Assessing Wetland Reclamation in the Alberta Oil Sands Region

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Table of Contents

Table of Contents

Disclaimer ii

Table of Contents iii

3. LIST OF TABLES, FIGURES, AND ACRONYMS 6

3.1 List of Tables 6

3.2 List of Figures 6

3.3 List of Acronyms 7

4. EXECUTIVE SUMMARY 8

5. INTRODUCTION 10

6. METHODOLOGY 15

6.1. Phase 1. Interpreting and synthesizing existing data for compiling in a georeferenced relational database 16

6.1.1 Compile an inventory and relational database 16

6.1.1A Compile existing data 16

6.1.1B Create and Maintain a Geodatabase 16

6.1.1.2 Convene and host a Created Wetland Research and Information Group (CWRIG) 16

6.1.1.3 Analyse environmental and biological/successional time trends in compiled data 17

6.1.1.4 Identify classes of young wetlands/age breakpoints 17

6.1.1.5 Identify age classes of young wetlands and age-specific breakpoints in key variables 17

6.1.1.5 Create a provisional list of candidate measures of success from CWRIG based on causal network analysis 18

6.1.1.6A Create an inventory of recently-appearing opportunistic and 'at risk' created wetlands (see 6.3.4B below) 18

6.2.1.7 Develop a sampling plan and standardized sampling methodology to evaluate and validate wetland performance measures 19

6.2 Phase 2. Field sampling young and maturing AOS wetlands to document age-specific ranges of natural variation in environmental conditions and biological responses (years 2-4) 19

6.2.2.1 Pilot Studies: 19

6.2.2.2 Field investigations of environmental stress-biological response relationships among age-classes of young wetlands 19

6.2.2.3 Wetland Assessment 20

6.3. Phase 3. Applying the Reclamation Assessment Approach to define measures of success for early successional stages of wetlands 21
6.3A.3.1 Identifying Principal Environmental Indices of Wetland Condition 21
6.3A.3.2 Defining thresholds that distinguish Reference and Degraded conditions along Reference- Degraded Continua 22
6.3A.3.3 Defining age class-specific thresholds that characterize reference-degraded conditions in constructed wetlands 22
6.3B.3.4 Assessing time trends in ecological condition and biological change 22
6.3B.3.5 Review Effectiveness of the RAA approach 23
6.3B.3.6. Review Program Findings/Limitations; Objectives for next cycle 23
7. PROJECT RESULTS 24
7.1 Phase 1 – Compile, & interpret existing data 24
7.1.1A Compiling, existing data 24
7.1.1.3 Identify common early successional time trends 24
7.1.1.4 Identify classes of young wetlands/age breakpoints 24
7.1.1.6A Compile inventory of candidate study wetlands 25
7.1.1B BWRAP Geodatabase development and implementation 26
7.1.1.2 Created Wetland Research & Information Group (CWRIG) Community of Practice 26
7.1.1.5 Create a provisional list of candidate measures of success from CWRIG based on causal network analysis 27
7.1.1.6A Create an inventory of recently-appearing opportunistic and 'at risk' created wetlands 27
7. 2. Phase 2 - Field sampling young and maturing AOS wetlands to document age-specific ranges of natural variation in environmental conditions and biological responses (years 2-4) 27
7.2.1.7 Develop a Wetland Sampling Plan and Standard Methods 27
7.2.2.1 Pilot Studies 27
7.2.2.2 Field investigations of environmental stress-biological response relationships among age-classes of young wetlands 29
7.2.2.3 Wetland Assessment 31
7.3. Phase 3 - Compiling/analysing data; State-and-Transition model to synthesize and interpret wetland development & persistence 33
7.3A.3.1 Identifying Principal Environmental Indices of Wetland Condition 34
7.3A.3.2 Defining thresholds that distinguish Reference and Degraded conditions along Reference- Degraded Continua 34

7.3A.3.3 Defining age class-specific thresholds that characterize reference-degraded conditions in constructed wetlands 34
7.3B.3.4 Assessing time trends in ecological condition and biological change 35
7.3B.3.5 Effectiveness of the RAA approach 35
7.3B.3.6 Program Findings/Limitations 36
8. CONCLUSIONS/KEY LEARNINGS 36
9. OUTCOMES AND IMPACTS 37
9.1 Project outcomes relative to Performance Metrics identified in the original application 37
9.1.1. Investment in 4 Core strategic Technology areas 37
9.1.2 Field pilots/demonstrations 37
9.1.3 Collaborators 38
9.1.4 Publications 39
9.1.5 Students Trained (M.Sc., Ph.D., Postdoc) & Jobs Created 40
9.1.6 Changes or updates to performance metrics and driving forces 40
10. OUTCOMES AND BENEFITS 40
11 RECOMMENDATIONS AND NEXT STEPS; Objectives for next cycle 41
11.1 Next steps and recommendations for further advancement of knowledge generated 42
12. KNOWLEDGE USE AND DISSEMINATION 46
12.1 Knowledge Use: 46
12.2 Knowledge Dissemination 47
13. LITERATURE CITED 48
LIST OF APPENDICES 53
Appendix 1 - Gantt Chart of BWRAP Activities January 2026 53
Appendix 2 - BWRAP Recaps of Summer Field Seasons 2021-2023 - Programs & Video Links 53
Appendix 3 - BWRAP-STSM-Course-Links 53
Appendix 4 - list of communication exercises (March 2026) 53
Appendix 5 – provisional list of publications in preparation (January 2026) 53

3. LIST OF TABLES, FIGURES, AND ACRONYMS

3.1 List of Tables

Table 1. Project Information (Non-confidential) 12
Table 2. Applicant Information (Non-confidential) 12
Table 3. Contributing Partners 13
Table 4. Partners and Supporters (Other than Funding Partners) 13

3.2 List of Figures

Figure. 1. Summary of the 3 BWRAP methodology phases & proposed objectives (activities) by year & season 15
Figure 2. Frequency distribution of wetlands sampled with reference to age in year of sampling ... 29
Figure 3. Frequency distribution of wetlands with reference to surface area 30
Figure 4. Frequency distribution of wetlands with reference to permanence class 31
Figure 5. Frequency distribution of wetlands with reference to specific conductance of surface water 31

3.3 List of Acronyms

ABMI	Alberta Biodiversity Monitoring Institute
AOS	Athabasca Oil Sands
BERA	Boreal Ecosystem Recovery and Assessment
BWRAP	Boreal Wetland Reclamation and Assessment Program
CABIN	Canadian Aquatic Biomonitoring Network
CFRAW	Carbon Dynamics, Food Web Structure & Reclamation Strategies in Athabasca Oil Sands Wetlands
COSIA	Canada's Oil Sands Innovation Alliance
CWRIG	Created Wetland Research Information Group
GIS	Geographic Information System
NSERC	Natural Sciences and Engineering Research Council of Canada
OSM	Oil Sand Monitoring Program
RAA	Reclamation Assessment Approach
RCA	Reference Condition Approach
RGB	Red-Green-Blue
ROVER	Remotely Operated Vessel for Environmental Research
SAV	Submergent Aquatic Vegetation
STSM	State-and-Transition Simulation Model
TITAN	Threshold Indicator Taxa ANalysis
UAV	Unmanned Aerial Vehicle

4. EXECUTIVE SUMMARY

Alberta's oil sands region (AOS) is dominated by a mosaic of uplands and wetlands that reflect differences in hydrology, topography and historical and ongoing successional processes operating since the last glaciation. To date, open pit mining has disturbed over 960 km^2 of boreal landscape. As such, postmining reclamation efforts include designing landforms that promote wetland formation. The two first full-scale wetland watersheds, built in the oil sands region (OSR) in 2010, became species rich and productive within their first few years of creation. Furthermore, landscapes reclaimed to produce upland ecosites have also proven to be sites of opportunistic wetland development. Seeps and naturally forming wetlands cover 10-17% of reclaimed areas. These promising findings lead to questions of what local landscape features determine where these newly-forming wetlands occur, to what extent they match prescriptions and predictions, and whether they will persist as areas of biodiversity as succession proceeds. There is currently relatively little guidance against which to evaluate the success of these efforts and to guide adaptive management. Few integrated criteria exist to assess overall effectiveness of wetland reclamation, despite extensive surveys and biological integrity indices derived from many previous studies.

The Boreal Wetland Reclamation Assessment Program (BWRAP) undertaken here formalizes a monitoring approach, methodology and a paradigm (the Reclamation Assessment Approach - RAA) for assessing the 'success' of wetlands forming in a reclaimed AOS landscape relative to natural reference wetlands of equivalent age. Data from early time-points, essential as a frame of reference for the RAA, were compiled, integrated, and assessed to document the range of natural variation in indicator variables for wetlands forming or created in mine-reclaimed landscapes, and compared to similarly aged wetlands forming in unmined reference landscapes. Such information will help to provide guidelines that will determine whether intervention may be required to maximize the likelihood of a wetland becoming self-sustaining and of ultimately exhibiting the ecological properties for which it was designed.

Over three years, a chronosequence of wetlands of varying age, size, permanence, and water quality was sampled to document environmental stress-biological response relationships and assess how relationships change as wetlands mature. Hydrology, water chemistry, riparian features (stresses) and biota (responses; aquatic invertebrates & vegetation) were assessed in 119 wetlands aged 2-40 years in mine lease reclaimed landscapes and adjacent reference landscapes. The range of natural variation (gradient) of each of three environmental stressor gradients was delineated to provide a reference against which changes in community composition and successional patterns of wetland vegetation, aquatic invertebrates, and avifauna could be documented. Composite measures representing indices of stress included "wetland permanence" (inferred from tracking wetland size (area & depth) within and among years, and water balance (evaporation/transpiration vs. surface/groundwater input ratios inferred from stable isotope ratios)), "water quality" (concentrations and relative composition of cations, anions, nutrients and organic compounds), and "landscape disturbance" (integrating drone-surveyed setting, local topography, vegetation, surrounding physical disturbances). Records were uploaded to a custom-designed searchable geospatial database created for the program.

The environmental features of wetlands in reclaimed vs. reference landscapes of equivalent age overlapped considerably. However, wetlands in reclaimed landscapes spanned a broader range of

stress than those located in reference landscapes. Specifically, the youngest wetlands in reclaimed landscapes exhibited greater stress scores (higher specific conductance, shorter hydroperiod, more extensive areal landscape disturbance) than their reference counterparts of equivalent age. Stress index scores of older wetlands in each landscape were more similar, either because conditions converge as wetlands age (e.g., through increased resilience against stress) or because only wetlands with particular attributes (large watersheds and/or surface areas) persist through time. Aquatic invertebrate and vegetation communities were both constrained by wetland permanence and water quality thresholds (insufficient data were collected to support analyses of the avifauna communities within and surrounding study wetlands). Distinct changes in community composition were observed along gradients of water quality (summarized by specific conductance) and wetland permanence (number of days per year during which surface water was present). In particular, specific conductance thresholds (provisionally identified at approximately 3,000 and 9,000 µS/cm) and wetland permanence thresholds (characterizing ephemeral/semipermanent and semipermanent/permanent wetland class boundaries, and characterized by wetland area and maximum depth) distinguished both aquatic invertebrate and vegetation assemblages. Notably, wetland age alone was a poor predictor of community composition. Instead, characteristics of the placement material and topsoil used to create reclamation landscapes tended to control wetland permanence and water quality attributes that in turn appear to determine the species present. However, wetlands forming on reclaimed landscapes tended to be more ephemeral and more saline than wetlands observed in reference landscapes.

The environmental and biological data collected were used to parameterize a State-and-Transition Simulation Model used to forecast the persistence and prevalence of wetlands and their biota from the present to the year 2100. Preliminary simulations performed to predict the frequency distribution of plant diversity and water quality in wetlands in the reclaimed landscape under the most likely successional trajectories were contrasted with counterfactual simulations representing the successional trajectories expected in reference landscapes. Simulations indicated that the cumulative area of wetlands supporting high vegetative diversity in reclaimed landscapes was much less than the anticipated cumulative area of high diversity wetlands that would occur in reference landscapes, largely due to the differences in wetland water quality and permanence. The precision of simulation forecasts could be increased by evaluating a spatially explicit version of the State-and-Transition model that reflected the topography of the mining companies' closure plans. However, predictions were also limited because the record of landscape reclamation is too short (< 50 years) for vegetation communities to reach 'maturity'. Nevertheless, the Reclamation Assessment Approach provides a credible study design by which to assess the early stages of succession in reclaimed landscapes relative to the patterns expected in reference landscapes.

Future investigations could incorporate trends in time with respect to wetland formation and persistence in landscapes with longer records of recovery following disturbance, such as wildfire or clearcut logging. Furthermore, recognition of the hydrological and biological connectivity among wetlands within hydrological response units (HRUs) suggests that landscape reclamation 'success' could be informatively modeled by considering the sustainability of the collective of hydrologically associated wetlands that constitute the mosaic of wetland habitats within an area of interest.

5. INTRODUCTION

The Project Type is Knowledge Generation.

Up to 60% of the natural landscape of northeastern Alberta and 64% of the oil sands surface mineable area is dominated by a mosaic of wetlands, including peatlands (Vitt et al. 1996; Rooney et al. 2012, respectively), reflecting hydrology, topography and successional processes operating since the last glaciation (Vitt et al 2011). At the same time, open pit bitumen mining is a dominant economic and ecological focus in Canada. Over 960 km^2 of the 4,800 km^2 surface mineable area in Alberta has been disturbed, leading to extraction and production of 1.65 million barrels/d of crude bitumen in 2023. Reclaiming these landscapes following closure of a mine has required the development of new knowledge and operational best practices for reconstructing forests and wetlands to achieve equivalent land capability. The two first full-scale wetland watersheds built in the oil sands region (OSR) both became species rich and productive within their first few years of creation (Vitt et al. 2016; Borkenhagen 2016; Popovic et al. 2022), moreso than their smaller constructed counterparts (Roy et al. 2016). Furthermore, landscapes reclaimed to produce upland ecosites have also proven to be conducive for opportunistic wetland development. Seeps and naturally forming wetlands cover 10-17% of reclaimed areas (Little-Devito et al. 2017); Hawkes 2017; Hawkes et al. 2025).

These promising findings lead to questions of what local landscape features determine where these newly-forming wetlands occur, to what extent they match prescriptions and predictions (Devito et al. 2012, Price et al. 2010), and whether they will persist as areas of biodiversity as succession proceeds. Such elements could be lines of evidence used by industry to support their statements of compliance with approved Life of Mine Closure plans. We operationally define success as being achieved when a new wetland is functionally equivalent to natural wetlands of comparable age; i.e. habitat is reclaimed and biodiversity is restored so that wetland communities become self-sustaining. However, there is currently relatively little guidance against which to evaluate the success of these efforts and to guide adaptive management.

