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

Hongren Shen[1, *], Bryan A. Tolson[1], James R. Craig[1], Robert A. Metcalfe[2, 3], Jonathan Romero-Cuellar[1], and ~~Jamie~~ James J. Luce[2, 3]

[1]Department of Civil and Environmental Engineering, University of Waterloo, Ontario, Canada
[2]Environmental and Life Sciences Graduate Program, Trent University, Ontario, Canada
[3]Aquatic Research and Monitoring Section, Ministry of Natural Resources, Trent University, Ontario, Canada

[*]*Correspondence to*: hongren.shen@uwaterloo.ca

Abstract. Dams, reservoirs, ~~and~~ waterpower facilities, and other water-control structures ~~are central to regional water management, but they~~ can ~~induce~~ modify streamflow and ~~alterations that~~ propagate their influence downstream through connected river networks, ~~and~~ complicating hydrologic ~~modeling~~modelling and aquatic ecosystem assessment. Large-domain assessments often rely on binary agency classifications at hydrometric gauges (e.g., "natural" and "regulated") or on storage- and discharge-based metrics that are difficult to apply consistently where operational data are incomplete. ~~Existing streamflow indicators often quantify alteration only at discrete locations (e.g., hydrometric gauges), thus limiting spatially continuous, subbasin-scale mapping of where upstream infrastructure may influence downstream flows.~~ We ~~propose~~ introduce the Streamflow Alteration Index (SAI), a parsimonious, network-based screening metric that estimates the percentage of upstream drainage area whose routed flow passes through mapped alteration signal sources. Under a first-order drainage-area scaling approximation, SAI provides a proxy for the fraction of streamflow potentially exposed to upstream alteration sources, rather than a measure of the exact magnitude of hydrologic alteration. ~~propagates point-based alteration signal sources downstream through a routing network to map potential alteration influence.~~ The framework ~~includes~~ comprises two paired indices, ~~:~~ SAI_I (0–100%) and SAI_II (0–100%), independently representing confirmed Level I and potential Level II sources; values are propagated downstream by drainage-area-weighted mixing and reset at new sources of the same level. We compiled 2,528 infrastructure records, of which 2,476 were retained after geospatial alignment and screening. Following source classification and consolidation of multiple records within the same subbasin, 643 unique subbasins were identified as Level I and/or Level II alteration signal locations. The resulting SAI v1.0 database provides province-wide subbasin and river-reach layers for screening potential instream alteration at gauged and ungauged locations. We evaluated SAI-derived natural, conditional, and altered classes against 148 Reference Hydrometric Basin Network (RHBN) gauges, 125 additional Water Survey of Canada (WSC) gauges labelled natural, and 215 WSC-regulated gauges. SAI classified 86% of both natural reference groups as natural, with no RHBN gauge classified as altered. Among WSC-regulated gauges, 26% were classified as altered, 40% as conditional, and 34% as natural, highlighting differences between binary agency labels and the SAI screening framework and identifying sites requiring follow-up assessment. SAI v1.0 therefore provides a practical, transparent, and reproducible screening baseline for large-domain hydrologic and ecological applications without requiring detailed operating rules and offers a scalable framework for broader network-based assessments of potential streamflow alteration. The SAI v1.0 dataset is available from Zenodo (~~:~~Shen et al., 2026~~)~~; doi:10.5281/zenodo.19547932).

~~representing two levels of influence derived from confirmed (Level I) and potential (Level II) alteration signal sources. We implemented SAI to develop the SAI v1.0 database for Ontario, Canada, using the Ontario Lake and River Routing Product Version 2 (OLRRP v2) network and an inventory of 643 alteration signal sources compiled from provincial datasets. The resulting product provides seamless, high-resolution, network-based, subbasin-scale mapping of streamflow alteration across Ontario and enables SAI estimates at both gauged and ungauged nodes within the routing network. We validated SAI by classifying subbasins containing hydrometric gauges as natural, conditional, or altered and compared these classes against two independent references: Reference Hydrometric Basin Network (RHBN)~~

Style Definition: Normal: Space After: 5 pt, Line spacing: 1.5 lines
Style Definition: Heading 1
Formatted: Affiliation
Formatted: Default Paragraph Font
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Heading 1, Snap to grid

~~gauges (with minimal human impact) and Water Survey of Canada (WSC) gauge "Natural" and "Regulated" labels. SAI shows strong agreement for gauges labelled natural: 86% of RHBN natural gauges and 86% of WSC-natural gauges are classified as natural by SAI. For WSC-regulated gauges, SAI classifies 74% as conditional or natural. Overall, SAI v1.0 provides a practical, objective screening product for large-domain hydrologic and aquatic applications without requiring detailed dam operating information, and it offers a scalable pathway toward national- to global-scale, network-based screening products for streamflow alteration.~~

1. Introduction

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).~~(Lehner et al., 2024)(Brogan et al., 2022; Habets et al., 2018; Schmadel et al., 2019)~~

Despite their societal benefits, the widespread construction and operation of dams and reservoirs have profoundly transformed natural flow regimes, altered sediment and nutrient fluxes, and generated substantial ecological and social trade-offs (Richter et al., 2010; Winemiller et al., 2016). 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). Dams and reservoirs can modify the magnitude, timing, frequency, duration, and rates of change of streamflow by storing, releasing, and diverting water. Such streamflow alteration is widely regarded as a first-order impact on fluvial systems, because flow regimes are fundamental drivers of riverine habitats and ecosystem processes (Burke et al., 2009; Jorde et al., 2007; Petts, 1984; Poff et al., 1997, 2010). Reservoir effects vary with storage capacity, operating practices, evaporation losses, hydroclimatic conditions, and network position, but commonly include attenuation of flood peaks and redistribution of flows through time; low flow responses may involve either augmentation or depletion (Brogan et al., 2022; Habets et al., 2018).

In this study, streamflow alteration denotes human-caused changes to natural streamflow patterns arising from instream structures and lake-outflow controls, primarily through the construction and operation of dams, reservoirs, and waterpower facilities. ~~(Brogan et al., 2022; Habets et al., 2018)~~Hereafter, the term "alteration" is used throughout, except where "regulation" is retained as part of established terminology, such as degree of regulation and the natural and regulated classifications used in HYDAT (Water Survey of Canada, 2024), or when following the terminology of cited studies.~~(Brogan et al., 2022; Habets et al., 2018)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, waterpower generation, and recreation (Maavara et al., 2020; Palmer and Ruhi, 2019; WCD, 2000). As documented in the Global Dam Watch database (Lehner et al., 2024), there are 41,145 barrier locations and 35,295 associated reservoirs globally, with a cumulative storage volume of 7,420 km^3 and a surface water area of 304,600 km^2. (Schmadel et al., 2019)More broadly, river networks worldwide are affected by many more instream structures, and the majority of large rivers worldwide are fragmented and regulated (Grill et al., 2019). Engineered watersheds have played a crucial role in enabling agricultural expansion, supporting urban water demands, mitigating natural disasters, and driving economic development (Lehner et al., 2011; WCD, 2000).~~

~~However, the widespread construction and operation of dams have profoundly transformed natural flow regimes, altered sediment and nutrient fluxes, and generated substantial ecological and social trade-offs (Richter et al., 2010; Winemiller et al., 2016). Dams and reservoirs can substantially modify the magnitude, timing, frequency, and duration of natural streamflows by regulating the storage and release of water. Such streamflow alteration is widely regarded as a first-order impact on fluvial systems, because flow regimes are a fundamental driver of riverine habitat and ecosystem processes (Burke et al., 2009; Jorde et al., 2007; Petts, 1984; Poff et al., 1997, 2010). In this study, streamflow alteration denotes human-caused changes to natural~~

~~streamflow patterns arising from instream structures and lake outflow controls, primarily through the construction and operation of dams, reservoirs, and waterpower facilities. Such alteration commonly dampens high flows, augments baseflows, and smooths natural variability, with widespread implications for river connectivity, ecosystem dynamics, and water resources management. Hereafter, the term alteration is used throughout, except where regulation is retained for consistency with established terminology (e.g., degree of regulation, HYDAT natural and regulated labels) and cited sources.~~

Streamflow alterations occur across temporal scales ranging from minutes to seasons, with particularly strong sub-daily variability downstream of hydropeaking waterpower facilities (WPFs). Hydropeaking refers to sub-daily operational changes in discharge used to match electricity generation to demand, which commonly produce~~s~~ higher releases during daytime, when electricity demand is greatest, and lower releases at night. This creates highly variable downstream hydraulic and habitat conditions at short-time scales (Bejarano et al., 2018; Kern et al., 2012). Because these fluctuations happen on sub-daily time scales, daily discharge records can mask key features of alteration such as ramping rates, the frequency of peaks, and the duration of high- and low-flow periods (Smokorowski, 2022). At longer (seasonal-to-annual) scales, reservoir operations commonly suppress flood peaks during wet periods and augment low flows during dry periods, which partially decouples discharge from natural hydroclimatic variability (Déry et al., 2016). The magnitude and spatial footprint of these alterations depend on interacting factors, including project purpose (e.g., flood control, waterpower, recreation), reservoir storage and dam operating rules, river-network configuration (e.g., reservoir size relative to inflow, cascades of dams and diversions, and channel hydraulics), and basin physiography and hydroclimate (Burke et al., 2009; Jorde et al., 2007).

A recent systematic review of 155 studies by Bipa et al. (2024) further showed that hydropeaking affects more than discharge alone: it can also modify water temperature, sediment processes, and dissolved gas conditions, with well-documented consequences for fish (e.g., movement, spawning, migration), benthic macroinvertebrates, and riparian vegetation. Global reliance on dams is expected to remain high or even increase in response to growing water stress, energy demand, and climate change, making robust assessment of dam impacts increasingly important (Steyaert et al., 2025; Tharme, 2003).

Streamflow alteration poses a persistent challenge for hydrologic modelling because many model applications assume natural conditions, whereas regulated flows reflect operational decisions in addition to hydroclimate and physiography. In process-based models, reservoir operations and other human-water processes are often simplified and poorly constrained, particularly at large scales, which can bias parameter estimation, reduce model transferability, and undermine predictions under changing conditions (Dang et al., 2020; Shrestha et al., 2024; Wada et al., 2017; Yassin et al., 2019; Zajac et al., 2017). Similar considerations apply to data-driven models: static catchment attributes can improve generalization across basins (Kratzert et al., 2019a, b), while regulation descriptors have been shown to improve prediction skill in human-altered catchments (Tursun et al., 2024). Flow alteration can also weaken assumptions of hydrologic similarity used in regionalization, complicating prediction in poorly gauged or ungauged basins (Blöschl, 2013; Dang et al., 2020; Du et al., 2022; Hrachowitz et al., 2013; Montanari et al., 2013). Recent data-driven studies further demonstrate that reference hydrology and hydrologic alteration can be reconstructed across large stream networks using gauged observations and geospatial predictors, enabling reach-scale estimates at ungauged locations (Lueders et al., 2026). These developments reinforce the need for scalable alteration assessments, consistent with regional environmental-flow frameworks that recognize the impracticality of evaluating rivers individually across large domains (Poff et al., 2010).

~~In the hydrologic modeling community, where model implementations can often assume natural conditions, streamflow alteration can negatively influence model calibration and validation. Symptoms include biased parameter estimation, reduced model transferability, and unreliable predictions under changing conditions. These impacts are especially pronounced in large-scale modeling, where reservoir operations and other human-water processes are difficult to represent consistently due to data limitations, simplified operating rules, and challenges in evaluation across large domains (Dang et al., 2020; Shrestha et al., 2024; Wada et al., 2017; Yassin et al., 2019; Zajac et al., 2017).~~

~~Assessing flow alteration is increasingly important for hydrologic modeling and water management purposes, and it is critical for both process-based and data-driven models. Altered flow regimes remain difficult to represent in process-based hydrologic models, especially at large scales where reservoir operations are often simplified and poorly constrained by observations (Wada~~

et al., 2017). Recent deep-learning rainfall-runoff studies showed that conditioning models on static catchment attributes substantially improves generalization across basins by helping networks learn basin-to-basin differences in storage and response behavior (Kratzert et al., 2019a, b). However, in human-altered rivers, discharge reflects not only hydroclimate and physiography but also operational decisions; incorporating regulation descriptors as attributes has been shown to improve prediction skill in regulated catchments (Tursun et al., 2024). Moreover, alterations can undermine parameter transfer in regionalization by breaking hydrologic similarity assumptions, thus complicating streamflow prediction in poorly gauged or ungauged basins (Blöschl, 2013; Dang et al., 2020; Du et al., 2022; Hrachowitz et al., 2013; Montanari et al., 2013). (Lueders et al., 2026)This need for scalable assessment is also consistent with regional environmental-flow frameworks that recognize the impracticality of evaluating hydrologic alteration on a river-by-river basis across large domains (Poff et al., 2010).

The impacts of dam and reservoir-caused alteration caused by dams and reservoirs on hydrology have been widely documented in recent decades (Déry et al., 2016; Grill et al., 2014; Habets et al., 2018; Lehner et al., 2011; Richter et al., 2010; Yang et al., 2022). In parallel, numerous indices have been developed to quantify regulation intensity and related impacts across river systems, ranging from storage-based metrics (e.g., degree of regulation) to fragmentation and connectivity metrics used in large-scale assessments (e.g., Nilsson et al., 2005; Grill et al., 2014), including reach-based, decadal dam impact metrics that propagate cumulative upstream storage effects through river networks (e.g., Wieczorek et al., 2021). Physically based indices have also been developed specifically to estimate flood peak attenuation by multiple reservoirs at the catchment scale. Cipollini et al. (2022) introduced an equivalent-reservoir index that accounts for reservoir number, relative location, storage characteristics, and climatic variability, while Cipollini et al. (2023) extended this framework to generic catchment geometries and arbitrary reservoir locations.

One of the most widely used storage-based measures is the degree of regulation (DOR), a residence time proxy defined as the ratio of the total reservoir storage capacity to the mean annual flow. Higher DOR values indicate greater potential for regulation influence. The DOR has been mapped globally and is included as an attribute in several global dam/reservoir datasets (Lehner et al., 2011, 2024; Nilsson et al., 2005; Yin et al., 2024). However, like all metrics, DOR has several limitations: (1) using total reservoir storage capacity (both active and dead storage) can overestimate regulation impacts (Kumar et al., 2022; Lehner et al., 2011); (2) global DOR estimates often rely on empirically inferred storage capacities and modelled mean annual river flow, which introduce substantial uncertainty (Lehner et al., 2011); (3) reservoir-by-reservoir DOR does not adequately represent cumulative effects of cascading reservoirs within a river network (Habets et al., 2018; Kumar et al., 2022); and (4) DOR is defined at a dam/reservoir and does not directly propagate downstream. Overall, these limitations make DOR less suitable for subbasin-scale hydrologic applications that require cumulative network effects, downstream propagation beyond the regulation sources, and strong grounding in local inventories to produce reliable spatial estimates of streamflow alteration.

