Yukon

MR-25-02

Application of a reference condition approach to characterize wetland recovery after placer mining disturbance

March 2025

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Government of Yukon
Fish and Wildlife Branch
MR-25-02

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Acknowledgements
This project would not have been possible without the collaborative work of the Fish and Wildlife Branch, Compliance Monitoring and Inspection, and Environment and Climate Change Canada.

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Suggested citation:
Willier C. 2025. Application of a reference condition approach to characterize wetland recovery after placer mining disturbance. Yukon Fish and Wildlife Branch Report MR-25-02, Whitehorse, Yukon, Canada.

Abstract

The Indian River watershed, a tributary of the Yukon River, has been an area of focused placer mining activity for more than a century, resulting in the loss or conversion of natural wetland ecosystems in the region. This study evaluates the health and recovery of post-placer mining open water ponds using a combination of the Reference Condition Approach (RCA; with benthic macroinvertebrates as indicators of ecosystem health) and a suite of simple wetland health metrics. We compared 16 open water sites, including natural wetlands, disturbed wetlands and placer ponds ranging in date of creation from 1984 to 2019, to understand their recovery trajectories. Placer mining has traditionally resulted in a reduction of the abundance of bog, fen and swamp wetlands, with areas converted to a mosaic of disturbed upland areas and open water ponds. Our study highlights the limitations of the RCA in fully capturing the substantial landform and functional changes caused by mining. We suggest that simpler, more efficient metrics could offer comparable insights. Ultimately, only 3 placer ponds studied were similar enough to the reference communities to be considered in reference. Moving forward, restoration efforts focused on establishing peat-accumulating wetlands may be more suitable for the recovery and long-term ecological health of the Indian River watershed.

Contents

Introduction

Wetlands are globally recognized for their essential ecosystem services, including water purification, carbon sequestration, flood control, and the provision of critical habitats for diverse flora and fauna. However, these systems are increasingly threatened by human activities that disrupt natural hydrological and ecological functions. In the Yukon, resource extraction is a primary driver of wetland loss, degradation and alteration, with placer gold mining standing out as a major driver of wetland change in the Klondike Goldfields.

The Indian River, a tributary of the Yukon River, lies within the Klondike Plateau ecoregion, south of Dawson City in the central portion of the territory. Mining activity has been occurring in this area for more than 125 years and today remains among the most productive for placer mining districts in the Yukon. Placer mining is a type of mining that involves extracting gold from stream bed (alluvial) deposits, often stripping unconsolidated sediment from large areas to reach ancient gold-bearing stream sediments. While the surrounding upland forested landscape of the Klondike Plateau remains largely intact, placer mining activity often overlaps, and therefore impacts, wetlands that formed in valley bottoms. In the Indian River valley, placer mining has converted impacted valley bottoms to a mixture of disturbed gravel-rich landscapes, interspersed with roads, artificial stream channels and shallow depressions which passively fill with water. Emergent marshes and open water habitats often develop where peatlands once existed, leading to the creation of wetland types that are naturally scarce in the Klondike Plateau but have become locally abundant along the Indian River due to the mining activities. Some ponds develop aquatic vegetation and are ringed by shrubs and trees, suggesting the potential to accumulate organic matter and eventually regenerate into peatlands. However, other ponds remain unvegetated, consisting mostly of exposed gravel substrate. To assess the effects of this conversion, we require a methodical monitoring program that can assess, evaluate and compare wetlands for the purpose of evaluating recovery of post-mining wetlands.

Wetland health assessment and evaluation refers to the process of measuring and determining the ecological condition, function, and overall health of a wetland ecosystem. This evaluation helps understand how well a wetland is functioning in terms of its ability to support biodiversity, store water, filter pollutants and provide habitat for wildlife. It can also assess the degree of human impact or disturbance on the wetland. There are many approaches to wetland evaluation that range from measuring a suite of variables, to measuring a single indicator. Developing an environmental monitoring program for Yukon wetlands requires an understanding of a) the indicators to assess aquatic ecosystem health, b) the study design to assess changes in these indicators, and c) the thresholds to determine when a change has occurred (Dubé 2003, Bailey et al. 2004, Kilgour et al., 2006). The selection of indicators to monitor environmental health depends, in part, on the underlying environmental protection goals and how those goals are interpreted (Munkittrick et al. 2000).

In 2008, we commissioned a review of methods for monitoring and assessing wetland health in the Yukon. The report (Reynoldson and Bailey 2009) recommended the testing of the Reference Condition Approach (RCA), which uses benthic macroinvertebrates as biological indicators of wetland health. Benthic macroinvertebrates are found in nearly all aquatic systems and are highly sensitive to anthropogenic stressors such as elevated sediment levels and pollution (Seakem Group Ltd., 1992; Mathers et al., 2017). Their abundance and species composition respond quickly to environmental changes, making them effective indicators of ecosystem health. Additionally, they are relatively easy to sample and analyze, which has led to their widespread use as one of the most reliable tools for assessing the health of aquatic systems.

The RCA is a widely accepted monitoring method used in national programs across Canada, Australia, and the UK. It is also recognized under Canada's federal Environmental Effects Monitoring (EEM) program. The RCA benefits from access to Environment and Climate Change Canada's Canadian Aquatic Biomonitoring Network (CABIN) online data system, which reduces technical effort and facilitates the integration of wetland and stream data (Environment Canada 2013).

To evaluate the utility of the Reference Condition Approach for evaluating wetland recovery in the Yukon, we conducted a study focused on comparing human-made ponds formed by placer mining, to natural open-water wetlands within the Indian River watershed. The human-made ponds we selected range in origin from 1984 to 2019; offering a 35-year time span to examine the differences in recovery trajectories. In this context, we evaluated whether benthic invertebrates, assessed through the RCA, could serve as effective indicators of wetland health, and identified the environmental factors that may influence the recovery of these human-altered wetlands.

Methods

In July 2021, we surveyed 16 open water wetland sites in the Indian River watershed (Figure 1). Our sample included 5 natural undisturbed wetlands, 2 natural disturbed wetlands, of which one was an old exploration site in a swamp riparian zone and the other a natural open water wetland that was being drained for future placer operations. We also surveyed 9 human-made placer ponds which range in year of origin from 1984 to 2019. We chose sites using the ABoVE: Landsat-derived Annual Dominant Land Cover (Wang et.al. 2019) and satellite imagery. Our goal was to include a wide range of origin-times for artificial ponds. We also drew upon the Yukon wetland database (100 sites) for our analyses by including data from 70 open water wetland reference sites, sampled between 2010 and 2021, from across the southern and central Yukon (Figure 2).

