Response to Referee Comments

Manuscript title: Network-Based Subbasin-Scale Mapping of Streamflow Alteration in Ontario, Canada

Manuscript number: ESSD-2026-286

Dear Editor and Referees,

We sincerely thank the editor and the three referees for their careful evaluation of our manuscript and for their constructive comments. We have revised the manuscript thoroughly in response to the issues raised during the interactive discussion. The comments have helped us improve the clarity, completeness, and presentation of the manuscript.

Below, we provide a point-by-point response to all comments. The original referee comments are reproduced in *italic*, followed by our responses in **bold** and a description of the corresponding changes made in the revised manuscript. Page and line numbers in our responses refer to the clean revised manuscript unless otherwise specified. Selected revised or newly added manuscript text is reproduced in boxes for ease of reference.

A marked-up version of the manuscript showing all revisions is also provided with the resubmission.

Response to Referee 1

General assessment

This is a timely database that provides quantification of the local and downstream influence of reservoirs on streamflow proxy across Ontario, Canada. A Streamflow Alteration Index (SAI) is presented, but not as a hydrologic metric, as a simpler areal metric. The value of a simple metric is a spatially complete picture of reservoir influence throughout a river network. This reviewer appreciates the presentation using two types to express some uncertainty. The reviewer also agrees with the routing approach using hydrologic sequencing and nodes. Well done. This reviewer has very little feedback regarding how to improve the presentation. Below are a few specific comments to consider for perhaps some improved clarity or suggestions for next steps.

Authors' response

We sincerely thank the referee for this encouraging assessment. We appreciate the referee's recognition of the value of the SAI as a simple, spatially complete indicator of potential streamflow alteration rather than as a direct hydrologic response metric. We also appreciate the positive evaluation of the dual SAI formulation and the network-routing framework based on hydrologic sequencing and nodes.

In response to the referee's specific comments, we have revised the manuscript to provide additional information on the minimum mapped waterbody size, dataset completeness, reservoir area and volume context, network fragmentation, potential dynamic extensions of the SAI, the role of waterbody geometry, and possible applications to water-quality assessment.

Comment 1.1 (Line 32 in the original manuscript)

What is the precision of Lehner 2024? Are these waterbodies 0.1 square km or above. Most ponds by number are smaller than that (e.g., https://doi.org/10.1029/2019GL083937). A reader may benefit from some size classification.

Authors' response

We thank the referee for pointing out the need to clarify the size coverage of the Global Dam Watch database. GDW v1.0 integrates multiple global source datasets with different inclusion criteria and therefore does not have a single, spatially consistent minimum reservoir-area threshold. Lehner et al. (2024) evaluated the size distribution of GDW records and found that the database is considered nearly complete for reservoirs between 10 and 1,000 km^2, becomes increasingly incomplete below 10 km^2, and contains virtually no reservoirs smaller than 0.1 km^2. We have added this size information to the revised manuscript to clarify the effective size coverage of GDW v1.0.

We also incorporated the referee's suggested reference, Schmadel et al. (2019), in the revised manuscript when discussing the underrepresentation and potential cumulative importance of small ponds. This clarification is documented in our response to Comment 1.5.

Changes in the manuscript

We added information on the size-dependent completeness of GDW in the Introduction. The revised Introduction text is provided below. Related revisions concerning small ponds are documented in our responses to Comments 1.5 and 3.4.

> Dams and reservoirs are among the most significant infrastructural interventions in freshwater systems, constructed to serve a range of human needs, including water supply, flood and drought control, irrigation, hydropower generation, and recreation (Lehner et al., 2011; Maavara et al., 2020; Palmer and Ruhi, 2019; WCD, 2000). Global Dam Watch (GDW) v1.0 compiles 41,145 documented river barrier locations and 35,295 associated reservoir polygons, representing a cumulative storage capacity of approximately 7,420 km^3

> and an artificial terrestrial surface water area of approximately 304,600 km^2 (Lehner et al., 2024). GDW records are thought to be nearly complete for reservoirs between 10 and 1,000 km^2, but become increasingly incomplete below 10 km^2, with almost no reservoirs smaller than 0.1 km^2 represented (Lehner et al., 2024). Relative to the millions of natural lakes around the world, these mapped reservoirs have artificially expanded the estimated global lake storage volume by about 4% and global lake surface area by about 11% (Lehner et al., 2024).

Comment 1.2 (Line 33 in the original manuscript)

It would be more useful to express as volume (% of total water volume) and area (% of drainage area) if possible for better context.

Authors' response

We agree that the absolute storage volume and surface area values benefit from additional relative context. Lehner et al. (2024) report that the reservoirs mapped in GDW v1.0 have increased the estimated global lake storage volume by about 4% and global lake surface area by about 11%. Lehner et al. (2024) do not report the mapped reservoir area as a percentage of drainage area, so we report the relative lake-surface-area measure available from that study.

Changes in the manuscript

The revised text on pages 1–2, lines 38–40, reads:

> Relative to the millions of natural lakes around the world, these mapped reservoirs have artificially expanded the estimated global lake storage volume by about 4% and global lake surface area by about 11% (Lehner et al., 2024).

Comment 1.3 (Line 36 in the original manuscript)

Other good citations regarding network fragmentation: https://doi.org/10.5194/hess-13-2413-2009 and https://doi.org/10.1126/science.1107887.

Authors' response

We thank the referee for suggesting these relevant studies. We have added Nilsson et al. (2005)**, which provides a global assessment of fragmentation and flow regulation in large river systems, and Döll et al. (2009), which examines global river flow alteration caused by reservoirs and water withdrawals. These studies are now cited together with the more recent global assessment by Grill et al. (2019).**

Changes in the manuscript

The revised text on page 2, lines 43–44, reads:

> Global assessments have documented widespread river fragmentation and flow alteration associated with dams, reservoirs, and water withdrawals (Döll et al., 2009; Grill et al., 2019; Nilsson et al., 2005).

Comment 1.4 (Line 128 in the original manuscript)

This reviewer agrees that a simple streamflow alteration metric is needed and useful.

Authors' response

Thank you for this supportive comment. We appreciate the reviewer's agreement on the need for a simple and practical streamflow alteration metric. This is the central motivation for developing SAI as a parsimonious, network-based screening metric that can be applied across large domains where detailed reservoir storage and operating information are generally unavailable. No manuscript revision was required in response to this comment.

Comment 1.5 (Line 171 in the original manuscript)

How comprehensive are these datasets? Meaning, are there other waterbodies perhaps missed? A reader would benefit from knowledge of completeness.

Authors' response

Thank you for this important comment. We agree that the scope and completeness of the six main data-source groups should be clarified. We have added three paragraphs at the end of Section 2.1 describing their intended coverage and principal limitations. Although none of these datasets constitutes a complete inventory of every waterbody, water-control structure, or hydrometric station in Ontario, together they represent, to our knowledge, the best available and most spatially comprehensive province-wide sources that can be consistently integrated for SAI development and evaluation.