Knowledge Gaps: Reclamation following mine closure requires new knowledge and techniques that can be used to develop operational best practices to ecologically reclaim (Gerwing et al. 2022) landscapes to achieve equivalent land capability. Documenting success or failure in the reclamation of wetland landscapes requires new scientific and technical expertise, which has been enabled by the activities of the Boreal Wetland Reclamation Assessment Program (BWRAP). Few integrated criteria exist to assess overall effectiveness of wetland reclamation, despite extensive surveys and biological integrity indices derived from many previous studies (vegetation: Rooney and Bayley 2011a. 2011b, Roy et al. 2016; aquatic invertebrates: Whelly 1998, Leonhardt 2003; amphibians: Schock et al. 2015; avifauna: Dagenais 2008, Nakhaie 2013, Beck 2015), and a framework to assess toxicological risks to biota (Arciszewski, et al. 2017). Proposed and current wetland impact assessment initiatives (Ciborowski et al. 2012, C2HM Hill 2013, ABMI 2015; OSM (Dube et al. 2018)) are designed to detect risks to mature systems (i.e. departure from the Reference Condition with respect to the range of natural variation observed in minimally disturbed ecosystems). Thus, these frameworks are not entirely applicable to young wetlands that have been constructed or have formed opportunistically in recently reclaimed mine lease areas.

The oil sands industry has been criticized for the relatively small area of leased lands that has been certified as ‘reclaimed’ (Grant et al. 2008, Rooney et al. 2012). This reflects both the relatively short

history of Athabasca oil sands (AOS) reclamation activities and a lack of criteria by which to assess aquatic and peatland systems (Gouin 2017; but see Poscente and Charette 2012; Nwaishi et al. 2015). Ciborowski et al. (2013) proposed a Reference-Degraded Continuum (RDC) approach to assess reclaimed AOS wetland landscapes - an extension of the Reference Condition Approach (RCA; Bailey et al. 2004; Hawkins 2010). The RCA classifies study sites relative to the range of natural variation observed at many reference locations, variously defined to be unaffected, minimally-influenced, or best achievable for a given biogeographic and ecological setting (Stoddard et al. 2006). Because reference locations in the RCA focus on 'climax', stable state or a mosaic of successional states, recovering or newly reclaimed areas require a different frame of reference. The Reclamation Assessment Approach (RAA; Ciborowski et al. 2013) constrains the RCA by considering the test sites relative to natural variation observed among reference sites of equivalent (young) age.

The project undertaken here formalizes a monitoring approach, methodology and a paradigm (the RAA) for assessing success of wetlands forming in a reclaimed AOS landscape or during early development relative to natural reference wetlands of equivalent age. Data from early time-points, essential as a frame of reference for the RAA, were compiled, integrated and assessed to document the range of natural variation in indicator variables for natural and constructed wetlands. Such information will ultimately help provide guidelines that will determine whether intervention (adaptive management) may be required to maximize the likelihood of a wetland becoming self-sustaining and ultimately of exhibiting the ecological properties for which it was designed. Such an approach requires collection and interpretation of diverse types of data (e.g., biological, physicochemical, ecohydrological) from a large suite of study locations over several years. However, increasingly affordable and sophisticated technology permitted us to conduct both in situ measurement and remote sensing at enough locations to make this unique program both feasible and powerful. Furthermore, a growing commitment to collaboration across institutions and stakeholders in the AOS region had made this program, the opportunity to acquire data across sampling domains, and to derive consensus on assessment approaches, especially timely.

Knowledge Description: The BWRAP lab developed the frame of reference needed to assess wetland reclamation success following open pit bitumen mining in the AOS using a new Reclamation Assessment Approach (Ciborowski 2021) and novel multivariate statistics to assess wetland dynamics and quantify environmental stresses that affect biota in 119 wetlands of varying ages, sizes, and origins. Data from surveys of vegetation, macroinvertebrate, and avifauna communities were summarized to create calibrated wetland bioindicators. Three composite wetland attributes of environmental stress – **water quality** (from lab analysis of water samples and manual and continuous in-situ measurements of specific conductance and dissolved oxygen); **permanence** (from continuous measurements of water depth; precipitation and evaporation records; stable isotopes of deuterium and oxygen; radon; wetland area and catchment size); and **riparian disturbance** (from drone-flown and satellite-derived imagery, including various human footprint datasets) are being calibrated to identify age-specific environmental thresholds (triggers) at which biota (bioindicator scores) are altered by each class of stress in young wetlands. The calibrated data were used to parameterize a recently-developed quantitative state-and-transition simulation model of wetland land units to evaluate effectiveness of wetland reclamation guidance, to identify best management practices, and to inform adaptive management of reclamation and closure planning processes. The overall objective of BWRAP is to formulate and validate a reclamation assessment approach for oil sands reclaimed wetlands.

Table 1. Project Information (Non-Confidential):

Alberta Innovates Project Number:	**212201350**
Milestone Report Number:	4
Reporting Period:	March 28, 2022 to December 31, 2025
Original Submission Date:	February 24 2026
Project Title:	Assessing Wetland Reclamation in the Alberta Oil Sands Region
Project Dates:	Project Start: March 28, 2022
	Project End: December 31, 2025
Project TRL:	Project Start: N/A
	Project End: N/A
Total Project Cost:	$4,242,881
Alberta Innovates Funding:	$500,000
AI Project Lead:	Dallas Johnson
Program/Call:	Land and Biodiversity – Continuous Intake

Table 2. Applicant Information (Non-Confidential):

Applicant (Organization):	**University of Calgary**
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Applicant Representative Name:	Peter F. Dunfield
Title:	Professor
Phone Number:	403-220-2469
Email:	pfdunfie@ucalgary.ca

FUNDING AND PARTNERS

Table 3. CONTRIBUTING PARTNERS:

Organization Name	Cash Funding	In-Kind Contribution	Commitment
COSIA	$1,250,000	$123,820	Completed
NSERC	$1,250,000		Completed
University of Calgary	$349,960		Complete
CFI	$673,277	$70,601	Completed
MITACS	$28,500		No Application

Table 4. PARTNERS AND SUPPORTERS (OTHER THAN CONTRIBUTING PARTNERS):

Organization Name	Nature of Support
Apex Resources Ltd	Collaborators Colin Daniel, Leonardo Frid and Diego Bilski are contributing expertise and support in State and Transition model development and operation.
Environment & Climate Change Canada	Collaborator John Headley (National Hydrology Research Laboratory (Saskatoon) and graduate student Ian Vander Meulen are analysing concentrations of acid-extractable organic compounds in water samples collected from study wetlands.
Alberta Environment & Parks	Collaborator Jean Birks is facilitating analysis of stable isotopes and co-supervising students engaged in wetland hydrology theses.
LGL Wildlife Ecology	Collaborator Virgil Hawkes is providing background expertise and mapping information on the distribution of wetlands developing and constructed in reclamation areas.
Athabasca University	Collaborator Scott Ketcheson is co-supervising a postdoctoral scholar and collaborating on hydrology, especially groundwater-surface water interactions.
Mount Royal University	Collaborator Felix Nwaishi is co-supervising students engaged in wetland water quality theses and harmonizing water quality analytic approaches.
Southern Illinois University	Dale Vitt has collaborated on wetlands assessments, especially relating to vegetation community ecology.
Thompson River University	Collaborators Jabed Tomal and Jan Ciborowski are continuing to develop statistical analytical approaches to detecting thresholds in multivariate data.

University of Alberta	Collaborator Kevin Devito has shared expert knowledge and remote sensing data for wetland delineations and inventories; Erin Bayne has collaborated on avifauna community assessment (acoustic recording).
University of Calgary	Numerous faculty are collaborating on various elements of the research program as follows: Jan Ciborowski (wetland ecology and early successional development; former PI), Douglas Muench (similarities in microbial processes between opportunistic and constructed wetlands), Faramarz Samavati (Computer/spatial modeling of wetland persistence), Greg McDermid (Coordinating database design & remote sensing), Eve Robinson (zooplankton of reclaimed and reference wetlands).
Western University (formerly University of Lethbridge)	Collaborator Laura Chasmer has assisted in coordinating site locations suitable for off-lease wetland sampling through remote sensing; co-supervising one student.
University of Waterloo	Rebecca Rooney is collaborating on State & Transition modeling and biological indicator development.
University of Windsor	Christopher Weisener is collaborating on studies of microbial transcriptomics to assess sediment biogeochemistry; co-supervising one student.

6. METHODOLOGY

The proposed BWRAP workplan consisted of 20 tasks grouped into three phases (summarized in Figure 1 and detailed below). Task numbering aligns with the narrative structure of the Methodology section herein and the following Results and Learnings section.

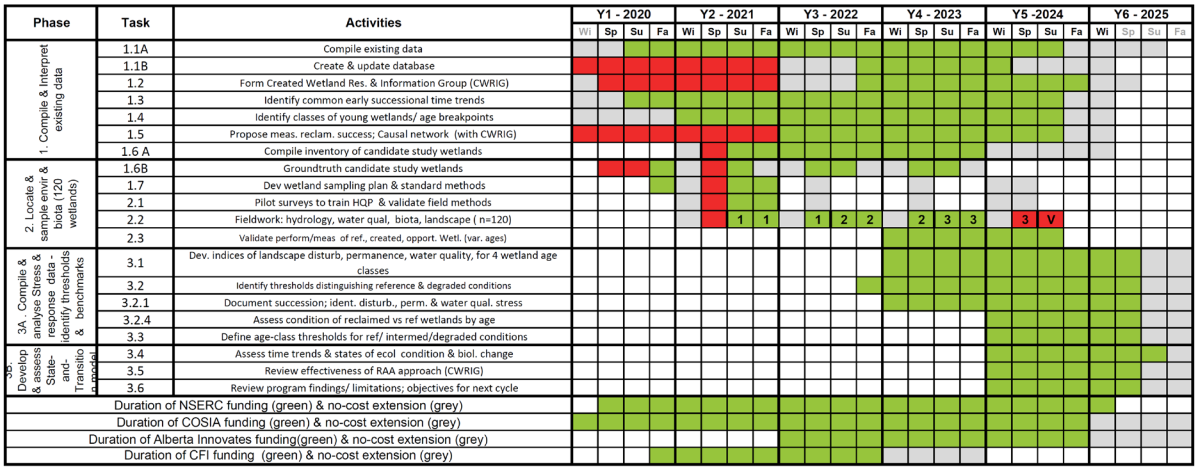


Figure 1. Top: Summary of the three phases of BWRAP and their component objectives (activities) by year and season as originally proposed. Green squares: seasons during which a task activity was undertaken or proposed; red squares: proposed activity was prohibited/delayed by COVID or other restrictions; grey squares: task preparations that were begun but will be interpreted/completed post-report. Numerals (1,2,3; Task 2.2) represent timing of field seasons 1,2 and 3, respectively; V= 'validation' season. Bottom: Summary of the period of funding by sources supporting BWRAP activities of the IRC (green squares) and no-cost extensions (grey squares).

The BWRAP research plan consisted of three overlapping phases to be executed over a 4-year span:

Phase 1. Custom-designing/adapting a searchable geodatabase to organize and house existing data compiled by other programs over the past 20 years (program years 1-2);
Phase 2. Field sampling within young and maturing AOS wetlands to document age-specific ranges of natural variation in environmental conditions and biological responses (program years 2-4), and
Phase 3. Using data acquired during phases 1 and 2 as a proof-of-concept application of the Reclamation Assessment Approach to define measures of reclamation success for early successional stages of wetlands forming or constructed in the AOS postmining landscape and in comparable unmined landscapes (years 2-5).

We endeavoured to describe the ecosystem structure and function of 120 wetlands to document the range of natural variation and understand the key features and successional process in naturally-forming ("opportunistic") wetlands in boreal post-disturbance landscapes. Wetlands ranging in age between 2 and over 45 years post-formation were assessed. Sixty of the wetlands were situated in oil sands lease area landscapes reclaimed following open pit mining activity. Sixty

other wetlands were to be located in areas that had not been reclaimed but in which other disturbances resulted in altered hydrology and the formation of wetlands of an equivalent range of ages (such as excavation of borrow pits or alteration of drainage following road construction or beaver activity). In all, 119 wetlands were included in the final dataset.

6.1. Phase 1. Interpreting and synthesizing existing data for compiling in a georeferenced relational database

6.1.1 Compile an inventory and relational database

6.1.1A Compile existing data

Archival, georeferenced environmental and biological wetland data were extracted from publications and theses, converted to standardized format, and made available to undergraduate and graduate
students who interpreted the information to test hypotheses developed for their research theses (described in more detail in Tasks 6.1.1.3 and 6.1.1.4, below).

6.1.1B Create and Maintain a Geodatabase

The BWRAP Wetland geodatabase was initiated in 2022 and implemented beginning in 2023 by PDF Programmer/developer Qing Ye (Richard) Zeng and Remote Sensing Technician Kwok-Kei (Maverick) Fong in collaboration with the Boreal Ecosystem Recovery and Assessment NSERC Alliance-funded project (BERA; www.bera-project.org). Dr. Zeng oversaw and managed the logistics and mechanics of dataset compilation and maintenance. He developed procedures to compile, standardize, and integrate the extensive but diffuse existing wetland information into a relational geodatabase of wetland history and features (containing tabular and spatial data) using a consistent terminology and populated with existing environmental and biological data and supplemented with the data gathered over the course of the BWRAP program (Zeng 2024a). BWRAP personnel worked collaboratively with BERA colleagues to draft a unified data management plan that maximized opportunities for data interoperability. Data collected over the course of the program were organized into standardized formats and uploaded to an interim ‘working data’ folder. Thereafter, data were Quality Checked, and standardized to ensure (as far as possible) compatibility with other regional programs' databases. Data organization and uploading guidelines were developed by the BWRAP database programmer (Zeng, 2025), who was ultimately responsible for uploading information to the actual database.

