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Jo-Annie Constantineau

Universite du Quebec a Montreal

Daniel Germain

germain.daniel@uqam.ca

Université du Québec à Montréal: Universite du Quebec a Montreal <https://orcid.org/0000-0003-4757-3124>

Research Article

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Torrential flooding across a humid Appalachian watershed: historical reconstruction and sub-watershed susceptibility

Jo-Annie Constantineau & Daniel Germain*

Department of Geography
Université du Québec à Montréal
Montréal (Québec)
H3P 3P8 CANADA
germain.daniel@uqam.ca; joannie.constantineau@gmail.com

*Corresponding author: germain.daniel@uqam.ca

ORCID: 0000-0003-4757-3124

Abstract: Torrential floods remain poorly documented in the humid Appalachian regions of eastern North America, where flood management has traditionally focused on large rivers, snowmelt, and ice-jam flooding. This study examines the spatial variability of torrential flood susceptibility among 86 level-2 sub-watersheds of the Chaudière River watershed (Québec, Canada) by integrating historical reconstruction, catchment morphometry, land-use analysis, and GIS-based multicriteria mapping. Documentary sources covering 1900–2023 identified 53 distinct flood dates and 185 event–locality records. Events occurred predominantly in July and August and were associated with thunderstorms, prolonged rainfall, and tropical or post-tropical weather systems. The analysis revealed substantial morphometric heterogeneity among recurrently affected catchments rather than a uniform physical signature. Historical descriptions and generally low catchment-scale Melton values were consistent with predominantly flood-driven torrential activity, although sediment-rich processes within smaller tributaries cannot be excluded. Settlement surfaces increased between 2000 and 2020, but their hydrological effects were not directly quantified. A susceptibility index combining slope, land cover, and substrate-based runoff potential showed partial correspondence with documented flood occurrence. The proposed approach provides a regional screening framework for identifying catchments requiring detailed hydrological and geomorphological investigation, rather than a predictive assessment of flood probability or risk.

Keywords: torrential flood; flood susceptibility; historical reconstruction; catchment morphometry; multicriteria analysis; Chaudière River

1. Introduction

Torrential floods can generate severe damage in mountain catchments through rapid increases in discharge, channel instability, bank erosion, and sediment transport (Borga et al. 2008; Marchi et al. 2010). Their localized occurrence and short response times complicate both their documentation and their assessment. Because these events frequently affect small and poorly gauged catchments, they are often incompletely represented in conventional hydrometric records and must be reconstructed from documentary or post-event evidence (Archer and Fowley 2021; Kaiser et al. 2021). Unlike flooding along large rivers, torrential activity in tributary catchments depends on the interaction between intense rainfall and local conditions governing runoff generation, flow concentration, channel response, and sediment availability. The spatial organization of rainfall relative to drainage pathways can interact with catchment physiography to produce markedly different flood responses among neighbouring basins exposed to the same storm system (Saharia et al. 2021). Understanding these interactions is essential for identifying susceptible catchments and supporting flood-risk management beyond the main river network.

Research on mountain hazards has extensively examined debris flows and other sediment-rich flows, but torrential activity also includes water-dominated floods capable of substantial erosion and sediment transfer (Amponsah et al. 2016; Bucala-Hrabia et al. 2020). Studies conducted in eastern Canada have demonstrated that high-energy water and hyperconcentrated flows can construct and reactivate forested alluvial fans under both intense rainfall and snowmelt conditions (Ouellet and Germain 2014). Nevertheless, research in humid Appalachian environments has remained largely restricted to individual fans or tributary-junction landforms rather than watershed-scale reconstructions of flood occurrence (Kochel 1990; Jennings et al. 2003; Juneau and Germain 2025). Assessing these systems requires consideration of catchment morphology, drainage organization, surface materials, and land cover, whose influence varies among environmental settings (Arango et al. 2021; Saharia et al. 2017). However, identifying these physical predispositions does not, by itself, establish where torrential floods have repeatedly occurred.

Historical reconstruction offers a complementary perspective by extending event inventories beyond available instrumental records and documenting the location, timing, and reported impacts of past floods (Boisson et al. 2022; Glaser et al 2010; Kaiser et al. 2021). Although documentary sources are uneven in spatial coverage and reporting intensity, they can reveal recurrent activity that short hydrometric records may not capture. Geo-historical studies have also shown that small tributaries can account for a substantial proportion of documented flood impacts, despite receiving less attention than the main river system (Boisson et al. 2022). However, one regional storm may generate multiple locality-based reports, and changes in documentary coverage and exposure may influence apparent flood patterns (Archer and Fowley 2021; Brázdil et al. 2024; Kaiser et al. 2021). Combined with geomorphological analyses, historical

evidence provides a basis for examining whether repeatedly affected catchments share particular physical characteristics.

GIS-based multicriteria approaches offer practical means of mapping relative flood susceptibility from topographic, land-cover, and runoff-related indicators (Arango et al. 2021; Costache et al. 2020; Shawky and Hassan 2023). Recent applications have increasingly combined catchment morphometry, anthropogenic land-use characteristics, and historical flood inventories to assess the spatial distribution of flood susceptibility (Corapci and Ozdemir 2024). Their interpretation nevertheless depends on the selection and weighting of variables, the spatial resolution and classification of the input data, and comparison with observed events. Integrating historical inventories with such assessments can help evaluate the correspondence between mapped predisposition and documented flood occurrence, while also identifying discrepancies requiring further investigation. In data-limited settings, these maps provide screening tools rather than estimates of flood probability, exposure, or risk.

The Chaudière River watershed in southern Québec provides an opportunity to examine these relationships in a humid Appalachian setting. Flood research in this region has largely addressed main-stem flooding associated with snowmelt, open-water conditions, and ice jams (Biron et al. 2020; Ghobrial et al. 2023; Quilbé et al. 2008; Roy et al. 2003), whereas rapid flooding in tributary catchments has received less attention. Previous work has documented tributary-junction fans along the Chaudière River and examined their relationships with catchment characteristics (Juneau and Germain 2025), providing a geomorphological basis for comparison with historical flood records. These results provide a geomorphological basis for comparison with historical flood records but do not document the recurrence of torrential events. The watershed combines contrasting physiographic and land-use conditions with documentary evidence spanning more than a century, allowing historical activity to be examined alongside the tributary-catchment characteristics and recent land-cover changes.