One of the most widely used storage-based measures is the degree of regulation (DOR), commonly defined as the cumulative upstream reservoir storage capacity relative to mean annual flow volume. Higher DOR values indicate greater potential for reservoirs to regulate downstream flow. DOR has been mapped along river networks and is included as an attribute in several global dam, reservoir, and catchment datasets (Lehner et al., 2011, 2024; Nilsson et al., 2005; Yin et al., 2024). However, like all metrics, DOR has several limitations. First, the use of total or gross reservoir capacity, including inactive or dead storage, may overestimate the storage volume that is operationally available to modify streamflow (Kumar et al., 2022; Lehner et al., 2011). Second, large-domain DOR estimates often depend on incomplete or empirically inferred reservoir capacities and modelled mean annual flow, introducing uncertainty into the resulting values (Lehner et al., 2011). Third, DOR is fundamentally a storage-based indicator of potential regulation and does not distinguish among reservoir purposes, operating regimes, seasonal management practices, or the timing and magnitude of releases. Consequently, similar DOR values may be associated with substantially different forms and magnitudes of hydrologic alteration. DOR is therefore useful for characterizing potential storage-based regulation, but it is not a direct measure of realized streamflow alteration.

Another commonly used concept for characterizing dam and reservoir impacts is the zone of influence (ZOI), which delineates the upstream and downstream river-network areas affected by a dam, reservoir, or WPF (SEI International, 2009; Stainton, 2012). The hydrologic ZOI provides a practical framing of the spatial footprint of flow regulation beyond the structure itself. The ZOI concept is also relevant in broader river management contexts, since flow alteration footprints can inform aquatic ecosystem assessment and impact evaluation, although the ecological consequences of regulation are not necessarily bounded

by simple hydrologic distance- or area-based rules (Metcalfe et al., 2013).

Stainton (2012) noted that the upstream ZOI is often straightforward to delineate (e.g., reservoir inundation), whereas the downstream ZOI is more difficult to define because it lacks a clear boundary and depends on operating regime, river hydraulics, and basin context. In this framing, the downstream ZOI extends from the tailrace to the point where operationally induced alterations become sufficiently attenuated or diluted that they are no longer discernible from background conditions. Stainton (2012) reviewed simple drainage area-based prediction rules, including a catchment-ratio threshold adapted from Petts (1978, 1979, 1980) and the British Columbia "area of impact" multiplier (Lewis et al., 2004), but showed that these heuristics can substantially under- or over-estimate influence when tested in Ontario basins. These studies highlight both the usefulness and the limitations of simple drainage area-based heuristics for delineating downstream alteration footprints and point to the need for approaches that more explicitly represent cumulative network effects and are better suited to large-sample hydrologic applications.

The decadal dam impact (DI) metric of Wieczorek et al. (2021) characterizes the degree of dam regulation for individual river reaches over time based on cumulative upstream reservoir storage, the relative drainage area represented by upstream dams, and the volume of precipitation within the reach drainage area. Unlike reservoir-level indices, DI is defined at the river-reach scale and explicitly represents cumulative upstream effects through the river network. This reach-based, temporally structured formulation is a major strength, as it moves beyond single-reservoir metrics and enables large-scale assessment of potential cumulative dam influence. However, DI remains fundamentally dependent on reservoir storage information and thus inherits limitations common to storage-based approaches, including uncertainty in reported or inferred storage capacity and the fact that storage alone cannot fully represent reservoir operations or actual streamflow alteration. Although DI is available for millions of river reaches across the conterminous United States (US), its transferability to Canada and other regions is constrained by incomplete reservoir storage information and by the current US-only coverage of the published dataset.

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.

To address this need, we introduce the Streamflow Alteration Index (SAI), a relatively simple network-based metric for screening and mapping potential streamflow alteration. SAI represents the potential influence of mapped instream alteration sources at any subbasin outlet along the river network. Specifically, SAI is defined as the percentage of upstream drainage area whose routed flow passes through one or more mapped alteration sources and, under a first-order drainage-area scaling approximation, provides a proxy for the fraction of streamflow potentially exposed to those sources. By propagating alteration signals downstream through the river network, SAI addresses a key limitation of many traditional metrics that focus on individual dams or reservoirs and do not explicitly represent the downstream propagation of their potential influence.

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.

Formatted: Indent: First line: 0"

~~To better quantify and map the impacts of streamflow alteration across basin drainage networks in Canada, we introduce a new, relatively simple streamflow alteration metric: the Streamflow Alteration Index (SAI). SAI represents the potential influence of dams and reservoirs at any location in a basin and supports spatially explicit mapping of streamflow alteration. Specifically, SAI is defined as the percentage of upstream drainage area that is routed through an alteration source and, by extension, provides a proxy for the fraction of streamflow at that point that passes through an upstream alteration source. By propagating alteration signals downstream through the river network, SAI addresses a key limitation of many traditional metrics that focus on individual dams or reservoirs and do not explicitly represent influence moving downstream from the alteration sources. (Cipollini et al., 2022, 2023)Moreover, SAI is designed to be practical in data-limited settings: unlike storage- or discharge-based indices (e.g., DOR and DI), it does not require detailed time-varying information (e.g., long-term streamflow or precipitation records) or hard-to-estimate infrastructure attributes (e.g., active reservoir storage). Instead, SAI relies on identifying a key static attribute—whether a dam or reservoir is expected to substantially modify downstream flows—and then propagating that influence through the river network. This design allows consistent application across large domains where operational and storage data are incomplete or unavailable. We developed the SAI v1.0 database for Ontario, Canada, leveraging the high-resolution Ontario Lake and River Routing Product Version 2 (OLRRP v2), which discretizes Ontario 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 hydrological subbasins and hydrometric gauges and include harmonized attributes describing alteration signal sources and gauge metadata.~~

Formatted: Normal

It should be noted that the present SAI framework focuses on flow alteration arising from instream structures and lake outflow control structures, including dams, reservoirs, waterpower facilities, and lockstations, that modify water levels, storage, and releases. Accordingly, it does not explicitly account for other anthropogenic influences on streamflow, such as wastewater treatment plant effluent, industrial discharges, irrigation withdrawals and return flows, managed aquifer storage and recovery, landscape change (e.g., urbanization), or inter-basin transfers and canal or diversion systems. Their relative importance varies among basins and may become substantial during low-flow periods~~In many basins, these influences are secondary relative to large dams, but they can still represent a non-trivial fraction of discharge during low-flow periods and may meaningfully affect flow magnitude and seasonality~~. These mechanisms are not incorporated here because consistent province-wide datasets are not available for all source types. Nevertheless, the SAI framework could be extended to include them in future applications where suitable databases and network attribution become available.

The remainder of this paper is structured as follows. Section 2 details the data sources and methodology for the development of the SAI v1.0 database for Ontario, as well as the approach to ~~validating~~ evaluating the database. Section 3 presents the SAI v1.0 database and the ~~validation~~ technical evaluation results. Section 4 discusses the intended use, limitations, and broader applicability of the dataset. Section 5 summarizes the main conclusions.

2. Materials and Methods

~~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.~~

~~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.~~

2.1 Data Sources

Six main ~~datasets~~ data-source groups ~~are~~ were used to develop and ~~validate~~ evaluate the SAI database for Ontario:

- **Ontario Lake and River Routing Product Version 2 (OLRRP v2):** The OLRRP v2 is a high-resolution, vector-based lake and river routing GIS product over the Province of Ontario (Shen et al., 2024) and is an update to OLRRP v1 introduced by Han et al. (2023). It supplies network topology and various subbasin, channel, and lake attributes required for hydrological ~~modeling~~modelling. 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. The OLRRP v2 connects 245,576 subbasins and 82,928 lakes (surface areas ranging from 0.1 km^2 to 4,506 km^2) and assigns 4,033 points of interest (POIs) to these subbasins and lakes. Lake polygons and attributes were ~~employed~~ obtained from the ~~the~~ HydroLAKES database (Messager et al., 2016). Each POI was treated as a pour point during the delineation process, ensuring accurate placement at subbasin outlets. These POIs were derived from multiple point-based datasets, including hydrometric monitoring gauges from the Water Survey of Canada (WSC). The OLRRP v2 demonstrated high spatial accuracy for POI locations, with 74% of WSC gauges showing less than 2% difference between their delineated and documented drainage areas. Only 4% of WSC gauges exhibit absolute drainage area differences greater than 10% (Shen et al., 2024). Overall, this product provides a high-resolution lake and river routing network for SAI development.

Ontario dams: Two provincial dam datasets provided by the Ontario Ministry of Natural Resources (MNR) were used: (1) the Ontario Dam Inventory (ODI), a point-based inventory of medium and large dams throughout Ontario that provides dam names and ownership information (Ontario Ministry of Natural Resources, 2014). We used the version accessed in January 2024. The ODI contains 1,839 records representing dams owned and managed by a variety of entities, including government agencies at federal, provincial, and municipal levels, conservation authorities, Indigenous communities, private owners, and Ontario Power Generation; and (2) a supplementary dataset of 393 Ontario MNR-operated dams that contains two additional attributes: dam operation status (operational or decommissioned) and dam purpose (e.g., flood control, low-flow augmentation, navigation, and recreation).

- ~~Three provincial dam databases provided by Ontario Ministry of Natural Resources (MNR) are used: (1) The Ontario Dam Inventory (ODI), which is a point-based inventory of medium and large dams throughout Ontario with dam names and dam owner information provided (Ontario Ministry of Natural Resources, 2014). We used the version accessed in January 2024. The ODI contains 1,839 dam points owned and managed by a variety of entities, including government agencies at federal, provincial, and municipal levels, conservation authorities, indigenous communities, private owners, and Ontario Power Generation; and (2) a dataset of 389 Ontario MNR-operated dams that contains two additional attributes, including dam operation status (operational or decommissioned) and dam purposes (e.g., flood control, low flow augmentation, navigation,~~

Formatted: Heading 2, Indent: First line: 0", Snap to grid

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Superscript

Formatted: Font: Not Bold

~~and recreation). Note that these two datasets have 347 dam points overlapping, and the total net count is 1,881.~~

Waterpower facilities (WPFs). We used the Waterpower Generation Stations dataset maintained by the Ontario MNR (~~retrieved the~~we used the version published in December 2024) to characterize potential streamflow alteration associated with waterpower infrastructure. For all 223 retrieved~~ 211~~ stations, the dataset provides an operation type field (OPERATION_TYPE), which distinguishes run-of-river facilities from plants designed for load-following (e.g., peak-load~~ing~~, intermediate) or pumped-storage operation. This field provides a general indication of how a facility is typically operated and of the management objectives that may influence water levels and downstream releases~~This field offers a descriptor of how a facility is typically operated and the management objectives that may drive water level and release decisions~~. The source also provides information on the purpose of the associated dam or reservoir (RESERVOIR_PURPOSE), where available, including whether waterpower is an identified purpose. In addition, we compiled the Water Management Plan (WMP) type associated with each river system by parsing the plan name, river name, and plan type reported in the *Maintaining Water Management Plans: Technical Bulletin* (Ministry of Natural Resources and Forestry, 2016). The bulletin classifies WMPs as simple or complex, providing a system-level indicator of operational context and the extent of coordinated water-level and flow management.

~~• used the river system plan type provided in the Ontario provincial Water Management Plan (WMP) (simple vs. complex; Ministry of Natural Resources (2016)) as a third, system-level indicator of operational context. This attribute is originally associated with rivers and WPFs, which reflects whether river operations are managed under limited control (simple) or under more coordinated, multi-structure planning (complex).~~

Lockstations. Lockstations were incorporated to represent flow regulation associated with navigational water-level management in Ontario. We digitized~~compiled 72~~ 73 lockstations located on the Trent-Severn Waterway, the Rideau Canal, and the Welland Canal, which collectively include the lock systems in the Trent River-Rice Lake-Kawartha Lakes-Lake Simcoe corridor, along the Rideau Canal, and along the Welland Canal between Lake Ontario and Lake Erie. Lockstation locations and supporting site information were obtained from the official Parks Canada lockstation directories and associated lockstation pages for the Trent-Severn Waterway and Rideau Canal, and from official Great Lakes St. Lawrence Seaway sources for the Welland Canal locks. These lockstations were treated as point-based infrastructure that can alter downstream streamflow through operational control structures (e.g., lock gates and related water-control works) and were integrated into the routing network as part of the SAI v1.0 alteration signal inventory.

Hydrometric Gauges: We compiled 1,015 hydrometric gauges from the Water Survey of Canada (WSC) that are embedded in the OLRRP v2 POI layer. Many of these gauges carry a WSC regulated/natural flag (Water Survey of Canada, 2024). However, the criteria and rationale used to assign these classifications are not fully documented, which can introduce uncertainty in analyses that distinguish regulated from natural conditions using WSC flags alone. Despite this limitation, the WSC regulation flag remains widely used in Canadian hydrological studies since it is currently the only publicly available, nationwide indicator of regulation status (Arsenault et al., 2020; de Rham et al., 2020). Here, we compare the WSC binary flag with SAI-derived conditions at gauge locations to assess their consistency and illustrate the additional spatial information provided by a network-propagated streamflow alteration metric. Of these 1,015 gauges, 488 met the gauge-status, record-length, and diversion-screening criteria described in Section 2.5 and were retained for evaluating SAI v1.0.~~Here, we compare the WSC binary flag with SAI-derived conditions at gauge locations to illustrate the added value of a spatially explicit, network-propagated streamflow alteration metric.~~

Reference Hydrometric Basin Network (RHBN): The RHBN is a subset of Canada's national hydrometric monitoring stations, maintained by the WSC. It features high-quality, long-term data from catchments with minimal human impacts, which

Formatted: Font: Not Bold

Formatted: Normal

Formatted: Normal

Formatted: Font: Bold

are essential for understanding natural hydrological variability and serve as a benchmark for climate-related studies (Brimley et al., 1999; Ouarda et al., 1999). The RHBN, updated in 2020, includes 1,027 stations across Canada, of which 15454 stations are within Ontario (Pellerin, 2019). Of these, 148 met the gauge-status, record-length, and diversion-screening criteria described in Section 2.5 and were retained as the primary natural-reference group for evaluating SAI v1.0. ~~These 154 stations are used as the primary reference to validate the proposed SAI database in this study.~~

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.

2.2 Geospatial Alignment and Screening of Candidate Records

The Streamflow Alteration Index (SAI) is calculated at the OLRRP subbasin scale, with subbasins roughly 4.3 km^2 in area on average. Accurate assignment of alteration signal sources, including dams, reservoirs, waterpower facilities and lockstations, to the correct OLRRP subbasins is therefore essential. We refer to this geospatial alignment process as snapping.

Alteration signal sources and hydrometric gauges were initially represented as point features. Since source datasets contain positional uncertainty, raw point locations do not always coincide with the correct rivers, lakes, or subbasin outlets in OLRRP. We aligned these points to the OLRRP network using a two-stage workflow: (1) automated snapping to the most plausible topologically consistent location, followed by (2) detailed manual review. Snapping was constrained by OLRRP lake and subbasin topology, feature names (string matching), and agency-documented drainage areas where available. Manual verification compared the snapped locations against satellite imagery and online basemaps (Google Maps and Esri Basemaps; Google, 2024; Esri, 2024).

Because the OLRRP network is pre-delineated and fixed, some points, particularly small run-of-river structures, may remain located within a subbasin after snapping rather than exactly at its outlet. Given the high spatial resolution of OLRRP, such

Formatted: Superscript

Formatted: Superscript

Formatted: Not Highlight

within-subbasin placement is expected to introduce limited spatial error in the SAI calculation.