6.1.1.2 Convene and host a Created Wetland Research and Information Group (CWRIG)

Understanding and integrating diverse measures of stressors and their interactions with biota over the geographic scale of the AOS requires groups of individuals who can collectively identify patterns and derive conceptual frameworks (Cheruvelil et al. 2014; Cheruvelil and Soranno 2018). The proposed, informal CWRIG was anticipated to facilitate dialogue among researchers, collaborators and stakeholders (government, Indigenous communities, industry, and citizenry; detailed in the Knowledge Mobilization section). The initiative was originally planned to be an open, self-assembled forum for discussion and synthesis. However, unanticipated events occurring over the course of the program (notably the COVID-19 pandemic’s effect on social gatherings beginning in 2020) pre-empted efforts to host introductory meetings for several years. Subsequent efforts

were delayed by concerns that public discussion of oilsands-related reclamation strategies might ultimately compromise the protection of information deemed to be confidential intellectual property. Consequently, an alternate model was developed.

6.1.1.3 Analyse environmental and biological/successional time trends in compiled data

6.1.1.4 Identify classes of young wetlands/age breakpoints

Beginning in 2020, senior undergraduate students compiled and analysed archival data to evaluate the environmental and biological changes associated with aging in constructed and opportunist wetlands in mine lease areas. The data had been collected during previous collaborative research programs studying wetlands constructed in oilsands lease areas, especially the Carbon Dynamics, Food Web Structure and Reclamation Strategies in Athabasca Oil Sands Wetlands (CFRAW) program (https://web2.uwindsor.ca/cfraw/index.htm) (Kovalenko et al. 2013). Individuals analysed colonization, spatial and temporal trends of aquatic invertebrates, wet meadow vegetation and submergent aquatic vegetation in and around young wetlands. Topics included assessments of the effects of wetland age and water quality (chemistry) on aquatic invertebrate community composition (Moore 2022), submergent wetland vegetation (Mebesius 2022), and emergent and wet meadow vegetation (Gillis 2022). Multivariate analyses were performed to assess the relative importance of wetland age since formation/creation and environmental stressors on the species richness, sequence and time frame of appearance/disappearance, and community composition of the biota. Data extracted from the inventory were used to build chronosequences (wetlands differing in ages and possibly successional states), and document time trends in key environmental variables and associated functional and biological characteristics of constructed and opportunistically-forming wetlands.

In each case, an investigator quantified the range of variation in the biological attributes at specific time points across the landscape's developmental history, and related those to processes and characteristics observed in mature natural wetlands. Key analyses included ordinating biological variables vs. wetland age and/or major environmental stressors (wetland permanence; specific conductance) and testing for the presence of thresholds in the range of variation using Piecewise Quantile Regression (Tomal and Ciborowski 2020). In addition, investigators tested for evidence of abrupt changes in community composition along age/stress gradients using Threshold Indicator Taxa Analysis (Titan; Baker and King 2010; King and Baker 2010).

Subsequently, Mark Patzer (M.Sc. 2024) compiled data from 'instrumented watershed' records of temperature, wind, precipitation and relative humidity to provide estimates of local water balance for our study wetlands and document how these features change as reclaimed landscapes undergo early succession.

6.1.1.5 Identify age classes of young wetlands and age-specific breakpoints in key variables

Progressive changes in hydrogeomorphology and water quality of developing wetlands should result in predictable accrual of biota and biodiversity, varying by wetland size, type, and hydrological regional unit. The development of 'measures of success' (diagnostic indicator variables) requires operational definitions of the most important environmental predictor variables (age since formation/creation, measures of stress, other covariates) and dependent response variables (performance measures amenable to calibration as biological indicators of reclamation

effectiveness). Thresholds in the predictor variables and the associated breakpoints observed in the response variables can be used as criteria by which to characterize wetlands (age classes, biological condition classes; Tomal and Ciborowski 2020). We used piecewise quantile regression, Titan (Baker and King 2010; King and Baker 2010; Bakker 2025) and other multivariate procedures to identify key thresholds in candidate environmental performance measures (age, size, topography, salinity, water persistence) to identify typology and condition classes of young wetlands. These classes are being used as biologically relevant candidate 'states' in the state-and-transition model for comparison with the Alberta Wetland Classification System state classes currently used to set wetland policy (see section 6.3A.3.2 below).

6.1.1.5 Create a provisional list of candidate measures of success from CWRIG based on causal network analysis

In parallel with inventory compilation and analyses (described above), we will develop suites of biological indices that reflect the 3 'currencies' by which ecosystem function is assessed - biodiversity (food web complexity, which fosters resilience), functional measures (flows of carbon, nutrients, water, contaminants, which reflect dynamics), and community compositional measures (changes in relative abundance of species, which document succession).

Lists of candidate bioindicators informative of environmental stresses for wetlands of each age class were inferred from Fuzzy Cognitive Mapping (Hobbs et al. 2002; Ozesmi and Ozesmi 2004; Ciborowski et al. 2012). Ciborowski et al. (2012) used FCMs to derive candidate stress and biological wetland condition indicators as part of a regional monitoring program to assess risks of natural wetland degradation adjacent to oil sands operations. FCM exercises were to be convened with expert CWRIG members led by the PI and Research Associate Gillian Donald to identify the drivers, abiotic stressor, and biological response variables thought to characterize young opportunistic and constructed wetlands in reclaimed and soil storage areas. These key candidate indicator variables were measured during wetland surveys in Phase 2 to assess the precision (variability) and accuracy (correctness of classification) of proposed stress-response relationships.

6.1.1.6A Create an inventory of recently-appearing opportunistic and 'at risk' created wetlands (see 6.3.4B below)

Assessing hydrological and biological changes during maturation of naturally-forming wetlands in the oil sands region: Research on developing wetlands in the AOS has focused on a relatively small number of constructed "demonstration wetland" locations (Gulley 2006, Kovalenko et al. 2013), but recently reclaimed natural (potential reference) wetlands must also be assessed. Candidate sites included soil and tailings sand storage areas having the longest development and reclamation history as well as recently developed lands on lease areas. Hawkes (2017) summarized analyses of aerial and satellite imagery between 2007 and 2016 to delineate and classify selected reclaimed locations prone to water accumulation, estimating that wetlands covered approximately 17% of the areas sampled. Similarly, Little-Devito et al. (2017) estimated that wetlands made up at least 10% of the reclaimed surface area, based on field surveys of other reconstructed upland sites. BWRAP's GIS team collaborated to determine the distribution of young, naturally- forming wetlands in reclaimed and soil/sand storage areas. We are creating a regional inventory of wetlands classified by size and age (referring to earlier aerial photos and satellite images). Based on size-frequency plots of the population of wetted areas, we selected a chronosequence of wetlands in the current landscape of varying, sizes and apparent permanence for sampling during phase 2 of the program.

6.2.1.7 Develop a sampling plan and standardized sampling methodology to evaluate and validate wetland performance measures

Current sampling methods and approaches documenting wetland components and conditions reflect programs' specific monitoring and assessment goals (e.g. ABMI, CABIN, OSM). We will develop standard methods (or harmonization criteria) for sampling AOS wetlands to provide data amenable for use in all programs' wetland performance measures. The RAA paradigm will focus on methods that generate data best suited for evaluating wetland performance and condition measures, incorporating protocols developed during the CFRAW program (which focused on young wetlands) to maximize comparability with archived data. We will produce a fieldwork standard operating procedure guide for selecting, ground-truthing, sampling, analyzing and reporting AOS wetland data and condition assessments.

6.2 Phase 2. Field sampling young and maturing AOS wetlands to document age-specific ranges of natural variation in environmental conditions and biological responses (years 2-4)

6.2.2.1 Pilot Studies: In 2020 and 2021, the PI led pilot study wetland surveys to train students, confirm the feasibility and effectiveness of the proposed methods, and to estimate among-wetland variability. In 2021, 40 wetlands of varying age and condition were located and sampled. The data confirmed the suitability/limitations of sampling methods and served as a proof of concept of our ability to achieve our fieldwork needs over the proposed time scale.

6.2.2.2 Field investigations of environmental stress-biological response relationships among age-classes of young wetlands

Landscape, hydrological, water chemical, and biological features of selected young wetlands were assessed over years 1-3 to test predictions of the models derived from the compiled database, and generate additional observations on the range of natural variation of key parameters. Data from suites of wetlands across the range of stress scores on the reference-degraded continuum are needed to calibrate estimates generated from the wetland inventory and additional predictive measures.

We assessed the condition of recently constructed marshes (e.g., Daly et al. 2012; Wytrykush et al. 2012) relative to older marsh-like systems identified in the wetland inventory, including both shallow reservoirs, and similar habitats at the margins of natural lakes. Variation among these waterbodies' characteristics were to be used to define the range of successful reclamation outcomes anticipated in the AOS reclaimed landscape after a time period equivalent to reaching 'maturity.' Wetlands selected for fieldwork were to be assigned to age classes (new - 3-6 y; young - 8-12 y; older 15-25 y; and maturing >40 y). Subsequent analyses (Phase 3) were to be performed on each age class. Aerial photos and satellite images (Google Earth) were examined to determine wetland location and apparent year of genesis. Candidate wetlands were ground-truthed by visiting each location to confirm accessibility and suitability features. Together, the research team developed a field sampling design and identified 120 wetlands (3 years x 40 wetlands/y) that were sampled in 2021-2023. The data collected were summarized following completion of the field program and used to confirm the validity of the proposed performance measures as indicators of wetland condition (Task 1.1.5). Subsequently, archival aerial photos, contemporary UAV imagery and satellite imagery (Sentinel I and II) of each wetland were digitized and analysed to determine wetland location and inferred age, size, and interannual variation in vegetation and open water

distribution (Task 1.6). In-place sampling and data-logging were used to document processes and dynamics within individual wetlands.

Remotely-sensed wetland attributes were interpreted using multivariate analyses to identify features that could correlate with or predict biological measures of wetland success. Image analysis modelling was performed to generate credible estimates of upland vegetation type and condition, wetland surface water area, soil moisture and riparian vegetation composition and condition (ground-truthed by on-site surveys) (Biederstadt 2025, Biederstadt et al. 2025 and PDFs collaborating with remote sensing colleagues; see 'collaborations' section). Additionally, data loggers were set in place in each wetland to record diel and seasonal variation in water depth, dissolved oxygen concentration, temperature, photoperiod and light intensity. Standard sampling protocols were used to characterize water, sediment and biological characteristics (Wendlandt 2023; Mombourquette 2023).

Wetland area (size) was determined for use as a covariate. Multivariate analyses were performed to combine the environmental variables assessed to create 3 composite 'stressor indices' operationally defined as 'landscape condition', 'permanence', and 'water quality'. Subsequently, (Phase 3, in progress) each index is being scaled to represent the full range of environmental conditions from 'minimally disturbed' (Reference) to 'maximally disturbed' (Degraded), as defined by the RAA (Ciborowski 2021). The wetlands' biological response variables are being ordinated relative to each of the stress indices.

6.2.2.3 Wetland Assessment

Each year, field sampling was conducted by groups of 4-8 research assistants organized into teams of two. Fieldwork teams each collected data ultimately used to define a stress composite index and determine the associated biological responses.

An ‘environmental features’ team assessed wetland morphometry features and collected samples of soil, surface water and groundwater, and deployed data loggers that recorded water level, dissolved oxygen concentration, conductivity, air and water temperature and photoperiod.

A geospatial team assessed wetland bathymetry and the distribution of submerged aquatic vegetation using a remotely operated Surface Autonomous Vessel (SAV). They also conducted aerial surveys of each wetland and its surrounding vegetation zones using an Ebee X fixed-wing UAV fitted with a 4-band multispectral camera. High spatial precision (5-10 cm) of the surveys was achieved by using a Trimble R2 Integrated Global Navigating Satellite System (GNSS) to collect Real-Time Kinematic (RTK) positioning data.

Three ‘Biota’ teams concentrated on sampling aquatic invertebrates (zoobenthos and zooplankton; 2021-2023), vegetation (2021-2023) and avifauna (2023 only), respectively. Detailed field sampling and laboratory processing methods are provided by Porter (2025; zoobenthos), Dvorak (2025; zooplankton) Mombourquette (2023) and Gillis (2025; vegetation). Avifauna observations were based on Marsh Monitoring protocols (10-minute point counts at 3 locations per wetland (Nakhaie 2013) supplemented with Automated Recording Unit records (Bayne et al. 2017).
Assemblages of each taxa group will be ultimately calibrated to multivariate stressor indices, providing biological indicators of wetland age-class specific condition. The M.Sc. member of each team derived methods of characterizing their composite stress index, documenting the index's relationship with underlying drivers, and interpreting the evolving differences in the stressor's

expression as wetlands age. The land/riparian sampling team documented topography, habitat heterogeneity, slope and aspect, and characteristics of emergent vegetation and wet meadow zones). They collected synoptic data that will contribute to defining the landscape/ disturbance stressor. Two 'open water' teams studied the permanence and water quality stress measures. The wetland permanence team measured bathymetry, area, and synoptic measures of hydrogeology - seasonal variation in depth, evapotranspiration, etc. The water quality team focused on water chemistry (especially ionic composition and ratios of isotopes, nutrients, dissolved oxygen, temperature) and associated biota (sediment, zoobenthos, submerged aquatic vegetation, zooplankton)

6.3. Phase 3. Applying the Reclamation Assessment Approach to define measures of success for early successional stages of wetlands

An essential feature of adaptive management is to document that changes observed in constructed wetlands are consistent with time-courses characteristic of naturally formed wetlands, ultimately leading to self-sustained units. Alternatively, interventions could be undertaken if trends indicate a risk of 'failure' that could be mitigated by suitable actions. We used the 2021-2023 field data coupled with archived wetland inventory information to examine the time trends and variation in performance attributes in wetlands of various ages since construction/ formation. The proof-of-concept application of the RAA incorporated the Phase 2 data to identify objective biological measures that young, constructed wetlands should meet to be classified as 'in a state of reclamation', i.e. on a trajectory likely to become self-sustaining in areas reclaimed from mining (Appendix 4). Analyses are in progress to derive indices characterizing the 3 principal types of environmental stress hypothesized to influence biota or biological processes, and to define the thresholds that distinguish the reference condition and the degraded condition of several age classes of constructed wetlands. Analyses to date have identified provisional thresholds distinguishing reference/nonreference and nonreference/degraded conditions for the water quality and wetland permanence stress axes. Efforts are still in progress to create wetland age-specific biological indices (zoobenthos, submergent aquatic vegetation, emergent vegetation, avifauna) that can diagnose whether or not a young wetland of a particular size and age class is in a state of recovery or whether intervention may be needed because particular environmental stressors are limiting the wetland's maturation. Activities undertaken and variables measured in each wetland are summarized in theses of (Wendland (2023) [hydrogeology], Mombourquette (2023) and Gillis (2025) [vegetation], and Porter (2025) [aquatic invertebrates and water quality]).