This study therefore aims to: (1) reconstruct the spatiotemporal distribution and documented hydroclimatic contexts of warm-season flood events with reported torrential characteristics over the archival search period 1900–2023; (2) characterize the hydrogeomorphological attributes of 86 level-2 sub-watersheds, examine their association with documented flood occurrence, and quantify land-use changes between 2000 and 2020; and (3) assess relative torrential flood susceptibility using a GIS-based multicriteria index and examine its spatial correspondence with historical flood occurrence. The study thereby provides a regional assessment of flood-dominated torrential systems and identifies catchments warranting more detailed investigation. The conceptual framework guiding this integration is presented in Section 2 and Figure 1.

2. Conceptual framework

2.1 Flood-dominated torrential systems

Torrential activity encompasses a range of hydrogeomorphological processes involving rapid runoff concentration, sediment mobilization, and channel adjustment in mountain catchments. These processes include water floods, hyperconcentrated flows, debris floods, and debris flows, with differing sediment concentrations, sediment-transport mechanisms, and flow behaviour (Costa 1984; Ouellet and Germain 2014; Pierson 2005). Rather than forming universally discrete categories, sediment-water flows may occupy transitional positions along a process continuum, which complicates their identification from historical or post-event evidence (Borga et al. 2014; Germain and Ouellet 2013). Rapid hydrological responses can therefore generate substantial geomorphic change without necessarily developing into debris flows.

In this study, the term *flood-dominated torrential systems* refers to catchments where the available evidence is consistent with activity predominantly involving rapid water flows capable of bank erosion, bed-material transport, channel widening, and sediment deposition. The term describes the dominant documented behaviour rather than an exclusive or permanent process category. Because debris floods remain water-driven but involve unusually high rates of coarse-sediment transport and bed mobilization, historical terminology alone cannot reliably distinguish them from water floods or debris flows (Church and Jakob 2020).

Documentary evidence provides information on observed event behaviour, whereas catchment morphometry helps assess whether physical characteristics are consistent with torrential processes (de Scally et al. 2010; Wilford et al. 2004). However, morphometric process domains overlap, and their thresholds vary among environmental settings (Bazilova et al. 2025). Indicators calculated for large catchments may also obscure the behaviour of smaller, steeper tributaries nested within them (Czuba and Foufoula-Georgiou 2015). Historical and morphometric evidence are therefore interpreted jointly without assigning a definitive process type to individual events.

2.2 Hydrogeomorphological predisposition and torrential flood susceptibility

Torrential flood occurrence reflects the interaction between hydroclimatic forcing and catchment conditions governing runoff generation, flow concentration, and sediment transfer. Watershed relief, drainage geometry, and channel organization provide a structural framework for hydrological response, while soils, surficial deposits, and land cover influence infiltration and water storage (Horton 1945; Najibi and Devineni 2023; Norbiato et al. 2008; Schumm 1956). Catchment slope, relief, area, and drainage configuration additionally influence sediment transfer and the hydrogeomorphic response produced at tributary outlets (Bertrand et al. 2013; Bazilova et al. 2025). These characteristics establish a physical

predisposition, but an event occurs only when hydroclimatic forcing exceeds relevant catchment thresholds (Borga et al. 2014).

Geomorphological features also provide evidence of past catchment behaviour. Alluvial fans record sediment delivery and deposition at tributary outlets, although their presence alone does not establish current activity or identify the processes responsible for their formation (Harvey 2012; Stoke and Maher 2015; Vincent et al. 2022). In humid, cold-temperate environments, forested fans may be constructed or reactivated by water-dominated or hyperconcentrated flows associated with intense rainfall and snowmelt, demonstrating that fan occurrence should not automatically be interpreted as evidence of debris-flow dominance (Ouellet and Germain 2014). Fan occurrence should therefore not automatically be interpreted as evidence of debris-flow dominance. Along the Chaudière River, tributary-junction fans reflect interacting morphometric, depositional, hydroclimatic, and anthropogenic controls (Juneau and Germain 2025).

Here, *torrential flood susceptibility* denotes the relative physical predisposition of a catchment to generate torrential flood responses. It is distinguished from hazard, which incorporates event probability and magnitude, and from risk, which also considers exposure and vulnerability. Urbanization, soil sealing, vegetation removal, and modifications to drainage pathways can alter infiltration, runoff connectivity, and response times (Feng et al. 2021; Yang et al. 2016). Land use is consequently treated as a potential modifier of physical susceptibility, not as a measure of societal vulnerability.

The operational index represents a subset of these controls through three variables: slope, land cover, and runoff potential inferred from surficial deposits. The latter is an ordinal proxy for substrate-related runoff-generating conditions, not a measured runoff coefficient. Catchment morphometry and alluvial-fan occurrence provide complementary interpretative evidence but are not components of the index. The index is therefore a screening-level representation whose spatial pattern depends on the input data and analytical choices rather than a complete process-based model of flood generation.

Recent work in the Chaudière watershed further shows that steepness, drainage organization, land-use resistance, and proximity to the channel network jointly influence potential hydrosedimentary connectivity (Bérubé et al. 2026). Such connectivity is conceptually related to torrential susceptibility but remains distinct from event occurrence because sediment and water transfers depend on the activation of structural pathways during particular hydroclimatic conditions (Bracken et al. 2015; Heckmann et al. 2018; Hooke and Souza 2021).

2.3 Linking historical evidence and spatial susceptibility

The framework combines three complementary components: historical reconstruction of torrential activity, characterization of catchment attributes, and multicriteria assessment of relative susceptibility (Figure 1). Historical records document event timing, location, and reported impacts, whereas spatial analyses describe environmental conditions potentially associated with catchment response. Comparing these components allows the study to examine whether recurrently affected tributaries also exhibit elevated physical predisposition (Corapci and Ozdemir 2024).

This comparison requires distinguishing regional meteorological episodes, distinct event dates, affected localities, documentary records, and catchment-level flood occurrences (Brázdil et al. 2024). A single episode may affect several municipalities and tributaries; multiple reports therefore do not necessarily represent independent events. Furthermore, records located only at the municipal scale cannot always be attributed confidently to a specific tributary or distinguished from mainstem flooding.

