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Aquatic Condition Index: optimization of a rapid wetland assessment tool for evaluating urban wetland health

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Abstract

Urbanization poses significant threats to wetland ecosystems, leading to habitat loss, hydrological alterations, and the introduction of invasive species that adversely affect essential ecosystem services. This widespread threat underscores the need to develop a robust management tool for gauging urban wetland health. The Aquatic Condition Index (ACI) was developed as a diagnostic tool for monitoring urban wetland health in Calgary, Alberta, Canada. The ACI evaluates wetland health by incorporating functional indicators (i.e., hydrological, ecological, and water quality functions) chosen by scientific experts to provide municipal wetlands with relative condition scores that can inform citywide habitat management budgeting and prioritization. Gathering the data necessary to generate wetland indicators for the ACI requires substantial financial resources, time, and a high degree of analytical expertise for data collection (e.g., field surveys). This investigation aimed to enhance the widespread applicability and cost-efficiency of wetland monitoring by optimizing the ACI. This optimization entailed a sensitivity-driven indicator reduction, which strategically minimizes the number of indicators essential for ACI calculations. Our findings demonstrate that the refined selection of indicators produces comparable results to the original ACI. This highlights the potential of transitioning to more rapid and cost-efficient monitoring methods, creating a streamlined approach to enhance the efficiency of monitoring and assessment processes. Ultimately, this approach can facilitate long-term urban wetland assessments and promote the sustainability and management of these vital urban features .

Keywords Aquatic condition index · Environmental assessment · Urbanization · Wetlands

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Introduction

Wetlands are important ecosystems that support various hydrological, ecological, biogeochemical, and socio-economic benefits. They function as vital habitats for numerous plant and animal species, offer recreational opportunities for communities, enhance water security, and help mitigate disturbances and natural hazards, e.g., flooding (Gren et al. 1994; Novitski et al. 1996; Mitsch and Gosselink 2000). Despite an array of ecosystem services, wetlands rank among the earth's most threatened ecosystems and are disappearing at an alarming rate (Creed et al. 2017). An estimated 21–35% of the world's wetlands vanished between 1970 and 2015, with regional hotspots experiencing > 50% loss (Fluet-Chouinard et al. 2023). Wetlands face numerous threats, including habitat degradation and loss, pollution, and climate change impacts, which are exacerbated in urban environments (Hu et al. 2017; Ballut-Dajud et al. 2022).

Urbanization contributes to habitat loss and fragmentation as wetlands are drained, filled, or converted for development (Ehrenfeld 2000, 2004; Palta et al. 2017). Furthermore, urbanized environments alter hydrological patterns, leading to changes in water flow, increased runoff, and reduced groundwater recharge (Johnston 1991; Brabec 2009). These hydrological modifications have been documented to exacerbate water quality issues by increasing nutrient and pollutant loads from urban runoff, ultimately leading to eutrophication (Paul and Meyer 2001; Verhoeven et al. 2006; Paul et al. 2017). Changes in hydrological regimes associated with wetland loss can also hinder groundwater recharge, potentially increasing the vulnerability of urban environments to both flooding and fire risks (Ameli and Creed 2019a, b; Nwaishi 2023). The introduction of invasive species is also common in urban environments, and these non-native species disrupt the ecological integrity of wetlands (Ehrenfeld 2008). Mitigating these urban impacts is crucial for the sustainability of wetland ecosystem functions and services (Gibbs 1993; Fluet-Chouinard et al. 2023), thus highlighting the need for effective management tools to gauge urban wetland health.

Current wetland monitoring and assessments encounter numerous constraints that affect scientists' and policymakers' ability to gauge wetland health (Van Dam et al. 1998; Gallant 2015; Hughes et al. 2016). Two common monitoring barriers are financial and time constraints (Caughlan and Oakley 2001). The financial investment required to create and implement a professionally monitored program is large, demanding in-depth technical and analytical expertise. Additionally, the time required for monitoring a single wetland is substantial, often due to logistical challenges. These constraints restrict the scale of monitoring efforts, highlighting an urgent need for comparatively inexpensive monitoring schemes applicable over larger scales (Van Dam et al. 1998). Wetland managers are increasingly emphasizing the need to optimize monitoring protocols to address the financial and time limitations inherent in traditional field-based methods. This optimization can be achieved by reducing the number of monitored indicators to a core set that are both practical (easy to collect or calculate) and do not require high taxonomic expertise (e.g., plant taxonomy).