Changes in the manuscript

We revised Section 2.1 by adding three paragraphs at its end to clarify the scope and limitations of the six main data-source groups used to develop and evaluate SAI v1.0 across Ontario. The first paragraph describes the intended coverage and principal limitations of each data-source group. The second discusses the implications of missing small waterbodies and water-control structures. The third outlines potential improvements in future SAI versions in Ontario and the minimum and supplementary data requirements for applying the SAI framework beyond Ontario. The revised text on pages 6–7, lines 240–262, reads:

> The six main data-source groups used in this study differ in scope and completeness, because they were developed for different hydrographic, infrastructure, monitoring, and reference network purposes. The OLRRP v2 provides province-wide river network coverage, but its HydroLAKES-derived lake layer only includes waterbodies with surface areas of 0.1 km^2 or greater; smaller ponds, including waterbodies smaller than 0.01 km^2 as considered by Schmadel et al. (2019), are therefore omitted. The Ontario Dam Inventory (ODI) focuses on medium-to-large dams, whereas the complementary Ontario MNR dataset includes only MNR-operated dams. Some small water-control structures, including culverts and small dams, may be underrepresented in the ODI and MNR dam datasets. The waterpower facility dataset provides broad coverage of known generation stations, although the availability and completeness of operational attributes vary among facilities. The compiled lockstation dataset covers the Trent-Severn Waterway, Rideau Canal, and Welland Canal, which include the major lock systems represented in this study. The WSC gauge network provides extensive federal hydrometric coverage but excludes gauges operated exclusively by other agencies, and its natural/regulated metadata are not fully documented for all stations.
>
> Despite these limitations, these sources represent, to our knowledge, the best available and most spatially comprehensive province-wide datasets that can be consistently integrated for SAI development. Missing or incompletely documented water-control structures may lead to underrepresentation of alteration sources; the implications of these omissions for SAI are discussed further in Section 4.
>
> Future versions of SAI in Ontario could reduce these uncertainties by incorporating higher-resolution hydrographic data, updated provincial and local inventories of dams and water-control structures, and more complete facility-specific operational metadata as these datasets become available. For applications beyond Ontario, implementation of the basic SAI propagation framework requires, at minimum, a topologically connected lake–river–subbasin network with drainage area attributes and a georeferenced inventory of dams,

> reservoirs, waterpower facilities, and other flow control structures that can be assigned to the network. Reproducing the SAI framework would additionally benefit from facility-specific information on operational status, purpose, regulation type, reservoir storage, and other indicators of expected alteration magnitude. Independent hydrometric classifications and streamflow observations would further support evaluation of the resulting SAI product.

Comment 1.6 (Line 527 in the original manuscript)

Spatially complete.

Authors' response

Thank you for this clarification. We agree that "spatially complete" is more accurate than "spatially continuous," because SAI provides values for all mapped subbasin outlets across the represented OLRRP network rather than representing a mathematically continuous spatial field. We have revised the terminology accordingly and clarified that "spatially complete" refers to coverage at the represented subbasin scale.

For consistency, we also replaced other occurrences of "spatially continuous" with "spatially complete" where referring to the spatial coverage of the SAI product.

Changes in the manuscript with this new terminology

See Section 2.4 on page 10, lines 379–383.

See Conclusions on page 21, lines 688–704.

Comment 1.7 (Line 533 in the original manuscript)

A spatial/static picture is valuable. How would one update the SAI for dynamic representation? A reader may benefit from a statement that with a SAI, a next step could be dynamic optimization to adjust the SAI as needed.

Authors' response

Thank you for this valuable suggestion. We agree that the current SAI v1.0 provides a static representation of potential streamflow alteration.

Because SAI is a screening index rather than an optimization model, we interpret "dynamic optimization" here primarily as dynamic updating or recalculation of the index as source inventories and operating conditions change. We clarify that an updated or dynamic representation of SAI could be developed in three complementary ways in the future.

We have added these distinctions to the Discussion and clarified that SAI v1.0 serves as a reproducible static baseline from which inventory-based updates, time-varying representations, and prospective scenario analyses can be developed.

Changes in the manuscript

We expanded Section 4 to describe three possible extensions of SAI. The revised text on page 19, lines 594–616, reads:

> SAI v1.0 provides a static screening baseline across the represented river network for characterizing potential streamflow alteration. This baseline can support broader-scale comparisons among subbasins and provide a reproducible benchmark from which updated or dynamic representations of SAI may be developed. Such extensions could take three complementary forms:

> (1) The alteration-source inventory can be updated as new information becomes available. Updates may include newly identified existing structures, improved local information on the operational significance of currently mapped facilities, or newly constructed, modified, or decommissioned dams, reservoirs, waterpower facilities, and other water-control structures. For regional or basin-specific applications, the province-wide inventory archived with SAI v1.0 can be supplemented with more detailed local information, the Level I and Level II classifications can be revised where appropriate, and SAI_I and SAI_II can then be recalculated. The publicly available SAI calculation code supports reproducible recalculation as the source inventory and associated metadata are improved.
>
> (2) The SAI framework could be extended to represent temporally varying operations. Some alteration sources may exert stronger influence only during particular seasons, hydrologic conditions, or operating periods. Seasonal or period-specific SAI values could therefore be calculated using different sets or classifications of active alteration sources for different time intervals. Where information on operating schedules, facility status, seasonal management practices, or reservoir releases is available, it could be used to define time-dependent alteration signals and generate corresponding time-varying SAI maps. Such an extension would preserve the existing network-propagation framework while allowing the represented alteration influence to vary through time.
>
> (3) The SAI framework could support prospective scenario analysis by introducing proposed or synthetic alteration sources into the routing network and recalculating their potential downstream influence. This capability could be used to compare alternative infrastructure locations, combinations of proposed developments, or infrastructure-removal scenarios and could support regional water-resources planning and cumulative-impact assessment. These applications would provide screening-level representations of the potential spatial extent of alteration rather than predictions of the exact magnitude or timing of streamflow change.

Comment 1.8 (Line 540 in the original manuscript)

Good point. Also consider some discussion around the idea that not all waterbodies are created equal, and their geometries may be another factor to consider in the SAI (https://doi.org/10.1038/s41467-018-05156-x). Also, while this approach assumes drainage area scales with streamflow, how could this SAI metric be used as a water-quality influence indicator?

Authors' response

Thank you for these important suggestions. We agree that not all waterbodies exert the same hydrologic influence. We also agree that the network-based structure of SAI could at least partially support water-quality applications. However, we want to clarify that SAI v1.0 is not itself a direct water-quality indicator because it does not represent constituent sources, concentrations, loads, or biogeochemical transformations.

We have added two paragraphs to Section 4 to discuss waterbody heterogeneity, possible source-specific weighting, and the potential development of a complementary water-quality influence indicator.

Changes in the manuscript

We added two paragraphs to Section 4 discussing differences among waterbodies in geometry, storage, connectivity, and network position, as well as the potential extension of the SAI framework to support a complementary water-quality influence indicator.

The first revised paragraph on page 20, lines 645–657, reads:

> Although SAI_I and SAI_II distinguish sources according to the confidence and expected influence of

alteration, all sources within a given level are assigned the same initial SAI value of 100%. The current formulation therefore does not explicitly account for differences in waterbody area, volume, depth, shape, storage relative to inflow and outlet configuration. These characteristics may influence storage, residence time, mixing, routing, and the magnitude and downstream persistence of alteration (Habets et al., 2018; Hudson et al., 2021). Schmadel et al. (2018), for example, showed that the local and cumulative effects of lakes and reservoirs on nitrogen removal depend on their relative size, shape, connectivity, and position within the river network. In particular, ponded-water roundness and alignment with the river network affected mixing and nitrogen-removal behaviour. Although their study focused on nitrogen processing rather than streamflow alteration, it illustrates the broader importance of distinguishing among waterbodies in network-based assessments. Future versions of SAI could therefore replace the uniform source values with source-specific alteration weights or attenuation functions informed by waterbody geometry, storage characteristics, operating information, hydrologic connectivity, and network position. Such refinements would require more complete and spatially consistent source attributes and additional validation, whereas SAI v1.0 intentionally retains a parsimonious formulation suitable for large-domain screening.