Historical inventories are influenced by settlement patterns, infrastructure exposure, source availability, and reporting practices (Boisson et al. 2022; Glaser et al. 2010). Apparent increases in documented flood occurrence may therefore reflect changes in archival coverage or exposure rather than changes in hydrological activity alone (Brázdil et al. 2024). Consequently, the absence of documented events cannot be interpreted as evidence of inactivity. Likewise, land-cover conditions observed between 2000 and 2020 cannot explain events occurring earlier in the inventory without additional evidence.

Agreement between mapped susceptibility and historical occurrence is therefore interpreted as evidence of spatial consistency, rather than as proof of predictive performance or causality. Discrepancies may reflect incomplete archives, uncertain event locations, spatial variability in rainfall, changes in catchment conditions, or limitations of the selected indicators and their weighting. Their comparison therefore constitutes an exploratory correspondence assessment rather than an independent validation. The framework maintains the distinction between documented activity, inferred physical predisposition, and the exposure and social vulnerability dimensions not measured in this study.

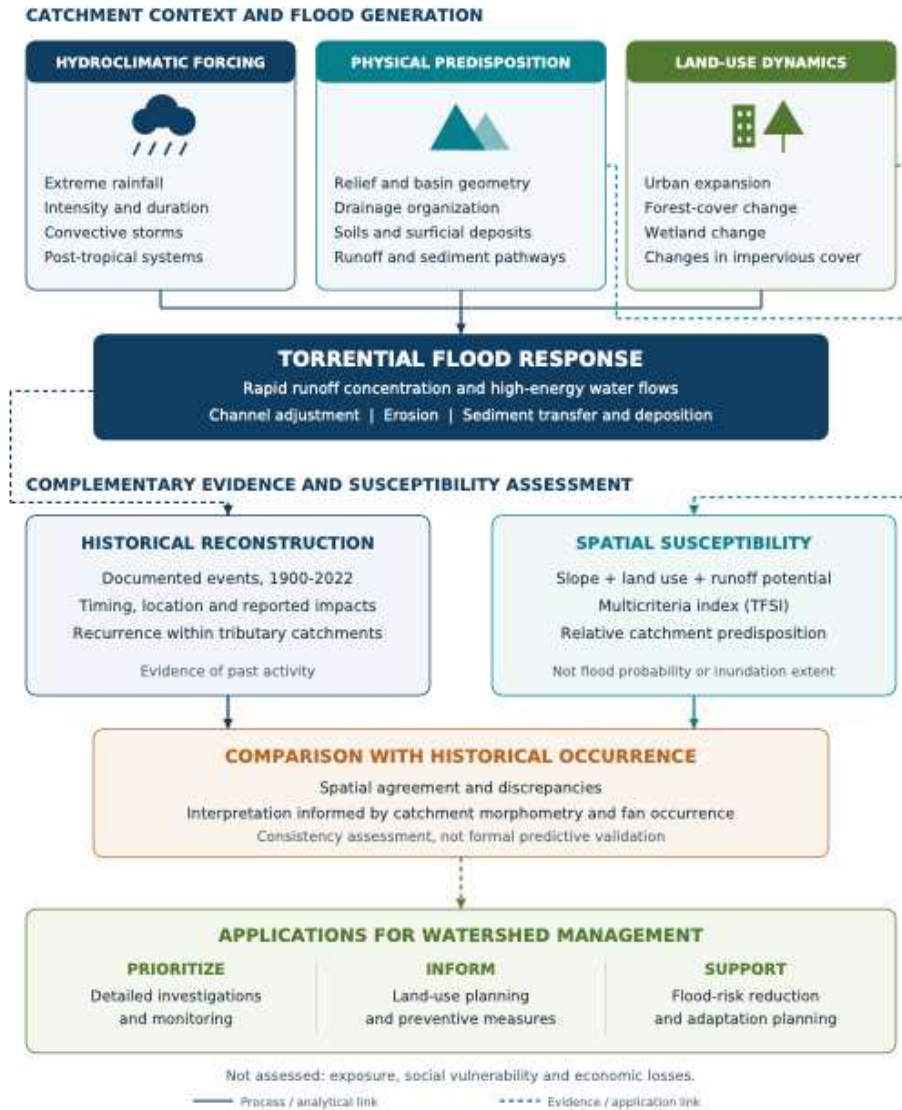


Fig. 1 Conceptual framework linking hydroclimatic forcing, catchment predisposition, and torrential flood susceptibility. Extreme rainfall interacts with geomorphological, surficial, and land-cover conditions to generate torrential flood responses. Historical reconstruction documents past activity, while spatial analyses characterize relative catchment susceptibility. Their comparison supports the identification of sub-watersheds requiring further investigation. The index represents relative physical susceptibility rather than event probability, inundation extent, vulnerability, or flood risk.

3. Study area

3.1. Geographic and physiographic setting

The Chaudière River watershed is located in southeastern Québec, Canada, on the south shore of the St. Lawrence River (Figure 2). Covering approximately 6,695 km², the watershed extends from Lake

Mégantic, near the Canada–United States border, to its confluence with the St. Lawrence River at Lévis. The Chaudière River flows predominantly northward over approximately 190 km (COBARIC 2014, 2022). The watershed is characterized by marked physiographic contrasts resulting from its position between the Appalachian Highlands and the St. Lawrence Lowlands. Elevation generally decreases from the Appalachian uplands toward the downstream plains, creating contrasting topographic settings along the drainage network. The folded and faulted Appalachian bedrock also exerts structural control on valley orientation and drainage geometry (Caron 2013).

The watershed is commonly divided into three geographic sectors (COBARIC 2014). The Upper Chaudière covers 45.8% of the watershed and constitutes its largest sector, characterized by Appalachian uplands, an incised main valley, and predominantly forested landscapes. Valley and tributaries are generally more confined than farther downstream. The Middle Chaudière accounts for 39.6% of the watershed and combines dissected terrain with an agricultural alluvial valley. Several tributaries descend from steep terrain into reaches of the main river, providing favourable settings for sediment storage at tributary-mainstem junctions (Juneau and Germain 2025). The Lower Chaudière covers 14.6% of the watershed and extends toward the St. Lawrence Lowlands, where gentler slopes, extensive agricultural land use, and greater urban development characterize the landscape. Clay-rich plains inherited from the postglacial Champlain Sea are also present in this downstream sector.