6.3A.3.1 Identifying Principal Environmental Indices of Wetland Condition

We incorporated both archived biological information (Mebesius 2021, Moore 2021, Gillis 2021) with field data collected between 2021 and 2023 to create environmental stressor indices of landscape/riparian zone condition, permanence, and water quality, respectively, for each of the 4 wetland age classes (research in progress). Each index will be scaled to the full range of possible stress observed in the study area (0 (minimal stress - 'reference') to 1 (maximum stress - 'degraded')). Taken together, we hypothesized that these 3 axes would represent the full range of stress to which a wetland may be exposed along the reference degraded continuum. The researchers' interpretation of how the underlying drivers contribute to their particular stress scores (mechanistically and statistically) and therefore determine a wetland's condition will ultimately answer question 3 posed within the IRC program: "What constructed landscape features promote formation of wetland resilient and persistent wetlands following bitumen extraction?"

Components provisionally contributing to indices of wetland permanence, water quality and riparian disturbance were identified by reference to the existing literature and assembled into hypothetical causal networks by BWRAP team members and collaborators, initially using fuzzy cognitive mapping protocols (Hobbs et al. 2002; Ozesmi and Ozesmi 2004; Ciborowski et al. 2012) and subsequently applying a causal analysis/structural equation modelling approach (Grace 2020; Grace 2024; Byrnes and Dee 2025). Originally, this exercise was anticipated to engage members of the CWRIG (6.1.1.5). Instead, the provisional maps and models were developed by BWRAP researchers and collaborating colleagues.

6.3A.3.2 Defining thresholds that distinguish Reference and Degraded conditions along Reference- Degraded Continua

Factors that limit rates of wetland development (above) are relatively well known. However, less is known about how quickly the limiting effects of the dominant stressors are attenuated. Age class-specific predictions of stress-response relationships hypothesized during Phase 1 (Section 6.1.1.3 nd 6.1.1.4) were evaluated for aquatic invertebrates and wetland vegetation with respect to gradients of wetland water quality and permanence (Section 6.3A.3.1 above). They described the relationships between environmental constraints (stressors) and the communities (biological assemblages) expected in young wetlands. For each age class of wetlands, multivariate analyses are in progress to create biological condition indices indicative of stress index scores. Biological condition indices will be plotted relative to stress gradients and their predictive capacity assessed. Findings of these analyses will address the question of "What environmental or biological indicators of young wetlands' resilience and/or persistence are important to ensuring sustained environment recovery after bitumen mining activities? In the interim, simple measures of biodiversity (taxa richness or Shannon diversity) were used to represent community condition. We tested for the presence of single or multiple thresholds in the range of natural variation using Piecewise Quantile Regression (Tomal and Ciborowski).

6.3A.3.3 Defining age class-specific thresholds that characterize reference-degraded conditions in constructed wetlands

Multivariate analyses of changes in community composition and breakpoints in ranges of natural variation along the chronosequence of wetland ages were performed for aquatic vegetation (Mebesius 2021, Gillis 2021, 2025) and aquatic invertebrates (Moore 2021, Rodrigues 2024, Porter 2025). Community-level thresholds were evident but weakly defined. The age-specific community assemblages within each wetland age class are being provisionally used to characterize a successional sere.

6.3B.3.4 Assessing time trends in ecological condition and biological change

(Develop a state-and-transition model documenting development of communities and associated stress characteristics of naturally forming wetlands (Appendix, Figure 5B). Thresholds identified for wetland age classes (within 6.3.3.3) were used as the criteria for defining wetland states at those time points in their development. Colleagues from Apex RMS worked with Research Associate Gillian Donald to build a state-and-transition model analogous to the conceptual model postulated by Frid and Rooney (2015) using SyncroSim state and transition simulation software (St-Sim; Daniel et al. 2016). The RAA-derived state and transition model will consist of multiple state classes (condition classes x age classes) as envisioned by the Ciborowski et al. (2013) adaptation of the Grant (2006) recovery theory (Ciborowski 2021). The compiled Phase 1 and Phase 2 data were synthesized by Research Associate Gillian Donald in consultation with contractors Apex RMS

to develop the model documenting development of communities and associated stress characteristics of naturally forming wetlands. A constructed wetland of a particular age class will be considered 'successful' if its biological attributes place it in the equivalent-to-reference portion of its corresponding age class.

6.3B.3.5 Review Effectiveness of the RAA approach (input from CWRIG)

As originally proposed, the findings of the BWRAP program were to be evaluated within the context of the Reclamation Assessment Approach, comparing the maturation patterns and biological communities of wetlands in reclaimed landscapes relative to wetlands of equivalent age developing in reference landscapes. The evaluation format was originally proposed to consist of a series of presentations and assessment workshops made up of industrial, academic and other members of the CWRIG.

6.3B.3.6. Review Program Findings/Limitations; Objectives for next cycle

This synthesis was anticipated to arise by drawing together information and feedback from presentations and discussions during assessment workshops with members of the industrial, academic and other members of CWRIG as outlined in section 6.3B.3.5 above with input and assistance from sponsoring agencies, COSIA. However, a critical mass of engaged participants is currently lacking. Alternatively, program findings, limitations and recommendations for continuing and future research were gathered and summarized from student theses, feedback received following invited presentations, and informal discussions with collaborators.

7. PROJECT RESULTS

A summary of the phases, detailed tasks and their state of completion is summarized in Figure 1. Task numbering aligns with the narrative structure of the Methodology section.

7.1 Phase 1 – Compile, & interpret existing data

7.1.1A Compiling, existing data
7.1.1.3 Identify common early successional time trends
7.1.1.4 Identify classes of young wetlands/age breakpoints

Beginning in 2020, senior undergraduate students compiled and analysed archival data to evaluate colonization time trends of aquatic invertebrates (Moore 2021), wet meadow vegetation (Gillis 2021) and submergent aquatic vegetation (Mebesius 2021). Subsequently, Mark Patzer (M.Sc. 2024) compiled data from 'instrumented watershed' records of temperature, wind, precipitation and relative humidity to provide estimates of local water balance (inputs and evapotranspiration) for a subset of our study wetlands and to document how these features change as reclaimed landscapes undergo early succession (Please see Appendix 4 for full citations of BWRAP student theses).

Moore (2021) Identified aquatic invertebrate community thresholds in response to various environmental gradients using Threshold Indicator Taxon Analysis (TITAN). Principal component analysis revealed that theenvironmental variables accounting for the most diversity in water chemistry among these wetlands included specific conductance, naphthenic acid concentration, sulfate concentration, and pH. Therefore, these parameters, along with wetland age, were investigated for the presence of thresholds. Values of specific conductance, sulfate concentration, and pH were compared to data from brine-contaminated wetlands in the Prairie Pothole Region (PPR), which also exist near oil and gas production infrastructure (Preston et al. 2018). Thresholds above which multiple (sensitive) species did not occur were identified for two parameters: specific conductance (1200 µS/cm) and pH (8.1). Similar thresholds were observed in data from the PPR wetlands, validating the occurrence of community change at these locations along similar specific conductivitance and pH gradients. Thresholds for naphthenic acids, sulfate, and wetland age were not evident in this study, possibly because sample sizes were small or because indicator taxa differ in their tolerance to these parameters.

Gillis (2021) analysed archival vegetation data collected from 19 young constructed or opportunistic wetlands developing on reclaimed landscapes, one of which was sampled annually from its inception until 5 years of age to determine if the successional changes discerned by analysing a chronosequence of wetlands differed from repeated measures collected from a single wetland. Threshold Indicator Taxa Analysis (Baker and King 2010) was performed to identify potential age-specific indicator taxa, and whether community thresholds existed across wetland ages. However, the sample size and range in values of 'age' were too small to provide reliable estimates. The vegetation composition of constructed and opportunistic wetlands was very similar, consisting of 36 common species. However, the percent cover of only three species (*Acorus calamus, Typha latifolia* and *Carex* spp) were significantly associated with wetland age.

Mebesius (2021) investigated how the composition and abundance of SAV varied with respect to salinity and time since wetland creation using archival data from 58 wetlands ranging in age from 1 to 29 years. Threshold Indicator Taxon Analysis (TITAN) was used to determine whether salinity thresholds

existed for SAV plants, and if they did, to determine whether these thresholds were age specific. Most wetlands had low species richness relative to the overall species richness of all wetlands, and few species were identified as indicator species by TITAN. All Indicator species identified by TITAN showed a negative relationship to increasing salinity. Two salinity thresholds were evident when examining data from all wetlands. However, no age-specific salinity thresholds were found when TITAN analyses were performed on smaller wetland groupings.

Patzer (2024) analysed precipitation and evapotranspiration records from six weather stations in three reclaimed landscapes to backcast and forecast meteorological trends. An autoregressive integrated moving average forecasting model was used to back-calculate trends in historical data from 2000 to 2022 and predict meteorological conditions until 2030. Estimates were to be used to infer likely effects on water volumes of opportunistic wetlands in the landscapes. Rates of annual evapotranspiration exceeded precipitation on an areal basis across the study area. Evapotranspiration gradually declined as landscapes aged. Water volumes in selected wetlands were quantified and analyzed in conjunction with the time series forecasts to support predictions on future water balance. Forecasts will contribute to the assessment of wetland persistence useful for future mine closure planning and provide complementary data for other water balance studies in the region.

7.1.1.6A Compile inventory of candidate study wetlands

In further support of these tasks and to elucidate our understanding of time trends in the formation and persistence of newly formed wetlands, we used detailed Landsat Satellite imagery to document the visually apparent year of genesis, interannual variation in size, and ultimate persistence of the focal study wetlands appearing in reclaimed and surrounding areas (M. Rahman in prep). We found that the 30-m resolution of the imagery was too coarse to be useful, given the relatively small size of study wetlands. Subsequently, some aerial imagery of mine leases was acquired (annual high-resolution (0.25-m) aerial photographs from 1984 to 2022) from which we documented the visually apparent year of genesis (first year in which open water appeared at a wetland location), interannual variation in size (standard deviation of change in wetland open water area between consecutive years), and ultimate persistence (proportion of years in which wetland open water was observed) of the BWRAP focal wetlands appearing in reclaimed and immediately adjacent areas (K. Fong, in prep).

Complementary research by M.Sc. student Erik Biederstadt (M.Sc. 2025; Biederstadt et al. 2025) documented intra-annual variation in surface water area based on Sentinel-1 and Sentinel-2 satellite imagery. Biederstadt et al. (2025) found that satellite-based imaging estimates of wetland surface water extent derived from Sentinel-1 and Sentinel-2 satellite multispectral data closely matched estimates derived from high-resolution UAV data ($R^2 = 0.92$, open water model; 0.90, open water + emergent vegetation model). Surface water dynamics were broadly similar between recently formed wetlands in reclaimed and reference landscapes, with larger wetlands exhibiting greater variability in water extent. Deeper and larger wetlands appear to be more vulnerable to fluctuations in water availability than smaller, shallow wetlands. Overall, Sentinel-1/2 imagery provides a reliable method for monitoring wetland surface water and intra-annual hydrodynamics. These exercises have provided crucial information on the size-frequency distribution of opportunistic wetlands forming in post-mining areas and their size trajectories and persistence over the almost 50-year history of the companies' mining efforts. The data are being incorporated into a complete inventory of wetlands in the lease and surrounding areas (Task. 1.6A; Mombourquette et al. in prep;, Gillis et

al. in Prep; Porter et al. In prep). This information has also been used to populate the state-and-transition model of wetland (Task 3.4; Bilski et al. 2024, Bilski et al. 2025).

7.1.1B BWRAP Geodatabase development and implementation

Creation of the BWRAP geodatabase was initiated in 2022 and implemented beginning in 2023 by Programmer/developer Qing Ye (Richard) Zeng and Developer Kwok-Kei (Maverick) Fong in collaboration with the *Boreal Ecosystem Recovery and Assessment* NSERC Alliance-funded project (BERA; www.bera-project.org). Beginning in 2024, the BWRAP and BERA researchers and students codeveloped a data management plan to ensure that standards and organization maximize interoperability and compatibility of data sets. The structure was modeled to mirror the Alberta Biodiversity Monitoring Institute's (ABMI) database in order to maximize compatibility and interoperability with the ABMI's system and holdings. Dr. Zeng also developed several operational tools to enhance database uploading, formatting and cataloguing, including an algorithm to automate daily data back-ups, and a data quality assessment tool that automatically screens uploaded datasets for out of range or missing values. Portals and sign-in protocols are available to provide varying degrees of access to BWRAP researchers, students, collaborators and industry partners (Zeng 2024a, 2024b, 2025). When fully populated, the portal will summarize holdings and show details and geographic locations of wetland imagery and features of origin, morphometry, hydrology, sediment and water chemistry, vegetation, aquatic invertebrates, avifauna and multivariate indices of environmental stress.

The database portal is actually a 'meta-database.' It is a spatially explicit catalog of BWRAP-relevant data. One can view a map of the study region, delineate an area in which to search and query the site for data that relate to the delimited area. One can then ask to download a copy of the data of interest. However, those data do not necessarily reside within the database itself. Current holdings are limited to archival theses and documents while final dataset integrity is assessed and quality checked for completeness.

7.1.1.2 Created Wetland Research & Information Group (CWRIG) Community of Practice

The proposed, informal CWRIG was anticipated to facilitate dialogue among researchers, collaborators and stakeholders (government, Indigenous communities, industry, and citizenry; detailed in the Knowledge Mobilization section). The initiative was originally planned to be an open, self-assembled forum for discussion and synthesis, building on regularly scheduled meetings hosted by COSIA beginning in 2019. However, unanticipated events occurring over the course of the program (notably the COVID-19 pandemic's effect on social gatherings beginning in 2020) pre-empted efforts to host introductory meetings for several years. Subsequent efforts were delayed by concerns that public discussion of oilsands-related reclamation strategies might ultimately compromise the protection of information deemed confidential intellectual property. Consequently, an alternate model was developed. Rather than creating a self-assembled CWRIG, BWRAP contracted with Apex RMS to develop a State-and-Transition Simulation Model (STMS; Daniel et al. 2016) that would use BWRAP-collected data to predict successional changes most likely to occur in wetlands forming on reclaimed vs. reference landscapes. Between October 2023 and March 2024, the methodology was presented by Apex as a 6-lecture virtual (online) course in model development open to all interested parties (further discussed as Tasks 6.3B.3.4, and 6.3B.5, below). Course participants were invited to attend one-hour lectures on STSM development. Each lecture was followed by an open discussion period wherein participants were asked to request further

information. Participants were also invited to comment on model assumptions, choice of variables, which were ultimately incorporated into later versions of the model. Lectures were recorded and uploaded to a publicly accessible venue (University of Calgary's Yuja platform; Appendix 2).