The City of Calgary, Alberta, Canada has reported a 90% reduction in wetland areas since European settlement began in the 18th century. Despite the rapid and extensive loss of prairie pothole wetlands in recent decades to land use and urban development, Calgary is still home to 2,720 wetlands (Nwaishi et al. 2023). A key piece of municipal policy, Calgary's Wetland Conservation Plan (Nwaishi 2023; Ramirez 2019), outlines alternatives for wetland conservation to guide future urban development. One key priority identified in the plan is the creation of a rapid, cost-effective diagnostic tool for assessing urban wetland health (Nwaishi et al. 2023; Sinnatamby et al. 2023). Thus, an Aquatic Condition Index (ACI) was designed to assist Calgary in the identification of areas for management action to improve wetland condition. The ACI incorporates subfunctional indicators for hydrological, ecological, and water quality functions selected by scientific experts to represent wetland conditions. These functions are generated using an integration of field-based measurements, visual observations, and GIS-based models (Nwaishi 2023). However, testing of the current ACI identified challenges in those field-based measurements, largely the high financial costs incurred for local government due to the number of parameters collected and the required specialist knowledge to collect specific indicator data. Ultimately, these barriers limit the City of Calgary's ability to conduct intensive sampling of wetlands across a wide geographic area.

Here we present the prototype ACI tool, with a focus on optimizing ACI performance and practicality by fine-tuning indicator selection, identifying the most sensitive and easy-to-measure ones. ACI optimization is crucial to minimize the time and resources needed to complete field surveys, all while ensuring a statistically robust methodology and responsive analytical tool. ACI optimization will aid in developing a rapid and more cost-effective tool, enabling broader geographical coverage by City staff and the capacity for sustained long-term monitoring efforts (Lee et al. 2023; Nwaishi 2023). The optimized ACI will undergo testing within Calgary to establish its reliability and validity as a rapid assessment tool across a range of urban wetland conditions. The optimized ACI could support evidence-based decision-making for the sustainable management of wetland ecosystems, extending its applicability to other urban wetlands.

Methods

Aquatic Condition Index (ACI) - prototype development

To guide the development of the ACI, the City of Calgary established an Advisory Committee. This committee brought together representatives from the City's urban conservation department, wetland and ecological experts, and an applied research institute. The committee defined three key objectives for the ACI tool: (1) develop a rapid assessment tool for city ecologists to facilitate the efficient evaluation of wetland condition; (2) design a tool that informs management decisions and prioritizes restoration efforts for urban wetlands; and (3) enable city-wide wetland condition modeling to predict the overall health of Calgary's wetland ecosystems.

The advisory committee conducted a review of published North American wetland assessment tools and identified a common set of indicators used to assess wetland conditions (Wardrop et al. 2007; Kentula and Paulsen 2019). From this assessment, 50 indicators were selected and grouped into subfunctions to represent the primary drivers of wetland condition, including hydrological, ecological, and water quality functions (Fennessy et al. 2007). Indicators were acquired using a combination of desktop and field observations. For desktop analyses, ArcGIS was used to extract indicators from geospatial information and historical records obtained from the City of Calgary. A list of the indicators with a detailed summary of methods and scoring can be found in Nwaishi et al. (2023). Subfunction and function calculations are further outlined in the *ACI calculation* section. Our objective was to refine the existing ACI by conducting tests and a sensitivity analysis of the indicators. This effort aims to create a more user-friendly tool to address the urgent need for wetland protection.

Site selection

Eighty wetlands were selected from the City of Calgary's merged wetland inventory ($n = 2{,}720$). Wetlands encompassed different gradients including urban catchment size, wetland naturalness (i.e., from utility retention ponds to near-natural wetlands), and geographic scope (i.e., city coverage). A field survey was conducted between late June to early August 2022, coinciding with the peak to late growing season. During the field assessment City parks ecologists were asked to identify indicators of low practicality, such as time consuming or technically challenging.