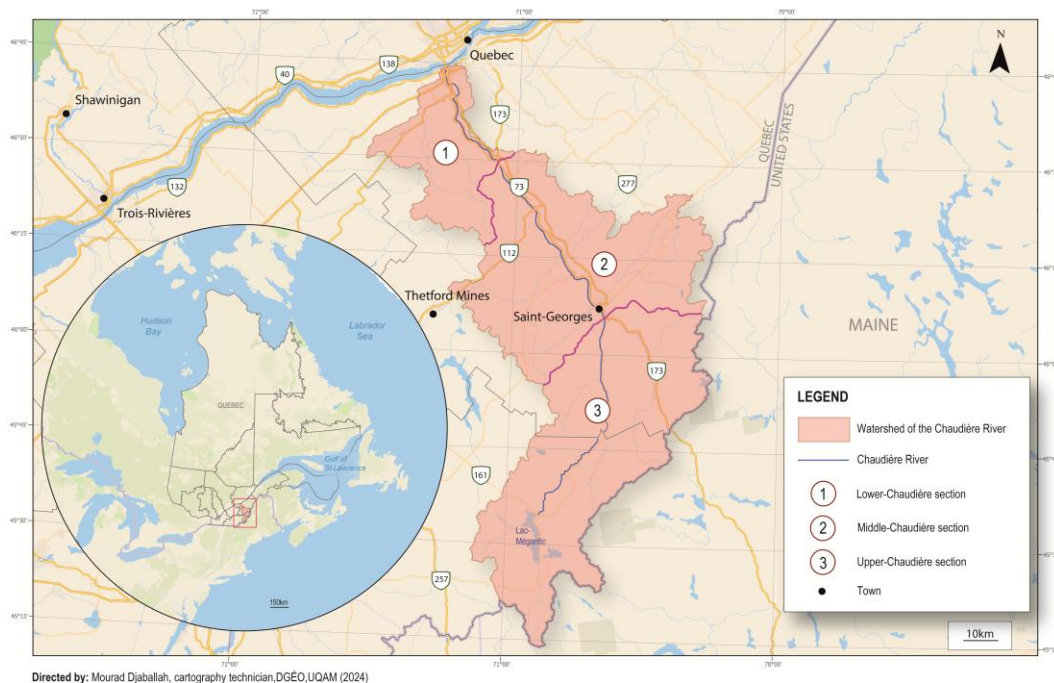


Fig. 2 Location of the Chaudière River watershed in southeastern Québec, Canada. The watershed extends from Lake Mégantic to the St. Lawrence River and is subdivided into three geographic sectors: the Upper, Middle, and Lower

Chaudière. The main river network and principal urban centres are also shown. The inset map indicates the regional location of the watershed within eastern Canada.

3.2 Hydrographic and geomorphological setting

The drainage network includes more than 390 rivers and streams and approximately 170 water bodies. Four major tributary catchments—the Beaurivage, Bras Saint-Victor, Famine, and du Loup—together drain approximately 46% of the watershed (COBARIC 2014). Tributaries vary considerably in drainage area, relief, and valley configuration, providing contrasting settings for runoff concentration and sediment transfer.

The geological framework inherited from Appalachian tectonic evolution and Quaternary glaciations contributes to this landscape heterogeneity. The Appalachian bedrock consists predominantly of folded and faulted sedimentary rocks, including sandstone, shale, and limestone (Caron 2013). Surface deposits include tills, glaciofluvial sediments, marine clays associated with the Champlain Sea transgression. Till is widespread in the uplands, glaciofluvial and alluvial sediments occur primarily in valleys, and fine-grained marine deposits characterize parts of the downstream lowlands (Caron 2013). These materials create spatially variable conditions for infiltration, runoff generation, erodibility, and sediment supply.

Alluvial fans occur at several tributary outlets, particularly along the Middle Chaudière, and document sediment delivery from tributaries to the receiving river (Juneau and Germain 2025). Their distribution reflects differences in catchment morphometry and depositional conditions at tributary–mainstem junctions, providing a geomorphological context for investigating torrential activity. Recent hydrosedimentary investigations have emphasized the contrast between the relatively low-gradient main stem and its steeper tributaries. Tributary catchments vary considerably in area, relief, and channel gradient, and several display high structural connectivity with the Chaudière River. This configuration favours rapid transfer of water and sediment from tributary networks while producing spatially localized erosion and accumulation along the receiving channel (Bérubé et al. 2026).

3.3. Climate, vegetation, and land use

The watershed spans climatic and vegetation gradients associated with its geographic extent and relief. It has a humid continental climate characterized by cold winters, warm summers, a mean annual temperature of approximately 3.5 °C, and mean annual precipitation of approximately 1,050 mm. The watershed includes the sugar maple–basswood and sugar maple–yellow birch bioclimatic domains (COBARIC 2014). Mixed deciduous-coniferous forests dominate much of the Appalachian sector, with progressively cooler forest conditions in the higher uplands.

Seasonal snow accumulation and melt influence river discharge, while rainfall also generates high flows during the warmer months. The regional hydrological regime therefore combines basin-wide spring snowmelt floods, occasional rain-on-snow events, and more localized responses to intense summer rainfall (Biron et al. 2020; Juneau and Germain 2025). These rainfall-driven responses may differ substantially between small tributaries and the main river. The present study focuses on documented torrential flooding rather than the full range of snowmelt, rainfall, and ice-jam floods affecting the watershed.

Land use reflects the strong environmental gradient between the Appalachian uplands and the downstream lowlands. Forests dominate the headwater regions, whereas agriculture occupies much of the central and lower watershed. Urban development is concentrated along the principal transportation corridors and within municipalities such as Saint-Georges, Beauceville, Sainte-Marie, and Lévis. This spatial contrast provides the context for assessing land-use changes between 2000 and 2020 and incorporating land-cover conditions into the susceptibility analysis.

4. Materials and Methods

4.1 Integrated methodological framework and spatial units

The methodological framework integrates multiple lines of evidence to investigate flood-dominated torrential systems within the Chaudière River watershed (Figure 3). The approach combines historical reconstruction, hydroclimatic records, catchment morphometry, land-use change analysis, and GIS-based susceptibility mapping.