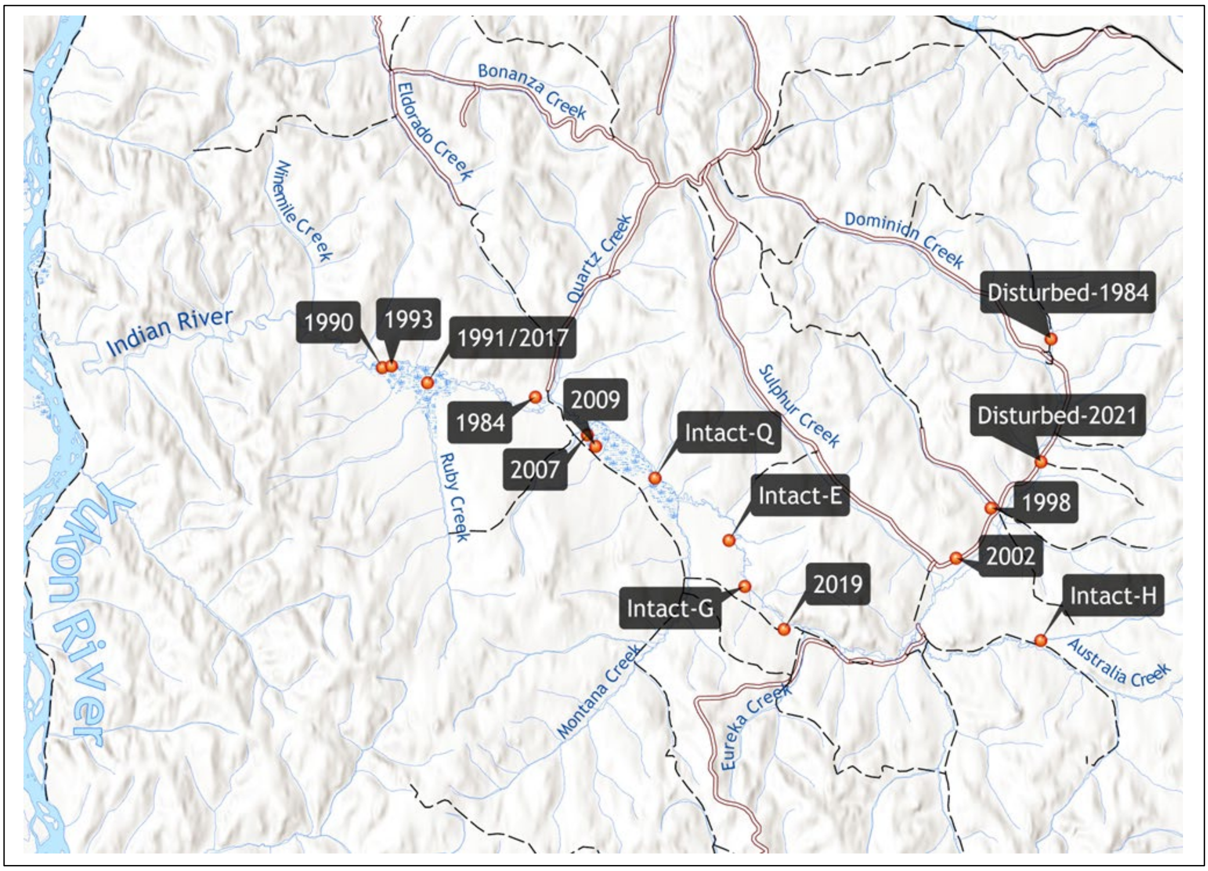

Figure 1. Sample locations in the Indian River valley. Sample site Intact-A has been removed from this map to protect the location due to its value as a mineral lick location for wildlife.