Geospatial tools such as ArcGIS were used to calculate catchment size and categorize the degree of naturalness, using piped stormwater infrastructure as a surrogate to represent human impact. Wetlands were classified as follows: Existing Retained Wetlands (ERW), Existing Modified Wetlands (EMW), Constructed Stormwater Wetlands (CSW), Naturalized Wet Ponds (NWP), and Utility Wet Ponds (UWP). Table S1 provides descriptions of these wetland types (Nwaishi et al. 2023), and their distribution in the City is shown in Fig. 1.

ACI calculation

Unweighted indicator scores were averaged to calculate major subfunctions (hydrological (H) function includes waterflow and water storage subfunctions, ecological (E) function includes ecological structure and composition subfunctions, and water quality (WQ) function includes filtration, source, and bioindicator subfunctions). Each subfunction score was calculated using a different suite of indicators selected by a panel of wetland scientists as described in Nwaishi et al. (2023). To improve the operational efficiency of the ACI tool, an approximation of the full penalized regression model (Harrell 2017) was used to identify the most important indicators for subfunctions within each of the three major functions (H, E, and WQ) to reduce model complexity, thus preventing overfitting and improving predictive performance. This approach is useful when multicollinearity issues arise among predictors (Harrell 2015). The model calculates the contribution and influence of each indicator in predicting the subfunction scores. Based on the results of the sensitivity analysis, indicators with lower importance (or greater redundancy) ($R^2 > 0.95$) were eliminated.

The reduced set of indicators was used to recalculate the subfunction scores. Recalculated subfunction scores were averaged to obtain the three function scores (H, E, and WQ). Data normalization was performed on the function scores to return values between 0 and 1, where 0 represents the lowest-ranked condition, and 1 represents the highest-ranked condition. The Min-Max technique was used to calculate normalized scores (X_{norm}) using the following formula:

$$X_{norm} = (X - X_{min}) / (X_{max} - X_{min})$$

where X is the original function or ACI score estimated for each wetland, X_{min} is the minimum score, and X_{max} is the maximum score.

The normalized function scores were then averaged to generate the ACI score, and the ACI scores were then normalized using the above method. Following normalization, ACI scores were categorized by quartiles into very low (first quartile), low (second quartile), moderate (third quartile), and high (fourth quartile). The workflow for calculating