Sub-watershed boundaries were obtained from Québec's multi-scale hydrographic basin dataset, distributed by the MELCCFP through Données Québec (MELCCFP 2023). Of the 93 level-2 sub-watersheds initially considered, seven were excluded because unresolved errors occurred during calculations based on the digital elevation model, leaving 86 units for catchment characterization and susceptibility assessment. Geospatial processing was performed in ArcGIS Pro.

The workflow comprises five successive stages (Figure 3): 1) historical reconstruction of warm-season flood events over the archival search period 1900–2023; 2) hydroclimatic characterization of documented events; 3) hydrogeomorphological characterization of sub-watersheds; 4) analysis of land-use dynamics; and 5) hydrogeomorphological susceptibility assessment followed by comparison with the historical flood inventory.

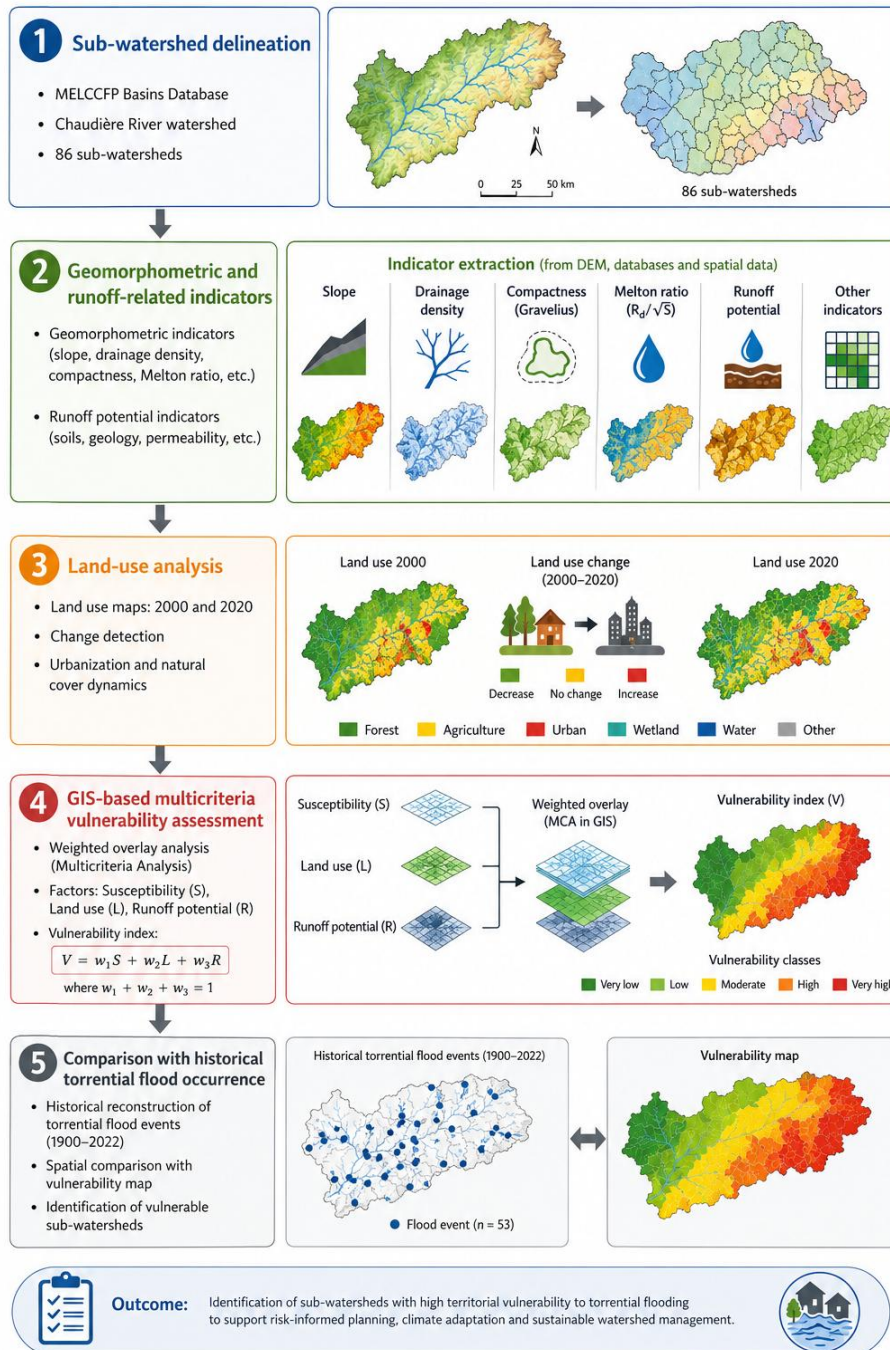


Fig. 3 Methodological framework used to assess relative torrential flood susceptibility in the Chaudière River watershed. The workflow integrates the selection of 86 level-2 sub-watersheds from existing boundaries, catchment morphometry, hydroclimatic records, land-use change analysis, GIS-based multicriteria susceptibility mapping, and comparison with historical torrential flood events documented between 1900 and 2023.

4.2 Historical reconstruction of torrential flood events and hydroclimatic characterization

The historical search targeted floods and high-flow events occurring mainly between June and September and associated with heavy rainfall or description of rapid hydrological or geomorphic response. Events involving anthropogenic aggravating factors, including channel obstructions and dam failures, were retained when they otherwise met the selection criteria. Records describing erosion or sediment transport could also be retained without explicit evidence of overbank flooding. No uniform instrumental rainfall-intensity or discharge threshold was applied across the historical period because of the limited spatial and temporal coverage of the available observations.

A historical inventory of flood events with reported torrential characteristics was reconstructed by integrating multiple documentary sources, including the Canadian Disaster Database (Public Safety Canada n.d.), Québec civil-security records (MSP n.d.), and AQUARISQ database (Ouranos 2015). Reports of the Commission des eaux courantes du Québec were consulted for 1912–1948. Additional searches covered digitized newspapers available through Bibliothèque et Archives nationales du Québec and media archives, including *Le Soleil*, *Le Devoir*, *La Presse*, *Radio-Canada*, *TVA Nouvelles*, and *En Beauce*. Each record included the event date or date range, affected locality, reported cause, available hydroclimatic information, damage, associated watercourse when identified, and documentary source. Records sharing the same event date and meteorological context were consolidated into a single regional event date, while affected localities were retained as separate event–locality records. The complete historical inventory, including event-locality records, reported triggers, hydrogeomorphic effects, impacts, documentary sources, and original excerpts, is provided in Online Resource 1. Event locations were georeferenced as points. Locations were classified as source-provided coordinates, locations inferred from identifiable landmarks, or approximate municipality-level locations. Points were intersected with level-2 sub-watershed boundaries. Municipality-level points were retained in the spatial inventory but were not interpreted as unequivocal evidence of flooding in a particular tributary.