The second revised paragraph on page 21, lines 676–681, reads:

SAI v1.0 should not be interpreted as a direct water-quality indicator. Nevertheless, dams, reservoirs, and other ponded waterbodies can influence nutrient retention, sediment transport, temperature, dissolved oxygen, and other water-quality processes through changes in storage, residence time, mixing, and biological activity (Maavara et al., 2020; Schmadel et al., 2018). SAI's network-based formulation could therefore provide a screening measure of the proportion of upstream flow potentially exposed to processing within such waterbodies. In this sense, SAI may serve as an explanatory attribute in water-quality assessments or as the structural basis for a complementary water-quality influence index.

Response to Referee 2

General assessment

The authors present two Streamflow Alteration Indices that have been developed and applied in the province of Ontario (Canada). The indices were relatively successfully compared to two Canadian databases. The approach offers strong spatial information, compared to traditional approaches that are typically applied only at gauged locations. The methodology is sound and the manuscript is well written, with relevant figures and tables. I only have a few minor suggestions that can be found in the attached file.

Authors' response

We thank the referee for the positive assessment of the study and for the helpful suggestions provided in the annotated manuscript. We have addressed all comments as detailed below.

Comment 2.1 (Lines 159–163 in the original manuscript)

Not truly methodology: "The impacts of streamflow alteration caused by dams and reservoirs manifest spatially rather than being confined to the point scale. Impacts generally diminish downstream from each alteration signal (or site) due to the mixing of the altered flow signals with the signal from natural incremental runoff. However, if a new alteration site is introduced along the way, the impacts may be amplified again. Therefore, identifying all likely sources of instream alteration is critical in mapping their impacts on streamflow in space".

Authors' response

We agree that this paragraph provides conceptual motivation rather than methodological detail. We have therefore removed it from the Materials and Methods section; the relevant concepts of downstream propagation and dilution are already described in the Introduction and Section 2.4.

Changes in the manuscript

The paragraph at the beginning of Section 2 has been deleted.

Comment 2.2 (Lines 164–169 in the original manuscript)

Delete "In this section, the data and methodology used to develop the Streamflow Alteration Index (SAI) are presented. Section 2.1 describes main data sources for identifying alteration signals and validating SAI results. Section 2.2 defines alteration signals and summarizes how they are identified from different data sources. Section 2.3 introduces how alteration signal points are snapped to the river network, which is the key data processing procedure in SAI development. Section 2.4 demonstrates the SAI calculation procedures. Section 2.5 describes how SAI results are validated against locations with reported regulation conditions".

Authors' response

We agree and have deleted this introductory paragraph as suggested.

Changes in the manuscript

The introductory paragraph describing Sections 2.1–2.5 has been removed.

Comment 2.3 (Line 423 in the original manuscript)

Replace "Shapefile" with plural form "Shapefiles".

Authors' response

Agree.

Changes in the manuscript

The revised text on page 14, lines 494–495, reads:

> The Esri Shapefiles are in the NAD 1983 Ontario MNR Lambert coordinate reference system (Lambert Conformal Conic).

Comment 2.4 (Lines 443–445 in the original manuscript)

Redundant "The subbasin polygon layer delineates 245,576 subbasins across Ontario and provides SAI_I and SAI_II values (in %) for each subbasin outlet. Subbasin boundaries and network topology are employed from the Ontario Lake and River Routing Product (OLRRP) v2, with a mean subbasin area of approximately 4.3 km^2."

Authors' response

We agree that these sentences repeat information provided earlier in the manuscript. We have removed the redundant text and retained a concise transition to Table 3.

Changes in the manuscript

The revised text on pages 14–15, lines 512–514, reads:

> The attribute fields of the subbasin polygon layer are documented in Table 3 and include: (1) the OLRRP v2 drainage region identifier (Region); (2) the unique subbasin identifier (SubId) and its immediate downstream identifier (DowSubId), which together define the directed river network topology; and (3) subbasin-scale SAI values (SAI_I and SAI_II).

Response to Referee 3

General assessment

This paper proposes a new method for assessing the sensitivity of runoff in Canadian watersheds to human alternations and provides a relevant dataset. The method is based on a strong assumption that runoff is proportional to catchment area; therefore, the estimated streamflow alternation Index (SAI) can be easily obtained by averaging upstream sub-basins that contain (100%) or do not contain (0%) alternation sources. This method is easy to implement, requiring only a well-developed river network system and a comprehensive inventory of alternation sources. I have two main concerns regarding this approach.

First, the assumption that streamflow is proportional to watershed area is overly simplistic. Streamflow is closely related to factors such as topography, soil type, snowmelt supply, and precipitation conditions. Please validate this assertion using hydrological models and explore potential uncertainties.

Authors' response

We agree that drainage area alone does not determine streamflow. In SAI, proportional drainage-area scaling is used as a parsimonious first-order approximation for downstream mixing rather than as a physical model of runoff generation. To assess whether this approximation is reasonable in Ontario, we analyzed long-term mean annual discharge at 327 WSC gauges. The fitted power-law exponents were close to one across Ontario and the three broad regional groupings (β = 0.936–1.013; R^2 = 0.967–0.991), indicating strong, near-linear scaling.

We used observed streamflow rather than hydrologic model simulations because the assumption being examined is the empirical relationship between long-term discharge and drainage area itself; hydrologic simulations would introduce additional uncertainty associated with model structure, meteorological forcing, calibration, and representation of regulated systems. We have added this Ontario-specific observed streamflow assessment in Appendix B and expanded Section 4 to discuss departures from proportional scaling as a source of uncertainty.

Changes in the manuscript

We revised Section 2.4 to provide the empirical basis, Ontario-specific assessment, and intended interpretation of the drainage-area weighting used in SAI. The revised text on page 10, lines 362–383, reads as follows:

> Our Streamflow Alteration Index (SAI) quantifies potential upstream alteration influence at locations along a river network, represented in this study by subbasin outlets. SAI is an area-based metric that propagates alteration signals through the drainage network, summarizing the percentage of upstream drainage area whose routed flow passes through locations containing alteration signal sources. The drainage-area weighting assumes that long-term streamflow is approximately proportional to contributing drainage area.
>
> Drainage-area scaling has long been used as a parsimonious approach for transferring streamflow information from gauged to ungauged locations, including in regional water-balance applications (Fry et al., 2013). Empirical studies have also identified simple scaling relationships between annual mean streamflow and drainage area across Canada (Yue and Gan, 2004), while more recent analysis across minimally disturbed catchments in the United States and Canada found approximately linear discharge–drainage area scaling for most hydrologic regions, with regional departures associated with runoff efficiency and hydroclimatic conditions (Erikson et al., 2024). To assess the applicability of this approximation within Ontario, we additionally examined the relationship between long-term mean annual discharge and drainage area at 327 WSC discharge gauges with at least 10 valid years of observations during 1990–2024. Because gauges were included irrespective of regulation status, this analysis characterizes the observed discharge–drainage area relationship across the broader Ontario hydrometric network rather than natural runoff scaling alone. The

fitted power-law exponents (β) were close to unity for Ontario as a whole and for three broad regional groupings, indicating strong, near-linear scaling at the spatial and temporal scales relevant to the present application (β = 0.936–1.013; R^2 = 0.967–0.991; Appendix B).