Points located on the main stems of the Ottawa and St. Lawrence rivers were excluded where their upstream contributing areas extended beyond the OLRRP domain and were therefore not completely delineated within the network. Records were also excluded where substantial spatial discrepancies could not be resolved through manual review or supporting information. A total of 2,528 candidate infrastructure records were compiled before geospatial screening. Following geospatial alignment and screening, 211 of 223 waterpower facility records, 1,803 of 1,839 Ontario Dam Inventory records, 389 of 393 MNR-operated dam records, and all 73 lockstation records were retained. In total, 2,476 records were retained and 52 were excluded, corresponding to an overall inclusion rate of approximately 98%.

The mean and median displacements between the original source coordinates and the final network-aligned locations were 77 and 15 m, respectively, for ODI records; 54 and 33 m for WPF records; and 32 and 13 m for MNR-operated dam records. Lockstations were digitized directly at their corresponding subbasin outlets and therefore required no additional spatial adjustment.

At least one retained ODI record and one retained MNR-operated dam record co-occurred in 347 OLRRP subbasins. Because a subbasin may contain multiple dam records within either dataset or across the two datasets, and the available information does not support reliable one-to-one matching among individual records, these 347 subbasins should not be interpreted as representing 347 duplicate dams. Accordingly, no deduplicated dam count was derived from this subbasin-level overlap. The final retained record counts are summarized in Table 1. Unless otherwise noted, all subsequent counts and statistics are based on the 2,476 retained records.

Formatted: Font: Not Bold

Formatted: Font: Not Bold

2.~~2~~ 3 Identification of Alteration Signal Sources

Alteration signal sources refer to point-based locations where streamflow is first modified by instream infrastructure, represented here by the outlet location of a dam, reservoir, waterpower facility, or lockstation. It should be noted that not all structures captured in available inventories meaningfully alter downstream streamflow. For example, small barriers (e.g., weirs) constructed primarily for local water-level augmentation have limited influence on discharge compared with actively managed reservoirs (e.g., facilities operated for flood control or waterpower generation). Consequently, a key step in developing the SAI database is to filter out sources that are likely to have minor impacts and retain those expected to produce substantial downstream alteration.

At the provincial scale, however, detailed operating rules and regulatory planning information are not consistently available for the thousands of structures managed by diverse entities (e.g., federal and provincial agencies, conservation authorities, the Ontario Ministry of Natural Resources, and private owners). Our assessment of minor versus major alteration therefore relies on information that is broadly available and consistently documented across datasets. We classified each candidate alteration signal source into one of three levels: confirmed (Level I), potential (Level II), and negligible (Level III). Level I sources are identified with high confidence as substantially modifying downstream streamflow. Level II sources are likely to affect streamflow but with greater uncertainty in the presence and magnitude of alteration, and a smaller expected influence than Level I. Level III sources are assumed unlikely to meaningfully alter streamflow and are treated as negligible or insignificant alteration sources for SAI mapping. These categories are summarized in Table 1, and Level I and Level II alteration signal sources are described further below. 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.~~These categories are summarized in Table 1, and Level I and Level II signals are described further~~

~~below.~~

Following geospatial alignment and screening, the 2,476 retained candidate records were evaluated to determine whether they represented confirmed, potential, or negligible streamflow alteration signals. For SAI initialization (Section 2.4), multiple records within the same subbasin were consolidated by source level, while subbasins containing both Level I and Level II records retained both classifications. This resulted in 643 unique subbasins containing at least one Level I and/or Level II alteration signal source. 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.~~In total, we identified 643 Level I and Level II signal sources from 2,475 candidates, where multiple signal sources within the same subbasin are counted once.~~

- **Confirmed alteration signal sources (Level I)**. Level I signals represent locations where streamflow alteration is expected to be substantial and is supported by strong evidence. For waterpower facilities (WPFs), we classify a facility as a Level I alteration source based on three operational indicators: (1) association with a complex Water Management Plan (WMP), which is typically developed for river systems with multiple WPFs and/or other control structures where coordinated operations exert substantial control over water levels and releases ~~(~~(Ministry of Natural Resources and Forestry, 2016)~~Ministry of Natural Resources, 2016)~~; (2) an operation type reported as pumped-storage, peak-load~~ing~~, or intermediate; or (3) the purpose of the associated reservoir is reported as waterpower in the WPF source dataset~~a reservoir purpose reported as waterpower~~. Moreover, all lockstations are treated as Level I signals, as they are operated as water-~~-~~control structures for navigation and water level management. 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.

- **Potential alteration signal source**s **(Level II).** Since complete and consistently documented information on the operational significance of individual control structures is rarely available at large scales (e.g., generally unavailable in Canada), we define Level II sources as features that are likely to influence streamflow but for which the magnitude and persistence of alteration are more uncertain and are generally expected to be smaller than those associated with Level I sources~~the magnitude and persistence of alteration are more uncertain, but likely less, than for Level I sources~~. Level II sources are identified using three complementary criteria: (1) All remaining WPFs in the provincial dataset that are not classified as Level I (i.e., facilities lacking strong indicators of substantial alteration but still plausibly capable of affecting flows); (2) Structures in the ODI whose metadata suggest control functions, including dams with names containing the keyword “control dam” and dams owned by conservation authorities or Ontario Power Generation (OPG). We include OPG-owned dams as potential alteration sources because OPG operates a large portfolio of waterpower infrastructure in Ontario, and ownership by a major waterpower operator is a practical proxy for the presence of active water-level and release management even when facility-specific operational details are not available; and (3) MNR dams that are operational (excluding decommissioned or non-operational structures) and whose stated purpose includes flood control and/or low-~~-~~flow augmentation. Together, these criteria provide a pragmatic, evidence-based way to capture plausible alteration signals where detailed operational data are unavailable.

- **Negligible alteration sources (Level III).** Level III sources represent inventoried control structures that are unlikely to meaningfully alter streamflow and are therefore treated as negligible alteration in this study. After identifying Level I and Level II alteration signal sources, all remaining structures in the ODI and the MNR dam dataset are assigned to Level III. These features may include small or pass-through structures, localized controls, or infrastructure with limited storage or operational influence, for which available metadata do not indicate active alteration (e.g., flood control, low-~~-~~flow augmentation, or waterpower-related management). Level III records are retained in the archived source table to document the screening decisions, but they are not used to initialize or propagate SAI values.~~Level III sources are retained to document screening decisions and avoid double counting, but they are not used to propagate alteration signals in the SAI calculations.~~

~~2.3 Geospatial Alignment for Alteration Signal Points~~

Formatted: Caption1

~~The Streamflow Alteration Index (SAI) is calculated at the OLRRP subbasin scale, with subbasins roughly 4.3 km2 in area on average. Accurate assignment of alteration signal sources, including dams, reservoirs, waterpower facilities and lock stations, to the correct OLRRP subbasins is therefore essential. We refer to this geospatial alignment process as snapping.~~

~~Alteration signal sources and hydrometric gauges were initially represented as point features. Since source datasets contain positional uncertainty, raw point locations do not always coincide with the correct rivers, lakes, or subbasin outlets in OLRRP. We aligned these points to the OLRRP network using a two-stage workflow: (1) automated snapping to the most plausible topologically consistent location, followed by (2) detailed manual review. Snapping was constrained by OLRRP lake and subbasin topology, feature names (string matching), and agency-documented drainage areas where available. Manual verification compared the snapped locations against satellite imagery and online basemaps (Google Maps and Esri Basemaps; Google, 2024; Esri, 2024). The final count of points after snapping is summarized in Table 1.~~

~~The OLRRP network is pre-delineated and fixed; thus, some points, particularly small run-of-the-river structures, may remain positioned within a subbasin after snapping rather than exactly at the subbasin outlet. This is acceptable for SAI because OLRRP subbasin resolution is quite high and so within-subbasin placement introduces limited spatial errors.~~

Table 1. Data sources, retained record counts after geospatial screening, and criteria used to classify candidate records as confirmed (Level I), potential (Level II), or negligible (Level III) alteration signals. Note: Alteration levels are assigned using dataset-specific evidence for streamflow alteration rather than facility type or reported purpose alone. A waterpower-related purpose is considered a Level I indicator only when reported in the dedicated WPF dataset, where more detailed operational information is available.~~Definitions and screening criteria used to classify alteration signal sources into confirmed (Level I), potential (Level II), and negligible (Level III) categories for Streamflow Alteration Index (SAI) development, based on waterpower facility and dam datasets in Ontario. "Number of sources" reports the count of points successfully snapped to the OLRRP river network and retained for analysis; records with large spatial discrepancies after snapping were excluded (see note below table).~~

Datasets	Descriptions	Number of ~~Sources~~Records	Level I ~~Criteria~~Criterion	Level II ~~Criteria~~Criterion	Level III ~~Criteria~~Criterion
Waterpower Facilities (WPFs)	Waterpower generation stations obtained from the Ontario MNR. Generation stations contain attributes such as the operation type (e.g., run-of-river, peaking ~~load~~, etc.), associated reservoir purposes (e.g., flood control, navigation, etc.), and water management plan type (complex vs. simple) (Ministry of Natural Resources and Forestry, 2016)	211	Associated with a complex Water Management Plan; classified as a pumped-storage, peak-load, or intermediate plant; or the purpose of the associated reservoir is reported as waterpower.~~Has a complex water management plan; or the operation type is pumped-storage plant, peak load plant, or intermediate plant~~	All remaining generation stations not included in Level I	Not applicable\
Ontario Dam Inventory (ODI)	The ODI provides medium- to large-sized dams along with attributes including their ownership and a name string across Ontario.	1803[1]	Not applicable\	Dams containing keyword "control dam" in their dam names; or dams owned by conservation authorities or Ontario Power Generation (OPG)	All remaining ODI records not included in Level II
MNR Dams	The Ontario MNR-operated dam datasets~~s~~ contains additional information not ~~within~~ available in the ODI, such as dam operation status and dam purpose.	389	Not applicable\	Operational dams whose stated purpose includes flood control and/or low-flow augmentation; decommissioned and non-operational dams are not assigned to Level II.~~Dams for flood control, and low flow augmentation; and dams are not decommissioned or~~	All dams not included in Level II

Formatted: Caption1, Indent: First line: 0", Snap to

Formatted: Caption1

Formatted: Font: 9 pt

Formatted: Don't adjust right indent when grid is defined, Don't snap to grid

Formatted Table

Formatted: Font: 9 pt

Formatted: Don't adjust right indent when grid is defined, Don't snap to grid

Formatted: Font: 9 pt

Formatted: Don't adjust right indent when grid is defined, Don't snap to grid

Formatted: Font: 9 pt

Formatted: Font: 9 pt

Formatted: Don't adjust right indent when grid is defined, Don't snap to grid

Datasets	Descriptions	Number of ~~Sources~~Records	Level I Criteria~~Criterion~~	Level II Criteria~~Criterion~~ ~~non-operational~~	Level III Criteria~~Criterion~~
Lockstations	Lockstations from the Trent-Severn Waterway, the Rideau Canal, and the Welland Canal are included as point-based signals representing navigational flow control structures.	~~72~~73	All lockstations	Not applicable	Not applicable

~~[a]The original Ontario Dam Inventory (ODI) includes 1,839 dam points. Of these, 36 were excluded from the alteration signal sources due to substantial spatial mismatches between the reported dam locations and the Ontario Lake and River Routing Product (OLRRP), which could not be resolved using secondary data sources or agency contact.~~

2.4 Streamflow Alteration Index (SAI)

In many hydrologic studies, including modelling applications, whether a location (e.g., a hydrometric gauge) is affected by upstream alteration is often represented using a binary agency flag (natural vs. regulated), while detailed reconstruction of dam operating rules is uncommon in large-scale applications.~~In many studies such as hydrologic modeling, whether a location (e.g., a hydrometric gauge) is affected by upstream alteration is often represented as a binary agency flag (natural vs. regulated), and detailed reconstruction of dam operating rules is uncommon in large scale applications.~~ Although explicit reservoir operating rules can improve model performance in regulated basins (Craig et al., 2020; Hughes et al., 2021; Salwey et al., 2024; Yassin et al., 2019), these data are rarely available consistently at large scales. Such practical constraints motivate spatially explicit, network-aware indicators of alteration that can be derived from limited but widely available information.

Our Streamflow Alteration Index (SAI) quantifies potential upstream alteration influence at locations along a river network, represented in this study by subbasin outlets~~the likely degree of streamflow alteration upstream of any location in a river network (e.g., a subbasin outlet)~~. 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.~~SAI is an area-based metric that propagates alteration signals through the drainage network, summarizing the percentage of upstream drainage area routed through locations that contain alteration signal sources.~~

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). ~~(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).

Accordingly, SAI uses proportional drainage-area scaling as a first-order mixing approximation rather than as a physical model

Formatted: Font: 9 pt
Formatted: Don't adjust right indent when grid is defined, Don't snap to grid
Formatted Table
Formatted: Font: 9 pt
Formatted: Don't adjust right indent when grid is defined, Don't snap to grid
Formatted: Heading 2, Snap to grid
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Font: Italic, Not Highlight
Formatted: Not Highlight
Formatted: Superscript, Not Highlight
Formatted: Not Highlight
Formatted: Normal

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. ~~Assuming streamflow is proportional to upstream drainage area, a SAI value of 30% at some point on the river network indicates that 30% of the streamflow at that point is routed through at least one upstream alteration source like a dam. We compute SAI at the subbasin scale (at the subbasin outlet points only) to support spatially continuous mapping of dam and reservoir-related alteration across large domains, including ungauged basins.~~

To reflect differences in confidence and expected influence among alteration sources, we compute two complementary indices: SAI_I, representing influence ~~alteration~~ associated with confirmed (Level I) sources, and SAI_II, representing influence ~~alteration~~ associated with potential (Level II) sources. The two indices are calculated independently: SAI_I is derived from Level I sources only and ranges from 0 to 100%, whereas SAI_II is derived from Level II sources only and ranges from 0 to 100%. Figure 1 illustrates the SAI calculations using a hypothetical subbasin-river network. The calculation procedure consists of three steps.

Step 1: Identify alteration signal sources. Identify all Level I and Level II alteration signal sources for the basin (subbasins B, E, G and M in Figure 1a). Signal source classification is described in Section 2.~~3~~2.

Step 2: Initialize SAI_I and SAI_II. For each subbasin, initialize the two indices based on the presence of alteration sources within the subbasin. If a subbasin contains one or more Level I sources, set SAI_I = 100%; otherwise set SAI_I = 0. If a subbasin contains one or more Level II sources, set SAI_II = 100%; otherwise set SAI_II = 0. Since the indices are independent, a subbasin containing both Level I and Level II sources is initialized as SAI_I = 100% and SAI_II = 100%.