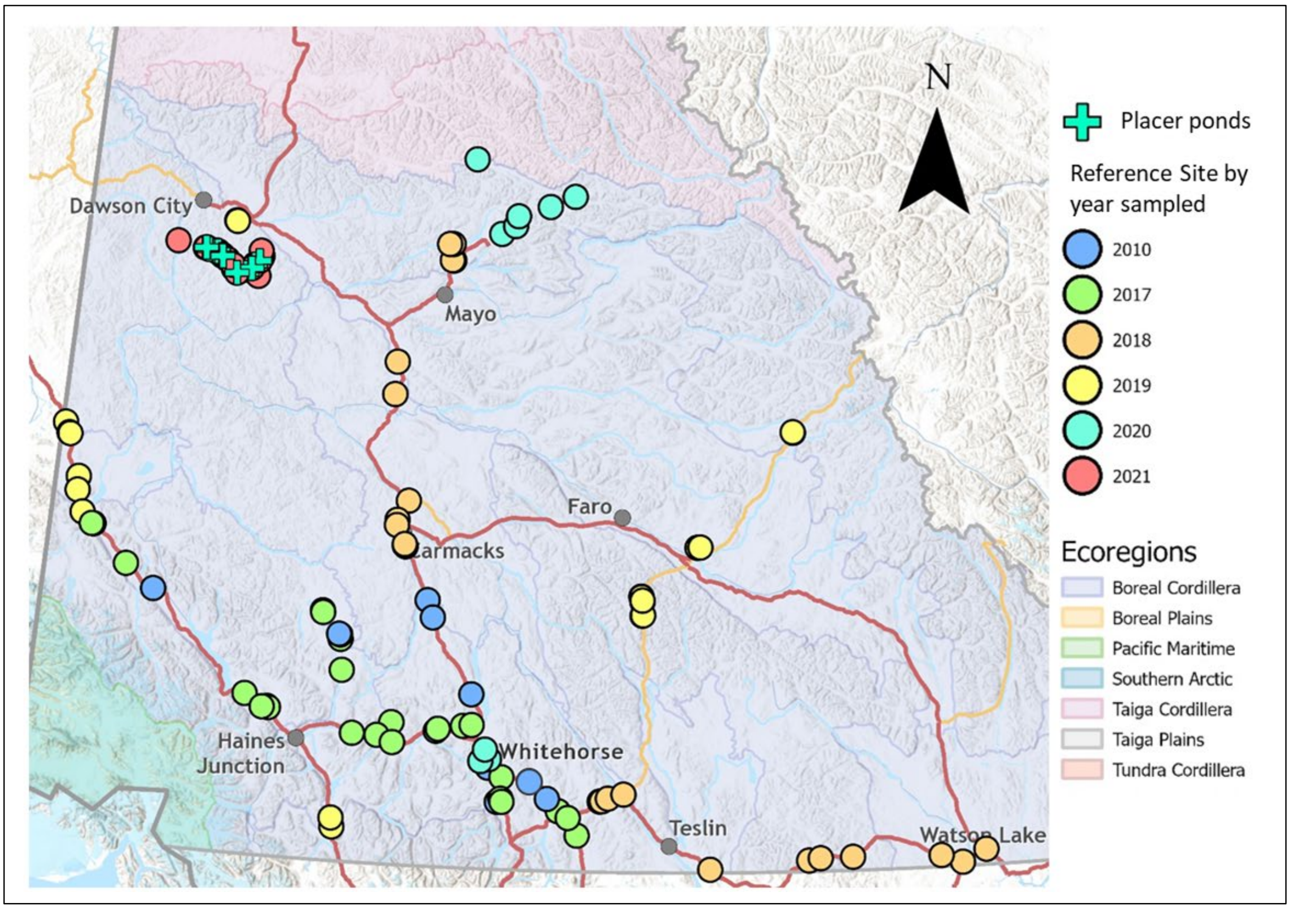

Figure 2. Yukon Wetland RCA reference wetland sites. Reference sites are indicated by solid circles (coloured by year sampled) and test sites are indicated by crosses.

Field measurements

Each of our study sites consisted of a shallow open water feature and included a 100 meter buffer around the wetted perimeter. Following the Preliminary Wetland Aquatic Biomonitoring Data Collection Manual (Bailey and Reynoldson 2009), at each site, we collected macroinvertebrates with a 500 µm dip net, collected water and soil samples for lab analysis, measured in-situ water chemistry with a multimeter, characterized vegetation cover and composition, measured water bathymetry, and collected drone imagery (see Appendix 1: Table1 for a list of variables collected at each site). We used a transect-based approach to characterize habitat and biota between, and within, wetland zones. We focused on two zones: the submergent and emergent zones.

The submergent zone is defined as the wetland area that has permanent standing water with < 10 % emergent vegetation cover and up to 2 m in depth. Submerged plants grow entirely under water and some species may have floating leaves or flowering structures that extend slightly above the surface. Non-rooted, floating vegetation may also be present in this zone.

Emergent zone is defined as the wetland area that has water present above the soil surface throughout most of the growing season during most years and ≥10% emergent vegetation cover. Emergent plants are rooted under water but most of their developing structures extend well above the water surface. In the Yukon, this zone often includes Swamp Cinquefoil (*Potentilla palustris*), Water Horsetail (*Equisetum fluviatile*) and Buckbean (*Menyanthes trifoliata*).

These zones typically form a radial pattern with rings forming on the gradient between open water and upland. We conducted wetland biomonitoring by dividing the wetland into 4 transects and sampling 1 submergent plot and 1 emergent plot along each of these transects (Figure 3). We then combined all the samples from each transect to make one representative sample for the emergent zone and one for the submergent zone. We collected macroinvertebrates separately from the submergent and emergent zones, because they differ in their species composition.

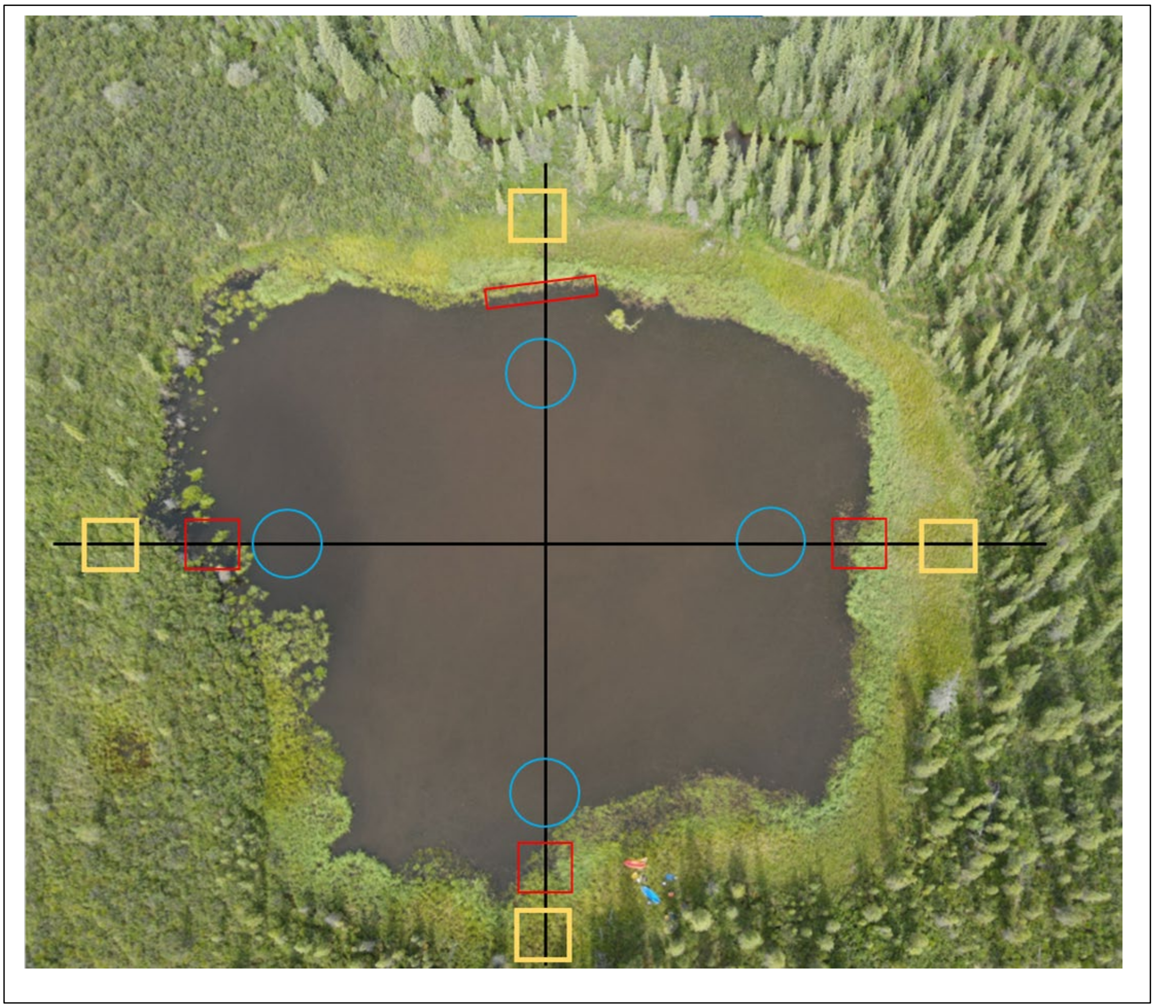

Figure 3. Vegetation, invertebrates, water bathymetry and water chemistry were measured along four transects at each site. Blue circles are submergent plots, red squares are emergent plots and yellow squares are marginal plots.