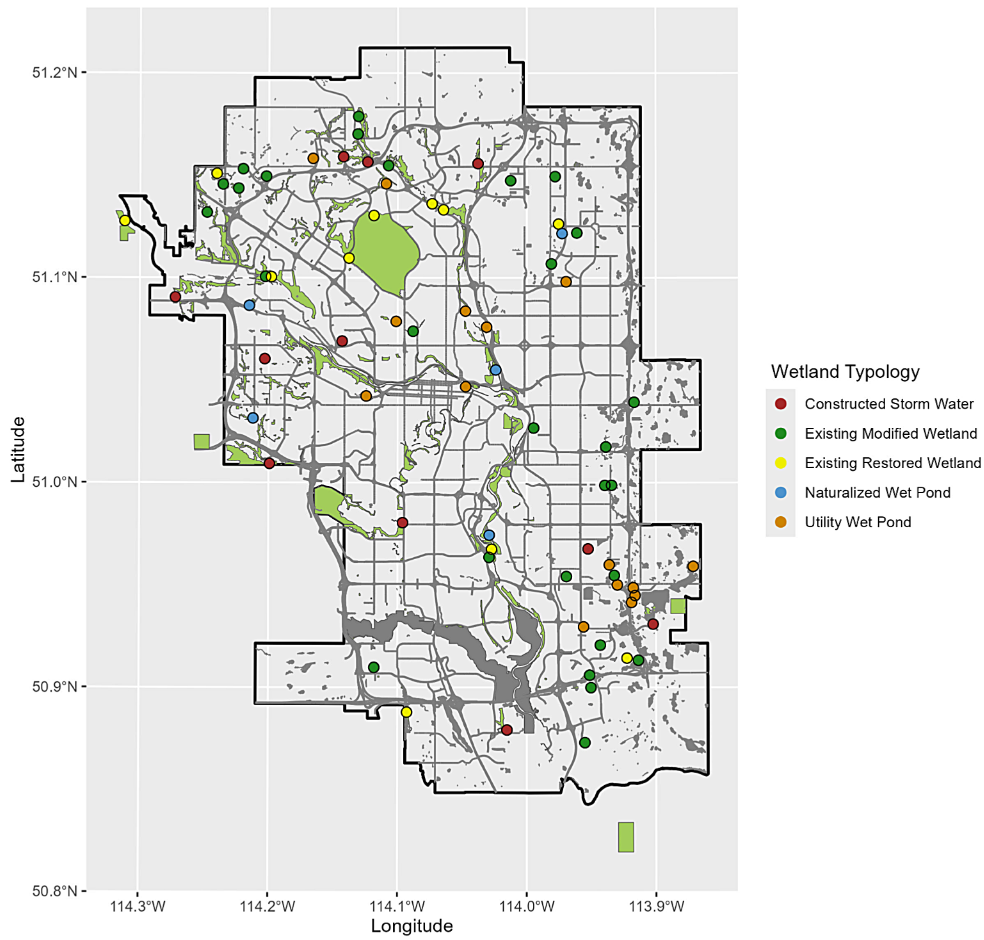


Fig. 1 Distribution of wetland types in 80 wetlands in Calgary surveyed between late June to early August 2022. (*source* Nwaishi 2023)

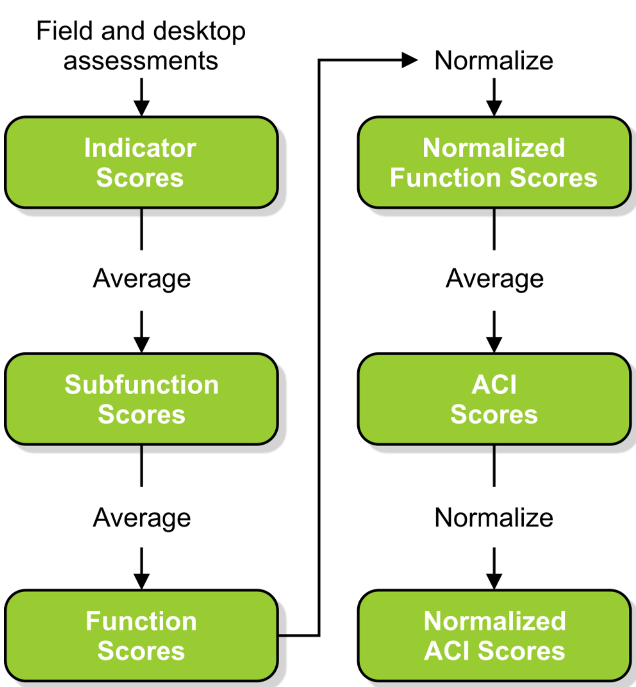


Fig. 2 Steps for calculating the Aquatic Condition Index (ACI) and assigning the ACI scoring category for each wetland

ACI scores and assigning ACI scoring categories is outlined in Fig. 2.

Results

Distribution of ACI scores across wetland types

The distribution of the 80 surveyed wetlands reveals the presence of localized pockets of high-scoring wetlands within the City (Fig. 3). Over 80% of NWP and UWP wetlands (i.e., least natural wetland types) fall within the very low to low-scoring categories (Table 1). In contrast, 65% of EMW wetlands (i.e., more natural wetland types) fall within the moderate to high-scoring categories, with EMW wetlands constituting the largest percentage of high-scoring wetlands (46%); 64% of ERW and 91% of CSW wetlands fall within the low to moderate scoring categories.

Sensitivity analysis: fine-tuning indicators

The H function consists of two subfunctions: waterflow comprising nine indicators and water storage comprising

