examines multiple indicators across multiple media, including air, water, land, wetlands, and groundwater (Environment Canada, 2011a; Figure 1). OSM also partitions programs into “focused studies” and “core monitoring”. Focused studies are diverse and include many different types of activities, including research and methods

development. Core monitoring programs include long-term routine programs such as water quality (Swanson, 2019a; Swanson, 2019b). A current emphasis of OSM is also expanding the role of community-based monitoring (e.g., Brunet et al., 2020) and inclusion of Indigenous Knowledge and Wisdom throughout the program, including establishing Indigenous representation within the program governance (Dubé et al., 2018).

Another objective of reconfiguring the regional monitoring in the OSR was increasing the quality of the work through external peer-review. While many papers have been published by researchers funded by this program (e.g., Summers et al., 2016; Makar et al., 2018; Landis et al., 2019), additional work also occurs in the region outside of the OSM funding envelope, including industry-funded research, compliance monitoring, provincial monitoring, and independent research (e.g., Shotyk et al., 2017; Redman et al., 2018; Fennell and Arciszewski, 2019). Since 2012 these research efforts have collectively produced hundreds of research papers.



**FIGURE 2 |** Status of historical and current monitoring or data collection entities operating in the Oil Sands region; AOSERP = Alberta Oil Sands Environmental Research Program; NRBS = Northern River Basins Study; NREI = Northern Rivers Ecosystem Initiative; RAMP = Regional Aquatics Monitoring Program; WBEA = Wood Buffalo Environmental Association; TEEM = Terrestrial Environmental Effects Monitoring; ABMI = Alberta Biodiversity Monitoring Institute; CEMA = Cumulative Effects Management Association; AENV = Alberta Environment; OSJI = Oil Sands Leadership Initiative; EMCLA = Ecological Monitoring Committee for the Lower Athabasca; PAZA = Peace Airshed Zone Association; LICA = Lakeland Industry and Community Association; SEWG = Sustainable Ecosystems Working Group; TEK = Traditional Ecological Knowledge; GWWG = Groundwater working group; SWWG = Surfacewater working group; RWG = Regional Working Group.



**FIGURE 3 |** Current administrative structure of the Oil Sands Monitoring program including central (red) administrative and governance committees (Indigenous Community Based Monitoring Advisory Committee; Oversight Committee; Science and Indigenous Knowledge Integration Committee), peripheral Technical Advisory Committees (in blue; e.g., Groundwater), and delivery partners (green) identified from the most recent publicly available workplans available (2017–2018) from <http://environmentalmonitoring.alberta.ca/activities/oil-sands-monitoring-projects/20172018-projects/>; not shown are additional linkages with Environment and Climate Change Canada, Alberta Environment and Parks, or industry organizations; PRAMP = Peace River Area Monitoring Program; See **Figure 2** for additional acronym definitions.

**TABLE 1** | Summary of when types of integration typically occur, how they are undertaken, their benefits, disadvantages, and potential outcomes.

Timing of integration	Type of integration	Study component combined	Formal and informal designations and mechanisms	Benefits	Disadvantages	Outcome
<i>a priori</i>	Full	Design, methods, sampling locations	Integrated design	Strongest inference; resource prioritization	Complex planning required	Actionable results; inform management decisions; testable hypotheses
	Design		Integrated data collection	Efficiencies of efforts	Necessarily short-term	Input into fully integrated design; testable hypotheses
<i>a posteriori</i>	Analysis	Data, results	Quantitative, or semi-quantitative techniques (scoring, ranking, and weighting), standardized effect sizes, meta-analyses	Ability to draw inferences at multiple spatio-temporal scales, generate new hypotheses	Sacrifice the greater statistical power of aligning sampling dates and methodologies	Testable hypotheses; input into integrated design
	Interpretation	Conclusions, hypotheses	Qualitative and semi-quantitative weight of evidence, synthesis reports, summary reports	Simple, common, easy; little to no oversight necessary; independent to semi-independent sources of information	Scope of questions limited; adopts previous limitations and assumptions of data and information	Testable hypotheses; input into integrated designs

**TABLE 2** | Attributes to consider in the integration of monitoring “early” (e.g., during design, *a priori*) or “later” (e.g., during interpretation, retrospectively, *a posteriori*) phases of the program and typical qualities (e.g., high, low) of applying integration during those study phases.

General attribute	<i>a priori</i>	<i>a posteriori</i>
Strength of inference	High	Low
Sensitivity to errors (e.g., poor site and indicator selection, etc.)	High	Low
Flexibility	Low	High
Administrative burden	High	Low
Common understanding of questions necessary?	Yes	No

Despite the initial aspiration for OSM to be a fully integrated program, much of the research remains isolated in individual research papers. A recent review of the regional ambient monitoring in the OSR concluded that more effort is needed to achieve the original objective of an integrated program (Hopke et al., 2016). While the initial efforts of integration were undermined by challenges with the timing of initial sampling and program roll-out, inertia from legacy monitoring programs, and the absence of a clear and coordinated strategic plan, we also suggest those early and continuing efforts are affected by the potentially unrecognized diversity of practices used to satisfy the delivery of an integrated program.