Step 3: Propagate indices through the river network. For a given static set of alteration signal sources and their classifications, deterministically traverse the routing network from headwaters to the outlet. ~~Computationally traverse the routing network from headwaters to the outlet.~~ For each downstream subbasin k, compute SAI_I and SAI_II as drainage-area-weighted averages of the indices of its directly connected upstream subbasins, as given by Eqs. (1) and (2), respectively. During the network traversal, if subbasin k contains a Level I alteration signal source, $\mathrm{SAI_I}_k$ is set to 100% regardless of upstream values (e.g., SAI_I ~~resetting~~ is reset to 100% ~~a~~at the outlet of subbasin G~~F~~ in Figure 1); similarly, if subbasin k contains a Level II signal source, $\mathrm{SAI_II}_k$ is set to 100%. This same-level "reset" reflects the assumption that all flow at the outlet of a source-containing subbasin has passed through at least one mapped source of the corresponding level; the index is therefore set to 100% before further downstream mixing. ~~This same-level "reset" reflects the assumption that once flow passes through a signal source, the corresponding alteration becomes locally dominant at that location and downstream of it.~~

$$\mathrm{SAI_I}_k = \begin{cases} 100\%, & \text{Subbasin } k \text{ contains Level I signal source} \\ \dfrac{\sum_{j=1}^{n}(\mathrm{SAI_I}_j \times D_j)}{D_k}, & \text{Subbasin } k \text{ contains no Level I signal source} \end{cases} \quad (1)$$

$$\mathrm{SAI_II}_k = \begin{cases} 100\%, & \text{Subbasin } k \text{ contains Level II signal source} \\ \dfrac{\sum_{j=1}^{n}(\mathrm{SAI_II}_j \times D_j)}{D_k}, & \text{Subbasin } k \text{ contains no Level II signal source} \end{cases} \quad (2)$$

~~$\mathrm{SAI_I}_k = \begin{cases} 100\%, \text{ Subbasin contains Level I signal source} \\ \frac{\sum_{j=1}^{n}(\mathrm{SAI_I}_j \times D_j)}{D_k} \times 100\%, \text{ Otherwise} \end{cases}$ (1)~~

~~$\mathrm{SAI_II}_k = \begin{cases} 100\%, \text{ Subbasin contains Level II signal source} \\ \frac{\sum_{j=1}^{n}(\mathrm{SAI_II}_j \times D_j)}{D_k} \times 100\%, \text{ Otherwise} \end{cases}$ (2)~~

Formatted: Font: Not Bold

Formatted Table

Formatted: Right

Formatted: Right

Formatted: Normal

where k is the index of a given subbasin within the routing network; n is the total number of subbasins immediately upstream of subbasin k (i.e., those directly draining into subbasin k), indexed by j; j denotes the jth directly connected upstream subbasin to subbasin k; D_k represents the total drainage area of subbasin k, encompassing its own area and the areas of all upstream subbasins; SAI_I_j and SAI_II_j represent the SAI values calculated for each directly connected upstream subbasin j. The resulting SAI values SAI_I_k and SAI_II_k are expressed as percentages.

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 ~~SAI values represent the expected degree of alteration 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. Downstream propagation follows a drainage~~-~~-area-weighted mixing assumption: SAI may decrease as unaltered incremental area or lower-SAI tributary inflows dilute an upstream signal or increase at confluences receiving higher-SAI tributary inflows~~alteration attenuates as incremental contributing area and tributary inflows add water from natural subbasins and dilute the upstream signal~~. This ~~behavior~~behaviour is illustrated in Figure 1b, where SAI decreases between confluences as contributing area increases, and step changes (i.e., resetting) occur at subbasins containing new sources. When a subbasin contains a new alteration source, the corresponding same-level index is reset to 100% ~~its source magnitude (SAI_I = 100% for Level I; SAI_II = 100% for Level II)~~ prior to further downstream propagation. Unlike indices based on the summed storage of all upstream reservoirs, this resetting rule is designed to track the spatial imprint of alteration signals along the network, so that SAI reflects downstream propagation and dilution rather than simple cumulative accumulation of upstream infrastructure. Furthermore, ~~since~~ because SAI_I and SAI_II are propagated independently, this formulation~~it~~ allows an upstream Level I signal to remain traceable downstream even after the network passes a Level II source, thereby avoiding artificial truncation by a weaker downstream Level II signal.

Overall, the SAI framework provides a parsimonious, network-based characterization of potential upstream alteration influence ~~streamflow alteration~~ at the subbasin scale that is readily interpretable for applications such as delineating downstream influence zones, screening hydrometric gauges for dam impacts, and supporting aquatic and ecological analyses, without requiring detailed dam or reservoir operating information. For subsequent applications, SAI_I and SAI_II values can be translated into categorical classes (e.g., natural, conditional, altered) using predefined thresholds (Section 2.5).

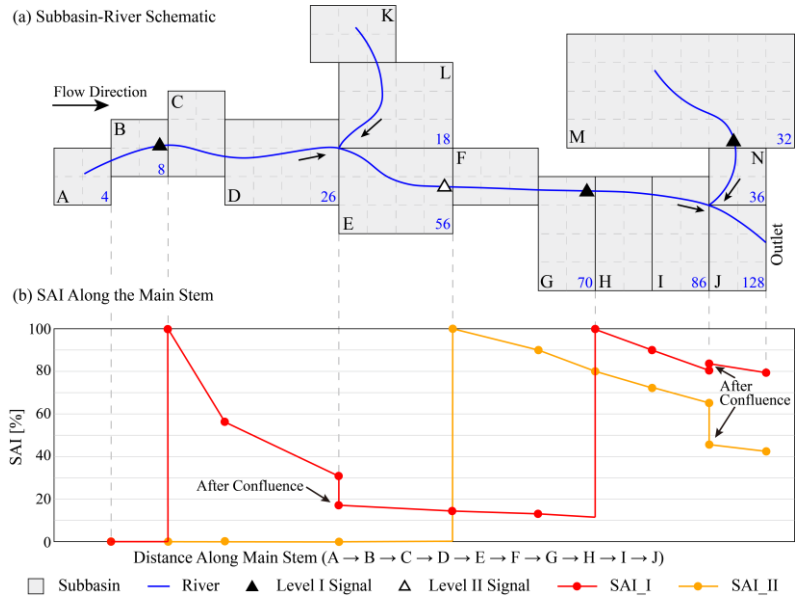


Figure 1: Conceptual illustration of the streamflow alteration index (SAI) propagation along a routing network. (a) A simplified subbasin-river schematic (lakes omitted for brevity) showing the main stem (A → B → C → D → E → F → G → H → I → J) with two tributaries (K → L and M → N) joining at subbasins E and J. Four alteration signal sources are located in subbasins B, E, G and M (filled triangle: Level I; open triangle: Level II). Subbasins are overlaid with equal-sized dashed grid cells to facilitate visual comparison of contributing areas, and blue numbers in the lower-right corners denote drainage area at the subbasin outlet (expressed as the number of dashed grid cells). (b) Example longitudinal profiles of SAI_I (red) and SAI_II (orange) along the main stem, illustrating (1) downstream attenuation (dilution) of alteration signals with increasing contributing area and tributary inflows, and (2) SAI resetting to 100% ~~source magnitude~~ when the flow passes a new same-level signal source (e.g., SAI_I resets to 100% at the outlet of subbasin G). Note that the lines connecting successive subbasin outlets are shown only to visualize changes along the main stem; the SAI calculation itself is performed only at discrete subbasin outlets.~~the SAI lines denote continuous changes in SAI along the flow path, with linear attenuation assumed within each subbasin, whereas the points reflect the discrete SAI values at subbasin outlets along the flowpath.~~ The paired points at ~~the outlets of~~ subbasins E and J show SAI values immediately before and after tributary confluence. The distance shown on the *x*-axis in panel (b) is approximate, since the river segments in panel (a) are schematic and not drawn to scale.

2.5 ~~Validation~~ Evaluation of SAI at Hydrometric Gauges

The accuracy and reliability of SAI depend on the completeness and quality of the datasets used to identify alteration signal sources. We therefore prioritized provincial inventories over global datasets such as the GeoDAR (Wang et al., 2022) and Global Dam Watch (Lehner et al., 2024) when developing SAI v1.0 for Ontario. Although global products provide broad coverage and have undergone quality control, our province-scale data source inspection showed that global sources can miss important dams, reservoirs, and major waterpower facilities in Ontario, which would lead to spatial under-identification of alteration signals and underestimation of alteration extent.

We retained only active Water Survey of Canada (WSC) streamflow and water level gauges for ~~validation~~ evaluation that had at least three years of observations during 1990 to 2024. This screening removes discontinued gauges and helps ensure that the selected gauges reflect alteration conditions over recent decades, which are more consistent with the present-day influence of dams and reservoirs. Although water diversions occur in Ontario and are represented in the OLRRP network through enhanced hydrologically conditioned flow directions, diversions reflect basin-scale redistribution rather than the instream dam and reservoir alteration targeted by SAI. Gauges primarily influenced by diversions were therefore excluded, including those associated with regulated diversion works and watershed diversions recognized under Ontario water management frameworks (International Joint Commission, 2020; Ontario Ministry of Natural Resources, 2017).

Formatted: Centered

Formatted: Caption1

After the screening, 488 WSC gauges remained for evaluation~~validation~~. These gauges are classified in the HYDAT database as either "Regulated" or "Natural" (Water Survey of Canada, 2024). Since the RHBN gauges are a subset of the WSC gauge network, 148 RHBN gauges were included within the 488-gauge WSC set. The evaluation ~~validation~~ dataset therefore comprised three gauge groups: (1) 148 RHBN natural gauges, (2) 125 WSC-natural gauges outside the RHBN set, and (3) 215 WSC-regulated gauges.

RHBN gauges have been previously screened to represent virtually natural streamflow conditions with high confidence (Brimley et al., 1999; Ouarda et al., 1999; Pellerin, 2019). By contrast, according to the HYDAT metadata (see Data Availability), WSC-regulated gauges are defined as gauging stations with an upstream regulating structure, such as a dam or weir. This classification is useful, but it is generally less certain than RHBN, because WSC regulation metadata are not as complete or consistently documented. Accordingly, comparison with the WSC regulated/natural classification should be interpreted only as a broad consistency check rather than as a rigorous validation of SAI.

We ~~validated~~ 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). For each gauge ~~(or subbasin)~~, we extracted the corresponding SAI_I and SAI_II values and assigned one of three categories: a location is *natural* if SAI_I $\leqslant$ 20% and SAI_II $\leqslant$ 40%; it is *altered* if SAI_I > 20%; and it is *conditional* otherwise (i.e., SAI_I $\leqslant$ 20% but SAI_II > 40%). This three-class scheme prioritizes SAI_I for identifying altered conditions, because Level I sources represent confirmed and typically stronger ~~regulation~~ alteration signals, while SAI_II is used to flag cases where alteration is plausible but more uncertain. Thus, the conditional class indicates limited confirmed alteration but elevated potential alteration influence.

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.

~~These classification thresholds were selected to provide a conservative separation between natural and altered conditions. We adopted an SAI_I threshold of 20% because Level I signals represent confirmed and typically stronger alteration, which should remain limited in natural basins. 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. These thresholds are used only for screening and classification in the validation analysis and related SAI-based applications; they do not affect the underlying SAI calculations.~~

3. Data Records and Technical Evaluation ~~Validation~~

This section describes the Streamflow Alteration Index (SAI) v1.0 database, including the GIS layers provided and their key attributes (Section 3.1), followed by the technical ~~validation~~ evaluation of the database (Section 3.2).

Formatted: Font: (Asian) +Body Asian (DengXian), (Asian) Chinese (Simplified, Mainland China)

3.1 SAI v1.0 Database

The SAI v1.0 database for Ontario is publicly available under the Creative Commons Attribution 4.0 International (CC BY 4.0) licencse at https://doi.org/10.5281/zenodo.19547932 (Shen et al., 2026). The release contains three primary data products:

- **Subbasin polygon layer (ontario_subbasin_sai_v1-0.shp):** An Esri Shapefile containing SAI values for all subbasins in the Ontario Lake and River Routing Product (OLRRP) v2 network.
- **River polyline layer (ontario_river_v2-0-1.shp):** An Esri Shapefile containing SAI values for all river reaches in the Ontario Lake and River Routing Product (OLRRP) v2 network, which is paired with the subbasin layer. Each river-reach feature carries the SAI_I and SAI_II values of its associated subbasin outlet; SAI is not recalculated continuously along individual reaches.
- **Alteration signal source table (ontario_alteration_signals.csv):** An ASCII (tabular) dataset describing all Level I, Level II, and Level III alteration signal sources in Ontario.

The Esri Shapefiles are~~is~~ in the NAD 1983 Ontario MNR Lambert coordinate reference system (Lambert Conformal Conic). The datasets and their attributes are described below.

(1) Ontario Alteration Signal Sources

This CSV table contains all 2,476 retained candidate infrastructure records evaluated in the SAI workflow, including their assigned Level I, Level II, or Level III classifications~~This CSV table contains all 2,475 alteration signal sources identified in Ontario and used in the SAI workflow (Table 1)~~. Since sources were compiled from multiple agencies and inventories, original metadata and attribute structures were not uniform. We therefore retained only the core fields required for signal identification and SAI processing and harmonized key identifiers and location fields to a consistent schema.

As summarized in Table 2, fields include: the OLRRP drainage region label (Region); the source dataset indicator (SRC_obs), which records the provenance of each record (e.g., provincial dam inventories, waterpower facility datasets, and lockstations); a source identifier (Obs_NM) and, where available, a descriptive name (Gauge_nm); the associated OLRRP subbasin identifier (SubId); geographic coordinates (Lat, Lon) referenced to NAD 1983; and binary indicators (Level_I, Level_II, Level_III) that flag whether the source is treated as a confirmed, potential, or negligible alteration signal for SAI mapping.

Name-related fields are not available for all source types. Records in the signal-source table can be linked to the subbasin polygon layer via SubId (recommended) to retrieve the corresponding SAI_I/SAI_II values and additional OLRRP v2 attributes for the hosting subbasin.

Table 2. Attributes in the alteration signal sources table of the Streamflow Alteration Index (SAI) v1.0 database for Ontario.

Attributes	Descriptions
Region	OLRRP v2 drainage region used as a delineation subdomain~~Drainage region of Ontario that served as subdomains in the OLRRP v2 delineation~~, including SW, NE, SE, NW, NC, FNE, FNC1, FNC2, and FNW.
SRC_obs	Source dataset associated with each infrastructure record.~~Source of the points. WSC: Gauge points from the Water Survey of Canada (WSC);~~ ODI: dam points from the Ontario Dam Inventory; MNR: dam points from the Ontario MNR; WPF: waterpower facility points from the Ontario MNR; LOCKSTATION: Lockstation records from the Trent-Severn Waterway, the Rideau Canal, and the Welland Canal.
Obs_NM	Source-record identifier reported by the originating agency; a unique identifier was generated where no valid identifier was available.~~The point of interest ID as reported by agency providing the location. A unique string is created for this ID if it is not provided in the original sources to track points in the SAI database.~~
Gauge_nm	Descriptive source name retained from the original metadata, where available.~~A name string for points preserved from their metadata of different sources if valid. This name attribute is also a description of the point such as implying if the dam is a control dam.~~

Formatted: Font: Bold

Formatted: Caption1

Formatted: Don't adjust right indent when grid is defined, Don't snap to grid

Formatted Table

Formatted: Don't adjust right indent when grid is defined, Don't snap to grid

Formatted: Don't adjust right indent when grid is defined, Don't snap to grid

Formatted: Don't adjust right indent when grid is defined, Don't snap to grid

Formatted: Don't adjust right indent when grid is defined, Don't snap to grid

Attributes	Descriptions
SubId	Unique identifier of subbasins in OLRRP v2.
Lat/Lon	NAD 1983 geographic coordinates.
Level_I	Binary variable to indicate if an alteration signal source is Level I.
Level_II	Binary variable to indicate if an alteration signal source is Level II.
Level_III	Binary variable to indicate if an alteration signal source is Level III.

(2) Ontario Subbasin-Scale SAI

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 km². A~~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).