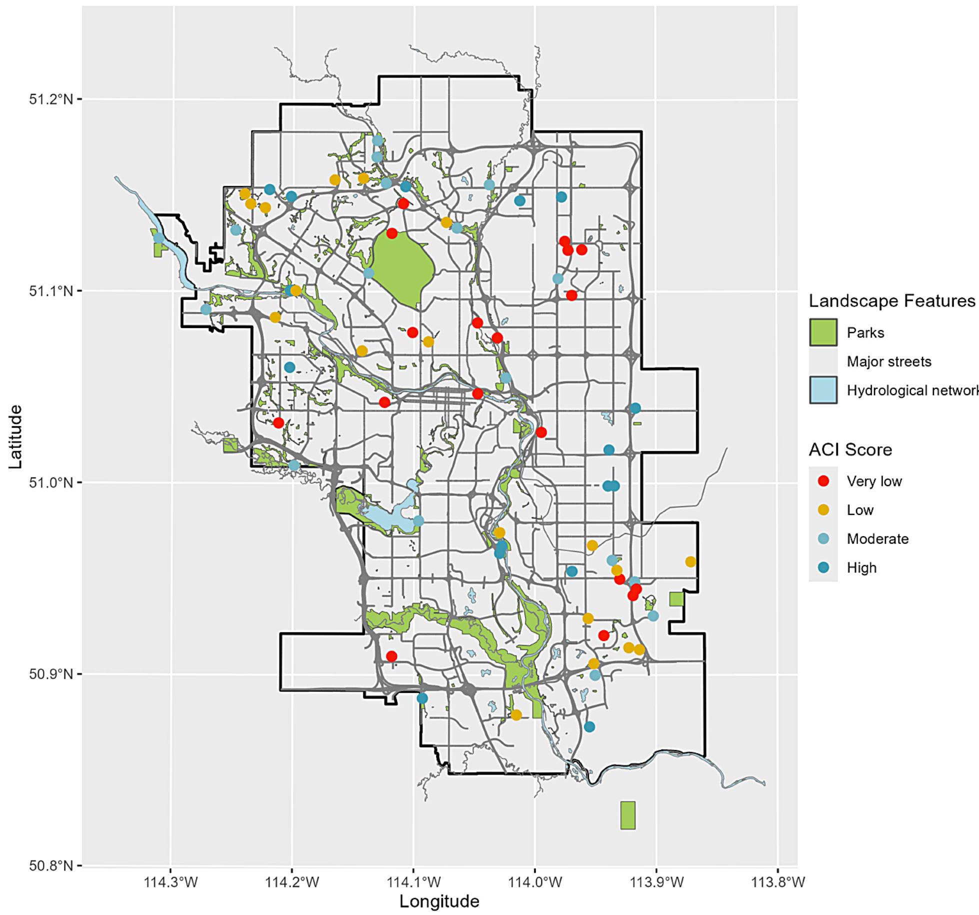


Fig. 3 Distribution of Aquatic Condition Index (ACI) categories in the 80 surveyed wetlands in Calgary

Table 1 Number of wetland types and proportions of Aquatic Condition Index (ACI) categories

Wetland type	Total sites	ACI scoring category (%)			
		Very low	Low	Moderate	High
ERW	11	18	36	28	18
EMW	28	14	21	19	46
CSW	11	0	36	55	9
NWP	5	40	40	20	0
UWP	15	67	20	13	0