## MODELS OF INTEGRATION

Within any monitoring application, integration refers to the straightforward act of combination. While the specifics, preferences, and traditions of integration may differ by discipline (e.g., Linkov et al., 2009), we suggest four hierarchical and general models are typically used to integrate monitoring programs: integrated interpretation, integrated analysis, and partially and fully integrated designs (Table 1). Based on this framework, monitoring

studies can be differentiated by the timing (when in a study cycle) and approach (what: data, conclusions, or designs) to integrate. The approaches to integration can also be differentiated by their attributes, including flexibility, strength of inference, sensitivity to errors, and administrative burden (Table 2).

### *A Posteriori* Integration

Integration of monitoring can occur in multiple ways, but when the combination comprises existing data, conclusions or information, this is considered here as a *posteriori* integration. A *posteriori* integration can, however, be further subdivided into integrated interpretation and integrated analysis.

#### Integrated Interpretation

Of the four general types of integration, the most common, recognizable, and straightforward is the contextualization of conclusions or information when reporting the results of a study. Here we call this form *Integrated Interpretation*. Integrated interpretation involves the combination of information simultaneously considering conclusions from several independent, but related studies, each potentially addressing a specific hypothesis or set of questions. Typically, integrated interpretation occurs as the discussion of results in

scientific publications. Methods, such as Weight-of-Evidence have also been developed and use quantitative, qualitative, or semi-quantitative techniques including scoring, ranking, and weighting to combine information (Burton et al., 2002b; Chapman et al., 2002). Broad approaches such as synthesis reports or general review papers (e.g., Mupepele et al., 2015) are common examples.

The benefits of integrated interpretation include quickly summarizing information and that *a priori* planning and administrative oversight are not necessary. Consequently, integrated interpretation can be done retrospectively with ease and the approach is flexible. The more closely the information aligns in space, time, or methodological approach, the stronger the combined interpretation, but even loosely associated information can be combined to generate novel and testable hypotheses.

Integrated interpretation is common within the OSM, reflected in hundreds of published research papers, each including, at minimum, the contextualization of results with previous findings (e.g., Landis et al., 2019) and synthesis of results (Davidson et al., 2020). OSM researchers have also published some review papers (e.g., Harner et al., 2018).

### Integrated Analysis

Integration also commonly occurs during analysis. In *integrated analysis*, data from disparate projects may also be combined to address new questions or hypotheses, or to decrease uncertainty around an established question or set of questions to generate novel results. Meta-analyses are a potent example of this type of integration (Lipsev and Wilson, 2001).

Benefits of integrated analysis include more accurate information or results (Bustamante et al., 2016) and the ability to draw inferences at multiple spatiotemporal scales (Bricker and Ruggiero, 1998; Haeberli et al., 2007). Combining data, rather than conclusions often allows evaluation of hypotheses that the original studies were not designed to directly test. Integrated analysis can be done retrospectively with ease if information is available, accessible, and relevant to the study questions of the investigator. Publicly available data can facilitate integrated analyses. Similar to integrated interpretation, integrated analysis does not necessarily require *a priori* administrative oversight, systematic planning, or coordinated collection of data. Integrated interpretations are also nested within integrated analyses. The relative simplicity of integrated analysis and its associated adaptability contributes to its popularity.

Within OSM, integrated analyses are facilitated both by direct researcher collaboration, but also by providing data on a publicly-accessible databases. Integrated analyses in OSM have included combining individual studies undertaken in overlapping periods to enhance interpretation (e.g., Fisher and Burton 2018; Eccles et al., 2019; Kilgour et al., 2019). Integrated analyses have also been conducted using closely related data collected by few researchers examining similar questions (Wasiuta et al., 2019) and may include digested data summarized for study areas in a weight-of-evidence approach (Culp et al., 2018; Culp et al., 2020), or the combination of several raw datasets for a originally

collected for different purposes, such as discharge and water quality (Arciszewski et al., 2018), discharge, air temperature, and health of fishes (Kilgour et al., 2019; Arciszewski and McMaster, 2021), and land use and water quality (Schwalb et al., 2015; Alexander and Chambers, 2016). Studies have also conducted formal geospatial analyses and modeling (Eccles et al., 2019) and compared novel measurement techniques with conventional emissions reporting (Li et al., 2017). Evaluations of the environmental effects of oil sands operations have benefited from some efforts to complete integrated regional analyses and interpretations (Alexander and Chambers, 2016; Culp et al., 2020). These analyses improved understanding of environmental stressors from oil sands operations, such as deposition models (Kirk et al., 2014; Wasiuta et al., 2019). The use of data products, such as standardized effect sizes, meta-analyses comparing strength of results and other methodological parameters (Lipsev and Wilson, 2001) has not yet been fully explored within OSM.

### Challenges and Limitations of a *Posteriori* Integration

While common and straightforward, there can be significant challenges with a *posteriori* integration. More specifically, the challenges include the misalignment of data sets and limitations in the information and data available. Within OSM, there have been challenges with timely and synchronous availability of related data sets, resulting in significant delays in releasing results and undertaking integrated analyses by third parties. A *posteriori* types of integration prohibit logistical and economical efficiencies associated with integrated designs and sacrifice the greater statistical power of aligning sampling dates and methodologies. These deficiencies are not limited to OSM, and previous studies have noted limitations of data availability (Parr et al., 2002; Nilssen et al., 2015), inaccessibility (Liu et al., 2012; Cronmiller and Noble, 2018a), fragmentation (Liu et al., 2012), and incompatibility (Janousek et al., 2019). Incompatibility can occur for many reasons, including differences in data types, resolution, or scales (Paul et al., 2000; Teatini et al., 2005; Liu et al., 2012; Bustamante et al., 2016; Cronmiller and Noble, 2018b). Limitations of data quality and accuracy (Teatini et al., 2005; Liu et al., 2012), or lack of familiarity with datasets among third-party users can also affect interoperability.