7.1.1.5 Create a provisional list of candidate measures of success from CWRIG based on causal network analysis

As detailed above, restrictions on public gatherings during the organizational phase of BWRAP curtailed efforts to create the proposed Research Information Group. Alternatively, weekly Zoom meeting were convened with the newly recruited cohort of students, research associates and (where available) collaborators to train and engage program members. Eminent wetland ecologists were invited to give online seminars and engage in follow-up discussions. In addition, students were encouraged to develop and present their ideas for developing hypotheses about wetland function and the methodology best suited to gather the data necessary to test the hypotheses. These ideas ultimately formed the basis for the list of candidate measures of success. Concepts and sampling methodology were presented to COSIA members, students' advisors and other interested attendees at BWRAP 'field season recap' symposia held annually in the winter/spring following a season of fieldwork. Presentations were recorded and uploaded to a publicly accessible venue (University of Calgary's Yuja platform; Appendix 2).

7.1.1.6A Create an inventory of recently-appearing opportunistic and 'at risk' created wetlands

Based on size-frequency plots of the population of wetted areas, we selected a chronosequence of wetlands in the current landscape of varying, sizes and apparent permanence for sampling during phase 2 of the program. Each year of fieldwork, details of each wetland's location, setting, morphometry and other environmental and biological features were assessed and summarized. The information is being compiled into 3 year-specific technical reports (Mombourquette et al. in prep, Gillis et al. in prep., Porter et al. in prep.) following the general format of an inventory of research wetlands created by Marlowe (2002) for Golder, Inc.

7. 2. Phase 2 - Field sampling young and maturing AOS wetlands to document age-specific ranges of natural variation in environmental conditions and biological responses (years 2-4)

Phase 2 of the BWRAP initiative focused on identifying, ground-truthing and sampling a suite of wetlands (40/y over 3 years) to provide a sample size amenable to multivariate analysis)) ranging in age from <5 to over 40 years and encompassing the range from minimal to maximal levels of 3 principal forms of stress/disturbance - permanence, water quality, and riparian anthropogenic disturbance. Between May and October 2021, 2022 and 2023, a total of 40, 40, and 39 wetlands, respectively were located and ground-truthed (Task 1.6B). Half of the wetlands were situated in reclaimed areas of the AOS mine leases. The other half of the wetlands were located outside of the lease areas.

7.2.1.7 Develop a Wetland Sampling Plan and Standard Methods

7.2.2.1 Pilot Studies

The standard sampling plans and methods (Task 1.7) developed in spring 2021 were consistently used over the 3 field seasons to ensure comparability of the data. New students were trained each spring (Task 2.1) at a field camp in spring 2022 and 2023, and in-house in 2024 (due to inclement

weather). During each field season, wetland hydrology, water quality, the biota, and each wetland's riparian landscape were assessed (Task 2.2) using the following protocols:

Between 1 July and 31 August 2021, near continuous-recording data loggers (15- or 30-min intervals) were deployed, measuring air and water temperature, dissolved oxygen concentration, water level, conductivity and light intensity. In addition, five 1-m deep piezometer wells were installed radially around each wetland to measure groundwater attributes and radon concentrations. Surface water was sampled at the same time as piezometer well sampling to determine stable isotope, cation and anion concentrations. Loggers were removed in late September/early October to avoid risk of damage by freezing. They were put back in place in May 2022 and left until the end of June. At that time, they were recovered and deployed in a new set of 40 wetlands until September 2022. In May 2023, they were re-installed at their original locations, and removed at the end of June. Loggers were installed in 37 of the final set of 39 wetlands in July or August 2023 and recovered in late September. As mentioned above, we were unable to re-deploy the loggers in spring 2024. Accordingly, we did not acquire measures of spring hydrology, surface/groundwater ratios or water quality for those wetlands. This may ultimately somewhat limit our assessment of the ranges of intra-annual variation in water level, specific conductance and dissolved oxygen. However, loggers were in place during the season in which biota were sampled, so the impacts and implications of not collecting spring data at the end of the final study year are relatively minor.

Aquatic invertebrates and wetland vegetation were studied at 5 radially-distributed locations around each wetland using D-frame dip nets (for benthic invertebrates) a plankton net (for zooplankton), and quadrat sampling (for vegetation; supplemented with walk-around surveying to detect rare species). Surveys were conducted in the year during which piezometer wells were installed at each wetland. Aquatic invertebrate samples were field-preserved and identified to the lowest practical taxonomic level in the laboratory. Vegetation community composition was assessed by examining the species present and their ground cover in 1-m^2 quadrats placed in the submergent (on floats), emergent, and wet meadow plant zone within each of 5 radial sectors surrounding a wetland. Subsequently, the above-ground biomass of quadrats containing monocultures of the 6 most frequently-occurring emergent or wet-meadow species were harvested during August in each wetland to provide a measure of net primary production. Soil samples were also collected to relate plant biomass to salinity, organic content, moisture-holding capacity, and texture. In 2023, samples of roots and soil from selected wetlands were collected for later evidence and genomic analysis of mycorrhizal associations.

Assessments of bathymetry and the distribution of submerged aquatic vegetation were to be made using a georeferenced, sonar-equipped autonomous floating vessel ("ROVER") each summer. However, operation of the ROVER proved to be frequently limited, especially in shallow wetlands, by substrate-to-surface growths of submergent aquatic vegetation, which had typically developed by early June. In such cases, general bathymetry and the location and depth at a wetland's deepest point were determined by taking soundings by wading (shallow wetlands) or from a Jon boat. Surface features of each wetland and its surrounding terrain were documented with approximately 10-cm resolution by flying a fixed-wing unmanned aerial vehicle equipped with a RGB Red-edge camera. Field data were uploaded to the geodatabase and analysed to delineate the areas of open water, emergent vegetation and wet meadow vegetation as well as proximity of linear features (roads, cutlines, power lines) and other disturbances. Georeference locations of the five piezometer wells

and the start and end points of the vegetation transects were incorporated into each wetland image to assist in the visual assessment of zone edges.

7.2.2.2 Field investigations of environmental stress-biological response relationships among age-classes of young wetlands

As described in previous sections, a total of 119 wetlands were investigated between 2021 and 2023. Equal numbers of wetlands were situated in wetlands forming on reclaimed landscapes in mine lease areas and in 'reference' (disturbed but unmined) landscapes situated outside lease areas. The frequency distributions of wetlands in each landscape class are illustrated in Figures 2-5.

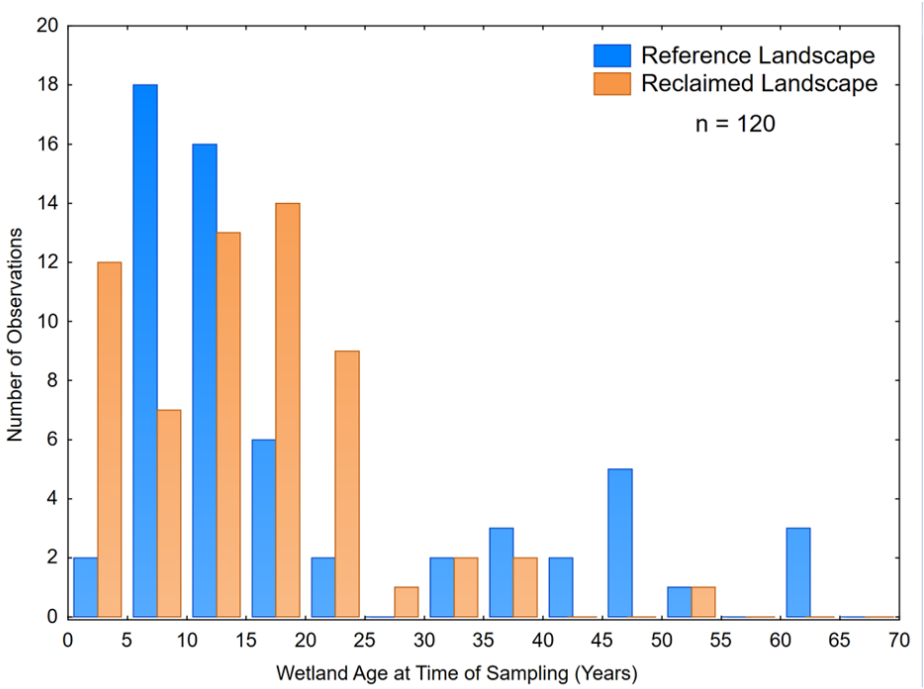


Figure 2. Frequency distribution of wetlands sampled with reference to age (first appearance of open water) in year of sampling. Blue: wetlands in reference landscapes; Orange: wetlands in reclaimed landscapes.

Wetlands sampled ranged in age from 1 year since the first appearance of surface water to over 40 (Figure 2). At least two wetlands from each landscape type were assessed for each decade of age up to 40 years. Age ranges and relative distributions were broadly equivalent except for the age extremes. Many more very young (<5 years old) wetlands on reclaimed landscapes were sampled than on reference landscapes. Similarly, the oldest wetlands (>45 years; not shown) were situated on reference landscapes.

The size of sampled wetlands was log-normally distributed (Figure 3). Most wetlands were less than 1 ha in open water area. Intermediate-sized wetlands (3-6 ha; largely flooded borrow pits) were situated on reference landscapes, but the largest wetlands studied were in reclaimed landscapes.

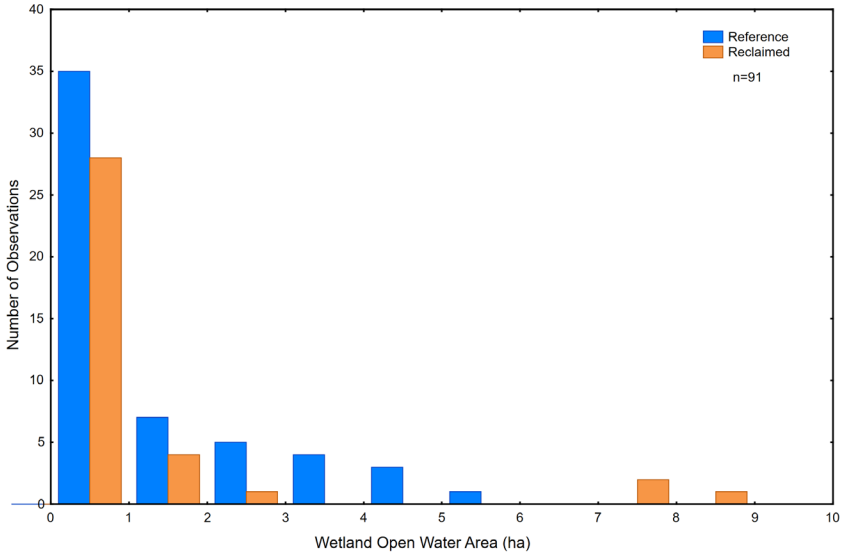


Figure 3. Frequency distribution of wetlands sampled with reference to surface open water area in year of sampling. Blue: wetlands in reference landscapes; Orange: wetlands in reclaimed landscapes (n=91).

Wetland permanence was restricted to the seasonal, semi-permanent and permanent Alberta wetland classes (Figure 4), with most wetlands being categorized as permanent based on their morphometry and vegetative characteristics. Permanent reference landscape wetlands were somewhat overrepresented, and seasonal and semi-permanent wetland classes were proportionately overrepresented.

The range of specific conductance values observed was much greater for wetlands in reclaimed landscapes than for wetlands in reference landscapes (Figure 5). Whereas most wetlands in both classes of landscape had specific conductance values less than 2,000 µS/cm, the greatest value observed in wetlands of a reference landscape were below 3,000 µS/cm, wetlands in reclaimed landscapes ranged as high as 9,800 µS/cm.

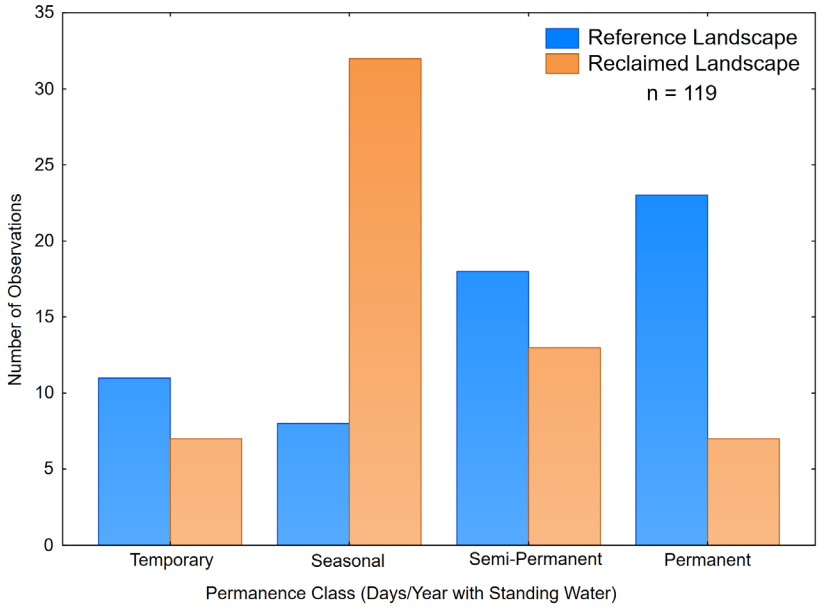


Figure 4. Frequency distribution of wetlands sampled with reference to permanence class according to the AB Wetland Classification System. Blue: wetlands in reference landscapes; Orange: wetlands in reclaimed landscapes (n=119).