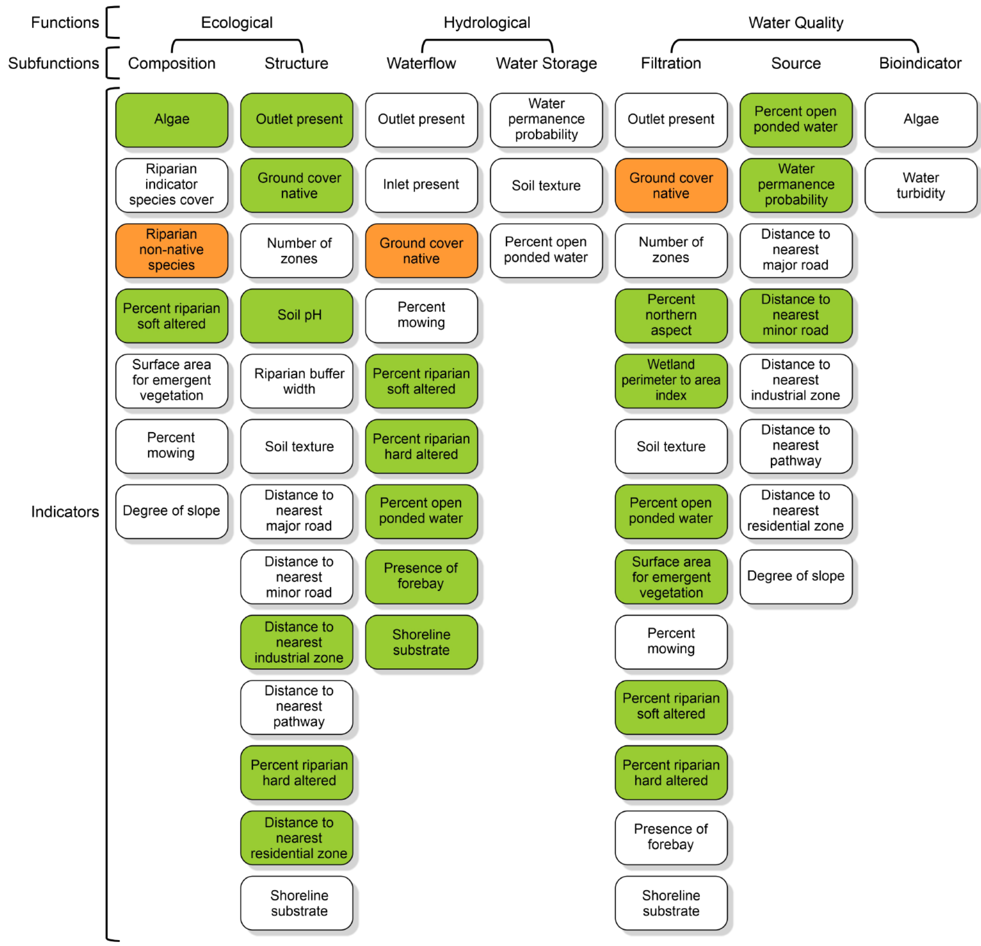
three indicators (Nwaishi 2023). The sensitivity analysis was not applied to the water storage subfunction, as the small number of indicators made it unsuitable for the analysis. The sensitivity analysis reduced the waterflow subfunction to three indicators, i.e., five were removed (Fig. 4). The 'Ground cover native' indicator was found to be important in the sensitivity analysis but was removed to generate an ACI tool with greater practicality, i.e., not requiring a field specialist with advanced plant identification skills, and a more efficient data collection process.

The E function consists of two subfunctions: ecological structure comprising 13 indicators and ecological composition comprising seven indicators (Nwaishi et al. 2023). The sensitivity analysis reduced the ecological structure subfunction to seven indicators (i.e., six were removed) and the ecological composition to four indicators (i.e., three were removed) (Fig. 4). Similar to the H function, while the 'Riparian non-native species' indicator was found to be important to the ecological composition subfunction score and the 'Ground cover native' indicator to the structural subfunction score, both were removed to generate an ACI tool with greater practicality.

The WQ function consists of three subfunctions: filtration comprising 13 indicators, source comprising eight indicators, and bioindicator comprising two indicators (Nwaishi 2023). The sensitivity analysis was not applied to the bioindicator subfunction, as the small number of indicators made it unsuitable for the analysis. The sensitivity analysis reduced the filtration subfunction to six indicators (i.e., seven were removed) and the ecological composition to five indicators (i.e., three were removed) (Fig. 4).

In total, 50 indicators were assessed in the sensitivity analysis, and 24 were eliminated, which translates to an almost 50% reduction of indicators. In some instances, indicators were removed in one subfunction but retained in another subfunction. A correlation analysis indicates a strong significant positive relationship between all normalized function and ACI scores (Fig. 5). The E function

Fig. 4 Aquatic Condition Index (ACI) tool indicators for each function and subfunction, with indicators removed through the sensitivity analysis highlighted in green and indicators removed to improve practicality of using the tool highlighted in orange