Challenges with a *posteriori* interpretation and analyses from the OSR highlight vulnerabilities of using data and information from multiple sources. In the OSR, studies have included, either directly or indirectly, inaccurate details of industrial sites, such as the placement of emission sources like upgrading complexes and the location of facilities and their operational status in the analysis and interpretation (Kurek et al., 2013; Kirk et al., 2014; Alexander and Chambers, 2016; Liggio et al., 2016; Summers et al., 2016; Mundy et al., 2019; Tetreault et al., 2020). Unfamiliarity with other features beyond industrial sources in the study area, such as potentially confounding influences of outboard motors on the accumulation of polyaromatic compounds in the sediments of remote lakes with a fly-in fishing lodge (e.g., Kurek et al., 2013) has also occurred. While the consequences of drawing conclusions based on incorrect information may be innocuous, it can inflate the Type I and Type II error rates and over- or

under-report effect sizes which affect priorities in follow-up research.

Addressing the challenges of existing datasets and information requires effort. Resolving interoperability issues may require collapse, reformatting, stretching, compression, interpolation, extrapolation, or other transformation or summarization to reconcile datasets (Posthuma et al., 2016). Indices are popular choices across multiple fields for combining and decomposing data (Tarassenko et al., 2006), but are also an imperfect solution (Green and Chapman, 2011). These approaches to integration may also lead to decision fatigue when combining data, especially where assessment criteria are not available (Vethaak et al., 2017) and complex analyses and unique workflows emerge (Botvinik-Nezer et al., 2020). Some questions, such as change relative to an unknown baseline cannot be addressed with integrated interpretation and analysis. While interpretation and analysis are common and straightforward approaches, these tools may also be cumbersome when addressing interdisciplinary questions, such as cumulative effects.

While not unique, programs relying on *a posteriori* integration can be more susceptible to scope creep than *a priori* approaches. While expansion is not necessarily disadvantageous, there can be temptation to continually add measurements or pursue potentially unnecessary precision (Lindenmayer and Likens, 2010) which may strain or otherwise re-prioritize funding. Subdivision, branching, and extension of study designs can create challenges for consistency of datasets and for the eventual use of the data in decision-making (Sarkar et al., 2020). Intentional management of routine and novel studies are required in monitoring (Wintle et al., 2010) even in cases where the intent is to transition the program from *a posteriori* to *a priori* integration.

Although it may be tempting to derive strong inferences and conclusions from integrated interpretation or integrated analysis, the information generated in a retrospective and integrated analysis adopts the limitations and assumptions embedded in the original papers or datasets (Liu et al., 2012; Arciszewski and McMaster 2021). The results of *a posteriori* integration are necessarily limited to hypothesis generation (Lindenmayer and Likens 2010; Arciszewski et al., 2017a; Arciszewski et al., 2017b) since there may be challenges with multi-causality of issues (Liu et al., 2012) and over-simplification of complex (multi-covariate) analyses (Nilssen et al., 2015). Consequently, retrospective analyses are associated with weak inferences (Yoccoz et al., 2001; Mupepele et al., 2015).

## A Priori Integration

While complete overlap is not required for a functional program, some *a priori* co-ordination of data collection, potentially involving multiple sub-projects, each with different investigators with differing expertise is commonly desired. The occurrence of some coordination and planning across groups, questions, approaches, or tools is considered here as *a priori* integration. *A priori* integration includes either the complete or partial design of a program prior to the collection of any data (e.g., Petitjean et al., 2020). Additionally, fully integrated studies may be part of a partially integrated program.

## Partially Integrated Design (Integrated Data Collection)

A partially integrated design examines some fraction of the complete set of questions, indicators, or environments a program is designed to address. Partially integrated designs are common in the scientific literature and include programs such as the collection of data from biological indicators along with information for some environmental contaminants (Cruz-Martinez et al., 2015).

Partially integrated designs have several advantages over *a posteriori* integration. Partially integrated designs can provide stronger inferences than *a posteriori* approaches and can also be done opportunistically; in practice some measurements can be added in an integrated design until field crews vacate a study area. Integrated collection can enhance the suitability of data for broader and more complex applications and analyses, such as the combination of reach-scale data in streams to watershed-level questions (Wrona et al., 2000). Integrated data collection can also improve the ability to validate or compare multiple overlapping datasets (Teatini et al., 2005; Vethaak et al., 2017) through the *a priori* adoption of data quality objectives. Similarly, integrated collection may reduce overall costs and avoid unnecessary duplication of effort (Nilssen et al., 2015).