Hydroclimatic conditions were examined using instrumental records and event-specific information contained in documentary sources. Monthly precipitation for 1913–2017 was obtained from Environment and Climate Change Canada’s Adjusted and Homogenized Canadian Climate Data for the Beauceville station (ID 7027283), selected because of its central location and long period of record. These data characterized the regional monthly precipitation context, whereas event-specific rainfall amounts and durations were obtained from documentary sources where available.

Discharge records were obtained from the Centre d’expertise hydrique du Québec for station 023402 on the Chaudière River at the Route 218 bridge in Saint-Lambert-de-Lauzon. Monthly mean and maximum discharges were examined, and daily values were consulted for documented event dates where available. The record begins in 1915 and contains a gap from 1927 to 1935. These mainstem data provided regional

hydrological context rather than measurements of tributary peak discharge. Reported meteorological causes and anthropogenic aggravating factors were recorded without assuming uniform instrumental verification.

4.3 Hydrogeomorphological characterization of sub-watersheds

A 10-m digital terrain model derived from lidar data distributed through the MRNF's Forêt Ouverte platform was used to characterize the predefined sub-watersheds. The variables calculated for each unit included drainage area, perimeter, mean catchment slope, mean channel slope, drainage density, Gravelius compactness coefficient, and Melton ruggedness number (Gravelius 1914; Horton 1945; Melton 1965; Wilford et al. 2004).

Drainage area and perimeter were calculated from the sub-watershed polygons, and terrain slope was summarized within each polygon. Channel elevation information was extracted by applying the ArcGIS Pro Add Surface Information tool to the hydrographic line layer, and mean channel slope was summarized by catchment. Terrain and channel slopes were expressed as percentages. Drainage density (D_d), Gravelius compactness (K_g), and Melton ruggedness (M) were calculated as:

$$D_d = \frac{L_t}{A} \quad (1)$$

$$K_g = \frac{P}{2\sqrt{\pi A}} \quad (2)$$

$$M = \frac{z_{max} - z_{min}}{\sqrt{A}} \quad (3)$$

where (L_t) is total mapped channel length, (A) is catchment area, (P) is catchment perimeter, and z_{max} and z_{min} are maximum and minimum elevations. Drainage density is expressed in km km^{-2} . Gravelius compactness and Melton ruggedness are dimensionless when all quantities are expressed in compatible units; catchment relief was therefore converted to kilometres when area was expressed in square kilometres. These indicators were used to compare catchment characteristics. Melton ruggedness was interpreted as a screening indicator of potential process domains following Wilford et al. (2004), rather than as direct evidence of processes operating during individual events.

Alluvial fan identification began with the inventory of Juneau (2020), which was checked and updated using 2015 orthophotographs and imagery available in Google Earth through October 2023. The identification and morphometric analysis of these tributary-junction fans are detailed in Juneau and Germain (2025). Fan occurrence was recorded for each level-2 sub-watershed as a binary variable. The

complete catchment-level dataset, including morphometric characteristics and mapped alluvial-fan occurrence for the 86 analyzed sub-watersheds, is provided in Online Resource 2.

4.4 Land-use dynamics

Land-cover conditions were examined for 2000, 2010, and 2020 using 30-m Canadian land-cover raster datasets distributed by Agriculture and Agri-Food Canada. Original classes were consolidated into settlement, water, forest, cropland, grassland, wetland, and other land. Changes in class area were calculated for the entire watershed for 2000–2010, 2010–2020, and 2000–2020.

Catchment-level change analysis was restricted to settlement surfaces. Raster Calculator and Zonal Statistics were used to summarize settlement change between 2000 and 2020 within each level-2 sub-watershed. Comparable sub-watershed change estimates were not retained for the other classes. Consequently, changes in overall land-cover composition were analyzed at the watershed scale, whereas settlement change was analyzed by sub-watershed.

4.5 Hydrogeomorphological susceptibility assessment and comparison with historical flood occurrence

Regional hydrogeomorphological susceptibility was evaluated using three environmental variables known to influence rapid runoff generation during extreme precipitation events: slope, land use, and runoff potential. The assessment combined terrain slope, land cover representing 2020 conditions, and an ordinal runoff-potential indicator derived from surficial deposits obtained from SIGÉOM (2022). Catchment compactness, drainage density, Melton ruggedness, and alluvial-fan occurrence were analyzed separately and were not components of the index. All three input layers were converted to a common 30-m cell size before integration.

Each input was assigned an ordinal score from 1 to 4, representing an increasing contribution to runoff-generating conditions. Slope scores were assigned as follows: $<3\% = 1$; $3-8\% = 2$; $8-13\% = 3$; $>13\% = 4$. Land-cover scores distinguished forest and water surfaces (1), shrubland, grassland, and wetlands (2), cropland and barren land (3), and urban land (4). Surficial deposits were assigned to runoff-potential groups adapted from Gagné et al. (2013). Although the classification comprised four possible groups, only groups A–C, corresponding to scores 1–3, occurred among the mapped deposits. This indicator is a substrate-based proxy, not a measured runoff coefficient.

Each variable was standardized on a scale ranging from 0 (lowest contribution) to 1 (highest contribution), using min–max normalization:

$$X = (X - X_{min}) / (X_{max} - X_{min}) \quad (4)$$

where X^* is the assigned ordinal score and X_{min} and X_{max} are the lower and upper bounds used for normalization. A weighted linear combination was then used to calculate the Torrential Flood Susceptibility Index (TFSI):

$$TFSI = 0.50S^* + 0.25L^* + 0.25R^* \quad (5)$$

where S , L , and R are the standardized slope, land-cover, and runoff-potential scores, respectively. The weights were prescribed from a literature-informed interpretation of the selected controls rather than calibrated against observed flood occurrence, and no sensitivity analysis was performed. The 30-m TFSI raster was averaged within each level-2 sub-watershed using Zonal Statistics as Table or Summarize Within.