We also added a new Appendix B (pages 23–24, lines 729–764) to document the methodology and results of this proportionality assessment. Appendix B reads as follows:

Appendix B. Empirical assessment of discharge–drainage area scaling in Ontario

To provide an Ontario-specific empirical assessment of the drainage-area scaling approximation used in SAI, we examined the relationship between long-term mean annual discharge and drainage area using Water Survey of Canada (WSC) discharge observations from the HYDAT database (Water Survey of Canada, 2024). The analysis covered complete calendar years from 1990 through 2024. We retained 327 discharge gauges with at least 10 valid years of observations, where a valid year was required to have at least 95% daily discharge coverage. Gauges were included irrespective of their WSC natural or regulated classification; the resulting sample therefore characterizes observed long-term discharge scaling across the broader Ontario hydrometric network rather than natural runoff scaling alone. For each gauge, long-term mean annual discharge was calculated from the available valid years.

Following the general power-law framework used by Erikson et al. (2024) to investigate drainage area and discharge relationship linearity, the discharge–drainage area relationship was represented as

$$Q = cA^{\beta} \tag{B1}$$

where Q is long-term mean annual discharge, A is OLRRP-derived delineated drainage area, c is a fitted coefficient, and β is the scaling exponent. Ordinary least-squares regression was performed in log–log space for Ontario as a whole and separately for three broad regional groupings representing major geographic and hydroclimatic differences across the province: South (SW and SE), North (NE, NC, and NW), and Far North (FNE, FNC1, FNC2, and FNW). Under this formulation, $\beta = 1$ corresponds to exact proportional scaling between long-term mean discharge and drainage area. The 95% confidence interval for β was calculated from the standard error of the fitted slope in log–log space using the Student's t distribution with n - 2 degrees of freedom.

Strong discharge–drainage area relationships were observed for Ontario and all three regional groupings (Figure B1). The fitted scaling exponent β was 0.967 for Ontario, 1.013 for South, 0.936 for North, and 0.967 for Far North, with coefficient of determination (R^2) values ranging from 0.967 to 0.991. These results indicate strong, near-linear scaling between observed long-term mean annual discharge and drainage area across the Ontario hydrometric network, while also showing modest regional departures from exact proportionality. Because the analysis includes both natural and regulated gauges, it should not be interpreted as an assessment of natural runoff scaling alone. Rather, together with the approximately linear relationships reported by Erikson et al. (2024) for minimally disturbed catchments, the Ontario analysis provides empirical support for using proportional drainage-area weighting as a parsimonious first-order approximation in SAI. The results do not imply that drainage area alone determines streamflow contributions at individual locations, as spatial variability in hydroclimate, physiography, water storage, and human regulation can produce departures from proportional scaling.

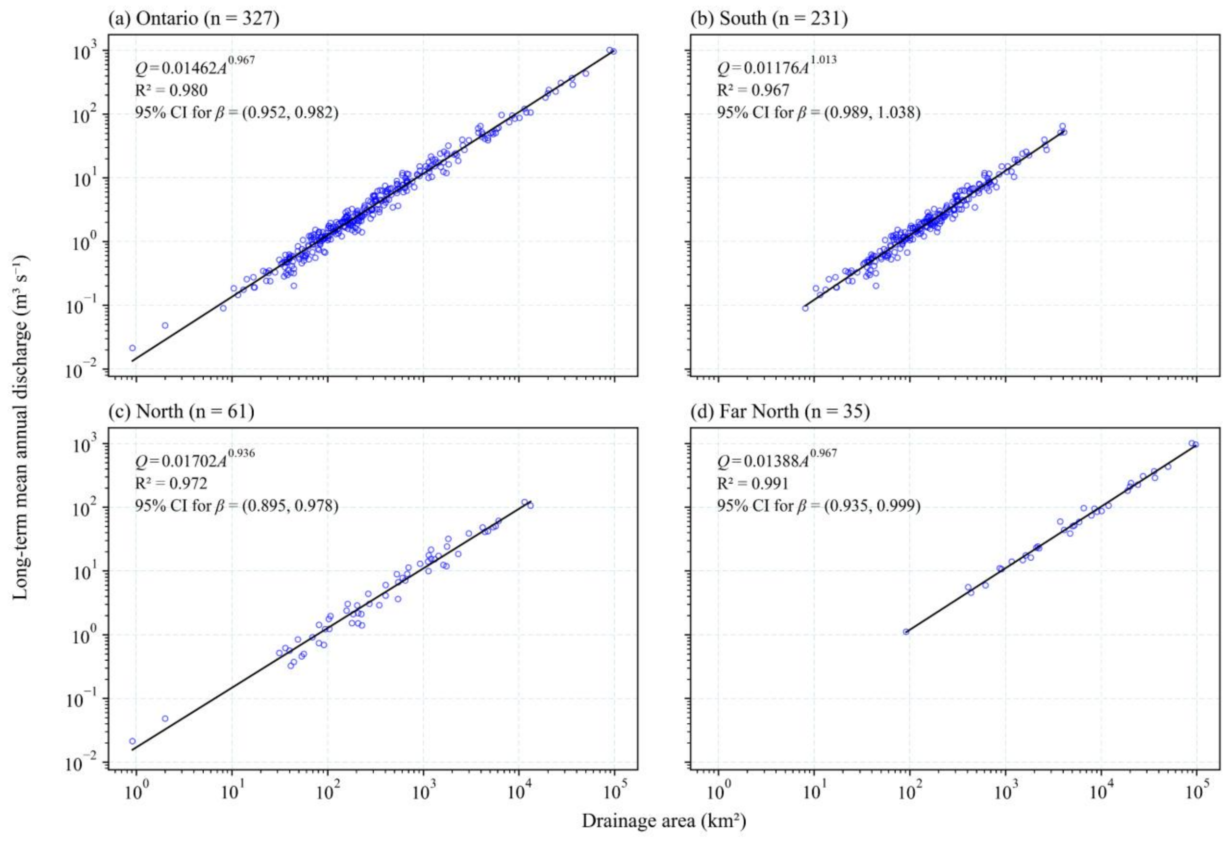

Figure B1. Log-log relationships between drainage area and long-term mean annual discharge for Ontario and three broad regional groupings: South (SW and SE), North (NE, NC, and NW), and Far North (FNE, FNC1, FNC2, and FNW). Each point represents a discharge gauge with at least 10 valid years of observations during 1990–2024, and n denotes the number of gauges included in each panel. The solid black line shows the fitted power-law relationship, $Q = cA^{\beta}$, where Q is long-term mean annual discharge, A is drainage area, and β is the scaling exponent; $\beta = 1$ corresponds to exact proportional scaling between discharge and drainage area. The fitted equation and coefficient of determination (R^2) are shown in each panel. The 95% confidence interval (CI) for β was calculated from the standard error of the fitted slope in log–log space using the Student's t distribution with n - 2 degrees of freedom.

Second, the validation method is too crude. The reference dataset contains only two classification labels—"natural" and "regulated"—while the SAI values are downsampled into three labels. However, we have two categories of SAI values, ranging from 0% to 100%. This gives the impression that SAI values are largely meaningless and that we can only perform approximate classifications. For example, if two sub-basins have SAI-I values of 0.6 and 0.8, respectively, can we say that the sub-basin with an SAI-I value of 0.8 is more vulnerable than the other? If not, what is the exact meaning of the SAI value? If so, how can this be verified?