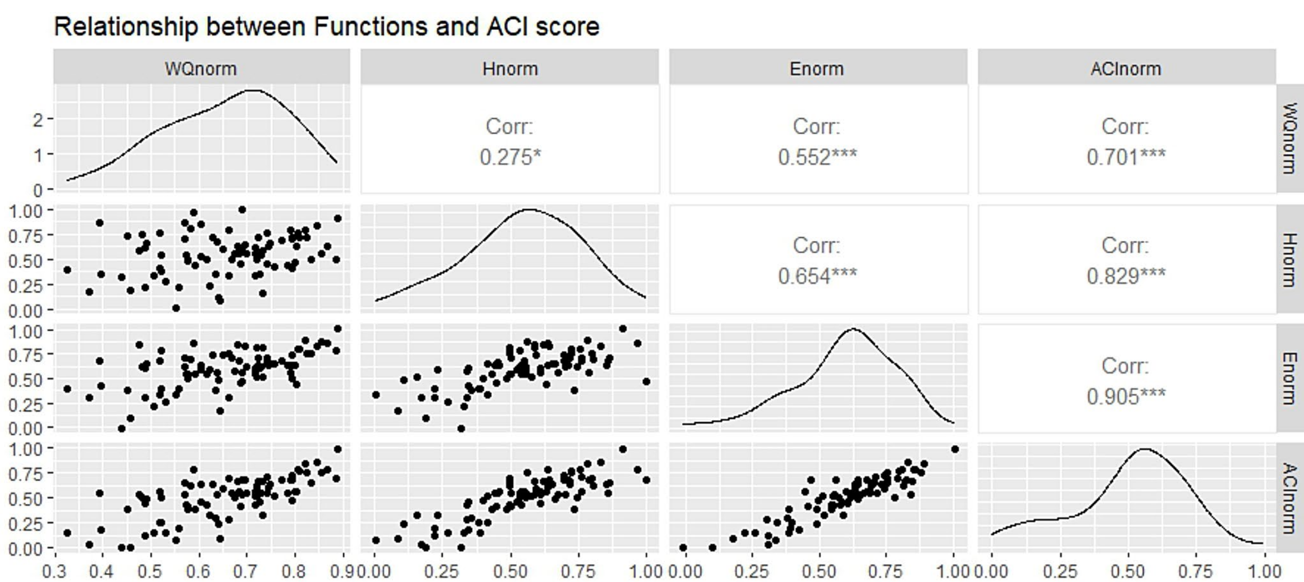


Fig. 5 Correlation analysis between the normalized Aquatic Condition Index (ACI) scores (ACInorm) and E (Enorm), H (Hnorm), and WQ (WQnorm) function scores

($R^2 = 0.91$, $p < 0.05$) is the dominant factor influencing the overall ACI score, followed by the H function ($R^2 = 0.83$, $p < 0.05$), with the WQ function ($R^2 = 0.70$, $p < 0.05$) having a smaller but significant positive relationship.

Comparing full vs. reduced indicator sets

When the reduced set of indicators was used to calculate the subfunction scores and subsequently the ACI scores, the resulting values closely aligned with the ACI scores obtained using the full set of indicators (Fig. 6). The strong significant relationship ($R^2 = 0.93$, $p < 0.0001$) between the reduced and full indicator ACI scores suggests that the reduced set of indicators retained key information necessary for assessing the functional attributes of wetlands.

ACI function scoring categories calculated from the reduced set of indicators marginally modified the distribution of ACI score categories within each wetland type, reclassifying some wetland sites that were situated at the boundary between two score categories (Table S2).

Discussion

There is a growing consensus on the need for cost-effective and rapid assessment tools for evaluating wetland function in urban areas, which will be crucial for prioritizing wetland conservation and restoration (Carletti et al. 2004; Lee et al.

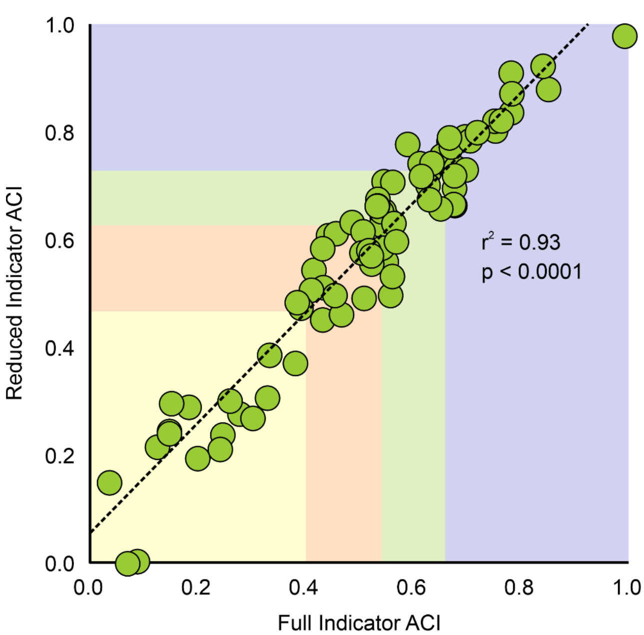


Fig. 6 Comparison between full and reduced indicator Aquatic Condition Index (ACI) scores. The first quartile of ACI scores (very low) is shown in yellow, the second quartile (low) is shown in orange, the third quartile (moderate) is shown in green, and the fourth quartile (high) is shown in blue

2023). The ACI framework provides a quantitative assessment of wetland function that facilitates comparison within and across different urban wetland types, offering baseline condition scores that can be re-assessed over time (Nwaishi et al. 2023). However, financial and time constraints associated with the ACI prototype have hindered its widespread adoption and there is a growing push by government and wetland managers to enhance its practicality.