GIS measurements

We derived several habitat variables using a geographic information system (GIS). For each site, we determined elevation and delineated the catchments (the upslope area that drains into the wetlands). For each catchment, we determined the percent land cover type, percent bedrock geology, climate normal (mean annual temp (°C), difference between mean temperature of warmest month and mean temperature of coldest month, and summer mean temperature) and the area burned by decade (Appendix: Table 2).

We also calculated additional variables within a 100 m buffer around each sample site. Using a combination of drone and satellite imagery we measured the percent of buffer consisting of exposed gravel (no vegetation), road or anthropogenic structures. We also extrapolated carbon content, within the buffer, based on wetland area. We used known average values for each wetland type: 0.095 g/cm^3 fens, 0.067 g/cm^3 for bogs, 0.123 g/cm^3 swamps, and 0.004 g/cm^3 in regenerating forest or shrubs (Loisel et al. 2014). In disturbed landscapes, we considered above ground biomass the primary contributor to carbon (Kurtz et al. 2013.) and assigned exposed gravel a carbon content value of zero.

Comparison

We compared the relative amounts of ecologically beneficial wetland characteristics (carbon, invertebrate abundance and species richness, plant cover and species richness, and non-gravel surfaces) and used these metrics to evaluate if the placer ponds had similar values for wetland health. We then compared key variables (soil texture, carbon, conductivity, total suspended solids (TSS), total dissolved solids (TDS), nitrogen, max depth, bank slope) that we selected based on ecological drivers presumed as potentially beneficial to biotic life for invertebrates and vegetation.

Next, we applied the RCA approach to assess ecological function in the placer ponds. With the RCA, we compare the benthic macroinvertebrates community of a potentially stressed ecosystem with that of unstressed reference sites that have similar environmental conditions. These reference sites use invertebrate taxonomic assemblage as a surrogate of community structure to describe the condition of the biological response variable.

To conduct the RCA, we collected benthic macroinvertebrates from natural undisturbed wetlands reference sites that characterize biological conditions in a range of natural states. At these sites, we measured key habitat variables that influence species occurrence including pH, nitrogen, specific conductance, dissolved oxygen and temperature. Similarly, we collected benthic macroinvertebrates and measured the same habitat variables from human-made placer ponds. From these two data sets, we created a predictive model that matched the observed pattern in the biological assemblage with conditions that describe a similar pattern in the habitat attributes (Reynoldson 2022; Appendix 1: Table 2). By measuring habitat characteristics unaffected by disturbance, we were able to select a set of reference sites to which a test site is compared; we call these reference groups. This allows us to determine the biota expected to be present for a given set of habitat conditions. Using this model, we determined the reference group using a Discriminant Function Analysis (DFA) to place the wetlands into the reference groups based on the variables in the RCA model. We compared each test site against its matched reference group using a Non-Metric

Multidimensional Scaling (NMDS) ordination, which is a multivariate statistical technique used to visualize and analyze the similarity of benthic macroinvertebrate communities.

The deviation between the biota observed at a test site and the expected biota under reference conditions is expected to measure the impact of human activity on the ecosystem (Bailey et al. 2004).

Results

Ecologically beneficial wetland indicators

We compiled collective statistics for the 16 shallow open-water sites. We created two visual representations of each site. The first is a composite of 6 wetland variables that contribute to healthy wetland ecosystems, represented as a hexagon (Figure 4). Each point on the hexagon indicates the relative value of each variable: carbon, insect abundance, insect species richness, plant cover, plant species richness and non-gravel surface (NGS) coverage. Hexagons that are wider and more even, indicate healthier wetlands. Overall, the intact wetlands scored higher in most categories. Most of the newer placer ponds, created between 1998 to 2019, scored lower in all 6 categories.