Since SubId and DowSubId follow the OLRRP v2 schema, users can link the SAI layer to the full OLRRP v2 attribute tables to retrieve additional subbasin- and reach-level descriptors (e.g., drainage area, river length, river slope, and other routing parameters) using table joins on SubId. A companion river-reach polyline layer is provided with a consistent identifier schema; however, the number of reach features is smaller than the number of subbasins, because some subbasins (e.g., headwaters) do not contain a mapped river reach.

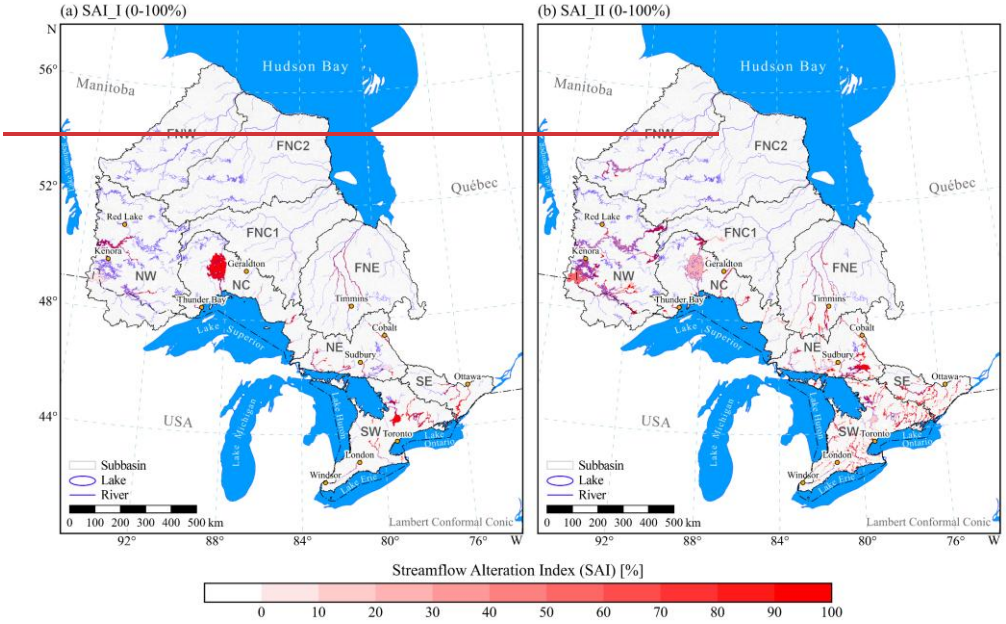
Table 3. **Attributes shared by the subbasin and river-reach layers of the Streamflow Alteration Index (SAI) v1.0 database for Ontario.** ~~**Attributes in the subbasin/river reach layer of the Streamflow Alteration Index (SAI) v1.0 database for Ontario.**~~

Attributes	Descriptions
Region	OLRRP v2 drainage region used as a delineation subdomain, including SW, NE, SE, NW, NC, FNE, FNC1, FNC2, and FNW.~~Drainage region of Ontario that served as subdomains in the OLRRP v2 delineation, including SW, NE, SE, NW, NC, FNE, FNC1, FNC2, and FNW.~~
SubId	Unique identifier of subbasins in OLRRP v2.
DowSubId	ID of downstream subbasin.
SAI_I	Percentage of upstream drainage area whose routed flow passes through at least one Level I alteration signal source at the outlet of the subbasin; used as a first-order proxy for potential upstream flow exposure to Level I sources.~~Streamflow alteration index value for Level I signal sources at the outlet of the subbasin, in percentage.~~
SAI_II	Percentage of upstream drainage area whose routed flow passes through at least one Level II alteration signal source at the outlet of the subbasin; used as a first-order proxy for potential upstream flow exposure to Level II sources.~~Streamflow alteration index value for Level II signal sources at the outlet of the subbasin, in percentage.~~

The Streamflow Alteration Index (SAI) v1.0 database provides a province-wide, subbasin-scale representation of upstream spatial exposure to mapped instream alteration sources by propagating point-based alteration signals downstream through the connected OLRRP v2 network~~The Streamflow Alteration Index (SAI) v1.0 database provides a province-wide, subbasin-scale representation of instream alteration by propagating point-based alteration signal sources downstream through the connected~~

Formatted: Don't adjust right indent when grid is defined, Don't snap to grid
Formatted Table
Formatted: Don't adjust right indent when grid is defined, Don't snap to grid
Formatted: Don't adjust right indent when grid is defined, Don't snap to grid
Formatted: Don't adjust right indent when grid is defined, Don't snap to grid
Formatted: Don't adjust right indent when grid is defined, Don't snap to grid
Formatted: Don't adjust right indent when grid is defined, Don't snap to grid
Formatted: Font: Bold
Formatted: Caption1
Formatted: Font: 9 pt
Formatted Table
Formatted: Font: 9 pt
Formatted: Font: 9 pt
Formatted: Font: 9 pt
Formatted: Font: Not Bold
Formatted: Font: 9 pt
Formatted: Font: 9 pt
Formatted: Font: Not Bold
Formatted: Font: 9 pt
Formatted: Font: 9 pt

~~OLRRP v2 network~~. The resulting spatial patterns of SAI_I (0–100%) and SAI_II (0–100%) are mapped across Ontario in Figure 2, revealing pronounced heterogeneity in potential alteration influence~~in streamflow alteration~~ within and among the nine drainage regions. To illustrate these propagation patterns more clearly at the regional scale, Figure 3 presents higher-resolution maps for the Southeast (SE) region, where the spatial imprint of individual signal sources and their downstream influence can be seen more clearly along connected river networks. 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.



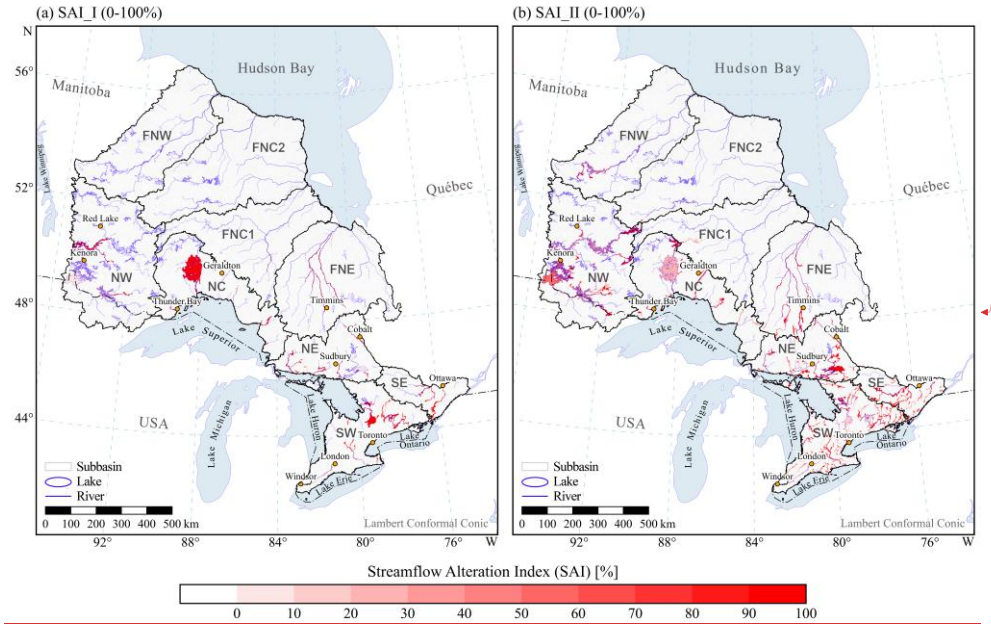


Figure 2: Spatial distribution of subbasin-scale (a) SAI_I and (b) SAI_II across Ontario. Subbasin boundaries (gray outlines; fill colors indicate SAI magnitude), rivers (blue lines; thicker lines indicate higher Strahler stream order), and lakes (blue outlined polygons; only lakes with area > 100 km^2 are shown) are from the Ontario Lake and River Routing Product Version 2 (OLRRP v2). Orange points are selected cities. Ontario is partitioned into nine independent drainage regions: Southwest (SW), Southeast (SE), Northeast (NE), North Central (NC), Northwest (NW), Far Northeast (FNE), Far North Central 1 (FNC1), Far North Central 2 (FNC2), and Far Northwest (FNW).

Formatted: Centered

Formatted: Caption1

Formatted: Font: 9 pt

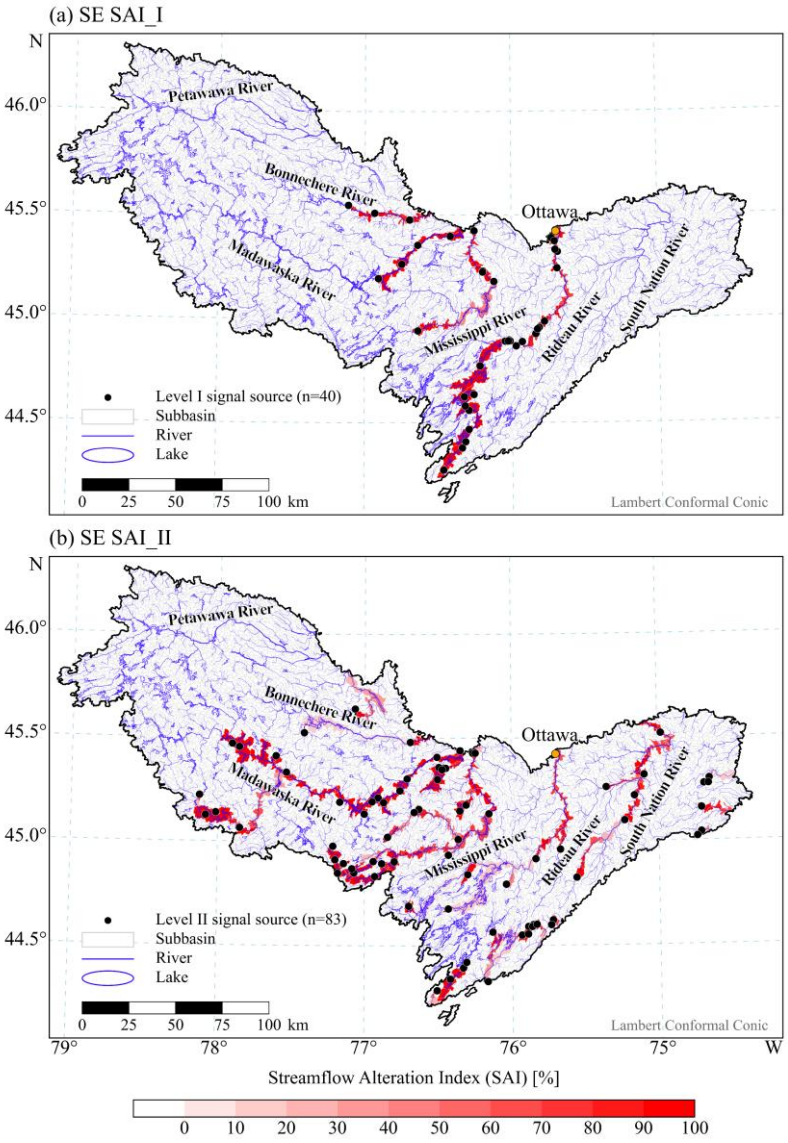


Figure 3: Higher-resolution maps of subbasin-scale (a) SAI_I and (b) SAI_II for the Southeast (SE) region of Ontario. Black points indicate Level I and Level II signal sources for SAI_I and SAI_II, respectively. Subbasin boundaries (gray outlines; fill colors indicate SAI magnitude), rivers (blue lines), and lakes (blue outlined polygons; all lakes are shown) are from the Ontario Lake and River Routing Product Version 2 (OLRRP v2).

~~Interactive high-resolution regional SAI maps are also available through the archived dataset, enabling users to explore local propagation patterns beyond the province-wide overview shown in Figure 2. The SE example in Figure 3 illustrates the finer spatial detail available in these regional products.~~

Formatted: Centered

Formatted: Caption1

3.2 Technical Evaluation ~~Validation~~ of SAI v1.0 Database

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. ~~To validate the database~~For this evaluation, we first extracted SAI_I and SAI_II values for the OLRRP v2 subbasins containing hydrometric gauges, then used these values to assign each hydrometric gauge to an SAI-based class~~then used these to assign hydrometric gauges a SAI-based gauge class~~ (natural, conditional, altered) ~~using~~ based on the thresholds defined in Section 2.5. We compared the resulting SAI classifications against two external reference-classification sources~~two independent reference datasets~~: Reference Hydrometric Basin Network (RHBN) gauges and Water Survey of Canada (WSC) gauge classifications (Section 2.5). ~~Validation~~ Evaluation gauges were organized into three reference groups: (1) 148 RHBN natural gauges, (2) 125 WSC-natural gauges outside the RHBN subset, and (3) 215 WSC-regulated gauges. Results are summarized in Figure 4.

Across gauges identified as natural by the reference datasets, SAI showed strong agreement. For RHBN natural gauges (n = 148), 86% were classified as natural by SAI and 14% as conditional, with no gauges classified as altered (Figure 4a). The 21 RHBN gauges assigned to the conditional class indicate that there may be some inconsistency with this high-confidence natural benchmark, which highlights that the present comparison should be interpreted as a screening-level consistency check rather than an exact validation~~validation is necessarily approximate rather than exact~~. For WSC-natural gauges outside the RHBN subset (n = 125), 86% were classified as natural, 12% as conditional, and 2% as altered (Figure 4b). Agreement was lower, as expected, for WSC-regulated gauges (n = 215), for which SAI classified 26% as altered, 40% as conditional, and 34% as natural (Figure 4c). At minimum, this result suggests that the WSC regulation flag is more inclusive than the narrower instream alteration definition represented by SAI and may include basins where the type or magnitude of alteration represented by the current SAI framework is limited or uncertain. ~~At minimum, this result suggests that the WSC regulation flag is relatively conservative and may include basins that are only slightly altered or uncertain with respect to the type of instream alteration represented by SAI.~~ Overall, the pattern of disagreement in Figure 4 is consistent with expectations: the least disagreement occurs for the highest-confidence reference dataset (RHBN), whereas the greatest disagreement occurs for the lower-confidence WSC-regulated class.

Disagreements between SAI-based classes and agency labels are expected for several reasons: (1) The reference classifications are not designed to isolate instream development impacts alone: RHBN screening may reflect broader watershed pressures beyond instream infrastructure, and the basis for WSC "natural" and "regulated" labels is not consistently reported at a level that enables one-to-one mapping to SAI; (2) SAI explicitly represents uncertainty through SAI_I and SAI_II by incorporating both confirmed and potential alteration signal sources, which can yield conditional classifications where evidence is incomplete; and (3) The alteration signal source inventory may be incomplete for some locations, which can lead to underestimation of alteration where regulation exists but is not represented in available datasets. More broadly, the mismatches in Figure 4 should be interpreted in light of uncertainty in both the reference labels and the SAI-based ~~target~~ classes, rather than as definitive classification errors in either dataset. These considerations motivate interpreting SAI as a practical screening tool that provides consistent, spatially comprehensive classifications, while allowing users to incorporate additional local knowledge (e.g., hydrograph inspection or consultation of detailed upstream dam and reservoir information) when agency labels and SAI classes disagree.

Despite these limitations, Figure 4 indicates that SAI v1.0 provides a practical provincial-scale screening tool. It preserves a large majority of gauges labelled natural by RHBN and WSC, while partitioning WSC-regulated gauges into altered, conditional, and natural subsets that can be prioritized for follow-up assessment.