Integrated collection of data can facilitate integrated analysis and interpretation. For example, use of remote cameras and automated recording units are not species-specific and data are subject to the detection parameters of the devices (Zwart et al., 2014). Additionally, while an investigator may be interested in one particular species, they may collect data on many more (e.g., Zwart et al., 2014). Researchers are, however, not required to include these additional data in their analyses, but may often choose to do so. Another benefit of collecting secondary data is in adaptive monitoring constructs (Arciszewski et al., 2017b); partially integrated design ensures that some relevant data may be available to more deeply probe any emerging patterns or hypotheses (Arciszewski et al., 2017a).

Maturation of the OSM program has been accompanied with the desire for, and in some cases delivery of, a transition of integration through interpretation and analysis toward data collection. While not available in the public domain yet, the Terrestrial Biological Monitoring program within OSM has begun this process with the Before-After-Dose-Response (BADR) design. These efforts were supported by establishing technical advisory committees whose mandate includes standardizing data collection methodologies at the regional scale. These committees augmented early commitments for integrated monitoring of related studies in the initial design of the program (e.g., Environment Canada 2011a). Committees also supported efforts to optimize sampling designs for water quality (Cooke et al., 2018) and air monitoring (Soares et al., 2018; Wentworth and Zhang 2018). Among OSM studies, integrated data collection is relatively common in the aquatic theme (e.g., Culp et al., 2020). Measuring multiple indicators is also common in terrestrial programs (Mahon et al., 2019).

In contrast to within-themes, few examples of partially integrated designs are available which cross themes in OSM,

but forest health is a prime example (e.g., Davidson et al., 2020). Expanding this approach to other studies within OSM has long been a goal (Dowdeswell et al., 2010). Importantly, however, the Forest Health example predates JOSM and is managed by a single administrative entity. Linkages of the forest health program to other study areas of OSM may be present, but these require deliberate and dedicated effort.

### Fully Integrated Design

In contrast to a partially integrated design, a fully integrated design is considered the complete overlap of all study parts to address a single scientific objective (e.g., Cash et al., 2003). It accomplishes this not only by coordinating experimental designs and/or analytical units (as occurs in integrated collection), but also by asking more complex questions spanning multiple disciplines (Parr et al., 2002; Wolska et al., 2007; Vethaak et al., 2017) to enhance the understanding of causality (Chapman et al., 2010; Liu et al., 2012; Sterling et al., 2014; Cronmiller and Noble 2018b). Integrated designs underlie effective monitoring of entire systems (e.g., Wolska et al., 2007; Liu et al., 2012; Vethaak et al., 2017) and promote more efficient use of funds and can enhance credibility (Cronmiller and Noble, 2018a; Cronmiller and Noble, 2018b). Consequently, integrated designs can provide data for high-impact work.

There are some examples of integrated designs for individual studies in OSM, including the benthic macro-invertebrate program (Culp et al., 2020) and the Enhanced Monitoring Program designed to inform mine water return (Hicks and Scrimgeour, 2019). Studies within theme areas may also include measurements linking themes, but are currently rare. One example is the Representative Sub-basins Study (REPS) used to conduct necessary focused integrated monitoring, process studies, and modeling to assess and predict casual linkages of oil sands operations to observed effects (e.g., Cardoso et al., 2020). Studies within the same environmental medium tend to be internally consistent and more amenable to *a priori* integration.

While there are examples of isolated integrated designs in OSM, the program has taken many steps, with varying level of success, to work toward a fully integrated monitoring design. Efforts to develop a fully integrated design consist of four main actions: 1) identification of a framework for integration and efforts to impress the importance of it to program participants 2) enabling program participants to achieve integration through program design, 3) publicly accessible databases, and 4) public reporting to increase transparency and accountability (e.g., annual public reporting of the program and annual work plans, public data access). An important step was recognizing the importance of both western science and local and Indigenous knowledge, and that braiding of the two information systems will be foundational to achieving an integrated design.

Program participants were supported to achieve the overall integrated design by: 1) establishing technical advisory committees whose mandate included project integration within and among media 2) posting annual work plans on open internet portals, 3) producing synthesis reports within media (e.g., Culp et al., 2020), 4) releasing technical reports describing efforts to

optimize the spatial and temporal design of water quality (Cooke et al., 2018) and air sampling (e.g., Soares et al., 2018; Wentworth and Zhang 2018), and 5) hosting technical workshops (Swanson, 2019a; Swanson, 2019b). While these efforts have been beneficial for program design and the understanding of ambient impacts, they require unexpectedly large initial and on-going time investments by scientists and managers, further underscoring the potentially high (and often front-loaded) investments of resources to reap the benefits of integrated design as a program matures.

### Challenges and Limitations of a *Priori* Integration

While collection of multiple datasets at sites of interest using fully or partially integrated design facilitates integrated analysis and interpretation, there are also associated challenges, limitations, and considerations. Within each OSM theme, such as water and land, each study tends to address closely related questions with strong historical linkages to techniques dominant in the study of these media. For instance, ecotoxicological studies tend to dominate the water theme and landscape and wildlife ecology tend to dominate terrestrial studies. While some studies which do not follow this tendency have been published (e.g., Mundy et al., 2019), typically the practices used within a theme area can limit opportunities for integration. A unifying approach within a theme may increase the likelihood of a broader integrated design, but approaches across specific media or indicators may be subject to potentially conflicting experimental designs and scales of analysis associated with the traditions of various disciplines requiring deliberate effort to reconcile.