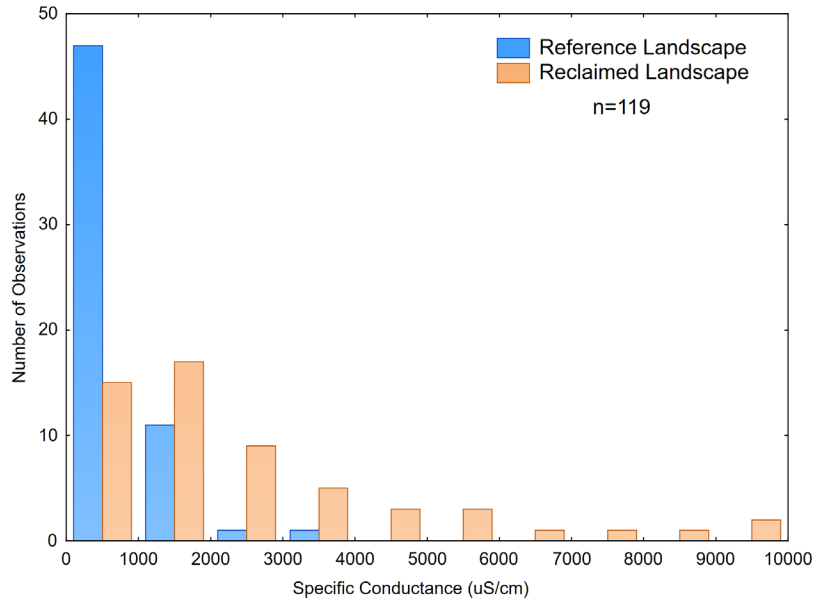


Figure 5. Frequency distribution of wetlands sampled with reference to specific conductance of surface water. Blue: wetlands in reference landscapes; Orange: wetlands in reclaimed landscapes (n=119).

7.2.2.3 Wetland Assessment

Thirteen students conducted fieldwork between 2020 and 2023 in support of wetland assessment investigations that led to publication of theses (in preparation for submission to peer reviewed journals). Areas of investigation included hydrology and water chemistry (Wendlandt 2023, Bishko,

in prep, Leng 2023 and in prep), vegetation (Mombourquette 2023, Corcoran 2023, Gillis 2025), and aquatic invertebrates (Vercruysse 2022, Rodrigues 2023, Yu 2024, van't Reit 2024, Porter 2025). Full citations are listed in Appendix 4. Data from these investigations contributed to creation of wetland permanence and water quality gradient indices and assessments of distribution of biological attributes along the age, permanence and water quality gradients. In addition to identifying community composition change points (indicative of thresholds) and diagnostic indicator species of each class, the data were used in parameterizing the State and Transition model (Section 7.3 below).

Vercruysse (2022) examined how aquatic invertebrate community composition varied as function of salinity (specific conductance) among a suite of 50 flarks and small ponds located in a naturally saline fen complex southwest of Fort McMurray. Vercruysse found diverse communities of aquatic invertebrates (damselflies, snails, mayflies, caddisflies) in wetlands whose conductivity was below a threshold of approximately 9,000 µS/cm and dipteran-dominated communities in waterbodies with higher conductivity. In 2023, loggers were deployed again in 6 of the study wetlands to track seasonal variation in salinity water level and dissolved oxygen concentration. Zoobenthos were also sampled for comparison with the 2020 sample series. Although conductivities in 2023 were greater than in 2021 due to an extended dry period, the 2023 data broadly mirrored the findings of earlier years.

Vegetation data collected from wetlands in 2021 surveys by Mombourquette et al. (Mombourquette 2023) were supplemented with vegetation surveys conducted in 2022 (Gillis et al. 2024; Gillis 2025) and 2023 (Jackson B.Sc. 2024). Generally, biomass of dominant plant species appears to increase with wetland age (Mombourquette M.Sc. 2023), whereas richness, diversity and community composition overall seem to show no clear pattern of change or a slight decline with age (Gillis et al. 2024; Gillis M.Sc. 2025). Soil salinity has a complex influence on biomass. In youngest wetlands (<5 y), biomass was uniformly low across the salinity gradient. Yet, a salinity threshold was clearly apparent in older wetlands. Biomass at maturity increased at a function of age in low-conductivity wetlands, but remained low in wetlands that had saline soils (Mombourquette M.Sc. 2023). Data from Gillis (2024) suggest that key stressors are stronger indicators of plant species diversity and community composition than age. Diversity was negatively associated with specific conductance but positively associated with permanence. Jackson (2024) reported that plant species richness exhibited a tolerance relationship to soil nutrient concentration, reaching highest values at intermediate concentrations of soil phosphorus. Overall, reference wetlands had markedly higher soil phosphorus concentrations than reclaimed wetlands.

Water quality and wetland permanence also influenced richness and community composition of aquatic invertebrates in study wetlands. Rodrigues (B.Sc. 2023) and Yu (B.Sc. 2024) found similar patterns in the relative frequency of occurrence of 3 families of snails in the wetlands surveyed in 2022 and 2023. Snails were absent in the youngest wetlands surveyed and older saline wetlands (conductivity >3,000 µS/cm) but were abundant in older, less saline wetlands. To better understand the putative effects of salinity on snail distribution and tolerance Van't Reit (B.Sc. 2024) adapted a snail embryo laboratory bioassay of Osborne et al. (2023) as proof-of-concept test of responses to wetland salinity and water quality. Survival, development and growth of embryos in egg masses of laboratory-cultured *Planorbella pilsbryi* were assessed over 10-day intervals in a dilution series of NaCl (positive and negative controls) and water from a young (3-y), saline (specific conductance 6,000 µS/cm) wetland sampled in 2023. Embryonic growth and development were slow and

markedly reduced at specific conductance >3,500 µS/cm of NaCl solution. Embryo development and biomass in the wetland water greatly exceeded all laboratory-created treatments.

Porter et al. (2024) and Porter (2025) studied the distribution of non-insect zoobenthos. She observed a strong association between the presence of such taxa (snails, worms, leeches, amphipods) and wetland permanence/ephemerality but not with wetland age. Presence and relative abundance of passive dispersers intolerant to desiccation (amphipods, some snails and leeches) and of univoltine active dispersers (some dragonflies) were strongly correlated with the longest hydroperiods. Occurrence of all aquatic macroinvertebrate taxa and functional groups was weakly positively correlated with longer hydroperiods, likely due to having longer periods of time available to establish populations in these habitats. Reclaimed and younger reference wetlands were most predictably characterized by shorter hydroperiods with elevated salinity, reflecting the influences of landscape construction and disturbance on wetland hydroperiod and community composition in these newly-forming landscapes.

Wendlandt (M.Sc. 2023; Wendlandt et al. 2024; supplemented with data collected in 2022 and 2023 by Bishko (in prep) and Leng (in prep)) analysed concentrations of radon, hydrogen and oxygen isotopes, and time trends in water level, specific conductance and temperature. He delineated study wetland hydrology along an ephemeral-permanent gradient characterized by relative contribution of surface vs. groundwater, wetland bottom profile and sediment permeability. Wendlandt (2023) found marked differences in hydrological features of wetlands on reclaimed vs. reference landscapes. Evaporative processes seemed to dominate water balances in small wetlands on reclaimed landscapes whereas water inputs determined balances in wetlands of reference landscapes. Water chemistry was affected by the properties of the surficial geology (of reference wetlands) or subsurface placement material (of wetlands in reclaimed landscapes). Wendlandt (M.Sc. 2023; Wendlandt et al. 2024) postulated that the hydrological characteristics and dynamics of wetlands in reclaimed landscapes were more similar to those of prairie potholes than to newly forming boreal reference wetlands in the landscape surrounding lease areas. Trends are being validated using the hydrological data collected in 2023 and more precise (UAV-based) estimates of wetland open water and catchment areas (McKinnon et al. in prep).

7.3. Phase 3 - Compiling/analysing data; State-and-Transition model to synthesize and interpret wetland development & persistence

In fall 2023, we organized and invited interested participants (the originally-proposed Community of Practice – Task 1.2) to enroll in a course in State-and-Transition Simulation Modeling (STSM) of wetland features in reclaimed and reference landscapes. The initiative was organized and synthesized by Research Associate Gillian Donald. Course Instructor Leonardo Frid (developer of several STSM models in the oil sands region) worked with Dr. Donald to organize a set of 6 monthly lectures/presentations using the BWRAP wetland information as a case study of how to undertake the various steps in model development, parametrization and its application/prediction. Lecture attendees provided perspectives based on their personal experience. Dr. Ciborowski and Dr. Donald worked with Apex RMS in between the course webinars to advance the development of the STSM and to prepare course presentations documenting the assumptions and components of the STSM for the BWRAP application. Recordings of the lectures and accompanying material produced between October 2023 and March 2024 were made publicly available on request (Appendix 2). A report

documenting the exercise was produced in late March (Bilski et al. 2024) detailing the components and assumptions of the model. In 2025, the preliminary data compiled during phase 3 were used in proof-of-concept model simulations to predict trajectories of the wetlands forming in reclaimed mining areas over a 100-y time frame. The results were presented at a public symposium attended remotely in November 2025, and summarized in a report of findings and future needs (Bilski et al. 2025).

7.3A.3.1 Identifying Principal Environmental Indices of Wetland Condition

Components provisionally contributing to indices of wetland permanence, water quality and riparian disturbance were identified by reference to the existing literature and assembled into hypothetical causal networks by BWRAP team members and collaborators, initially using fuzzy cognitive mapping protocols (Hobbs et al. 2002; Ozesmi and Ozesmi 2004; Ciborowski et al. 2012) and subsequently using a causal analysis/structural equation modelling approach (Grace 2020; Grace 2024; Byrnes and Dee 2025). Details of the candidate variables are provided by Wendlandt (2023; wetland permanence and surface water quality), Mombourquette (2023) and Gillis (2025; emergent zone water quality), and Porter (2025; wetland permanence and water quality).

Elements of the various components of each network are still being quality assured. Consequently, interim 'working' indices were created and scaled to the range of measurements available from the wetland data available at the time of analyses (sample sizes described in section 7.2.2.2).

An interim wetland permanence index was generated based on the available wetland morphometry data (Brooks and Hayashi 2003; open water area and maximum depth) created by performing a principal coordinates analysis to relate the two variables and ranging the predicted values from zero to one.

An interim water quality index was generated by performing principal component analysis on a data set incorporating surface water concentrations of cations, anions, nutrients and naphthenic acids. The index was based on principal component scores of an axis exhibiting high loadings of Ca, Na, SO_4, Cl, specific conductance and naphthenic acids. The principal component scores for each available wetland were ranged from zero to one and used as the index score.

Landscape data on which to base the disturbance index are still being compiled.

7.3A.3.2 Defining thresholds that distinguish Reference and Degraded conditions along Reference- Degraded Continua

7.3A.3.3 Defining age class-specific thresholds that characterize reference-degraded conditions in constructed wetlands

Multivariate analyses were conducted to document the presence, absence or relative abundance of aquatic invertebrates (Vercruysse 2022; Rodrigues 2023; Porter 2025) and wetland plant species occurring in the various wetland zones (Mombourquette 2022, Corcoran 2023, Jackson 2024, Gillis 2025). Redundancy Analysis performed to relate associations between dominant species and key environmental variables confirmed the importance of specific conductance and wetland permanence for vegetation (Gillis 2025) and aquatic invertebrates (Porter 2025). Common species' ranges of tolerance to axes of permanence, specific conductance and wetland age were identified using Indicator Species Analysis (Dufréne and Legendre 1997) and tested for evidence of community thresholds using Titan (Baker and King 2010). Although marked differences in community

composition of both vegetation and aquatic invertebrates were observed among classes of wetland permanence and water quality, community-level thresholds were not sharply defined. This was especially true of analyses of wetland age. Nevertheless, piecewise quantile regression (Tomal and Ciborowski 2020) of Shannon diversity and/or taxa richness identified at least two thresholds for vegetation and aquatic invertebrates along the provisional permanence and water quality stressor axes. We have described these as putative thresholds distinguishing wetlands falling into classes of "equivalent to reference" (below the lower environmental change point), "equivalent to degraded" (above the upper environmental change point), or "neither reference nor degraded" (between the two change points).

7.3B.3.4 Assessing time trends in ecological condition and biological change

The environmental and biological data collected were used to populate State-and-Transition Simulation Model to forecast the persistence and prevalence of wetlands and their biota from the present to the year 2100. Preliminary simulations performed to predict the frequency distribution of plant diversity in wetlands in the reclaimed landscape were contrasted with the anticipated counterfactual frequency distribution of diversity in wetlands that might form in reference landscapes. Simulations indicated that the cumulative area of wetlands supporting high vegetative diversity in reclaimed landscapes was much less than the cumulative area of high diversity wetlands that would occur in reference landscapes, largely due to the differences in wetland water quality and permanence.

Because the current iteration of the model is not spatially explicit, these assessments treated the reclamation landscape as topographically homogeneous, and assigned wetlands to random locations within reclaimed area. The total area of wetlands increased through time according to the forecasted schedule of reclamation proposed by oil sands companies' closure plans. The precision of simulation forecasts could be increased by evaluating a spatially explicit version of the State-and-Transition model that reflected the anticipated topography of landscapes in the mining companies' closure plans.

However, predictions were also limited because the record of landscape reclamation is too short (<50 years) for vegetation communities to reach 'maturity'. Nevertheless, the Reclamation Assessment Approach provides a credible study design by which to assess the early stages of succession in reclaimed landscapes relative to the patterns expected in reference landscapes.

7.3B.3.5 Effectiveness of the RAA approach

As originally proposed, the findings of the BWRAP program were to be evaluated within the context of the Reclamation Assessment Approach, comparing the maturation patterns and biological communities of wetlands in reclaimed landscapes relative to wetlands of equivalent age developing in reference landscapes. The evaluation format was originally proposed to consist of a series of presentations and assessment workshops with participation of a broad range of industrial, academic and other members of the CWRIG. However, only limited opportunities for engagement have been realized to date. Plans for a final series of presentations and discussion forums engaging industrial partners and academic collaborators are in progress and are anticipated to provide a critical review of the effectiveness and limitations of the RAA proof-of-concept exercise.

7.3B.3.6 Program Findings/Limitations

Please see sections 9 and 11 for a summary of findings, an evaluation of how well performance metrics were attained, limitations of the program and recommendations for continued research to resolve unanswered questions.