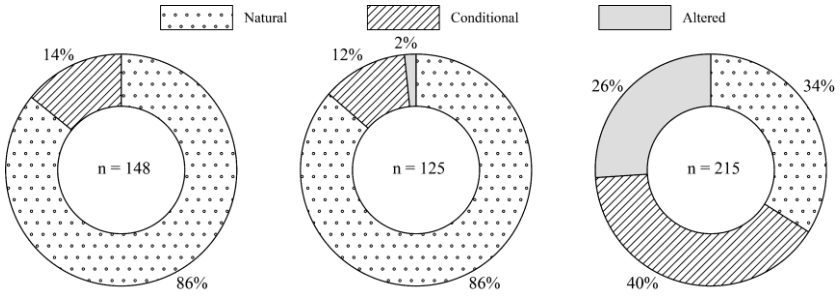


Figure 4. Summary of the Streamflow Alteration Index (SAI) ~~validation~~ evaluation results for three reference gauge groups: (a) RHBN natural gauges, (b) WSC-natural (non-RHBN) gauges, and (c) WSC-regulated gauges. Donut charts show the proportion of gauges assigned to each SAI class (natural, conditional, altered) based on the classification rules in Section 2.5. Natural is defined as SAI_I ≤ 20% and SAI_II ≤ 40%; altered is defined as SAI_I > 20%; all remaining cases are classified as conditional. The number of gauges in each reference group (n) is shown at the center of each chart, and percentages indicate the share of gauges in each SAI-based class.

4. Discussion and Limitations

The Streamflow Alteration Index (SAI) is not intended to quantify the precise magnitude of streamflow alteration at a specific location—for example, the volume of water stored in reservoirs, operating releases, or detailed changes in hydrograph magnitude and timing relative to natural conditions. Instead, SAI is designed as a network-wide screening metric that quantifies upstream spatial exposure to mapped alteration sources using the percentage of upstream drainage area whose routed flow passes through those sources.

~~The Streamflow Alteration Index (SAI) is not intended to quantify the precise magnitude of streamflow alteration at a specific location—for example, the volume of water stored in reservoirs, operating releases, or the detailed changes in hydrograph magnitude and timing relative to natural conditions. Instead, SAI is designed to provide a spatially continuous, network-based screening metric with an approximate degree of alteration computed based on the percentage of upstream drainage area routed through an upstream alteration source. Since SAI does not require site-specific observations or dam operating rules, it is readily applicable at large spatial scales. Therefore, SAI values should be interpreted as indicating the presence and potential influence of instream alteration rather than its absolute hydrologic magnitude. For example, a large main-stem subbasin downstream of a major dam may exhibit an SAI value comparable to that of a smaller tributary affected by a smaller structure, even though the underlying volumes of altered flow may substantially differ.~~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

Formatted: Centered

Formatted: Caption1

Formatted: Font: 11 pt

Formatted: Font: Not Bold

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.

In practice, SAI helps delineate the potential downstream footprint of instream alteration and identify hydrometric gauges that may be influenced by upstream dams and reservoirs. This capability reduces uncertainty when screening hydrometric gauges, particularly for large monitoring networks where "natural" versus "regulated" labels are not always accompanied by transparent, consistent criteria. As demonstrated in Section 3.2, SAI aligns strongly with RHBN natural gauges and provides a consistent, network-wide complement ~~spatially comprehensive complement~~ to agency classifications when selecting calibration and validation data for large-domain hydrologic ~~modeling~~modelling.

A key limitation is that SAI v1.0 targets instream alteration signals and does not explicitly represent landscape-driven alterations (e.g., land-use change, drainage modifications, agriculture, or urbanization). As a result, gauges classified as natural by SAI may still be affected by non-structural watershed pressures that are outside the scope of the current signal inventory. Hydrologic modellers should therefore treat SAI as an initial filter and incorporate additional information, such as land-use datasets, water withdrawals, or hydrograph-based diagnostics, when evaluating gauge suitability for specific applications. Even so, SAI can reduce the initial workload by identifying gauges with clear evidence of upstream instream alteration. ~~SAI can significantly reduce the initial workload by removing gauges with clear evidence of upstream instream alteration.~~

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).

~~(2024)~~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.

Formatted: Indent: First line: 0", Space After: 8 pt, Line spacing: Multiple 1.08 li, Snap to grid

Formatted: Font: Not Bold

~~Another limitation is that downstream attenuation in SAI is represented using a drainage area-weighted mixing assumption only. In reality, subbasins with similar drainage area may differ in their effective attenuation capacity because of lakes, wetlands, channel storage, and routing characteristics. In particular, subbasins containing lakes may exert stronger flow-buffering and hydrograph-smoothing effects than lake-free subbasins of comparable size (Hudson et al., 2021). As a result, the current formulation should be viewed as a first-order approximation of downstream dilution rather than a full representation of hydrologic attenuation processes.~~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.

A further methodological simplification is that Level I and Level II signals are propagated independently. As a result, a downstream Level II source does not attenuate or replace an upstream Level I signal. This ~~behavior~~behaviour was intentional, because Level I signals dominate the identification of altered sites in the current screening framework, and preserving their traceability helps avoid artificial suppression by more uncertain downstream Level II sources. Therefore, this simplification is expected to have limited effect on the final natural–conditional–altered ~~altered–natural–conditional~~ classification, although it may not fully represent more complex interactions among sequential source types along the same river path.

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.

~~Moreover, incomplete or uncertain inventories of dams and waterpower facilities can lead to underestimation of alteration where infrastructure is missing from available datasets. We therefore recommend using SAI v1.0 as a preliminary reference for gauge screening and for interpreting model performance in Ontario, followed by targeted basin-specific review where needed, especially where SAI_II is elevated, which may indicate potential alteration influence with higher uncertainty.~~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

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Superscript

Formatted: Font: Not Bold

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. ~~(Schmadel et al., 2018)~~

The evaluation against independent reference classifications ~~The successful validation~~ and the demonstrated utility of SAI v1.0 in Ontario suggest strong potential for extending the methodology to broader spatial domains. Ongoing advances in large-sample dam and reservoir inventories, together with the increasing availability of high-resolution hydrographic routing frameworks at national, continental, and global scales, make it feasible to implement the SAI framework beyond Ontario and to develop network-based screening products that support more consistent assessment of instream alteration for hydrologic and ecological applications at large scales.

5. Conclusions

We developed the Streamflow Alteration Index (SAI) v1.0 database for Ontario to provide a spatially complete, subbasin-scale screening product that maps how exposure to upstream instream alteration signal sources propagates downstream across a connected hydrographic network. ~~We developed the Streamflow Alteration Index (SAI) v1.0 database for Ontario to provide a spatially continuous, subbasin-scale screening product that maps the downstream influence of instream alteration signal sources across a connected hydrographic network.~~ The database includes paired indices (SAI_I and SAI_II) that represent two different levels of alteration influence based on confirmed and potential sources, enabling consistent classification of ~~streamflow at~~ subbasin outlets ~~(~~and ~~thus~~ hydrometric gauge locations~~)~~ as natural, conditional, or altered. Our SAI v1.0 database and province-wide interactive map enable water resources researchers and practitioners to quickly assess upstream spatial exposure to mapped alteration sources at subbasin outlets and corresponding river reaches and, under the drainage-area scaling approximation, use this information as a first-order proxy for the proportion of streamflow potentially exposed to those sources, while accounting for differences in source confidence~~Our SAI database and suite of online maps across Ontario enable water resources researchers and practitioners to quickly assess the potential degree of streamflow alteration for any point on the surface water network in Ontario, while accounting for differences in source confidence~~.

~~Validation~~ Evaluation against independent reference classifications indicates that SAI classified 86% of RHBN natural gauges and 86% of WSC-natural gauges as natural~~,~~. Among WSC-regulated gauges, 26% were classified as altered, 40% as conditional, and 34% as natural. ~~while 74% of WSC-regulated gauges were classified as conditional or natural.~~

Overall, SAI v1.0 offers a practical, network-based tool for large-domain hydrologic and ecological applications, including gauge screening, model calibration/validation support, and basin-scale prioritization of locations potentially affected by upstream alteration. Future work will focus on improving alteration source inventories, extending the framework to larger scales (e.g., national applications across Canada), and integrating complementary information to better represent non-structural watershed alterations.

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.

Formatted: Font: Bold

Formatted: Indent: First line: 0", Space After: 8 pt, Line spacing: Multiple 1.08 li, Snap to grid

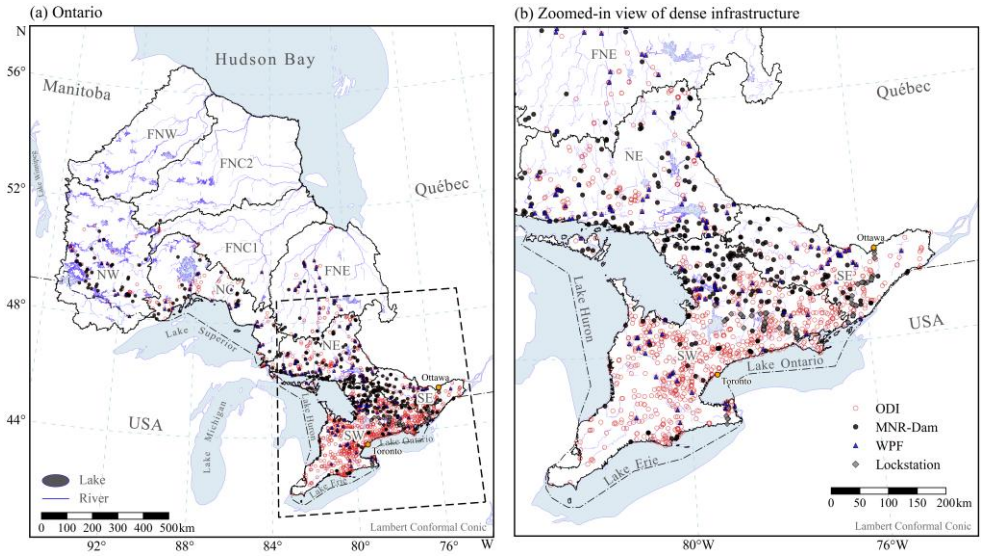


Figure A1. Spatial distribution of the 2,476 infrastructure records retained for identifying potential streamflow alteration sources across Ontario. (a) Province-wide distribution of records from the Ontario Dam Inventory (ODI), Ontario Ministry of Natural Resources (MNR), Waterpower Facilities (WPFs), 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).

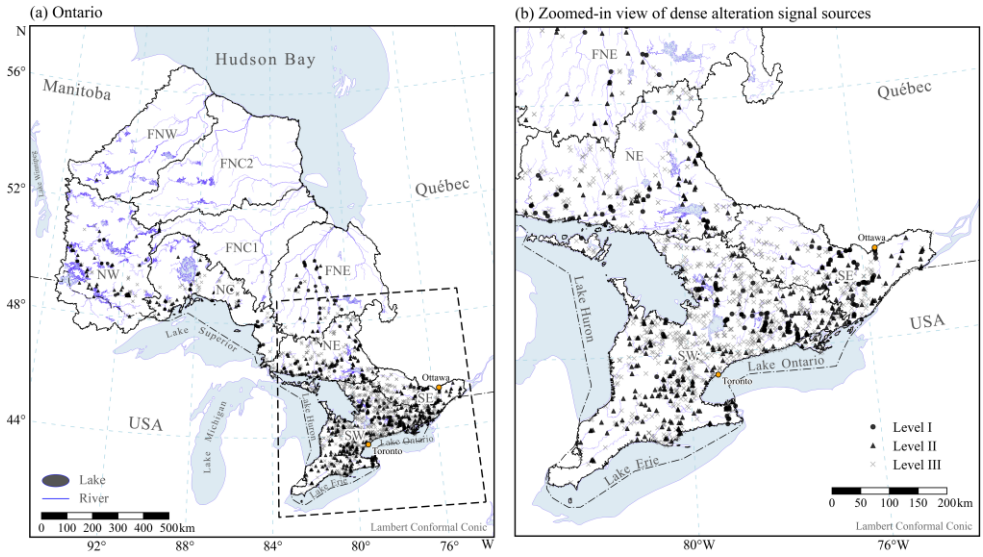


Figure A2. Spatial distribution of the classified alteration signal sources across Ontario. (a) Province-wide distribution of Level I (confirmed), Level II (potential), and Level III (negligible) alteration signal sources. Following subbasin-level consolidation, Level I and/or Level II sources occurred 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

Formatted: Caption1

Formatted: Superscript

Formatted: English (United States)

Formatted: Caption1

(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).

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

$$Q = cA^{\beta} \quad \text{(B1)}$$

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.

Formatted: Superscript
Formatted: Font: 10 pt, Italic
Formatted: Space Before: 6 pt, After: 6 pt, Line spacing: Multiple 1.1 li
Formatted Table
Formatted: Font: 10 pt
Formatted: Right, Space Before: 6 pt, After: 6 pt, Line spacing: Multiple 1.1 li
Formatted: Font: Italic
Formatted: Font: Italic
Formatted: Font: Italic
Formatted: Font: Not Bold
Formatted: Font: Italic
Formatted: Font: 10 pt
Formatted: Font: Not Bold

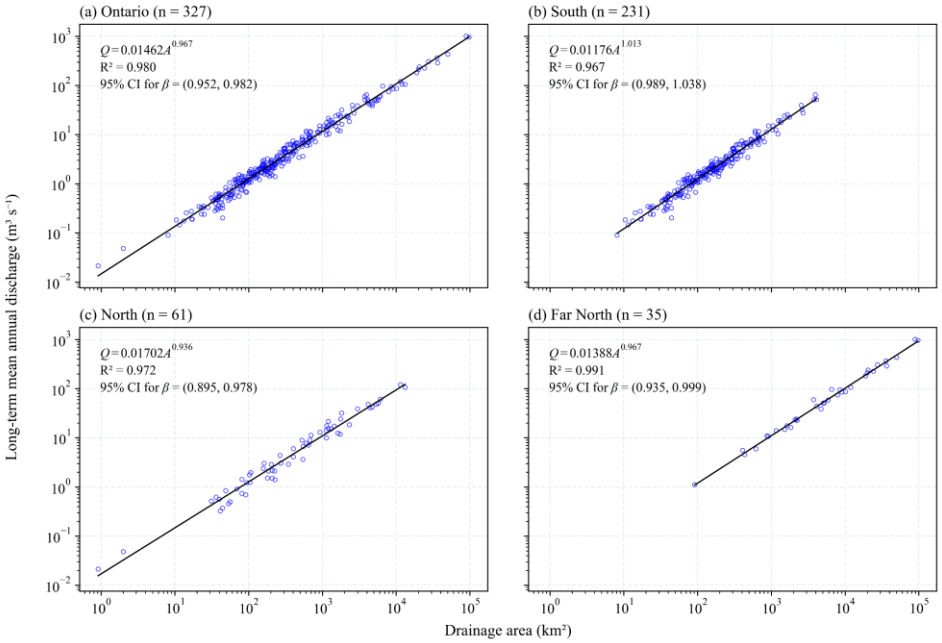


Figure B1. Log-log relationships between drainage area and long-term mean annual discharge for Ontario and three broad regional groupings: South (SW and SE), North (NE, NC, and NW), and Far North (FNE, FNC1, FNC2, and FNW). Each point represents a discharge gauge with at least 10 valid years of observations 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.