Within a theme, there can still be challenges to overcome to develop an integrated design. For example, within OSM chemical measurements, such as water (Wasiuta et al., 2019) or air quality (Makar et al., 2018) may be instantaneous, near-continuous, or continuous, whereas physical measurements, such as flow may be summarized daily (Arciszewski et al., 2018), and measurements of biota may reflect annual, seasonal, weekly, or daily conditions (McMaster et al., 2018). Some relevant information, such as precipitation may also be interpolated (Alexander et al., 2020). Further, measurements of water quality may be done at more locations than where biological monitoring occurs (Glozier et al., 2018; McMaster et al., 2018) and may be automated and transmitted remotely (Fang et al., 2014). In these scenarios, data collection might also include the use of instruments at remote locations where deployment and retrieval are comparatively less expensive and time-consuming than more frequent visits (Zwart et al., 2014).

While simultaneously establishing multiple monitoring projects at the same locations may economize logistical effort and cost, resulting issues of sampling design, particularly with respect to spatial scales, may negate these efficiencies. Integrating these datasets *post hoc* may be onerous and burdensome (Burton et al., 2015). For example, collecting and analyzing all data available made available through remote cameras or automated recording units also increases the risks of the Sharpshooter Fallacy (Arciszewski et al., 2017b). There may



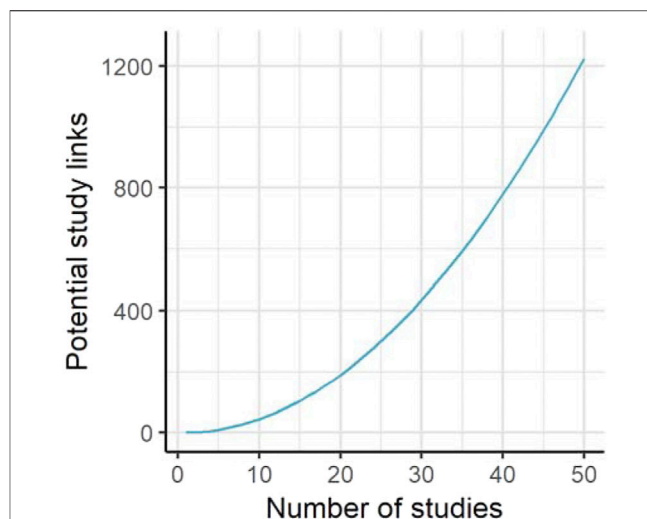
also be temptation to collect data which could or might be useful and strain funding envelopes. Furthermore, not all measurements are possible with field probes, such as total alkalinity of a water sample.

While there has been more recent effort expended by the governing committees within OSM to integrate the programs, historically the individual project leads were responsible for integrating their work. A key emerging challenge to developing an integrated program in the OSR is communication across the organizational structure. OSM functions under a semi-distributed model with geographically dispersed groups of individuals from the Provincial and Federal governments, local community members and representatives, private contractors, and non-governmental organizations. Difficulty of communicating a clear direction on what constitutes integrated monitoring and how it can be achieved, unclear roles and responsibilities, or a lack familiarity among participants on how to effectively operate within an integrated program, a lack of investment, travel restrictions, or all of the above can influence the development of an integrated program. The semi-distributed model across multiple monitoring partners or subcontractors may also not automatically or effectively address any potential competing financial self-interests for the limited funding pool. More deliberate effort may be required by all participants to facilitate the development of an integrated design.

Administratively, all types of integrated monitoring are best served by a strategic planning framework (Liu et al., 2012). While an integrated design requires deep foresight (Culp et al., 2000), it can also be onerous and difficult to initially plan, especially in a multi-stakeholder environment (Munkittrick et al., 2019). Failing to plan properly prior to the initiation of monitoring may lead to increased management and operational costs and loss of institutional or sectoral support (Reynolds et al., 2011). The administrative challenges are also compounded at large spatial scales (Culp et al., 2000) and iterative planning cycles are likely necessary to eventually build toward a rigorous integrated design.

Monitoring programs, irrespective of their approach for integration, are sensitive to changes in political whim and shifting economic priorities (Cronmiller and Noble 2018b). There may also be differences among participants regarding the goals, operation, tools, and approaches of the monitoring (Parr et al., 2002; Liu et al., 2012; Nilssen et al., 2015; Cronmiller and Noble 2018b). Highly focused *a priori* designs examining esoteric measurements may be more sensitive to these changing priorities than generic *a priori* programs or *a posteriori* programs. Highly focused programs can also create inertia. Through inertia associated with previous monitoring efforts in a region there may also be attempts to salvage existing designs and a reluctance to adopt alternative approaches (Arciszewski et al., 2017b; Jones et al., 2017). Consequently, where *a priori* designs are narrowly defined to determine the extent of change in a single indicator, they are at greater risk to these forces compared to programs based on integrated interpretation and analyses.