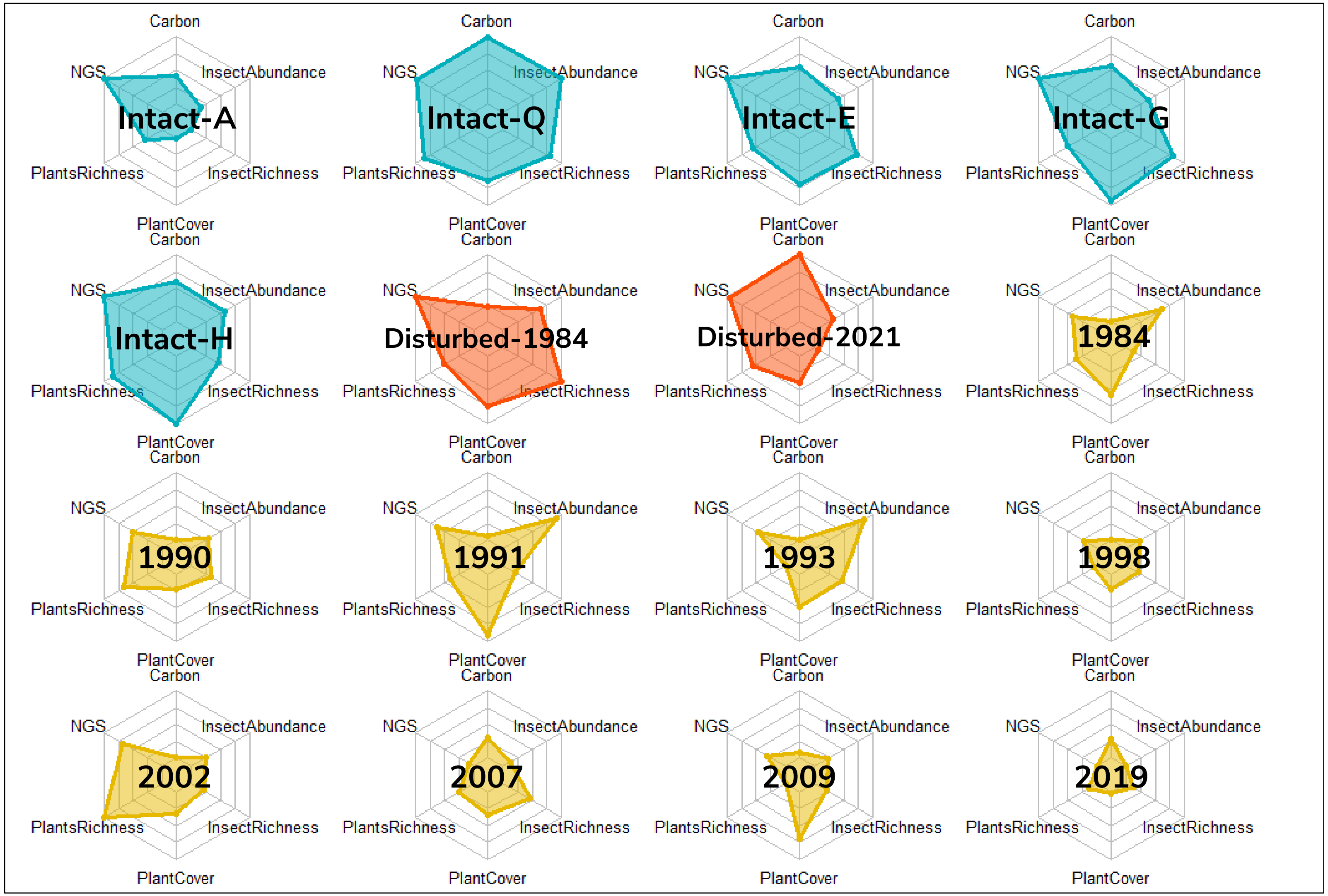

Figure 4. Radar plots of wetlands (natural: blue, disturbed: orange) and placer ponds (yellow) with explanatory variables that are generally considered valuable ecological features in wetlands: carbon, insect abundance, insect richness, plant cover, plant richness and non-gravel surfaces (NGS).

The second visual representation we created is a composite of variables that affect benthic macroinvertebrates, in the form of a heptagon (Figure 5). These variables influence the type and abundance of benthic macroinvertebrates but on their own, these values do not indicate wetland health. Each point on the heptagon is a score for the following 7 variables: soil texture, bank slope, max depth, nitrogen, TDS, TSS and conductivity. Human-made placer ponds and natural wetlands similarly had very low to insignificant levels of heavy metals, so we chose not to include this metric in the comparison analysis. The variables we used are generally considered influential for the suitability of the wetland habitat for benthic macroinvertebrates (Bailey et al. 2004). Round and medium-sized heptagons indicate the wetland has good conditions for invertebrate life whereas large spikes indicate extreme conditions. For example, the site named Intact-A, had very high specific conductance, indicating saline conditions.

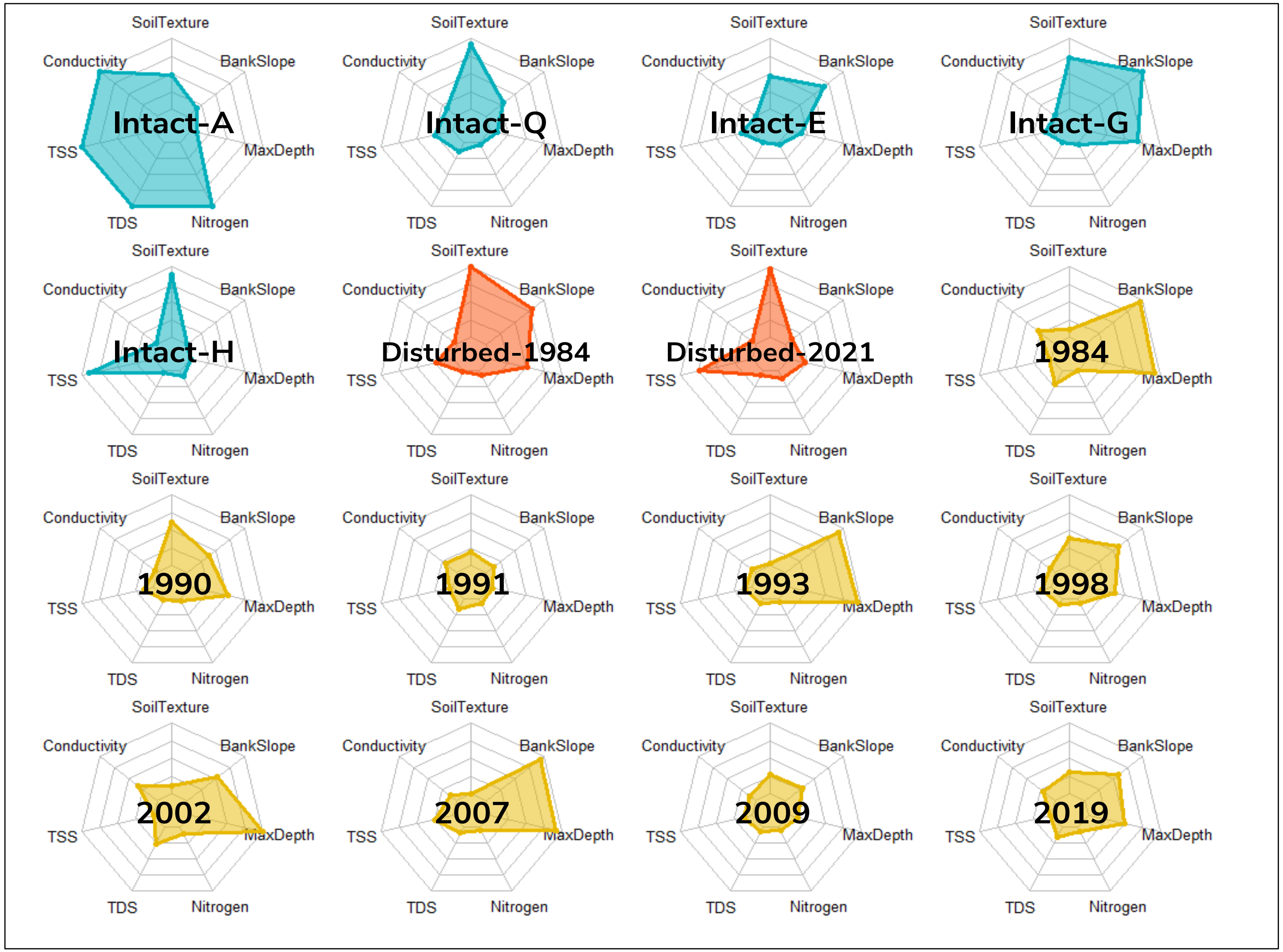

Figure 5. Radar plots of wetlands (natural: blue, disturbed: orange) and placer ponds (yellow) with explanatory variables that can influence the suitability of the wetland habitat indefinitely.