Authors' response

We thank the referee for raising this important concern regarding the interpretation and evaluation of the continuous SAI values. First, however, we address the comment that the validation method is too crude.

The natural, conditional, and altered classes are screening categories used to compare SAI with the available categorical RHBN and WSC information; they do not replace the underlying continuous SAI values.

Changes in the manuscript

We revised the terminology and description of the hydrometric-gauge comparison to make clear that the categorical RHBN/WSC comparison provides a screening-level consistency check rather than validation of the numerical magnitude of continuous SAI values. Section 2.5 is now titled "Evaluation of SAI at Hydrometric Gauges," and Section 3.2 is now titled "Technical Evaluation of SAI v1.0 Database."

We clarified in Section 2.5 that the natural, conditional, and altered thresholds are pragmatic screening criteria rather than calibrated or universal thresholds of hydrologic alteration, and that they do not affect the underlying continuous SAI calculations. The revised text on page 13, lines 472–480, reads:

> These classification thresholds were selected to provide a conservative separation between SAI-based screening classes. We adopted an SAI_I threshold of 20% because Level I signals represent higher-confidence and typically stronger evidence of alteration, which should remain limited in basins classified as natural. This threshold is also consistent with agency instream flow assessment practice, which commonly applies pragmatic decision rules to delineate downstream impact limits for waterpower projects, including watershed-area scaling criteria such as the "5 times drainage area" rule described by Lewis et al. (2004). We adopted an SAI_II threshold of 40% because Level II signals indicate potential rather than confirmed alteration, and thus a somewhat more permissive threshold is appropriate. Both thresholds are pragmatic screening criteria rather than calibrated or universal thresholds of hydrologic alteration; they are used only for classification in the evaluation and related SAI-based applications and do not affect the underlying continuous SAI calculations.

The revised text on page 13, lines 465–466, describes the comparison and now reads:

> We evaluated SAI v1.0 by comparing SAI-derived conditions at hydrometric gauge locations against independent agency classifications from the WSC and the Reference Hydrometric Basin Network (RHBN).

And the opening of Section 3.2 on page 17, lines 547–548, now reads:

> This evaluation is intended to assess the usefulness of SAI as a screening dataset for instream alteration, rather than to verify the exact magnitude of the estimated hydrologic alteration at individual sites.

In order to address the comment regarding the meaning of SAI, please note the formal definition of SAI included in the original submission and retained in the revised manuscript, which reads (page 10, lines 362–366): "SAI is an area-based metric that propagates alteration signals through the drainage network, summarizing the percentage of upstream drainage area whose routed flow passes through locations containing alteration signal sources. The drainage-area weighting assumes that long-term streamflow is approximately proportional to contributing drainage area."

Beyond the above, we further clarified the interpretation using an example SAI value immediately after presenting the empirical support for the drainage-area scaling approximation. The revised text on page 10, lines 379–383, reads:

> Accordingly, SAI uses proportional drainage-area scaling as a first-order mixing approximation rather than as a physical model of runoff generation. Under this approximation, a SAI value of 30% at a subbasin outlet on the river network is interpreted to mean that approximately 30% of the streamflow has passed at least one mapped upstream alteration source. We compute SAI at the subbasin scale (at the subbasin outlet points only) to support spatially complete mapping of potential instream alteration across large domains, including ungauged basins.

We further clarified continuous SAI values in Section 2.4. The revised text on page 11, lines 408–412,

reads:

> SAI values quantify upstream spatial exposure to mapped alteration sources and, under the drainage-area scaling approximation described above, provide a first-order proxy for the fraction of flow passing at least one mapped upstream alteration source at each subbasin outlet along the routing network (Figure 1b). SAI_I ranges from 0 to 100% and reflects the degree of influence associated with confirmed (Level I) sources, whereas SAI_II ranges from 0 to 100% and reflects the degree of influence associated with potential (Level II) sources.

Third, we expanded the limitations discussion to explicitly describe uncertainties associated with drainage-area weighting and the spatial simplification introduced by subbasin-scale evaluation. The revised text on page 20, lines 629–644, reads:

> Another limitation is that downstream alteration impact in SAI is represented using drainage area alone. This assumes that long-term streamflow is approximately proportional to contributing drainage area. Erikson et al. (2024) found approximately linear discharge–drainage area scaling for most hydrologic regions across the United States and Canada, but also identified systematic regional departures associated with differences in runoff efficiency and hydroclimatic conditions. Our Ontario-specific analysis similarly showed strong, near-linear scaling between long-term mean annual discharge and drainage area across the province and three broad regional groupings, while also indicating modest departures from exact proportionality (Appendix B). Streamflow is therefore not determined by drainage area alone: spatial variability in precipitation, evapotranspiration, snow accumulation and melt, soils, geology, groundwater contributions, lakes, wetlands, and other physiographic controls can produce departures from proportional scaling. In addition, subbasins with similar drainage area may differ in their effective alteration impact attenuation capacity because of lakes, wetlands, channel storage, and routing characteristics; subbasins containing lakes, for example, may exert stronger flow-buffering and hydrograph-smoothing effects than lake-free subbasins of comparable size (Hudson et al., 2021).
>
> A related spatial simplification arises because SAI is evaluated at subbasin outlets: a source located within a subbasin is treated as influencing the full flow at that outlet. This approximation does not resolve within-subbasin routing and may locally overestimate exposure where a structure affects only part of the flow reaching the subbasin outlet, although the relatively fine OLRRP v2 discretization limits the spatial scale of this effect.

Comment 3.1 (Line 128 in the original manuscript)

L128, finally we reach the topic of this study. The previous introduction is a bit lengthy. Besides, it omits the introduction about the particularity of the study region, i.e., why do we need to implement a case study here?

Authors' response

We agree that the Ontario-specific motivation should be established before introducing SAI. We have added a paragraph explaining why Ontario is well suited for this application: it combines extensive hydrometric monitoring and water-control infrastructure with the high-resolution, connected OLRRP v2 network, while detailed facility-specific storage and operating information remains incomplete.

We revised the following paragraph introducing SAI so that it now follows directly from this Ontario-specific motivation and more clearly explains the role of the OLRRP v2 network and the data-limited setting addressed by SAI. We also consolidated and reorganized portions of the background discussion so that the Ontario-specific motivation now leads directly into the introduction of SAI.

Changes in the manuscript

We added a new paragraph immediately before the introduction of SAI and revised the following paragraph accordingly. The revised text on page 4, lines 135–143, now reads:

> Ontario, Canada, provides a useful domain for developing and evaluating a new and improved streamflow alteration index. The province combines large and hydrologically diverse lake and river networks with extensive hydrometric monitoring and numerous dams, waterpower facilities, and other water-control structures, creating a practical need to identify locations potentially affected by upstream alteration across a large domain. Such identification is key for hydrologic modelling and other water resources applications. The Ontario Lake and River Routing Product Version 2 (OLRRP v2) provides a high-resolution, topologically connected hydrographic network suitable for spatial propagation of alteration signals, while detailed facility-specific storage and operating information remains incomplete for many locations (Shen et al., 2024). This combination of practical need, detailed network information, and incomplete operational data makes Ontario well suited for developing a parsimonious, network-based approach to estimating streamflow alteration.