8. CONCLUSIONS/KEY LEARNINGS

The environmental features of wetlands in reclaimed vs. reference landscapes of equivalent age overlapped considerably. However, the population of wetlands studied in reclaimed landscapes spanned a broader range of stress than those from reference landscapes. Youngest wetlands in reclaimed landscapes exhibited greater stress scores (higher specific conductance, shorter hydroperiod, more extensive areal landscape disturbance) than reference counterparts of equivalent age. Stress index scores of the older wetlands studied in each landscape were more similar to one another, possibly because a) conditions converge as wetlands age; or b) wetlands with particular attributes (e.g., large watersheds and/or surface areas) are more likely to persist through time and accordingly were more likely to be selected for the study. Both aquatic invertebrate and vegetation communities were constrained by wetland permanence and by water quality thresholds (insufficient data were collected to support analyses of the bird communities in and surrounding study wetlands). Distinct differences in community composition were observed with respect to stresses relating to water quality (summarized by specific conductance) and wetland permanence (number of days per year during which surface water was present). Specific conductance thresholds (provisionally identified at approximately 3,000 and 9,000 µS/cm) and wetland permanence thresholds (characterizing ephemeral/semipermanent and intermittent/ permanent wetland class boundaries, and characterized by wetland area and maximum depth) distinguished both aquatic invertebrate and vegetation assemblages. Wetland age alone was a poor predictor of community composition. Instead, characteristics of the placement material and topsoil used to create reclamation landscapes tended to control the wetland permanence and water quality attributes that appear to determine the species present. Specifically, wetlands forming on reclaimed landscapes tended to be more ephemeral and more saline than wetlands observed in reference landscapes. Combined, this suggests that the biota characterizing wetlands forming on reclaimed landscapes reflect the wetlands' permanence and water quality features as dictated by landscape topography and construction features. If the thresholds provisionally identified by the current research truly determine the likelihood that particular ecological communities will persist, then reclaimed landscapes could be designed to promote the formation of wetlands that fall within the desired threshold limits.

The BWRAP study was designed to assess the features and ecological condition of individual wetlands. However, the functional attributes and integrity of the broader landscape likely reflect the biological, hydrological and geochemical fluxes among multiple component wetlands, which span a range of sizes and chemical features (Little-Devito et al. 2017; Hawkes et al. 2025). An important avenue for future investigation would be to determine the natural size-frequency distribution of young wetland classes and to assess biodiversity at the reclamation landscape level (Ciborowski et al. 2013; Eaton et al 2014). Recommendations for landform design could ultimately be based on knowledge of the range and relative abundance of wetland types that maximize the ecological services provided at the level of entire hydrological response units.

9. OUTCOMES AND IMPACTS

9.1 Project outcomes relative to Performance Metrics identified in the original application

9.1.1. Investment in 4 Core strategic Technology areas

Three project targets were proposed for this metric all of which were partially or completely achieved. The targets were:

Data-Enabled Innovation (Computing, Machine Learning, Data Analytics, Cloud Computing)
Digital Transformation for Business Innovation (Visualization, Geomatics , Geospatial Technology)
Clean technology (Water retention strategies)

The following performance metrics were met:

1. Computing – The BWRAP/BERA geospatial relational database has been created and is in a beta-testing phase. A State & Transition model was developed to predict successional trajectories & the probability of wetland persistence, and the anticipated diversity of vegetation ('success') under different scenarios.
2. Digital transformation – Drone high-resolution imagery was collected from or acquired for 109 of 119 wetlands sampled. Cloud computing was used to generate wetland & landscape digital surface models. RGB imagery from the remaining locations was acquired from other sources. Images were visually assessed to delineate the areal extent and shape of open water & vegetation zones. A statistical model was developed, using Sentinel I and II imagery and applied to delineate & infer inter- and intra-annual variation in open water area of 51 of the study wetlands over the study period. We also Identified environmental thresholds that sustain criteria for wetland 'success' (e.g. desired levels of biodiversity, carbon accrual, clean water storage). We anticipate that this will ultimately allow companies to design reclaimed landscapes that produce wetlands falling within the thresholds.
3. Water Retention Strategies - Field-collected data are still being analysed. We have determined evapotranspiration vs. Inflow estimates of various classes/ages/ landscapes to determine wetland features that maximize water retention. These architectures will be recommended to sponsors.

9.1.2 Field pilots/demonstrations

The project had proposed to conduct fieldwork on up to 120 wetlands to determine environmental and biological characteristics of waterbodies varying in landscape setting, age, size, permanence, water quality features and degree of riparian disturbance.

Between 2021 and 2023 we piloted proof-of-concept synoptic wetland assessment techniques leading to indices of wetland success assessed by proposed standard harmonized operating procedures. We located, ground-truthed and sampled 119 wetlands (40/year) to determine hydrology, bathymetry, water chemistry, terrain, riparian disturbance and biological community composition (microbes, mycorrhizae, vegetation, macroinvertebrates, avifauna).

9.1.3 Collaborators

Over the course of the program, we interacted with 26 academic or Government collaborators associated with 19 institutions. Eleven of these individuals became associated with the program after its inception. The remainder were included within the original program proposal. In addition, we collaborated (received detailed guidance or data from 9 industrial research personnel from 3 oil sands mining companies.

The following collaboration partners agreed to be involved with the program. Names of key individuals and (where appropriate) their role/expertise are listed in parentheses.

Collaborating Organizations:

Apex Resource Management Solutions, Ltd.
(Colin Daniel, Leonardo Frid, Diego Bilski; State & Transition modelling)
Alberta Environment and Parks
(Danielle Cobbaert - remote imagery & disturbance layers)
Alberta Biodiversity Monitoring Institute
(database harmonization)
Boreal Environment Reclamation Assessment program - BERA
(Greg McDermid; NSERC Alliance program)
Canadian Aquatic Biomonitoring Information Network (CABIN) programs
COSIA Land EPA
(Suncor (Jon Hornung Liaison & student mentor; Sarah Kohl-Smith GIS))
(Syncrude (Carla Wytrykush Liaison & student mentor; Ararat Cheema GIS; Jessica Piercey water quality & student mentor))
(CNRL (Jeremy Reid Liaison; Devon Versnick-Brown Liaison; Rob Vassov field guidance; Joanne Hogg, field guidance)
Environment & Climate Change Canada, National Hydrology Research Lab
(John Headley, Ian Vander Meulen; acid-extractable organic compound analysis).
Innotech Alberta
(Jean Birks - stable isotopes; grad student coadvisor)
Keyano College
(Dana Schock; proposed - source of interns for summer training)
LGL Limited
(Vigil Hawkes – remote sensing imagery- Suncor lease area opportunistic wetlands)
McMurray Métis
(Ronald Lake Bison Herd community monitoring team)

Home institutions of collaborating individual researchers:

Athabasca University
(Scott Ketchison; hydrology, especially surface-groundwater interactions; postdoctoral scholar coadvisor
Mount Royal University
(Felix Nwaishi; water quality & reclamation strategies; grad student coadvisor)
Thompson River University
(Jabed Tomal; statistical analysis)
University of Alberta
(Kevin Devito, hydrology & wetland survey data; Erin Bayne, avifauna)

University of Calgary

(Jan Ciborowski; early successional development, former PI; Peter Dunfield, microbial ecology; Douglas Muench, microbial processes; Faramarz Samavati, modeling wetland persistence; Greg McDermid, coordinating geodatabase development; remote sensing, Eve Robinson, zooplankton)

University of Lethbridge

(Laura Chasmer; remote sensing; grad student coadvisor)

University of Waterloo

(Rebecca Rooney; State & Transition modelling; fuzzy cognitive mapping)

University of Windsor

(Christopher Weisener, biogeochemistry & microbial genomics)

Southern Illinois University

(Dale Vitt; wetland vegetation)

Colorado State University

(David Cooper; wetland vegetation)

9.1.4 Publications

The BWRAP initiative had proposed to produce a total of 50 peer-reviewed publications in addition to 5 conference proceedings. To date, BWRAP has generated 132 publication units, the great majority of which are theses, technical reports and contributed conference abstracts and presentations.

Because the overall findings represent the synthesis of data collected over 3 field seasons, most data elements have only recently been compiled an interpreted and are now being prepared for submission as publications. BWRAP hosted and recorded the proceedings of 4 symposia attended by collaborators, industry sponsors and other interested individuals. Three of these were summaries of fieldwork activities and findings following the 2021,2022 and 2023 field seasons (program and video links outlined in Appendix 2). Additionally, the rationale and methodology associated with developing the BWRAP state-and-transition simulation model to predict possible trajectories of wetland hydrological and ecological condition were presented in a course format in the form of 6 online lectures in Fall 2023/winter 2024 (summarized in Appendix 3). The model was populated with BWRAP data in 2025 as data were compiled, and a proof-of-concept demonstration of the model and some preliminary findings were presented in an online meeting in November 2025 (Appendix 3).

The 132 publication contributions completed to date include the following

1 peer-reviewed publication (multiple publications in prep.)
4 conference proceedings/symposia
16 research and technical reports
9 M.Sc. theses
15 undergraduate theses and major papers.
15 Invited seminars and addresses
52 contributed conference presentations
20 Graduate and Undergraduate student seminars

Please see Appendix 4 for full bibliography.

9.1.5 Students Trained (M.Sc., Ph.D., Postdoc) & Jobs Created

The BWRAP initiative had proposed that 36 students would be trained comprising, 50.33 student years. The students were to have been a combination of undergraduate, M.Sc., and Ph.D. students and Postdoctoral/Research Associates. The limitations on travel and associated restrictions imposed by the COVID-19 pandemic greatly limited the program's ability to recruit graduate students – especially at the Ph.D. and postdoctoral levels. However, this limitation was more than compensated for by successful recruitment of senior undergraduate and Masters-level students from local universities, largely at the recommendation and with active assistance of BWRAP collaborators,

Ultimately, 57 highly qualified personnel were trained, representing the following groups:

10 undergraduate research assistants
15 undergraduate thesis/major paper students
9 M.Sc. Students
18 Research technician positions
5 PDF/Research Associates

Please see Appendix 4 for a full listing of students trained and their research activities.

In terms of employment (jobs created) 3 limited-term positions were created and maintained over the course of the program - 1 database programmer (2022-2025) (shared - continuing), 1 GIS manager (2022-2025) (shared - continuing), 1 administrative manager (part-time; 2020-2025). Please see Appendix 4 for a full listing of individuals and their responsibilities.

9.1.6 Changes or updates to performance metrics and driving forces

The BWRAP evaluation format was originally proposed to consist of a series of presentations and assessment workshops, engaging with participation of a broad range of industrial, academic and other members of the CWRIG. Significant socioeconomic events occurred during the 6-year period of the BWRAP program, including quarantines imposed by the COVID-19 pandemic, institutional reorganization, and regulatory, and reporting policies. These restrictions greatly limited opportunities for creating and engaging with a CWRIG Community of Practice. Consequently, the findings described above as the outcomes and recommendations outlined below have not had the benefit of review or input from the extensive suite of collaborators, colleagues and industrial scientists who would otherwise have contributed to the completion steps and syntheses. It is anticipated that these individuals will be engaged as the remaining analyses are completed and presented in suitable forums. Their perspectives and review comments will be welcomed and adopted as appropriate at that time.

10. OUTCOMES AND BENEFITS

Industrial Relevance and Benefits: The preliminary findings of the BWRAP program have advanced our knowledge and understanding of the status and some of the key processes and ecological states associated with early succession in wetlands forming in landscapes undergoing reclamation in the boreal zone. The detailed analyses and assessments of the effects of environmental stressors on biological communities conducted to date have identified important drivers of the composition of these young communities. Few, if any, other studies have undertaken a coordinated comparative

and functional approach that attempts to both predict the status and validate predictions about the future states of young wetlands according to a regional monitoring approach.

Following completion of our analyses, the summary and reporting of successional changes among wetland age-classes and their classification as 'successful' or not will be of tremendous value in allowing oil sands lease holders to evaluate the effectiveness of their efforts to build self-sustaining wetlands in reclamation landscapes. It is anticipated that the final recommendations will provide evidence to both define 'success' with respect to developing self-sustaining and biodiverse wetlands in the boreal region, and will help identify the resources, time, and adaptive management actions that may be needed to ensure that success is achieved. This is essential in allowing oil sands mining companies to calculate the costs of re-establishing a viable landscape for closure and of generating credible assessments of the effectiveness of those efforts.

Companies engaged in oil sands mining and in situ activities must outline how they will reclaim the land upon closure. However, there are currently only limited quantitative standards against which to measure the biological success of wetland reclamation efforts. The BWRAP initiative has used the Reclamation Assessment Approach to create such a framework, in collaboration with Canada's Oil Sands Innovation (Pathways Alliance), which will directly benefit from the framework and its implementation.

It is anticipated that COSIA's member companies will be able to apply the RAA framework to measure the success of wetlands in reclamation landscapes within their lease areas, and determine when intervention could be undertaken to ensure wetlands' ecological success. Although developed as a proof-of-concept for wetlands, the paradigm is amenable to use in predicting the ecological viability of young ecosystems developing on other landforms as well (including terrestrial and lake features). In addition, BWRAP has trained 57 new highly qualified personnel who have gained a unique understanding of the AOS region, the reclamation field assessment process, and technical skills surrounding the newly developed framework. BWRAP's collaborative efforts with COSIA and other academic and industrial partners have provided a new cohort of HQP possessing a unique skillset. They are currently contributing to the workforce and are already demonstrating potential to become leaders in their field. Over its 5-year term, BWRAP engaged 9 M.Sc. students, 15 undergraduate thesis/major paper students, 10 undergraduate research assistants, 18 research technician positions and 5 PDF/Research Associates. The knowledge gathered and IP created has generated 132 publication units including theses, technical reports, conference presentations, and manuscripts (see Appendix 4), most of which will be incorporated into peer-reviewed publications over the next 2-3 years.

11 RECOMMENDATIONS AND NEXT STEPS; Objectives for next cycle

Over three field seasons the BWRAP initiative collected a wealth of environmental and biological data. Preliminary analyses to date have demonstrated the range of natural variation in environmental features among wetlands, and have identified or verified the attributes most important in determining biological conditions and function. Nevertheless, significant elements of the data set are still being compiled or synthesized and must be quality assured before being integrated into the geospatial database. The BWRAP members and collaborators are actively engaged in the synthesis and writing processes to integrate the findings to create a final set of conclusions and recommendations. We anticipate that data compilation will be completed by early fall and will have been compiled and made available through the geodatabase by the end of fall 2026. In parallel, those data will be used for additional simulations conducted using the State and

Transition Simulation model to more confidently predict the characteristics of wetlands within reclaimed lease areas over the next 75 years. BWRAP intends to summarize and present its findings-to-date at a Workshop or Symposium at the end of 2026, ideally in partnership with COSIA.