Reference Condition Approach

For each placer pond, we identified the corresponding wetland reference group for comparison. Six placer ponds and 2 disturbed natural wetland sites matched with reference Group 2, which contained 20 reference wetlands. Sites 2007 and 2009 and the 2 disturbed natural wetlands had equal probability of belonging to either Group 2 or Group 3. Group 3 contained 9 reference wetlands. For this reason, we tested them in both groups.

We then compared each wetland's aquatic assemblage to the reference set, to determine whether the invertebrate community fell within three confidence intervals: 90%, 99%, and 99.9% (Appendix: Table 3). These are the equivalent of setting P levels at 0.10, 0.01 and 0.001 rather than the typical P = 0.05 (or 95%) in standard statistical tests of significance. This provides four possible conditions for a test site:

> Band 1 – inside the 90% ellipse, which indicates the reference condition,
>
> Band 2 – between 90 and 99% ellipse, which indicates mild divergence from the reference condition,
>
> Band 3 – between 99 and 99.9% ellipse which indicates divergence from the reference condition, and
>
> Outside Band 3 – >99.9% ellipse which indicates extreme divergence from the reference condition.

Based on the RCA groups described in the Reynoldson 2022 models, we created two 3-Dimensional NMDS ordinations, the first was Group 2 and the second Group 3 (Figure 6 and Figure 7, respectively). None of the sites sampled in the Indian River watershed matched with Group 1. We overlaid Band 1 (90% confidence) to highlight sites with benthic macroinvertebrate communities within reference. The NMDS for Group 2, with a stress value of 0.2021, indicates a moderate fit. In contrast, the Group 3 NMDS, with a stress value of 0.1209, shows a relatively good fit (Kruskal, 1964).

For both Group 2 and Group 3, all natural undisturbed wetlands, were found to be within Band 1, with benthic invertebrate communities in reference.

In Group 2, we determined 5 sites had benthic macroinvertebrate communities that diverged from reference: 1991, 1998, 2002, 2007 and 2019.

In Group 3, we determined 4 sites had benthic macroinvertebrate communities that diverged from reference: Disturbed-1984, Disturbed-2021, 2007 and 2009.

The disturbed ponds were generally more like the reference communities (e.g., closer to Band 1 [green circle in the figure]) than the placer ponds. Ultimately, only 3 placer ponds were similar enough to the reference communities to be considered in reference: 1990, 1993 and 1984.

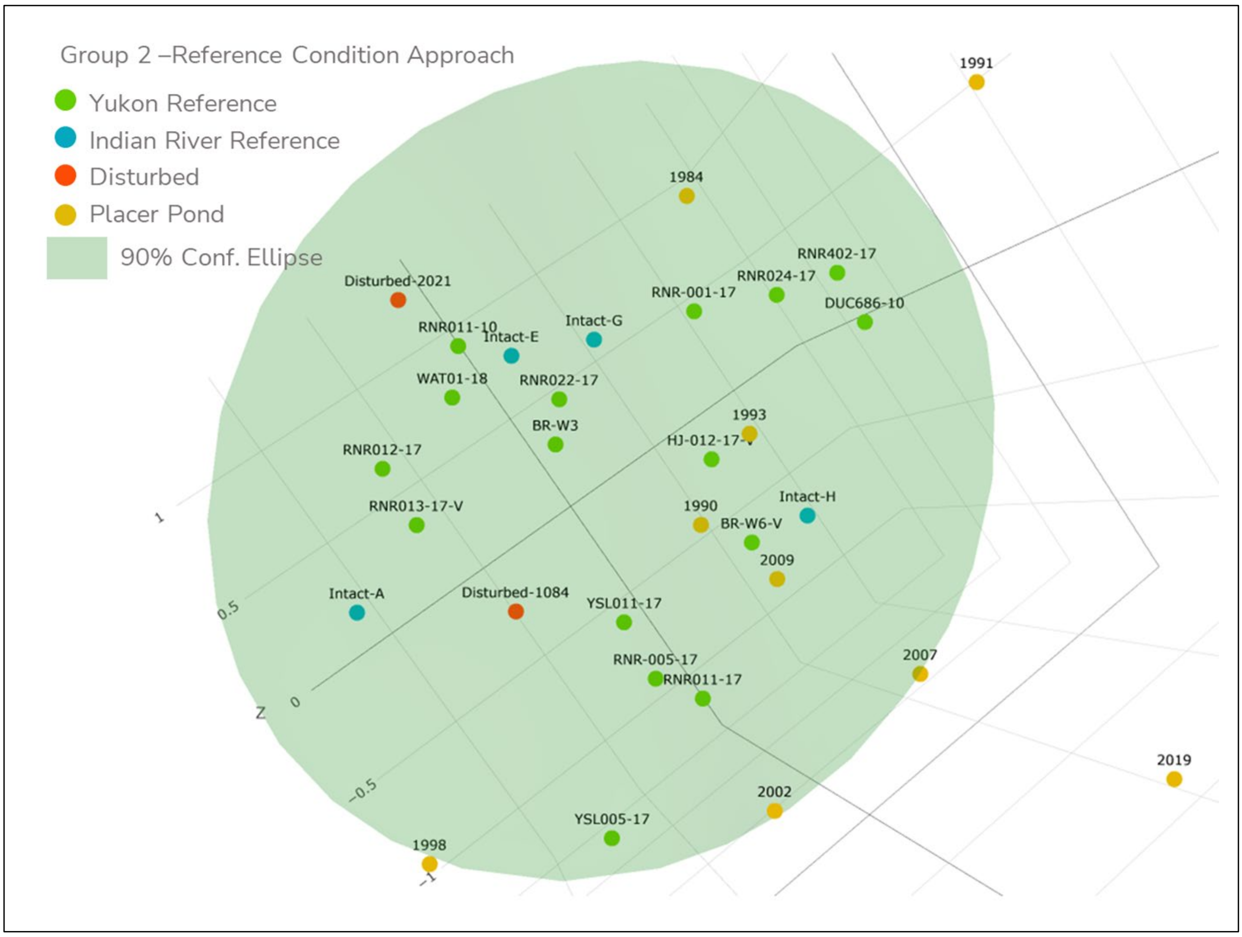

Figure 6. This is a non-metric multidimensional scaling (NMDS) plot for Group 2. It is a 3-dimensional graph that shows the similarities between benthic invertebrate communities. Sites that are closer together have similar assemblages of benthic invertebrates. The green ellipse encompasses sites that are within the 90% confidence band and are considered in reference.

Figure 7. This is a non-metric multidimensional scaling (NMDS) plot for Group 3. It is a 3-dimensional graph that shows the similarities between benthic invertebrate communities. Sites that are closer together have similar assemblages of benthic invertebrates. The green ellipse encompasses sites that are within the 90% confidence band and are considered in reference.