The optimization of the indicator selection enhanced the practicality of the ACI tool for assessing and monitoring wetland conditions. Reducing the indicators to a smaller subset and excluding those requiring a high level of expertise (e.g., plant identification) enhances data collection, ultimately reducing costs associated with the ACI tool for the City of Calgary. The strong relationships observed between the full and reduced indicator values indicate both the reliability and validity of the reduced indicator approach and that the sensitivity analysis achieved the objective of improving the operational efficiency of the ACI tool by identifying the most important and easy-to-measure indicators. The WQ function scores showed poorer correlation ($r = 0.70$) with ACI scores than other functions. We recommend focusing on identifying stronger desktop-based indicator methods to improve WQ subfunctions to enhance overall ACI performance.

Using the ACI, we demonstrate varying levels of wetland functionality in urban environments. Wetland types designed for stormwater storage (UWP, NWP, CSW, and EMW) with lower E function scores showed lower ACI scores, while wetlands with more natural and diverse ecological attributes exhibited higher scores, with the exception of some ERW wetlands in highly disturbed land settings. By understanding the distribution of ACI scores across different wetland types, policymakers and practitioners can prioritize conservation and restoration efforts accordingly. For instance, the City could focus on restoration of EMW and ERW systems with lower scores, particularly those modified for stormwater management, to improve core functions and overall ACIs.

Developing an economically viable alternative for resource-intensive urban wetland health assessments and long-term change monitoring is a decisive consideration in the face of an unpredictable funding landscape for municipal environmental monitoring. This is compounded by rapid rates of urbanization that cities like Calgary are still undergoing, and model-predicted increases in climate instability that result in more frequent, damaging high-intensity, short duration precipitation extremes (Salimi et al. 2021). The ACI provides a comprehensive and efficient means of assessing and detecting changes in wetland conditions in Calgary, which can be adapted for the same purpose in other municipalities. The refined ACI showcases a practical, rapid wetland health diagnostic tool, that is being employed by the City of Calgary to identify improvement opportunities at underperforming or unexpectedly low scoring wetlands. Prior to development of the ACI as a standardized condition assessment tool that can be applied to any of Calgary's diverse spectrum of wetland and stormwater ponds, municipal staff were unable to objectively determine where to invest limited resources for maximum wetland health outcomes citywide. Calgary only has a small handful of truly natural or existing retained wetlands (ERW), as most wetlands across the built environment have been modified to serve the critical stormwater management function needed by surrounding Calgary communities.

Conclusions

The ACI tool provides a foundation for practitioners and policymakers to make informed decisions regarding wetland conservation, management, and restoration, ultimately leading to improved wetland conditions and ecosystem resilience. The City of Calgary plans to integrate the revised aquatic condition assessment tool into the municipal natural park health assessment rotation, visiting wetlands on a 5-year basis or as needed in response to major climate impacts and/or restoration work. Building a long-term inventory of wetland health will allow scientists and practitioners to gauge the ACI's sensitivity to management interventions (e.g., invasive species removal) and to assess how different management tactics affect its performance in capturing these alterations. To enhance operational efficiency and build upon the ACI tool, we recommend exploring the possibility of shifting to exclusively remote-based indicators to further reduce costs and integrating machine learning approaches to predict wetland conditions at a landscape scale.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11252-024-01596-0.

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Author contributions FN, TSL, and IFC conceived and designed the study. FN, TSL, AA, KB, and VAC assisted with data collection and performed statistical analyses. KJE and IFC wrote the first draft of the manuscript; subsequent drafts were edited by KJE and reviewed and commented upon by all authors. All authors have read and approved the final manuscript.

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Data availability Data sets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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