Flexibility of studies may also be reduced when integration occurs during design, but strength of inference is reinforced and



**FIGURE 4 |** The number of potential links between individual studies as the number of studies increases within an integrated program. Potential study links are calculated as  $Ns * (Ns - 1) / 2$  where  $Ns$  is the number of studies; If a program consists of 10 component studies, there are theoretically 45 possible linkages between the studies, each of which needs to be considered. If there are 15 studies, the number of potential linkages increases to 105.

expanded for known questions (Table 2). The capacity to successfully address large questions requiring integrated data may lead to compromises and difficulty addressing more nuanced questions with a single design (Lindenmayer and Likens, 2010). This is especially salient in programs like OSM where researchers and scientists conduct massive annual sampling campaigns (Figure 1). A likely outcome of a broad design is the loss of specificity, but a gain in generality (e.g., Hughes et al., 1990). Technical challenges of integration are also compounded when studies examine many indicators in a large area; the number of potential linkages among studies grows multiplicatively (Figure 4). Adequately addressing the exponential linkages within a single integrated design can be daunting when the means do not match the ends.

Other challenges could affect *a priori* integration. Although designed perfectly, an integrated study may also not be executed to the same degree due to logistical or weather-related issues, equipment loss, failure, or vandalism, and other reasons (including regional health orders) leading to unintended gaps in data and ultimately incorporating some of the challenges of integrated analyses. Additionally, if integration is improperly applied during program or study design, results can hinder or constrain future scientific treatment of the program objectives. For example, prematurely integrating studies in early stages may unnecessarily compromise optimal sampling locations or conditions for a particular parameter by accommodating collection of accessory samples (Parr et al., 2002) or a study design optimized for one parameter may be applied to another (Emmerton et al., 2018). This may lead to over-powering analyses of some parameters while under-powering others (Arciszewski et al., 2018), or limit potential future analyses of the data and utility of conclusions (Ferretti and Chiarucci, 2003).

While planning is necessary, over-planning is also possible. Imposing a rigid (integrated) design, which is simple to administer, risks entrenchment (Arciszewski et al., 2017b) and alienation and disengagement of potential participants (Lindenmayer and Likens, 2010). There may also be a desire by some participants to integrate all existing long-term datasets, sites, and projects (Parr et al., 2002) which may or may not serve the goals of the program.

## BENEFITS OF NOT INTEGRATING

In addition to the difficulties associated with integrated monitoring, which may discourage researchers from participating in such programs, there are also conceptual and operational advantages of isolating some or many studies. Where the criteria to clearly indicate degradation or meaningful changes are absent, interpreting the results from monitoring systems and making regulatory decisions can be challenging (Munkittrick et al., 2019). Having separate data collections and/or analyses examining similar program components or questions can be beneficial for making stronger inference *via* multiple lines of independent evidence. Independent and overlapping study components can reveal consistent information if the system is sufficiently understood, and this “monitoring of the monitoring” can be a wise addition to any program (Chapman et al., 2002; Arciszewski et al., 2017b). Such approaches can reveal weak understanding, and while uncommon early in the design stages of regional monitoring programs, can foster long-term credibility. However, this approach also suggests all monitoring may be immature and impossible to perfectly design to anticipate all possible data needs in the future. However, some tools and approaches are better suited for future needs than others (Lindenmayer et al., 2015).

## OVERCOMING CHALLENGES TO ACHIEVE INTEGRATED ENVIRONMENTAL MONITORING

Regional monitoring programs conducted across large spatial scales, with multiple participants, would likely benefit from integration. Developing and operating an integrated monitoring program requires careful consideration of several general aspects, including the need for clear objectives, a strategic plan, and commitment to follow the intended (strategic) course (e.g., Dowdeswell et al., 2010). These general guidelines, however, will also be accompanied by tactical, technical, social, and administrative aspects specific to the scientists, stakeholders, and governors of the particular program in question requiring resolution to develop a suitable program.