Historical occurrence counts were compared descriptively with mean sub-watershed TFSI values. For Figure 9, the 86 sub-watersheds were grouped into four occurrence classes: 0, 1–4, 5–9, and ≥ 10 documented occurrences. Sub-watersheds with at least three occurrences were additionally retained as a recurrently affected group for the morphometric summary in Table 2. These thresholds are descriptive grouping criteria and do not represent hydrological recurrence intervals. The comparison considered the distribution of susceptibility values and spatial correspondence with documented occurrences. No inferential test or predictive validation was performed.

5. Results

5.1 Historical distribution of documented flood events

Historical reconstruction identified 53 distinct event start dates within the archival search period 1900–2023, represented by 185 event–locality records (Online Resource 1). The earliest tabulated event occurred in 1912 and the latest in 2023 (Figure 4a). These records include reported tributary responses and mainstem flooding; the number of locality-based records therefore exceeds the number of regional episodes.

The temporal distribution of documented events exhibits marked interannual variability. Of the 53 distinct dates, 31 occurred from 2000 onward. Using five-year intervals beginning in years divisible by five, the largest count occurred in 2005–2009, with 13 events, followed by 2015–2019, with nine. Earlier intervals generally contained fewer records, although six events were documented in 1995–1999. These counts describe the distribution of documented activity rather than a reporting-adjusted trend in flood frequency.

Within the June–September selection window, August accounted for 20 events and July for 18, compared with eight in September and seven in June (Figure 4b). July and August together represented approximately 72% of the inventory. No comparison with winter or spring occurrence was possible because these seasons were excluded from the historical search criteria.

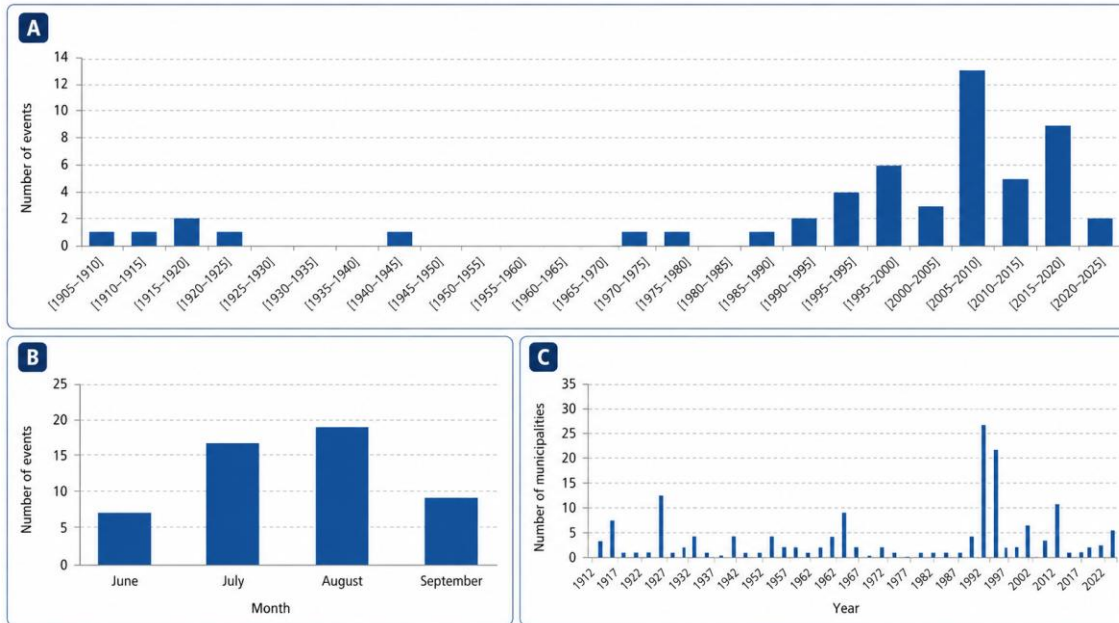


Fig. 4 Temporal distribution of documented flood episodes: a) counts by five-year interval over the archival search period 1900–2023; b) counts by month within the June–September selection window. Counts are based on distinct event start dates rather than the number of affected localities.

The spatial distribution of documented events was uneven, with numerous records concentrated in the Middle Chaudière and near the main river and its principal tributaries (Figure 5). Overall, 49 of the 102 municipalities in the watershed had at least one documented occurrence. Sainte-Marie, Saint-Georges, and Beauceville were among the most frequently affected municipalities. Most episodes affected five municipalities or fewer, whereas the events of 1 July 2002 and 4 August 2003 affected 27 and 21 municipalities, respectively.

Eleven level-2 sub-watersheds had at least three recorded occurrences in the catchment summary. The largest counts were reported for Bras Saint-Victor (27), des Fermes (12), Beaurivage (10), and Morency and Famine (eight each). These catchment-level counts are distinct from the 53 regional event dates and remain subject to the spatial precision and aggregation of locality-based records.