Data Availability

The Streamflow Alteration Index (SAI) v1.0 database developed in this study, including the subbasin polygon layer, river polyline layer, alteration signal source table, and accompanying documentation, is archived on Zenodo under the Creative Commons Attribution 4.0 International (CC BY 4.0) licence: https://doi.org/10.5281/zenodo.19547932 (Shen et al., 2026). ~~The dataset should be cited as follows:~~

~~The Zenodo metadata record is publicly accessible. During manuscript review, the data files are available to editors and reviewers through the anonymous access link below. The files will be made openly available upon publication.~~

~~https://zenodo.org/records/19547932?token=eyJhbGciOiJIUzUxMiJ9.eyJpZCI6IjhiZTE0YmE5LTUxOTQtNGNiNS04MzA4LTVkNTBhZGZlNjNhNCIsImRhdGEiOnt9LCJyYW5kb20iOiI2ODUyNTIyNjZlYTIxMWIyNzM3MDe5MGMzN2VkOTgxZiJ9.meylZOwiZ3MMBAniEtaGmkYl9MuIiK3vf70rhgKtsLZBNNc-PgV9yWyUhLC5p4tubkLiWTT5kn7ChlbgXRKgwQ~~

A **province-wide interactive map** of SAI v1.0 is available at:

https://www.arcgis.com/apps/mapviewer/index.html?webmap=71a9a1859b13409bb85d9d1a8fc31bb3

The map includes OLRRP v2 subbasin, river, and lake layers; SAI_I and SAI_II; and Level I, Level II, and Level III alteration signal sources. Users can interactively explore the map at different spatial scales and inspect the attributes associated with each layer. The corresponding GIS shapefiles and alteration signal source table are also available from Zenodo (https://doi.org/10.5281/zenodo.19547932) for download and local analysis. ~~An interactive online SAI map for Ontario will be~~

Formatted: English (United States)

Formatted: Caption1

Formatted: Font: (Asian) Times New Roman, Font color: Black, English (United Kingdom), Superscript, Kern at 16 pt

Formatted: Font: (Asian) Times New Roman, Font color: Black, English (United Kingdom), Superscript, Kern at 16 pt

Formatted: Font: Bold

Formatted: Font color: Blue

Formatted: Hyperlink, Font color: Blue

~~released upon publication. For manuscript review, an example interactive map for the Southeast (SE) drainage region is available below.~~

~~https://www.arcgis.com/apps/mapviewer/index.html?layers=b58a3e73e15d4f0ea61e1f5e62a2acde~~

Most input datasets used in this study are publicly available from their original sources. The supplementary dataset of Ontario MNR-operated dams is not available for public download, as described below. The input data sources and access information are as follows:~~All input datasets used in this study are publicly available from their original sources:~~

Ontario Lake and River Routing Product~~,~~ Version 2 (OLRRP v2): available through Shen et al. (2024). OLRRP website at:

~~-~~https://uwaterloo-olrrp.shinyapps.io/OLRRP-V2/

- ~~**Ontario Dam Inventory (ODI)**: available from the Ontario Ministry of Natural Resources (MNR) through Ontario GeoHub:.~~

~~Download at:~~ https://geohub.lio.gov.on.ca/maps/mnrf::ontario-dam-inventory/about

Waterpower Generation Stations: available from the Ontario Ministry of Natural Resources through Ontario GeoHub: https://geohub.lio.gov.on.ca/documents/waterpower-generation-stations/about

Water Management Plan (WMP) classifications: the simple and complex Water Management Plan classifications used in this study were parsed and compiled from the report *Maintaining Water Management Plans: Technical Bulletin* published by the Ontario Ministry of Natural Resources and Forestry (2016): https://files.ontario.ca/technical-bulletin-maintaining-wmps.pdf

Hydrometric gauge data: Water Survey of Canada hydrometric data are available from the HYDAT database: https://collaboration.cmc.ec.gc.ca/cmc/hydrometrics/www/

HYDAT metadata documentation is available at: https://collaboration.cmc.ec.gc.ca/cmc/hydrometrics/www/ECDataExplorer_EN.pdf

Reference Hydrometric Basin Network: RHBN documentation and data access are available from Environment and Climate Change Canada: https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity/monitoring/survey/data-products-services/reference-hydrometric-basin-network.html

Lockstation locations and information: official sources were used for the Trent-Severn Waterway, Rideau Canal, and Welland Canal: https://parks.canada.ca/lhn-nhs/on/trentsevern/visit/posteeclusage-lockstation

https://parks.canada.ca/lhn-nhs/on/rideau/visit/posteeclusage-lockstation

https://greatlakes-seaway.com/en/the-seaway/our-locks-and-channels/

- **Ontario MNR-operated dams**: the supplementary dataset of 393 MNR-operated dams was provided by the Ontario Ministry of Natural Resources and is not available for public download. The harmonized locations, identifiers, and Level I–III classification fields derived from this dataset and used in the SAI workflow are included in the archived alteration signal source table.~~Hydrometric gauge data (Water Survey of Canada, WSC): available from the HYDAT database.~~

~~Download at: https://collaboration.cmc.ec.gc.ca/cmc/hydrometrics/www/~~

Formatted: Font color: Auto
Formatted: Font: Bold
Formatted: Hyperlink
Formatted: Hyperlink, Font color: Blue
Formatted: Font: Bold
Formatted: Normal
Formatted: Font: Bold
Formatted: Font color: Blue
Formatted: Hyperlink, Font color: Blue
Field Code Changed
Formatted: Font: Bold
Formatted: Font: Bold
Formatted: Font color: Blue
Formatted: Hyperlink, Font color: Blue
Field Code Changed
Formatted: Font: Not Bold
Formatted: Hyperlink, Font color: Blue
Formatted: Font: Not Bold
Formatted: Hyperlink, Font color: Blue
Formatted: Font: Not Bold
Formatted: Hyperlink, Font: Not Bold, Font color: Blue
Formatted: Normal
Formatted: Font: Not Bold
Formatted: Hyperlink, Font color: Blue
Formatted: Font: Not Bold
Formatted: Font: Not Bold

~~Metadata file: https://collaboration.cmc.ec.gc.ca/cmc/hydrometrics/www/ECDataExplorer_EN.pdf~~

- ~~Reference Hydrometric Basin Network (RHBN): documentation and data access available at: https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity/monitoring/survey/data-products-services/reference-hydrometric-basin-network.html~~
- ~~Trent-Severn Waterway National Historic Site: https://parks.canada.ca/lhn-nhs/on/trentsevern/visit/posteeclusage-lockstation~~
- ~~Rideau Canal National Historic Site: https://parks.canada.ca/lhn-nhs/on/rideau/visit/posteeclusage-lockstation~~

~~Welland Canal locks: https://greatlakes-seaway.com/en/the-seaway/our-locks-and-channels/~~

Formatted: Font color: Auto

Code Availability

Formatted: Font: Bold

The scripts used to calculate and propagate SAI values through the OLRRP v2 routing network are archived in a public GitHub repository below. These scripts reproduce the core SAI calculation workflow used to generate the SAI v1.0 database.

https://github.com/hongren-shen/streamflow-alteration-index/tree/main

Author Contributions

Hongren Shen led the study, including data compilation and processing, methodological development, SAI calculation, analysis, figure preparation and visualization, and manuscript writing and revision. **Bryan A. Tolson** and **James R. Craig** contributed to methodological design, interpretation of results, figure visualization, and manuscript revision. **Robert A. Metcalfe** and **James J. Luce** ~~**Jamie Luce**~~ contributed data resources, interpretation of results, and manuscript revision. **Jonathan Romero-Cuellar** contributed to interpretation of results and manuscript revision. All authors reviewed and approved the final manuscript.

Formatted: Font: Bold

Competing interests

The authors declare that they have no conflict of interest.

Disclaimer

Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors. Views expressed in the text are those of the authors and do not necessarily reflect the views of the publisher.

Acknowledgements

The authors thank the Ontario Ministry of Natural Resources, the Water Survey of Canada, Parks Canada, and other organizations that maintain and provide access to the datasets used in this study. We also thank the three anonymous referees for their constructive comments and suggestions, which helped improve the manuscript.

Financial Support

This research was supported by a 2022–2026 Collaborative Research Agreement between the Ontario Ministry of Natural Resources and the University of Waterloo, led by Principal Investigator Bryan A. Tolson. The agreement supported Hongren Shen's research appointment.~~This research was supported by a 2022–2026 Collaborative Research Agreement between the Ontario Ministry of Natural Resources and the University of Waterloo (Principal Investigator Dr. Bryan Tolson) and this funding supported Dr. Shen.~~

References

Arsenault, R., Brissette, F., Martel, J.-L., Troin, M., Lévesque, G., Davidson-Chaput, J., Gonzalez, M. C., Ameli, A., and Poulin, A.: A comprehensive, multisource database for hydrometeorological modeling of 14,425 North American watersheds, Sci. Data, 7, 243, https://doi.org/10.1038/s41597-020-00583-2, 2020.

Bejarano, M. D., Jansson, R., and Nilsson, C.: The effects of hydropeaking on riverine plants: a review, Biol. Rev., 93, 658–673, https://doi.org/10.1111/brv.12362, 2018.

Bipa, N. J., Stradiotti, G., Righetti, M., and Pisaturo, G. R.: Impacts of hydropeaking: A systematic review, Sci. Total Environ., 912, 169251, https://doi.org/10.1016/j.scitotenv.2023.169251, 2024.

Blöschl, G.: Runoff Prediction in Ungauged Basins: Synthesis Across Processes, Places and Scales, Cambridge University Press, 491 pp., 2013.

Brimley, B., Cantin, J., Harvey, D., Kowalchuk, M., Marsh, P., Ouarda, T., Phinney, B., Pilon, P., Renouf, M., Tassone, B., and others: Establishment of the reference hydrometric basin network (RHBN) for Canada, Environ. Can., 41, 1999.

Brogan, C., Burgholzer, R., Keys, T., Kleiner, J., Shortridge, J., and Scott, D.: The Cumulative Role of Impoundments in Streamflow Alteration, JAWRA J. Am. Water Resour. Assoc., 58, 119–133, https://doi.org/10.1111/1752-1688.12979, 2022.

Burke, M., Jorde, K., and Buffington, J. M.: Application of a hierarchical framework for assessing environmental impacts of dam operation: Changes in streamflow, bed mobility and recruitment of riparian trees in a western North American river, J. Environ. Manage., 90, S224–S236, https://doi.org/10.1016/j.jenvman.2008.07.022, 2009.

Cipollini, S., Fiori, A., and Volpi, E.: A New Physically Based Index to Quantify the Impact of Multiple Reservoirs on Flood Frequency at the Catchment Scale Based on the Concept of Equivalent Reservoir, Water Resour. Res., 58, e2021WR031470, https://doi.org/10.1029/2021WR031470, 2022.

Cipollini, S., Volpi, E., and Fiori, A.: Toward a Catchment-Scale Assessment of Flood Peak Attenuation by Multiple Reservoirs, Water Resour. Res., 59, e2022WR032821, https://doi.org/10.1029/2022WR032821, 2023.

Craig, J. R., Brown, G., Chlumsky, R., Jenkinson, R. W., Jost, G., Lee, K., Mai, J., Serrer, M., Sgro, N., Shafii, M., Snowdon, A. P., and Tolson, B. A.: Flexible watershed simulation with the Raven hydrological modelling framework, Environ. Model. Softw., 129, 104728, https://doi.org/10.1016/j.envsoft.2020.104728, 2020.

Dang, T. D., Chowdhury, A. F. M. K., and Galelli, S.: On the representation of water reservoir storage and operations in large-scale hydrological models: implications on model parameterization and climate change impact assessments, Hydrol. Earth Syst. Sci., 24, 397–416, https://doi.org/10.5194/hess-24-397-2020, 2020.

Déry, S. J., Stadnyk, T. A., MacDonald, M. K., and Gauli-Sharma, B.: Recent trends and variability in river discharge across northern Canada, Hydrol. Earth Syst. Sci., 20, 4801–4818, https://doi.org/10.5194/hess-20-4801-2016, 2016.

Döll, P., Fiedler, K., and Zhang, J.: Global-scale analysis of river flow alterations due to water withdrawals and reservoirs, Hydrol. Earth Syst. Sci., 13, 2413–2432, https://doi.org/10.5194/hess-13-2413-2009, 2009.

Du, T. L. T., Lee, H., Bui, D. D., Graham, L. P., Darby, S. D., Pechlivanidis, I. G., Leyland, J., Biswas, N. K., Choi, G., Batelaan, O., Bui, T. T. P., Do, S. K., Tran, T. V., Nguyen, H. T., and Hwang, E.: Streamflow Prediction in Highly Regulated, Transboundary Watersheds Using Multi-Basin Modeling and Remote Sensing Imagery, Water Resour. Res., 58, e2021WR031191, https://doi.org/10.1029/2021WR031191, 2022.

Erikson, C. M., Renshaw, C. E., and Magilligan, F. J.: Spatial variation in drainage area — Runoff relationships and

1114 implications for bankfull geometry scaling, Geomorphology, 446, 108998, https://doi.org/10.1016/j.geomorph.2023.108998,
1115 2024.

1116 Esri: World Topographic Map / World Imagery Basemap, 2024.

1117 Fry, L. M., Hunter, T. S., Phanikumar, M. S., Fortin, V., and Gronewold, A. D.: Identifying streamgage networks for
1118 maximizing the effectiveness of regional water balance modeling, Water Resour. Res., 49, 2689–2700,
1119 https://doi.org/10.1002/wrcr.20233, 2013.

1120 Google: Google Maps base layer, 2024.

1121 Grill, G., Ouellet Dallaire, C., Fluet Chouinard, E., Sindorf, N., and Lehner, B.: Development of new indicators to evaluate
1122 river fragmentation and flow regulation at large scales: A case study for the Mekong River Basin, Ecol. Indic., 45, 148–159,
1123 https://doi.org/10.1016/j.ecolind.2014.03.026, 2014.

1124 Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H.,
1125 Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M. E., Meng, J., Mulligan, M., Nilsson,
1126 C., Olden, J. D., Opperman, J. J., Petry, P., Reidy Liermann, C., Sáenz, L., Salinas-Rodríguez, S., Schelle, P., Schmitt, R. J.
1127 P., Snider, J., Tan, F., Tockner, K., Valdujo, P. H., van Soesbergen, A., and Zarfl, C.: Mapping the world's free-flowing rivers,
1128 Nature, 569, 215–221, https://doi.org/10.1038/s41586-019-1111-9, 2019.

1129 Habets, F., Molénat, J., Carluer, N., Douez, O., and Leenhardt, D.: The cumulative impacts of small reservoirs on hydrology:
1130 A review, Sci. Total Environ., 643, 850–867, https://doi.org/10.1016/j.scitotenv.2018.06.188, 2018.

1131 Han, M., Shen, H., Tolson, B. A., Craig, J. R., Mai, J., Lin, S. G. M., Basu, N. B., and Awol, F. S.: BasinMaker 3.0: A GIS
1132 toolbox for distributed watershed delineation of complex lake-river routing networks, Environ. Model. Softw., 164, 105688,
1133 https://doi.org/10.1016/j.envsoft.2023.105688, 2023.

1134 Hrachowitz, M., Savenije, H. H. G., Blöschl, G., McDonnell, J. J., Sivapalan, M., Pomeroy, J. W., Arheimer, B., Blume, T.,
1135 Clark, M. P., and Ehret, U.: A decade of Predictions in Ungauged Basins (PUB)—a review, Hydrol. Sci. J., 58, 1198–1255,
1136 2013.