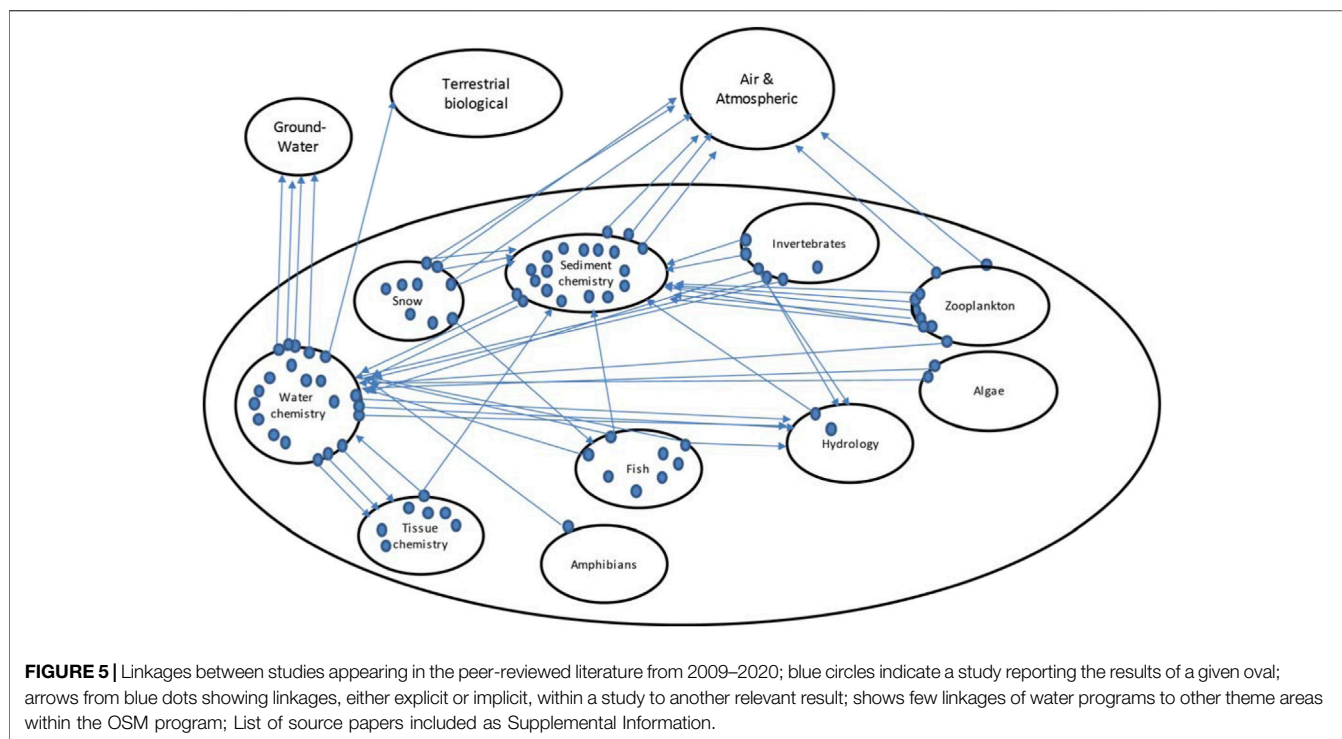
The first aspects requiring resolution is when and what to integrate. Integration of a design early in monitoring is best used where clear technical questions, a common understanding of objectives (Fancy et al., 2008), and rigorous statistical design (Ferretti and Chiarucci, 2003) are defined. If these attributes are

unknown, uncertain, questionable, or tenuous, a fully integrated design, though promoted by program managers, may not be possible or desirable and may be counter-productive (Vos et al., 2000). What type of integration to use also requires consideration. The various trade-offs involved in integrating monitoring (Table 2) affect the desired or most appropriate type of integration.

While when and what to integrate may influence the monitoring and management decisions, integration may also adapt to the evolving needs of the program or its technical sophistication. The type of integration desired or used within a given monitoring program may be affected by the desires of individual stakeholders and communities, changes in governance, or institutional inertia. Creating a hierarchy of monitoring and management decisions (Arciszewski et al., 2017b; Munkittrick and Arciszewski 2017) can be incorporated into an adaptive framework (Somers et al., 2018) to provide the needed flexibility, while retaining consistency and integration in key components and sites. Tiering of a program also provides rationale for some necessary changes in monitoring activities.

Updating the approaches to integration may naturally follow from *a posteriori* to *a priori* approaches as a program matures. As integration potentially moves from *a posteriori* forms to *a priori*, the needs will change and costs for administration, coordination, and data warehousing will typically increase. The focus of the questions (and the ability to adopt interdisciplinary questions) will also likely increase as can efficiency and ease of operation for individual participants and the program as a whole reflecting the natural progression towards routinized monitoring. While routinization of data collection and measurement techniques can be massively beneficial, its major disadvantage is that a highly focused and fully integrated design can also become entrenched, inflexible, and eventually irrelevant (Arciszewski et al., 2017b). As we have discussed already, there are strategies to mitigate these potential problems.

While an initial integrated design may emerge, forced periodic updates and additional measurements or approaches that can be integrated later in the study process, such as interpretation (Lindenmayer and Likens, 2010). Regular updates over a fixed period, such as five years may be a reasonable balance between a program which changes every year and a permanently static program (Cooke et al., 2018). The duration of the fixed update period may also be initially short when information is sparse and uncertain, but may alter as knowledge deepens and experience matures into wisdom. However, other administrative constraints, such as finding and hiring suitable candidates may also inform the appropriate planning cycle. Accounting for periodic updates in the planning and design of a program suggests that an optimal design may initially be based on integrated collection, which is also partially-integrated design. Similar to mathematical modeling (Timoshevskii et al., 2003), an algorithm to select optimal complexity of the monitoring program may be useful. Developing a model to determine the optimal complexity of an integrated monitoring program may be beneficial, as has been demonstrated in other aspects of monitoring (e.g., Wintle et al., 2010), but also requires its own effort and will likely be challenging in its own right.



Other factors will also affect the optimal integration for a given program, including the complexity, specificity, and number of the monitoring questions. Complex and specific questions may require complex and specific designs, but they may not necessarily be used to constrain the remainder of the program. Keeping some questions and studies separate from the larger design may improve the overall quality of the program, including OSM's practice of dividing core and focused studies. In addition, limiting integration to a manageable unit, such as "surface water" is likely advantageous, but partitioning collections further into watersheds, sub-watersheds, or another meaningful spatial unit may also be necessary (Vos et al., 2000; Vaughan et al., 2009). These mixed designs may be a powerful compromise between the technical and administrative demands. For example, some degree of integrated interpretation may always be involved in study systems where a single governing body does not control all monitoring and research activities and as knowledge of a particular topic becomes more nuanced and the questions become more focused (i.e., Kelly et al., 2009; Zhang et al., 2016; Chibwe et al., 2019; Ahad et al., 2021).