Discussion

The results of this study highlight that natural wetlands support greater biodiversity and contain more ecologically beneficial wetland characteristics, such as carbon and vegetated areas, compared to placer ponds. This was illustrated in radar plots which showed that, in every wetland health metric we measured, almost every natural wetland had relatively higher scores than the placer ponds. The one exception was a site called: Intact-A. The saline nature of Intact-A likely explains its low vegetation cover and the lowest aquatic insect diversity among all sites. Despite these atypical ecological metrics, Intact-A may play a critical ecological role by providing salts and minerals for wildlife, filling a unique niche.

The benthic macroinvertebrate communities in older placer ponds generally showed greater similarity to the benthic macroinvertebrate communities in reference wetlands. Among the oldest placer ponds—1984 to 1993—most were within the range of reference conditions.

Site 1991 was considered out of reference; however, this site was reworked in 2017; effectively resetting the disturbance timeline (Figure 8).

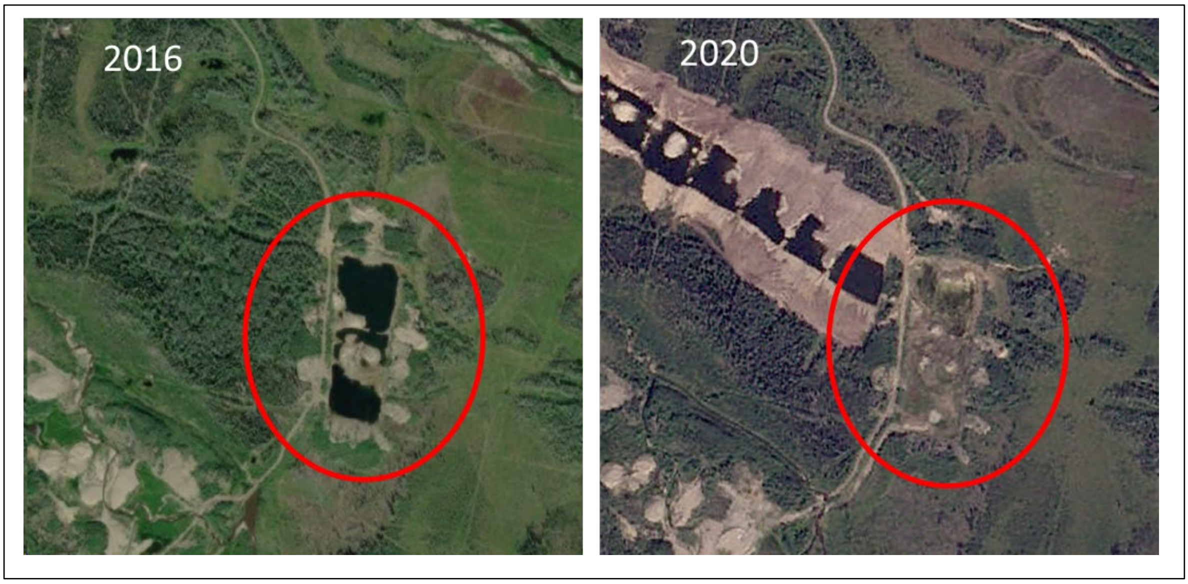

Figure 8. Satellite imagery of Site 1991 in 2016 and 2020, showing how the site was reworked with the addition of sediments from operations to the west prior to 2020.

Interestingly, Site 1991 exhibited unique characteristics compared to the other placer ponds. It had some of the highest plant cover among the created ponds (Figure 9), with a mixture of weedy species like Narrow-leaved Hawksbeard (*Crepis tectorum*) and upland species like Trembling Aspen (*Populus tremuloides*).

Figure 9. Peat forming vegetation from Intact-E (left) and fine sediments and high vegetation cover in Site 1991 (right).

Additionally, Site 1991 featured finer sediments, with shallower and warmer water, like those of Intact-A and Disturbed-2021. Notably, these two sites also exhibited high aquatic insect abundance but low diversity. Site Intact-A had an average water temperature of 26.7 °C, the highest of all our sites. Temperature influences community patterns such that species distribution reflect their specific thermal preferences (Haidekker, 2004). Warm temperatures can increase productivity, promoting the growth of algae and other food sources (Lamberti, 1985).

Site Disturbed-2021 is a natural wetland that was undergoing drainage for future placer operations, resulting in a significant drop in the water table (> 1 m); leaving only a few centimeters of water in most areas. The average water temperature was 20 °C. This substantial disturbance, and subsequent increased temperature, may explain its high aquatic insect abundance despite low diversity, a trend like what was observed in Site 1991.

Site 2009 had high vegetation cover and was within reference conditions when compared to Group 2, although when tested against Group 3, it fell into Band 3, which is out of reference. This wetland supported a substantial cattail (*Typha latifolia*) marsh on one end, contributing to abundant vegetation but low plant diversity. Cattails, while creating valuable habitat for certain aquatic insects, are relatively rare in the Yukon and are typically associated with human disturbance.

Site Disturbed-1984, an old exploration site located in a swamp riparian zone, represents a complex interplay between natural and disturbed conditions. Although never fully mined, the disturbance from excavation equipment left steep banks and deep open water, limiting suitable habitat for benthic macroinvertebrates. Despite being out of reference, the site scored highly for other ecological values such as abundant vegetation, plant diversity and carbon storage.

Three of the oldest sites—1984, 1990 and 1993—are adjacent to large, intact natural wetlands (Figure 10). For example, Site 1984, is situated next to a fen and swamp complex that comprises a significant portion of the site's catchment area. Both Sites 1990 and 1993 are connected to the Indian River, with evidence of beaver activity, including a small lodge at Site 1993. The proximity of these sites to natural wetlands suggests that edge effects may be influencing ecological dynamics. Edge effects refer to the ecological changes that occur at the boundaries between different habitat types—in this case, between placer ponds and natural wetlands. Edge areas often feature distinct environmental conditions that can influence species richness and abundance. While edge effects may increase species diversity, they can also challenge specialist species, which may struggle to thrive in transitional zones between disturbed and natural habitats.

Figure 10. Satellite imagery showing the three older sites 1984, 1990, and 1993 adjacent to large intact natural wetlands.

Conclusions

In our study, we examined 16 open water sites within the Indian River watershed, including 5 natural wetlands, 2 disturbed wetlands and 9 placer ponds. Among the disturbed sites, three were considered "in reference", likely because they were older and had developed more substantial benthic macroinvertebrate habitats, particularly in their large emergent zones. However, even these “in reference” sites do not resemble or function like the natural wetlands such as bogs, fens, and swamps, that are common in this region and likely present prior to mining operations.