Comment 3.2 (Lines 128–144 in the original manuscript)

L128-144, here it only highlights the merits of the new SAI metric. Before that, the authors need to explain the principle of this metric, what exact data it relies on ("whether a dam or reservoir is expected to substantially modify downstream flows" is too vague, is there a database for this purpose?), why it could address the data limitation problem, what is the magic code that makes it more efficient than the previous approaches.

Authors' response

We agree that the required inputs and calculation principle should be stated more explicitly. SAI requires two primary types of information: (1) a topologically connected lake–river–subbasin network with drainage-area attributes and (2) a georeferenced inventory of candidate flow-control structures with metadata sufficient for source classification. In Ontario, these are provided by OLRRP v2 and the infrastructure datasets described in Sections 2.1 and 2.3 and Table 1.

Once the sources are classified, SAI is calculated through a deterministic traversal of the river network using drainage-area-weighted mixing and same-level resetting. Its practical advantage is therefore its relatively limited and spatially consistent data requirements compared with approaches requiring reservoir storage, discharge, operating rules, or response parameters.

Changes in the manuscript

We revised the Introduction to state the required inputs, source-classification information, network-propagation procedure, and data advantage of SAI more explicitly. The revised text on pages 4–5, lines 151–166, now reads:

> Moreover, SAI is designed to be practical in data-limited settings. Storage- and discharge-based indices such as DOR and DI require quantities such as reservoir capacity and mean flow, while physically based flood-attenuation indices require additional reservoir and catchment response parameters, such as storage coefficients, travel-time characteristics, and climatic inputs (Cipollini et al., 2022, 2023). By contrast, SAI requires two primary types of information: a topologically connected lake–river–subbasin network with drainage-area attributes and a georeferenced inventory of candidate flow-control structures with metadata sufficient to classify their likely alteration influence. In the Ontario application, candidate sources are classified using documented source attributes including facility operation type, reservoir purpose, and dam ownership. Once the sources are classified, SAI is calculated through a static, deterministic traversal of the river network, with alteration signals propagated downstream using drainage-area-weighted mixing and then reset when a new source of the same level is encountered. This parsimonious formulation avoids requiring consistently available quantitative information such as reservoir storage capacity, mean discharge, detailed

> operating rules, release time series, or reservoir-response parameters, thereby enabling consistent application across large domains where such information is incomplete or unavailable. We developed the SAI v1.0 database for Ontario using OLRRP v2, which discretizes the province into nearly 250,000 subbasins with an average area of 4.3 km^2 (Shen et al., 2024). The database provides subbasin-scale SAI maps and associated GIS layers that support the classification of subbasin outlets and hydrometric gauge locations as natural, conditional, or altered, together with a harmonized table describing alteration signal sources.

Comment 3.3 (Line 225 in the original manuscript)

L225, please add a map to show the locations/spatial coverage of these datasets.

Authors' response

We agree and have added Appendix A to show the spatial coverage of the compiled infrastructure datasets. Figure A1 maps the 2,476 retained ODI, MNR, WPF, and lockstation records using both province-wide and zoomed-in views; Figure A2 shows the corresponding Level I–III alteration signal classifications.

Changes in the manuscript

We added a new Appendix A, including Figures A1 and A2, to show the spatial distributions of the infrastructure records retained after geospatial alignment and screening and the resulting Level I–III alteration signal classifications, respectively. We also added the following sentence to Section 2.3 on page 8, lines 319–320:

> The spatial distributions of the compiled infrastructure records and the resulting Level I–III alteration signal classifications are shown in Figures A1 and A2, respectively.

The new Appendix A and Figures A1 and A2 are provided below.

> **Appendix A. Spatial distribution of infrastructure records and alteration signal sources**
>
> Figures A1 and A2 provide province-wide and detailed views of the spatial distributions of the 2,476 infrastructure records retained after geospatial alignment and screening (Section 2.2) and their resulting alteration signal classifications (Section 2.3), respectively. Figure A1 shows the compiled records from the four infrastructure datasets, whereas Figure A2 shows the resulting Level I, Level II, and Level III alteration signal sources. Following subbasin-level consolidation, Level I and Level II sources occurred in 643 unique subbasins and were retained for SAI initialization, whereas 1,288 records were classified as Level III and treated as negligible.

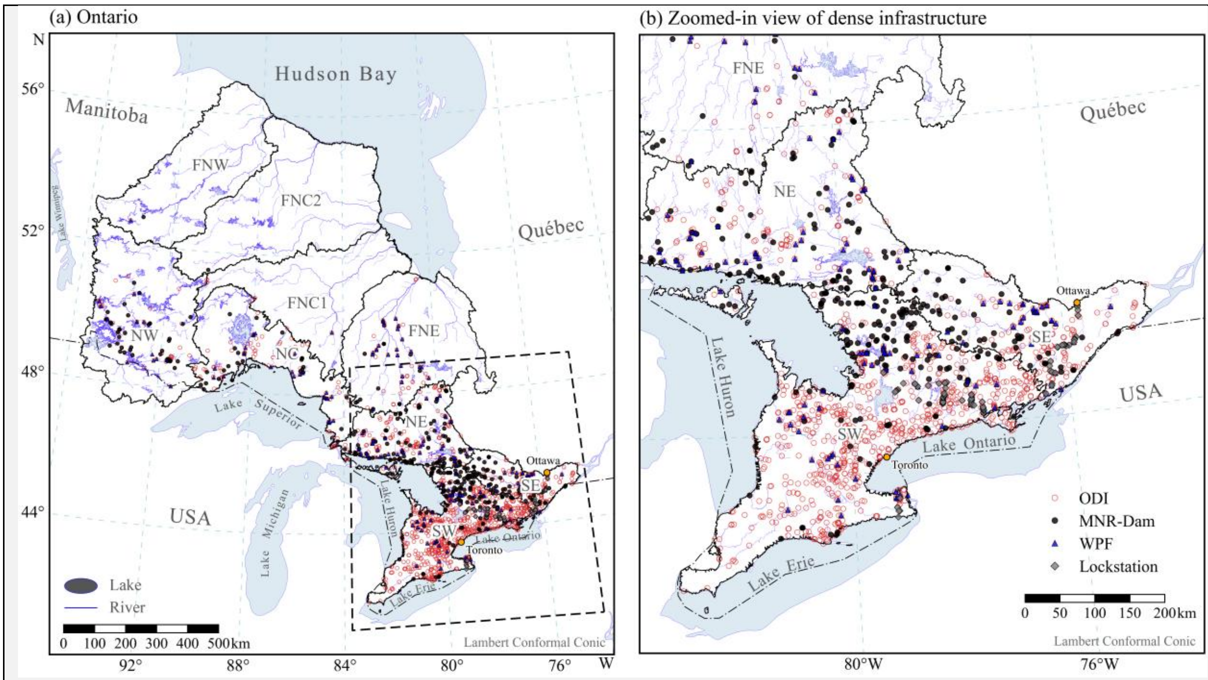

Figure A1. Spatial distribution of the 2,476 infrastructure records retained for identifying potential streamflow alteration sources across Ontario. (a) Province-wide distribution of records from the Ontario Dam Inventory (ODI), Ontario Ministry of Natural Resources (MNR), Waterpower Facilities (WPFs), and lockstation datasets. (b) Zoomed-in view of infrastructure-dense areas. The dashed box in panel (a) indicates the spatial extent shown in panel (b). Rivers (blue lines; thicker lines indicate higher Strahler stream order) and lakes (blue polygons; only lakes with areas > 100 km^2 are shown) are from the Ontario Lake and River Routing Product Version 2 (OLRRP v2).