1137 Hudson, D. T., Leach, J. A., Webster, K., and Houle, D.: Streamflow regime of a lake-stream system based on long-term data
1138 from a high-density hydrometric network, Hydrol. Process., 35, e14396, https://doi.org/10.1002/hyp.14396, 2021.

1139 Hughes, D., Birkinshaw, S., and Parkin, G.: A method to include reservoir operations in catchment hydrological models using
1140 SHETRAN, Environ. Model. Softw., 138, 104980, https://doi.org/10.1016/j.envsoft.2021.104980, 2021.

1141 International Joint Commission: An Overview of Great Lakes Diversions, International Joint Commission, 2020.

1142 Jorde, K., Burke, M., Scheidt, N., Welcker, C., King, S., and Borden, C.: 23 Reservoir operations, physical processes, and
1143 ecosystem losses, in: Developments in Earth Surface Processes, vol. 11, edited by: Habersack, H., Piégay, H., and Rinaldi, M.,
1144 Elsevier, 607–636, https://doi.org/10.1016/S0928-2025(07)11151-2, 2007.

1145 Kern, J. D., Characklis, G. W., Doyle, M. W., Blumsack, S., and Whisnant, R. B.: Influence of deregulated electricity markets
1146 on hydropower generation and downstream flow regime, J. Water Resour. Plan. Manag., 138, 342–355, 2012.

1147 Kratzert, F., Klotz, D., Herrnegger, M., Sampson, A. K., Hochreiter, S., and Nearing, G. S.: Toward Improved Predictions in
1148 Ungauged Basins: Exploiting the Power of Machine Learning, Water Resour. Res., 55, 11344–11354,
1149 https://doi.org/10.1029/2019WR026065, 2019a.

1150 Kratzert, F., Klotz, D., Shalev, G., Klambauer, G., Hochreiter, S., and Nearing, G.: Towards learning universal, regional, and
1151 local hydrological behaviors via machine learning applied to large-sample datasets, Hydrol. Earth Syst. Sci., 23, 5089–5110,
1152 https://doi.org/10.5194/hess-23-5089-2019, 2019b.

1153 Kumar, H., Hwang, J., Devineni, N., and Sankarasubramanian, A.: Dynamic Flow Alteration Index for Complex River
1154 Networks With Cascading Reservoir Systems, Water Resour. Res., 58, 1–25, https://doi.org/10.1029/2021WR030491, 2022.

1155 Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome,
1156 J., Nilsson, C., Robertson, J. C., Rödel, R., Sindorf, N., and Wisser, D.: High-resolution mapping of the world's reservoirs and
1157 dams for sustainable river-flow management, Front. Ecol. Environ., 9, 494–502, https://doi.org/10.1890/100125, 2011.

1158 Lehner, B., Beames, P., Mulligan, M., Zarfl, C., De Felice, L., van Soesbergen, A., Thieme, M., Garcia de Leaniz, C., Anand,
1159 M., and Belletti, B.: The Global Dam Watch database of river barrier and reservoir information for large-scale applications,

Sci. Data, 11, 1069, https://doi.org/10.1038/s41597-024-03752-9, 2024.

Lewis, A., Hatfield, T., Chilibeck, B., and Roberts, C.: Assessment Methods for Aquatic Habitat and Instream Flow Characteristics in Support of Applications to Dam, Divert, or Extract Water from Streams in British Columbia – Final Version, BC Ministry of Water, Land & Air Protection and Ministry of Sustainable Resource Management, 2004.

Lueders, M. B., McManamay, R. A., Oliver, J. A., Young, D., Bean, P., and Mayes, K.: Reconstructing Long-Term Historical Hydrologic Alteration to Support Environmental Flows in Texas, River Res. Appl., rra.70172, https://doi.org/10.1002/rra.70172, 2026.

Maavara, T., Chen, Q., Van Meter, K., Brown, L. E., Zhang, J., Ni, J., and Zarfl, C.: River dam impacts on biogeochemical cycling, Nat. Rev. Earth Environ., 1, 103–116, https://doi.org/10.1038/s43017-019-0019-0, 2020.

Messager, M. L., Lehner, B., Grill, G., Nedeva, I., and Schmitt, O.: Estimating the volume and age of water stored in global lakes using a geo-statistical approach, Nat. Commun., 7, 1–16, https://doi.org/10.1038/ncomms13603, 2016.

Metcalfe, R. A., Mackereth, R. W., Grantham, B., Jones, N., Pyrce, R. S., Haxton, T., Luce, J. J., and Stainton, R.: Aquatic Ecosystem Assessments for Rivers, Science and Research Branch, Ministry of Natural Resources, Peterborough, Ontario, 2013.

Ministry of Natural Resources and Forestry: Maintaining Water Management Plans: Technical Bulletin, 2016.

Montanari, A., Young, G., Savenije, H. H. G., Hughes, D., Wagener, T., Ren, L. L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli, B., Arheimer, B., Boegh, E., Schymanski, S. J., Di Baldassarre, G., Yu, B., Hubert, P., Huang, Y., Schumann, A., Post, D. A., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z., and Belyaev, V.: "Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022, Hydrol. Sci. J., 58, 1256–1275, https://doi.org/10.1080/02626667.2013.809088, 2013.

Nilsson, C., Reidy, C. A., Dynesius, M., and Revenga, C.: Fragmentation and flow regulation of the world's large river systems, Science, 308, 405–408, https://doi.org/10.1126/science.1107887, 2005.

Ontario Ministry of Natural Resources: Ontario Dam Inventory, 2014.

Ontario Ministry of Natural Resources: Lakes and Rivers Improvement Act Administrative Guide, Ontario Ministry of Natural Resources, 2017.

Ouarda, T., Rasmussen, P., Cantin, J., Bobée, B., Laurence, R., and Hoang, V.: Identification d'un réseau hydrométrique pour le suivi des modifications climatiques dans la province de Québec, Rev. Sci. Eau J. Water Sci., 12, 425–448, https://doi.org/10.7202/705359ar, 1999.

Palmer, M. and Ruhi, A.: Linkages between flow regime, biota, and ecosystem processes: Implications for river restoration, Science, 365, eaaw2087, https://doi.org/10.1126/science.aaw2087, 2019.

Pellerin, J.: Updating the Canadian Reference Hydrometric Basin Network to detect climate-related trends in streamflow, Master's Thesis, University of Waterloo, 2019.

Petts, G. E.: The Adjustment of River-channel Capacity Downstream from Reservoirs in Great Britain, Ph.D. thesis, University of Southampton, 1978.

Petts, G. E.: Complex response of river channel morphology subsequent to reservoir construction, Prog. Phys. Geogr., 3, 329–362, 1979.

Petts, G. E.: Long-term consequences of upstream impoundments, Environ. Conserv., 7, 325–332, 1980.

Petts, G. E.: Impounded rivers: perspectives for ecological management, Wiley, 1984.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E., and Stromberg, J. C.: The natural flow regime, BioScience, 47, 769–784, 1997.

Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B. P., Freeman, M. C., Henriksen, J., Jacobson, R. B., Kennen, J. G., Merritt, D. M., O'keeffe, J. H., Olden, J. D., Rogers, K., Tharme, R. E., and Warner, A.: The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards, Freshw. Biol., 55, 147–170, https://doi.org/10.1111/j.1365-2427.2009.02204.x, 2010.

de Rham, L., Dibike, Y., Beltaos, S., Peters, D., Bonsal, B., and Prowse, T.: A Canadian River Ice Database from the National Hydrometric Program Archives, Earth Syst. Sci. Data, 12, 1835–1860, https://doi.org/10.5194/essd-12-1835-2020, 2020.

Richter, B. D., Postel, S., Revenga, C., Scudder, T., Lehner, B., Churchill, A., and Chow, M.: Lost in development's shadow: The downstream human consequences of dams, Water Altern., 3, 14, 2010.

Salwey, S., Coxon, G., Pianosi, F., Lane, R., Hutton, C., Bliss Singer, M., McMillan, H., and Freer, J.: Developing water supply reservoir operating rules for large-scale hydrological modelling, Hydrol. Earth Syst. Sci., 28, 4203–4218, https://doi.org/10.5194/hess-28-4203-2024, 2024.

Schmadel, N. M., Harvey, J. W., Alexander, R. B., Schwarz, G. E., Moore, R. B., Eng, K., Gomez-Velez, J. D., Boyer, E. W., and Scott, D.: Thresholds of lake and reservoir connectivity in river networks control nitrogen removal, Nat. Commun., 9, 2779, https://doi.org/10.1038/s41467-018-05156-x, 2018.

Schmadel, N. M., Harvey, J. W., Schwarz, G. E., Alexander, R. B., Gomez-Velez, J. D., Scott, D., and Ator, S. W.: Small Ponds in Headwater Catchments Are a Dominant Influence on Regional Nutrient and Sediment Budgets, Geophys. Res. Lett., 46, 9669–9677, https://doi.org/10.1029/2019GL083937, 2019.

SEI International: Strategic Environmental Assessment of the Hydropower Master Plan in the Context of the Power Development Plan VI: Final Report, 2009.

Shen, H., Han, M., Tolson, B., and Metcalfe, R. A.: The Ontario Lake and River Routing Product Version 2 (OLRRP V2), https://doi.org/10.5281/zenodo.14225103, 2024.

Shen, H., Tolson, B., Craig, J., Metcalfe, R. A., Romero-Cuellar, J., and Luce, J.: Streamflow Alteration Index (SAI) v1.0 Database for Ontario, Canada, https://doi.org/10.5281/zenodo.19547932, 2026.

Shrestha, P. K., Samaniego, L., Rakovec, O., Kumar, R., Mi, C., Rinke, K., and Thober, S.: Toward Improved Simulations of Disruptive Reservoirs in Global Hydrological Modeling, Water Resour. Res., 60, e2023WR035433, https://doi.org/10.1029/2023WR035433, 2024.

Smokorowski, K. E.: The ups and downs of hydropeaking: a Canadian perspective on the need for, and ecological costs of, peaking hydropower production, Hydrobiologia, 849, 421–441, https://doi.org/10.1007/s10750-020-04480-y, 2022.

Stainton, R. T.: Hydrologic Zone of Influence Downstream of Waterpower Facilities: Literature Review and Analysis of Potential Methods to Support Prediction in Ontario Rivers, Institute for Watershed Science, Trent University, Peterborough, Ontario, Canada, 2012.

Steyaert, J. C., Sutanudjaja, E. H., Bierkens, M., and Wanders, N.: Data derived reservoir operations simulated in a global hydrologic model, Hydrol. Earth Syst. Sci., 29, 6499–6527, https://doi.org/10.5194/hess-29-6499-2025, 2025.

Tharme, R. E.: A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers, River Res. Appl., 19, 397–441, https://doi.org/10.1002/rra.736, 2003.

Tursun, A., Xie, X., Wang, Y., Peng, D., Liu, Y., Zheng, B., Wu, X., and Nie, C.: Streamflow Prediction in Human-Regulated Catchments Using Multiscale Deep Learning Modeling With Anthropogenic Similarities, Water Resour. Res., 60, e2023WR036853, https://doi.org/10.1029/2023WR036853, 2024.

Wada, Y., Bierkens, M. F. P., de Roo, A., Dirmeyer, P. A., Famiglietti, J. S., Hanasaki, N., Konar, M., Liu, J., Müller Schmied, H., Oki, T., Pokhrel, Y., Sivapalan, M., Troy, T. J., van Dijk, A. I. J. M., van Emmerik, T., Van Huijgevoort, M. H. J., Van Lanen, H. A. J., Vörösmarty, C. J., Wanders, N., and Wheater, H.: Human–water interface in hydrological modelling: current status and future directions, Hydrol. Earth Syst. Sci., 21, 4169–4193, https://doi.org/10.5194/hess-21-4169-2017, 2017.

Wang, J., Walter, B. A., Yao, F., Song, C., Ding, M., Maroof, A. S., Zhu, J., Fan, C., McAlister, J. M., Sikder, S., Sheng, Y., Allen, G. H., Crétaux, J. F., and Wada, Y.: GeoDAR: georeferenced global dams and reservoirs dataset for bridging attributes and geolocations, Earth Syst. Sci. Data, 14, 1869–1899, https://doi.org/10.5194/essd-14-1869-2022, 2022.

Water Survey of Canada: National Water Data Archive (HYDAT), 2024.

WCD: Dams and Development: A New Framework for Decision-making : the Report of the World Commission on Dams, Earthscan, 457 pp., 2000.

Wieczorek, M. E., Wolock, D. M., and McCarthy, P. M.: Dam impact/disturbance metrics for the conterminous United States, 1800 to 2018, https://doi.org/10.5066/P92S9ZX6, 2021.

Winemiller, K. O., McIntyre, P. B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., Baird, I. G., Darwall, W., Lujan, N. K., Harrison, I., Stiassny, M. L. J., Silvano, R. A. M., Fitzgerald, D. B., Pelicice, F. M., Agostinho, A. A., Gomes, L. C., Albert, J. S., Baran, E., Petrere, M., Zarfl, C., Mulligan, M., Sullivan, J. P., Arantes, C. C., Sousa, L. M., Koning, A. A., Hoeinghaus, D. J., Sabaj, M., Lundberg, J. G., Armbruster, J., Thieme, M. L., Petry, P., Zuanon, J., Vilara, G. T., Snoeks, J., Ou, C., Rainboth, W., Pavanelli, C. S., Akama, A., Soesbergen, A. V., and Sáenz, L.: Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong, Science, 351, 128–129, https://doi.org/10.1126/science.aac7082, 2016.

Yang, X., Pavelsky, T. M., Ross, M. R. V., Januchowski-Hartley, S. R., Dolan, W., Altenau, E. H., Belanger, M., Byron, D., Durand, M., Van Dusen, I., Galit, H., Jorissen, M., Langhorst, T., Lawton, E., Lynch, R., Mcquillan, K. A., Pawar, S., and Whittemore, A.: Mapping Flow-Obstructing Structures on Global Rivers, Water Resour. Res., 58, 1–10, https://doi.org/10.1029/2021WR030386, 2022.

Yassin, F., Razavi, S., Elshamy, M., Davison, B., Sapriza-Azuri, G., and Wheater, H.: Representation and improved parameterization of reservoir operation in hydrological and land-surface models, Hydrol. Earth Syst. Sci., 23, 3735–3764, https://doi.org/10.5194/hess-23-3735-2019, 2019.

Yin, Z., Lin, P., Riggs, R., Allen, G. H., Lei, X., Zheng, Z., and Cai, S.: A synthesis of Global Streamflow Characteristics, Hydrometeorology, and Catchment Attributes (GSHA) for large sample river-centric studies, Earth Syst. Sci. Data, 16, 1559–1587, https://doi.org/10.5194/essd-16-1559-2024, 2024.

Yue, S. and Gan, T. Y.: Simple scaling properties of Canadian annual average streamflow, Adv. Water Resour., 27, 481–495, https://doi.org/10.1016/j.advwatres.2004.02.019, 2004.

Zajac, Z., Revilla-Romero, B., Salamon, P., Burek, P., Hirpa, F. A., and Beck, H.: The impact of lake and reservoir parameterization on global streamflow simulation, J. Hydrol., 548, 552–568, https://doi.org/10.1016/j.jhydrol.2017.03.022, 2017.