For example, site 2019 illustrates the significant changes caused by mining. Prior to mining (in 2016), the site contained 80% fen and 15% swamp but by 2020, this site was transformed to 74% exposed gravel, 21% open water and only 5% fen. The Reference Condition Approach (RCA) used in our study is not well suited to reflect these significant ecosystem and landform changes.

Natural wetland soils were richer in fine particles (clay and silt) compared to placer pond soils. Additionally, natural wetlands exhibited greater plant species richness and vegetation cover. In contrast, disturbed sites had more weedy and upland plant species. Interestingly, placer ponds adjacent to intact wetlands had higher ecological metrics, suggesting that proximity to natural areas may support ecological recovery.

The RCA found that the benthic macroinvertebrate communities in older ponds showed signs of returning to reference levels. We noted that other metrics (e.g., vegetation cover, gravel exposure) showed similar patterns. Given the RCA’s labor-intensive nature, and its inability to quantify major ecosystem conversion or landform changes, we should investigate the use of simpler metrics to more efficiently provide comparable insights.

Our use of the RCA diverges from its traditional application, which focuses on river systems impacted by pollutants. For example, one of the earliest applications of the RCA occurred in the Great Lakes Basin of Canada (Reynoldson et al. 1995). Researchers used benthic macroinvertebrates to assess the impacts of various stressors, including industrial pollution and agricultural runoff, on freshwater river ecosystems. In Australia, the RCA was adopted early on to assess freshwater river ecosystems in the Murray-Darling Basin, to detect the effects of agricultural runoff (Davies, 2000). In contrast, our study examined visibly impacted wetlands with no detectable chemical pollutants. This difference in context raises questions about the RCA’s utility for wetlands impacted by placer mining where visible disturbances, such as loss of peatlands, are evident without extensive sampling.

Our study indicates that 35 years may not be enough for placer ponds to fully resemble natural wetlands. It is important to note that many of these ponds, particularly older ones, were initiated at a time when placer operators were not required to do post-mining reclamation. Most of the ponds we visited were likely the result of passive reclamation where the surface topography is contoured and then left to natural revegetation. Without active or directed wetland reclamation, some characteristics are starting to return to a reference state, but other critical features, such as peatland accumulation, remain absent.

Moving forward, we recommend working with Indigenous governments and the placer industry to establish clear goals and reclamation practices that prioritize and facilitate peatland recovery.

Additionally, a comprehensive, long-term approach is needed to track recovery progress. The RCA offers valuable insights but falls short of fully capturing the ecological changes observed following placer mining, and as a result we do not recommend using it in isolation for evaluating wetland recovery after intensive landscape changes (e.g., mining). Further work remains to develop effective and cost-efficient metrics for tracking recovery of wetlands in the territory.

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Appendix 1

Table. 1. Field measurements.

Value	Measurement	Description
Vegetation	Plants richness	Number of different plant species present at a site.
	Plant cover	Proportion of the ground covered by plant leaves, stems, branches, and other above-ground plant parts.
	Gravel cover	Proportion of the ground made up of coarse gravel with no plant material.
Insects (Benthic invertebrates)	Invertebrate richness	Number of different aquatic insect families present at a site.
	Invertebrate abundance	Number of aquatic insects in a standard sample.
Soil and peat	Soil texture	Percent sand and silt in a soil sediment sample.
	Carbon	Tonnes of carbon per buffer extrapolated from wetland type
Water	Conductivity	The ability of water to conduct an electric current, which indicates the presence of dissolved ions and salts.
	TSS	Total Suspended Solids, refers to the concentration of solid particles that are suspended in water.

	TDS	Total Dissolved Solids, represents the total concentration of inorganic and organic substances that are dissolved in water.
	Nitrogen	Organic Nitrogen, and Inorganic (Ammonium, Nitrate, Nitrite)
Pond shape (Bathymetry)	Max Depth	The depth of the water at the deepest point
	Bank Slope	Average % slope measured along bathymetry transects

Table. 2. GIS derived model variables, used to determine the group.

Habitat variable	Description	Source
Elevation	Elevation from 30m DEM	Open Data Yukon Government
Climate values	Climate variables e.g. mean annual temperature (°C), frost-free period etc..	AdaptWest Project. 2021. Gridded current and projected climate data for North America at 1km resolution, generated using the Climate NA v7.01 software (T. Wang et al., 2021). Available at adaptwest.databasin.org.
%Landcover type	NASA above land cover % in watershed	Wang, J.A., D. Sulla-Menashe, C.E. Woodcock, O. Sonnentag, R.F. Keeling, and M.A. Friedl. 2019. ABoVE: Landsat-derived Annual Dominant Land Cover Across ABoVE Core Domain, 1984-2014. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1691
%Bedrock Geology	Bedrock Geology % in watershed	Yukon Geological Survey, 2021. Yukon digital bedrock geology. Yukon Geological Survey, https://data.geology.gov.yk.ca/Compilation/3 [accessed November 1, 2021].
Burn area by Decade	Area m^2 burned in Decade	Yukon Government Forest Fire Inventory

Table. 3. Reference and test sites. Reference sites were used to build the model to assign test sites to their groups. Note that Intact G and Intact Q were assigned to the incorrect site when run through the model they trained. * Denotes sites that were in reference when classified as a group 2 but out of reference in group 3.

Site	Type	prob1	prob2	prob3	Assigned group	Band#
Intact-A	Ref	0.017998	0.92505	0.056952	2	-----
Intact-G	Ref	0.018082	0.101798	0.88012	~2	-----
Intact-H	Ref	0.280796	0.602785	0.116419	2	-----
Intact-E	Ref	0.079299	0.6895	0.231201	2	-----
Intact-Q	Ref	0.068655	0.636255	0.29509	~3	-----
1984	Test	0.031375	0.860136	0.108489	2	1
1990	Test	0.021448	0.756828	0.221723	2	1
1991	Test	0.018393	0.874561	0.107046	2	2
1993	Test	0.047544	0.612695	0.339761	2	1
1998	Test	0.274357	0.561784	0.163859	2	2
2002	Test	0.161703	0.742546	0.095752	2	2
2007	Test	0.075173	0.544538	0.380289	2 or 3	2
2009	Test	0.081572	0.516457	0.401971	2 or 3	3*
2019	Test	0.081195	0.741183	0.177622	2	2
Disturbed-1984	Test	0.100688	0.342164	0.557149	2 or 3	2
Disturbed-2021	Test	0.100532	0.5952	0.304268	2 or 3	2