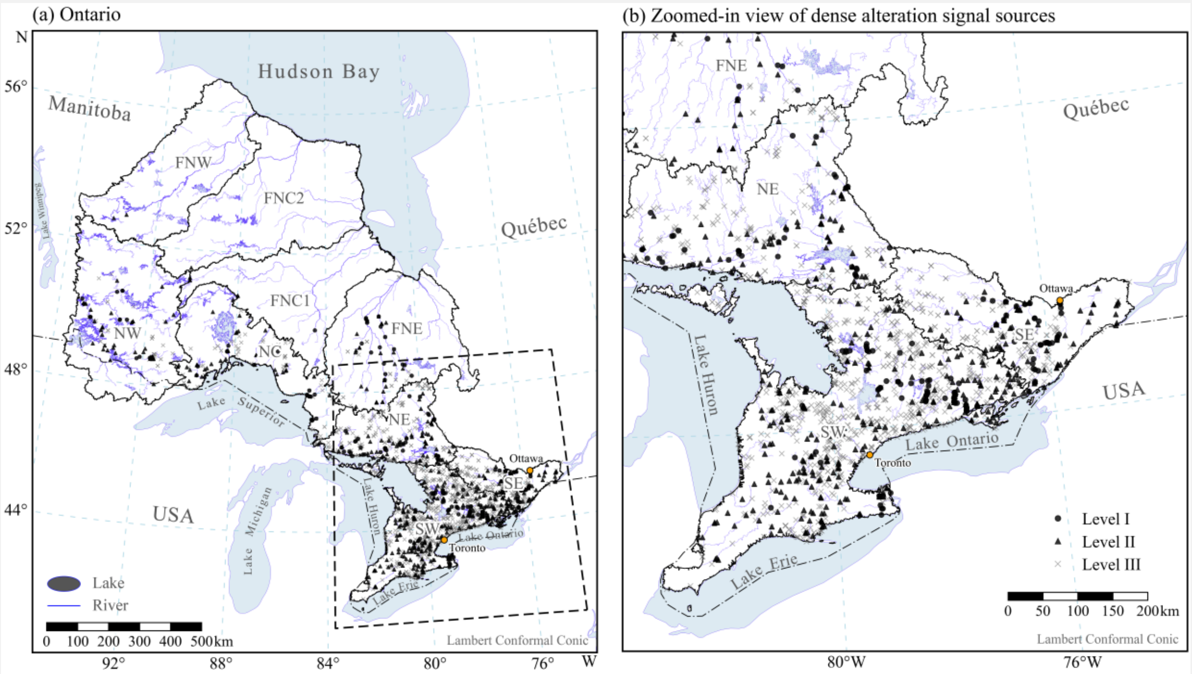

Figure A2. Spatial distribution of the classified alteration signal sources across Ontario. (a) Province-wide distribution of Level I (confirmed), Level II (potential), and Level III (negligible) alteration signal sources. Following subbasin-level consolidation, Level I and/or Level II sources occurred in 643 unique subbasins, whereas 1,288 candidate records were classified as Level III. Level I and Level II sources are retained for Streamflow Alteration Index (SAI) initialization, whereas Level III sources are treated as negligible and excluded from SAI initialization and propagation. (b) Zoomed-in view of alteration signal-dense areas. The dashed box in panel (a) indicates the spatial extent shown in panel (b). Rivers (blue lines; thicker lines indicate higher Strahler stream order) and lakes (blue polygons; only lakes with areas > 100 km^2 are shown) are from the Ontario Lake and River Routing Product Version 2 (OLRRP v2).

Comment 3.4 (Line 225 in the original manuscript)

How complete are these datasets? Is it possible that the dataset is incomplete in some particular regions or for small-scale facilities?

Authors' response

We address these questions by revising Section 2.1 so that it now describes the scope and principal limitations of each alteration signal data-source group, the focus of ODI on medium-to-large dams, and the restricted scope of the MNR-operated dam inventory. The new Appendix A also provides a direct view of the spatial coverage of the compiled records.

We also expanded Section 4 to clarify that the compiled infrastructure inventory should not be considered exhaustive.

Changes in the manuscript

We added the following clarification to Section 2.1 on pages 6–7, lines 240–254:

The six main data-source groups used in this study differ in scope and completeness, because they were developed for different hydrographic, infrastructure, monitoring, and reference network purposes. The OLRRP v2 provides province-wide river network coverage, but its HydroLAKES-derived lake layer only includes waterbodies with surface areas of 0.1 km^2 or greater; smaller ponds, including waterbodies smaller than 0.01 km^2 as considered by Schmadel et al. (2019), are therefore omitted. The Ontario Dam Inventory (ODI) focuses on medium-to-large dams, whereas the complementary Ontario MNR dataset includes only MNR-operated dams. Some small water-control structures, including culverts and small dams, may be underrepresented in the ODI and MNR dam datasets. The waterpower facility dataset provides broad coverage of known generation stations, although the availability and completeness of operational attributes vary among facilities. The compiled lockstation dataset covers the Trent-Severn Waterway, Rideau Canal, and Welland Canal, which include the major lock systems represented in this study. The WSC gauge network provides extensive federal hydrometric coverage but excludes gauges operated exclusively by other agencies, and its natural/regulated metadata are not fully documented for all stations.

Despite these limitations, these sources represent, to our knowledge, the best available and most spatially comprehensive province-wide datasets that can be consistently integrated for SAI development. Missing or incompletely documented water-control structures may lead to underrepresentation of alteration sources; the implications of these omissions for SAI are discussed further in Section 4.

The expanded discussion of the compiled records on pages 20–21, lines 664–675, now reads:

Moreover, the compiled infrastructure inventory should not be considered exhaustive. Although multiple known provincial and sector-specific datasets were harmonized to provide broad spatial and facility-type coverage, their completeness cannot be independently verified for every region or facility type, and small, perhaps locally managed and privately owned structures may be missing. In addition, the HydroLAKES-derived OLRRP v2 lake layer excludes waterbodies smaller than 0.1 km^2, including many small ponds and impoundments. Although individually small, these waterbodies can collectively alter annual discharge, low and peak flows, and hydrograph timing, while also exerting substantial cumulative effects on nutrient and sediment retention (Brogan et al., 2022; Habets et al., 2018; Schmadel et al., 2019). For SAI specifically,

> omissions of control structures are expected to be less consequential when they involve structures with primarily localized water-level effects, which would generally be treated as negligible (Level III) alteration sources and excluded from SAI initialization. However, omission of facilities that substantially regulate streamflow would lead to underestimation of alteration along their downstream river networks. We therefore recommend using SAI v1.0 as a network-wide screening reference, supplemented by targeted basin-specific review and additional local infrastructure information where available.

We also added Appendix A to show the spatial distributions of the compiled infrastructure records and resulting alteration signal classifications. Section 2.3 now states on page 8, lines 319–320:

> The spatial distributions of the compiled infrastructure records and the resulting Level I–III alteration signal classifications are shown in Figures A1 and A2, respectively.

Comment 3.5 (Line 272 in the original manuscript)

L272, again, we need a map to show the distributions of these three sources.

Authors' response

As described in our response to Comment 3.3, Figure A2 has been added to show the province-wide and detailed distributions of Level I, Level II, and Level III alteration signal sources.

Changes in the manuscript

Please see Appendix A and Figure A2 described in our response to Comment 3.3.