Many potential solutions are related to organization and administration. The administration of the program defines how decisions are made, the deliverables and reporting schedules, how (and to whom) funding is allocated, and how and if changes can be made. The challenges of administration can, however sometimes match or exceed the technical challenges of monitoring. OSM underwent four major governance changes in its first eight years and has become an administratively integrated program, but retains some pre-existing initiatives and relies on both Governments, external independent contractors, Universities, and communities to deliver monitoring results

(Figure 3). There are also requirements for the results to appear in the peer-reviewed literature. Given the distribution of partners among organization of the need to publish in the peer-reviewed literature, much of the results reported remain isolated to a given theme or to a single indicator suite, such as water chemistry (Figure 5). Recognizing and understanding the practical challenges limiting the integration of a program when it is a stated goal is the key to successfully enhancing the performance of the monitoring program to detect relevant change and provide robust answers to decision-makers. These attributes include the desired strength of inference, the sensitivity of the program to errors, the flexibility to adapt, an acceptable administrative burden, and how clearly understood the questions must be (Table 2).

Planning is necessary to develop an optimal monitoring program (Reynolds et al., 2011). Planning for integration can be facilitated by conceptual effect models (Bunn et al., 2010) to focus attention. Conceptual models appear in many guises, including in Environmental Impact Assessments describing the expected interactions between human industrial developments and natural environments to guide decisions. While describing linkages between chemical, physical, and biological processes and components (Born and Sonzogni, 1995), conceptual models of environmental effects are analogous to systems-based monitoring (Fancy et al., 2008). Conceptual stressor-pathway-effect models, while likely incomplete (Munkittrick et al., 2000), are also useful tools for organizing monitoring, studies within monitoring programs, and the linkages between them (Bunn et al., 2010). Conceptual models are broadly applicable as tools of integration (e.g., Liu et al., 2012), which have been recommended by OSM (Swanson,

2019a; Swanson, 2019b) and have been used to explore the environmental issues affecting the oil sands region in Alberta, Canada, including seepage from tailings ponds (Fennell and Arciszewski, 2019). Conceptual models can also form the basis of empirical models. Planning of integrated monitoring may also require detailed design documents, but can also include later “plans to plan” when regional programs are in their infancy and after pilot programs are complete (Environment Canada, 2011a). While they may be useful, CMs can also be unwieldy (Suter, 2016).

Among the many solutions to improve organization and administration, better communication and collaboration among various participants is likely a disproportionately beneficial addition (Gibbons et al., 2008). Soft-skills, such as mutual understanding, open communication, incentives, power sharing, and mutual trust as important factors in the collaboration of policy-makers and researchers (Briggs, 2006). Other researchers also suggest fostering relationships, active and regular communications, contact mapping, secondments and joint appointments, and annual science-policy conferences will improve programs involving researchers and policy-makers (e.g., Gibbons et al., 2008) and researcher-to-researcher interactions (Cooke and Hilton, 2015). There, however, also needs to be recognition that monitoring decisions, like many others, are often based on incomplete information and the discretion of multiple participants including the stakeholders and the principal investigators. Hindsight will invariably reveal incorrect decisions, but these should be viewed as unavoidable and opportunities to improve the future monitoring, not as abject failures (Lindenmayer et al., 2015).

## CONCLUSION

Integration is a natural feature of scientific practice and is very well understood conceptually when applied as interpretation within a single publication. However, as the spatial, temporal, and technical scope and demands of a monitoring program increases, so do the challenges of integration. In this paper, we explored the concept and practice of integration for environmental monitoring programs to facilitate understanding, including the benefits, limitations, challenges, and potential solutions.

The optimal form of integration depends on the goals of the program and its desired attributes, including the desired strength of inference. A fully integrated design may, or may not be desirable in many situations, but is the ideal choice when monitoring questions are clearly understood and technical approaches are widely accepted. In these cases, measurements of the environment will, by default, become part of a larger analytical framework and design providing strong inferences and answers to management questions.

Inconsistency in approaches and deliberate integration of multiple regional studies can be both beneficial in some respects, and harmful or limiting in others. Consequently, the choice of the optimal form of integration for a given program also depends on other factors. While the simplest to design and operate, integrated interpretation may not adequately address the questions a monitoring program is charged with answering. Where questions and approaches are not widely understood, practices of scientific disciplines are not aligned, or another source of uncertainty affects the monitoring, a partially integrated design may be most desirable and optimally complex to address questions. Given the discussion above, there is likely no single ideal way to integrate and decisions on how and when to do so must be considered carefully and with explicit purpose. The degree of integration may also change over time and designs need to anticipate and accommodate changing priorities, understanding, tools, and approaches. In summary, greater recognition of the diversity of practices and approaches possible to fulfill the general demands for an “integrated monitoring program” will benefit all involved.

## AUTHOR CONTRIBUTIONS

TA: Conceived work; wrote initial draft of manuscript; revised manuscript; DR: wrote initial draft; revised and edited subsequent drafts; KM: edited and revised draft manuscript; GS: edited and revised draft manuscript.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2021.666698/full#supplementary-material>

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**Conflict of Interest:** Authors TA and DR were employed by the Oil Sands Monitoring Program.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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