11.1 Next steps and recommendations for further advancement of knowledge generated

The BWRAP has documented the range of variation in a large population of wetlands of varying ages forming in reclamation landscapes. BWRAP has provisionally identified thresholds for two key stressors - water quality and permanence - that constrain the biota forming the communities of those systems. In addition, the research undertaken has assessed the landscape features and wetland morphometry contributing to those stressors. We anticipate that this knowledge can ultimately help guide the landform architects and geotechnical engineers who design reclamation landscapes to create designs that will promote the formation of wetlands with functional capability equivalent to the original landform. The quality and certainty of these preliminary findings would greatly benefit from the development of a second phase of BWRAP to allow further detailed analysis, interpretation and synthesis of the unparalleled dataset created to date. Efforts are being made to maintain the current collaborations. It is hoped that additional potential partnerships can be realized to advance the development and learnings from this project.

Short-term completion recommendations:

- Analyse and incorporate the remaining logger data for water level (permanence), conductivity (permanence and water quality), and DO (productivity and water quality)

- There is still a need to refine (train) and validate indices of wetland permanence, water quality and riparian disturbance.

- Refine the predictions of the STSM model by adjusting the boundaries of the permanence and water quality class states. Furthermore, ongoing work will continue to define the categories and boundaries of the disturbance quality states.

- Work with industry partners to acquire supplemental, historical and contemporary UAV and LiDAR data for reclamation areas. BWRAP collected single-visit high quality UAV imagery of the open water and immediate surroundings of most study wetlands. This permitted us to develop digital surface models, but we lacked the data to create high resolution digital terrain models of the broader reclamation landscape.

- BWRAP was only able to monitor avifauna in one season. Completion of this work would provide considerable value to reclamation and mine closure planners. An alternate approach to generate data for incorporation into the STSM is to consider using existing survey data from selected time series and chronosequence studies (e.g. Dagenais 2009; Nakhaie 2013; Foster et al 2012. 2017) to develop that index.

- Create and run a spatially explicit version of the State-and-Transition Simulation Model that incorporates broader reclamation landform topography through the use of detailed digital elevation models.

Although the Oil sands mining companies file life-of-mine closure plans and annual updates with the Alberta Energy Regulator, the most recent landscape outlines of the companies' plans available to BWRAP were from 2016. Plans of this vintage did not recognize or delineate the potential for opportunistic wetlands to develop in upland landscapes. Accordingly, the current iteration of the State-and-Transition Simulation Model is not spatially explicit. The simulations performed treated the reclamation landscape as topographically homogeneous, and assigned wetlands to random locations within reclaimed area. However, more recent versions of closure plans do identify reclamation landforms designed to promote the formation of wetlands in upland areas. A useful 'next step' to assessing reclamation success would entail providing BWRAP with current predicted closure topography and more current closure plans. This would allow BWRAP to create a spatially explicit version of the model, which would improve the realism and utility of model predictions. Alternatively, BWRAP could use the geospatial dataset of the Suncor reclamation landscapes (described by Hawkes et al. (2025)) to spatially delineate the distribution of true wetlands and use the STSM to predict those changes. However, BWRAP lacks similar information for reference areas, which are necessary for comparative estimates. One possibility might be to use existing data to assess size-frequency distribution of wetlands in a chronosequence (or time series) of recently disturbed (i.e., burned) areas using Sentinel data (as per Biederstadt et al. 2025) or other available surveys. Hawkes and Gerwin (2021) compared the trajectory of increasing similarity of anuran, small mammal and bird community composition among mature, burned, logged and reclaimed forest stands of various ages. An assessment of wetland development and size-frequency distribution based on aerial photography might provide a suitable time series of wetland appearance and persistence that could be compared to the BWRAP-acquired information on relationships among wetland morphometry, water quality, permanence and biological diversity to infer local and cumulative landscape biodiversity.

Longer-term completion recommendations:

- Acquire a longer term chronosequence record that can track wetland development to a state of vegetation maturity in wetland riparian zones and catchments, perhaps by using imagery and automated assessment (Biederstadt et al. or ABMI) to examine wetland size-frequency distributions in a post-fire chronosequence (for reference benchmarks).

An important limitation of the BWRAP study is that its study domain was limited by the age of the oldest reclaimed landscapes.

- Contrast/compare chronosequence findings with time series assessments.

Relatively long (25-year) time series (water quality; perhaps permanence and selected biological surveys) are available for selected wetlands that were part of the BWRAP inventory (Natural Wetland, Shallow Wetland, High Sulphate, 4-m CT, Sand Pit, etc.). It would be informative to contrast these time series with the chronosequence portfolio of wetlands.

- Develop or support a mechanism to restore opportunities for in-person researcher/manager/industry gatherings to collaboratively develop and compare research needs and plans

A program like BWRAP is multidisciplinary and can't function optimally without a means of regular panel coordination. The consortium of oil sands companies have had remarkable achievements in proposing and undertaking landscape reclamation in numerous mined areas, including designing and creating the first world's full-scale, fen and water-capped lake prototypes. These initiatives have been successful because the industry researchers and project managers recruited and convened expert panels of scientists with diverse skills who collaboratively developed and assessed the methodology and research leading to the landforms' creation. However, the last 6 years have seen fewer opportunities to engage in that type of research-industry engagement. The gradual amalgamation of companies has led to loss of industrial researchers. Furthermore, travel restrictions caused by the COVD-19 pandemic, coupled with increasing use of technology that replaces in-person gatherings with remote meetings have also made it increasingly difficult to foster the level of continued engagement that has previously been so effective. It is hoped that supporting organizations will work to restore opportunities for open forums and restore a community of practices that can both encourage and facilitate the sorts of transdisciplinary collaboration that has been so effective. The collaboration should also support participation of interested Indigenous communities and their Knowledge Holders to provide opportunities for inclusion of Indigenous Knowledge research methodologies and cross-cultural learning and knowledge exchanges.

- Return to available data (& literature) to get a best estimate of initial peatland formation & sustaining conditions; we know from literature that limits are variability in water level and water quality; mosses are important indicators of incipient peatland development; perhaps suggest a community-based monitoring program to assess early signs consistent with peatland early stages, , including approaches to promote the establishment of peatland mosses on mineral / semi-terrestrial soils;

Efforts to engage with Indigenous communities was met with limited success; We approached 7 communities & meet to discuss collaborations with 3 groups. Ultimately, BWRAP was able to develop meaningful interactions with McMurray Metis and provide support and reciprocal engagement to sample wetlands within the range of the Ronald Lake Bison herd, providing them with water quality data, used by BWRAP as reference information. Efforts to recruit summer interns from Fort Mckay First Nation were unsuccessful due to logistical limitations. Ultimately, efforts to build stronger collaborations will likely need a longer period of integration.

- Develop a long-term strategy for archiving the physical samples collected (specimen curation, reference collection, bulk samples and original data sheets. We need a similar strategy for housing and maintaining the geodatabase.

- Integrate individual wetland measures to assess 'success' at the Hydrological Response Unit (HRU) level.

The program was directed to understanding wetlands' hydrological, geological and biological features and their interactions as a function of 4 key attributes: age, permanence, water quality, disturbance. Accordingly, wetlands were selected using a factorial design to the extent possible, rather than matching study systems to the frequency distribution of existing wetland sizes, ages and classes. This design was employed to generate a relatively balanced dataset that could be

used to populate the STSM and infer likely changes in wetland features as they age. However, it was not a representative survey (unlike studies of Devito et al. 2019 and Hawkes et al. 2018; 2025). Furthermore, the limited duration of the study and availability of candidate wetland data necessitated using a chronosequence rather than a times series approach. The limitations of this design have been well reviewed (Johnson and Miyanishi 2008; Walker et al. 2010; Banet and Trexler 2013).

One of the key findings of our work was that the morphometry and landscape context (placement materials and surface substrate) of study wetlands exert a greater effect on biological features than time since a wetland's genesis. This likely is partly a reflection of the relatively young age of the lease-area landscapes since reclamation of open pit mining began. Farnden (2021; 2023) observed that the accrual of upland vegetation biodiversity in reclaimed landscapes was only around 50% of the species richness of reference mature forest stands. In retrospect, it appears that the existing reclamation landscape has not aged enough to provide for complete establishment of a mature ecosystem. Although we recognize that the rising E/T demands of maturing landscapes are expected to alter wetland water balances enough to possibly alter wetland permanence classes (Vitt et al. 2012), the time series over which this apparently occurs exceeds the age of the oldest study wetlands.

Mature peatlands have a post-fire disturbance-recovery time averaging 123 years (Wieder et al. 2009; Nelson 2018), during which time they initially lose but eventually recover their carbon accrual balance capacity. This timeframe is 3 times the age of the AOS post-mining reclamation landscape. Ultimately, most boreal wetlands of indeterminate age gradually accrue sufficient organic material to become peatlands. The key determinants of peat-forming community establishment are stable water levels and relatively low salinity (Zoltai and Vitt 1995). Our preliminary analyses to date suggest that neither of these attributes are characteristic of the study wetlands that have formed in reclamation landscapes. These findings are expected to be corroborated by our detailed analyses of water level loggers documenting daily and intra-annual water levels.

Thus, three remaining avenues of investigation are to

a) develop an unbiased and more extensive dataset from which to estimate of the size frequency and relative permanence distribution of wetlands present in young landscapes; and

b) study a series of landscapes that can provide a longer chronosequence or time series of time since genesis.

c) Broaden the scale of analysis and measures of success from that of individual wetlands to the Reclamation Landscape (hydrological response unit) scale.

BWRAP's study design concentrated on the condition of individual wetlands even though wetlands are nested within HRUs and connected hydrologically and biologically. A continuation or second phase of BWRAP should consider expanding to a landscape scale of assessment. The biologically successful landscape should likely have a spectrum of wetland permanence classes promoting landscape biodiversity; In early years, Sandhill has higher biodiversity than reference wetlands, reflecting heterogeneity of microhabitats. This was seen in the vegetative diversity of the BWRAP chronosequences.

Perhaps the most practical and promising approach would be to use remote sensing records of boreal landscapes subjected to wildfires or clearcutting at various periods of time. Extensive historical records of these events occur in boreal Alberta. Although State and transition (and other) modeling has been proposed to study such events (Frid and Daniel 2012), the research has emphasized time trends in the forest vegetation rather than wetland landscapes.

Analysis of the data to date suggest that biota of wetlands in reclaimed landscapes are broadly similar to the biota of wetlands in reference landscapes that correspond in measures of water quality and permanence; however reclaimed landscapes support wetlands that have broader ranges of water quality and variation in permanence that result in communities that would not be considered equivalent to reference. Completion of data analysis and interpretation, and the inferences tested through refined State-and-Transition Simulation Modelling is expected to refine and corroborate these preliminary conclusions and provide predictions that may lead to refined guidelines for wetland assessment and recommendations for creating diverse and self-sustaining wetlands in landscapes reclaimed from oil sands mining.

12. KNOWLEDGE USE AND DISSEMINATION

12.1 Knowledge Use:

Numerous tools created through the BWRAP have potential for uses beyond the scope of oil sands wetland remediation. For example, the stressor and biological response indices could be used to support regional monitoring efforts (e.g., Oil Sands Monitoring; Mahoney et al. 2022; Cobbaert et al. 2025; coordinated by Alberta Environment and Parks' Environmental Monitoring and Science Division) and could ultimately be expanded for use by other provinces and at a national level. Indeed, the boreal region represents 60% of Canada's land area. Improved reclamation outcomes also support Government of Alberta policy objectives as articulated in the Alberta Research and Innovation Framework (https://www.alberta.ca/assets/documents/arif-report.pdf), specifically to conserve biodiversity, restore Alberta's landscapes and manage water sustainably.

BWRAP was able to engage with several First Nation and Métis Nations, and established a working partnership to assist with one ongoing community-based monitoring initiative. In the longer term, BWRAP is anticipated to create additional benefits for First Nations and Métis peoples by refining the newly-developed biological indicators of ecological condition that can be used to anticipate the success of reclaiming land to its natural condition for traditional use, community engagement, and utilization of traditional ecological knowledge.

It is hoped that the findings, monitoring approaches and analytical techniques developed or validated by BWRAP will create positive impacts beyond the province of Alberta, as many industrial and resource-based initiatives create large tracts of disturbed land across the country. Indeed, the boreal region represents 60% of Canada's land area. The Reclamation Assessment Approach has tremendous potential to be applied in other landscapes and biomes and can potentially serve as a guide for developing monitoring programs and measures of success tailored to the unique stressors and biological response variables of each system. It therefore presents an opportunity to improve the environmental impact of resource-based activities across the country.

Canadians, specifically Albertans, have developed and are implementing a province-wide Wetland Policy, aimed at maintaining our valuable wetland resources. The findings of BWRAP have contributed to that initiative, specifically in expanding the ability to measure and understand our wetland resources, and perhaps in ultimately re-defining the way we consider wetland restoration timelines and endpoints in a variety of disturbed landscapes. It is in Canada's best interest to show the world that mining companies are able to return wetlands to their pre-disturbed state. This will instill worldwide confidence in our oil sands and broader mining industries as a proactive sector, led by the most Highly Qualified Personnel and as a socially responsible place in which to invest.

12.2 Knowledge Dissemination

Appendix 4 summarizes the information units derived to date. It includes 15 undergraduate and 9 graduate theses, but only 2 peer reviewed publications to date. BWRAP researchers are completing numerous manuscripts and anticipate submission of 3-5 more publications in 2026. Others are at the conceptual stage of development (Appendix 5). Over 20 publications are expected to be completed and disseminated over the next 2-3 years as model results are finalized.

Any continuation of the BWRAP would benefit from a funding source that could promote open access publication of manuscripts. The potential for integration of BWRAP with other monitoring organizations, such as the ABMI or Oil Sands Monitoring program could be an avenue for continuing the program, but would depend on confidentiality considerations.

Current results are expected to be presented at regional, national and international Symposia as opportunities arise. In 2026, abstracts for presentation have been submitted or are in preparation for The Society of Canadian Aquatic Scientists/International Association for Great Lakes Research (May, Winnipeg MB), Canadian Ecotoxicity Workshop (October, Saskatoon, SK), International Mine Tailings Conference (December, Edmonton, AB); COSIA Wetland Working Group (provisionally; November, Calgary, AB), and a final summary/synthesis presentation organized by COSIA (provisional; December, Calgary, AB). Continuing collaborations are anticipated with existing collaborators, COSIA members and especially with the new Alberta Wetland Community of Practice (Nwaishi et al. in prep)

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LIST OF APPENDICES

Appendix 1 - Gantt Chart of BWRAP Activities January 2026

Appendix 2 - BWRAP Recaps of Summer Field Seasons 2021-2023 - Programs & Video Links

Appendix 3 - BWRAP-STSM-Course-Links

Appendix 4 - list of communication exercises (March 2026)

Appendix 5 – provisional list of publications in preparation (January 2026)