Comment 3.6 (Line 288 in the original manuscript)

Table 1. All dams belong to Level II, even if one has the power generation purpose?

Authors' response

We clarify that alteration levels are assigned using dataset-specific evidence rather than facility type or reported purpose alone. A waterpower-related purpose is treated as Level I evidence only when reported in the dedicated Waterpower Facility dataset, where more detailed operational information is available. ODI and MNR-dam records are instead classified using their respective Level II criteria, and remaining records are assigned to Level III.

Changes in the manuscript

We clarified this distinction in Section 2.3 and Table 1.

The revised text on page 8, lines 311–314, now reads:

> The classification is evidence-based and dataset-specific, reflecting the strength and consistency of the information available from each source dataset rather than facility type or reported purpose alone. Consequently, similar facility attributes reported in different inventories do not necessarily provide the same level of evidence for streamflow alteration.

We also added the following clarification to the description of Level I alteration signal sources on pages 8–9, lines 328–330:

> Accordingly, a waterpower-related purpose reported in the broader ODI or MNR dam inventories is not, by itself, considered sufficient evidence for a Level I classification because these inventories do not provide the

same consistently documented operational information available for WPF records.

The caption of Table 1 (page 9, lines 351–354) was revised accordingly to clarify that the Level I, Level II, and Level III classifications are based on dataset-specific evidence rather than facility type or reported purpose alone.

Comment 3.7 (Line 305 in the original manuscript)

L305, "Assuming streamflow is proportional to upstream drainage area", this is a very strong assumption.

Authors' response

We agree. This concern is addressed in our response to the General Assessment, including the Ontario-specific empirical assessment of discharge–drainage area scaling and the expanded discussion of associated uncertainty.

Changes in the manuscript

Please see our response to the General Assessment. The Ontario-specific analysis is documented in Appendix B and Figure B1, with the corresponding limitation discussed in Section 4.

Comment 3.8 (Line 443 in the original manuscript)

L443, what is the criterion (level, size?) for defining a subbasin?

Authors' response

The subbasins are inherited from OLRRP v2. Subbasin outlets were defined using a 5,000-cell flow accumulation threshold, lake outlets, and points of interest (POIs), resulting in an average subbasin area of approximately 4.3 km^2.

Changes in the manuscript

We clarified the OLRRP v2 subbasin-delineation criteria in Section 2.1. The revised text on page 5, lines 185–190, reads:

Shen et al. (2024) defined OLRRP v2 subbasin outlets at locations reaching a flow accumulation threshold of 5,000 30 m × 30 m grid cells, at lake outlets, or at points of interest (POIs) included in OLRRP v2. These criteria result in an average subbasin area of approximately 4.3 km^2, ensure that each represented lake is fully contained within a single subbasin, and allow a complete upstream contributing catchment to be delineated for each POI.

Comment 3.9 (Line 464 in the original manuscript)

Fig. 2, it is difficult to see the details.

Authors' response

We agree that Figure 2 is primarily a province-wide overview and that subbasin-level detail is difficult to discern at manuscript-page scale. We have improved its readability by lightening the background water bodies, using muted colours for background labels, and slightly thickening regional boundaries. These changes help draw attention to the SAI patterns while retaining the geographical context. The final Figure 2 has been prepared at 900 dpi, while Figure 3 provides a more detailed regional view of the Southeast region. We have also directed readers to the province-wide interactive map and downloadable GIS layers

for detailed exploration.

Changes in the manuscript

We clarified the complementary roles of Figures 2 and 3 and added a reference to the interactive map for detailed exploration. The revised text on page 15, lines 528–531, reads:

> Figures 2 and 3 are intended to provide province-wide and regional overviews of SAI spatial patterns, respectively. For more detailed exploration, subbasin-level SAI values, alteration signal sources, OLRRP v2 hydrographic layers, and their associated attributes can be viewed through the interactive online map described in the Data Availability section.

The interactive map is documented in the Data Availability section (pages 24–25, lines 768–773).

Additional Author-Initiated Revisions

In addition to the changes made in direct response to the reviewers' comments, we made a small number of additional clarifications and editorial/documentation refinements for consistency and completeness. These additional revisions do not affect the SAI calculations or the results reported in the manuscript. As such, corresponding manuscript excerpts are not reproduced here because these changes are readily visible in the tracked-changes manuscript. Minor grammatical, formatting, and typographical corrections are not listed individually.

Author-Initiated Revision A.1: Correction of an author name and affiliation

We corrected the name of co-author James J. Luce in the author list and Author Contributions section, and corrected his institutional affiliation in the author list.

Author-Initiated Revision A.2: Additional comparison with physically based reservoir-impact indices

In the Introduction, we added references to the physically based flood-attenuation indices of Cipollini et al. (2022, 2023) and briefly clarified how their data requirements differ from those of SAI. Related discussion of existing storage-based and reach-based alteration metrics was also refined for clarity.

Author-Initiated Revision A.3: Expanded discussion of hydrologic modelling and data-driven assessment

In the Introduction, we consolidated the discussion of why streamflow-alteration information is important for process-based modelling, data-driven prediction, and regionalization. We also added recent work demonstrating reach-scale reconstruction of reference hydrology and hydrologic alteration at ungauged locations.

Author-Initiated Revision A.4: Abstract update

We revised the Abstract to better reflect the current interpretation and implementation of SAI, including the drainage-area-based screening formulation, independent propagation of SAI_I and SAI_II, infrastructure and alteration-source counts, hydrometric evaluation results, and the Zenodo DOI.

Author-Initiated Revision A.5: Clarification of data provenance and accessibility

In Data Sources, we clarified the provenance of the Waterpower Generation Stations attributes and the independently compiled Water Management Plan classifications. We also clarified the restricted availability of the supplementary MNR-operated dam dataset and added source-specific access information to the Data Availability section.

Author-Initiated Revision A.6: Expanded documentation of geospatial alignment and candidate-record screening

We reorganized the Materials and Methods section so that geospatial alignment and screening precede alteration-source classification. Section 2.2 now documents the automated and manual snapping workflow, screening criteria, and exclusions.

We also report the mean and median alignment displacements for each source dataset and clarify that ODI and MNR-dam records co-occur in 347 OLRRP subbasins, which should not be interpreted as 347 duplicate dams.

Author-Initiated Revision A.7: Clarification of the SAI equations and propagation description

We corrected the written form of Eqs. (1) and (2) by removing an extraneous final multiplication by 100%. This was a typographical error in the manuscript and did not affect the implemented SAI calculation or any reported results. We also replaced "Otherwise" with explicit conditions specifying that the current subbasin contains no alteration signal source of the corresponding level. In addition, we clarified the independent propagation and same-level resetting of SAI_I and SAI_II and revised Figure 1 and its caption accordingly.

Author-Initiated Revision A.8: Clarification of the gauge-screening and evaluation description

We clarified the distinction between the 1,015 WSC gauges embedded in OLRRP v2 and the set of 488 SAI evaluation gauges retained after gauge-status, record-length, and diversion screening. The corresponding clarification updates can be found in Sections 2.1, 2.5, and 3.2.

Author-Initiated Revision A.9: Expanded data-product and availability documentation

We expanded the Data Records and Data Availability sections to document the three primary SAI v1.0 products, their key attributes and coordinate reference system, links among the source, subbasin, and river layers, and the interpretation of river-reach SAI values. We also added the province-wide interactive map, public calculation-code repository, and Zenodo DOI.

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