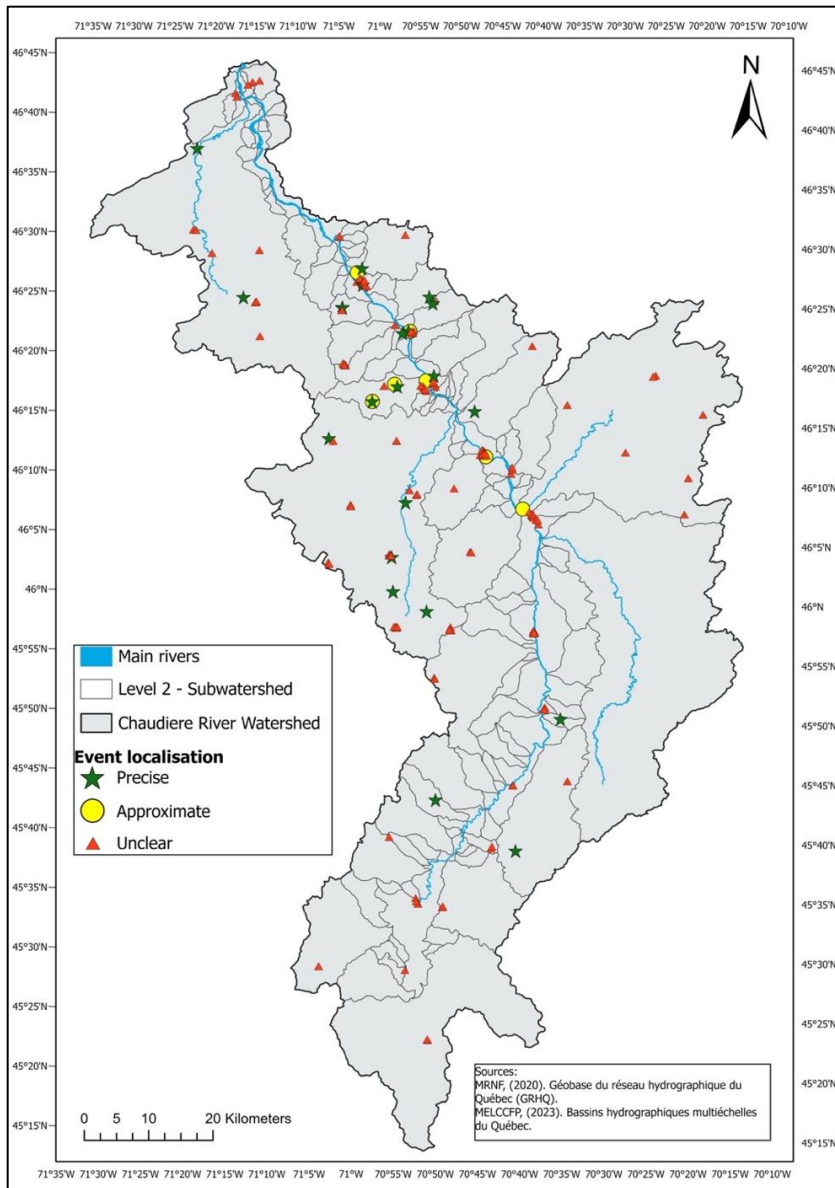


Fig. 5 Spatial distribution of flood records retained in the historical inventory for the Chaudi  re River watershed over the archival search period 1900–2023. Symbols distinguish three levels of location precision: source-provided coordinates, locations inferred from identifiable landmarks, and approximate municipality-level locations. Points represent reported affected locations rather than necessarily the sites of flood initiation; multiple locations may correspond to the same event.

5.2 Hydroclimatic conditions and reported aggravating factors

The documentary inventory includes floods associated with thunderstorms, prolonged rainfall, and tropical or post-tropical weather systems. Eleven events were explicitly associated with severe thunderstorms in the documentary sources. The reported precipitation amounts and durations varied among events, encompassing both short, intense episodes and rainfall accumulated over several days.

For the event of 1 July 2002, documentary sources reported 58 mm of rainfall in four hours. The event of 4 August 2003 involved a reported 71.1 mm over a few hours, within a longer three-day period of abundant rainfall. These two episodes produced geographically extensive impacts across the watershed. Records also associated flooding with Tropical Storm Doria in 1971, the remnants of Hurricane Belle in 1976, and Hurricane Irene in 2011. Approximately 50 mm of precipitation was reported in less than 30 hours during Doria, between 50 and 75 mm during Belle, and nearly 100 mm in 24 hours during Irene. These values originate from event descriptions and do not represent a spatially uniform rainfall measurement across all affected catchments.

The monthly precipitation and discharge series showed several coincident periods of high precipitation and elevated mainstem discharge, but this correspondence was not consistent for every documented event. Some event dates coincided with relatively low daily discharge at the mainstem gauge. Thus, documented local flooding was not invariably accompanied by a pronounced discharge response at the downstream station. Historical descriptions reported rapid water-level rises, damaged or overtopped crossings, erosion, sediment deposition, and localized infrastructure damage. The event of 13 August 1990 at Saint-Georges provides a documented example of tributary flooding: reports identified the ruisseau d'Ardoise as a major source of damage and described an upstream dam failure, bank erosion, slope failures, and sediment-laden flooding (Le Soleil 1990).

Anthropogenic aggravating factors were also documented in earlier events. Accounts of the June and July 1917 floods described timber accumulations and structures associated with log storage that obstructed flow along the Chaudière River (Bourbonnais 1917; Grenier 2005). These records identify event-specific combinations of rainfall, obstructions, and infrastructure failure, rather than a single triggering mechanism shared by all inventoried floods.

5.3 Hydrogeomorphological characteristics of the analyzed sub-watersheds

Morphometric analyses revealed pronounced variability among the 86 level-2 sub-watersheds of the Chaudière River watershed (Online Resource 2). Tabulated mean catchment slopes ranged from 0.31% to 11.01%, while mean channel slopes ranged from 0.70% to 5.41%. The relationship between mean catchment slope and mean channel slope was generally positive, although catchments with and without mapped alluvial fans overlapped (Figure 6a).

Sub-watersheds with repeated historical occurrences did not exhibit uniformly steep mean slopes. Among the 11 units with at least three recorded occurrences, mean catchment slopes ranged from 1.26% in Famine to 7.69% in Nadeau. Bras Saint-Victor, which had the largest recorded count, had a mean catchment slope

of 1.85%, compared with 5.83% in Savoie. The hydrogeomorphological characteristics of the 11 sub-watersheds with at least three documented flood occurrences are summarized in Table 2. Drainage organization also varied among these recurrently affected units. Their tabulated drainage densities ranged from approximately 0.97 to 2.10 km/km², and their Gravelius coefficients ranged from 1.34 to 2.01. The recorded occurrences therefore encompassed catchments with contrasting drainage densities and degrees of compactness.

According to the morphometric appendix, alluvial fans were identified in 25 of the 86 sub-watersheds, approximately 29% of the analyzed units. Their distribution was concentrated in the Middle Chaudière, with additional occurrences in the Upper Chaudière and none reported in the Lower Chaudière (Figure 6c). Five of the 11 sub-watersheds with at least three historical occurrences had a mapped fan: des Fermes, Nadeau, Savoie, Bélair, and Chassé. Fan occurrence was therefore not a shared characteristic of all recurrently affected units.

Melton ruggedness values ranged from 0.005 to 0.104 across the 86 sub-watersheds (Figure 6b). All values were therefore below 0.11 at the spatial scale of the level-2 units. However, they characterize the analyzed level-2 units rather than every smaller tributary within them. No event was explicitly classified as a debris flow in the documentary inventory; this documentary result should not be interpreted as evidence that debris-flow activity is entirely absent from the watershed.

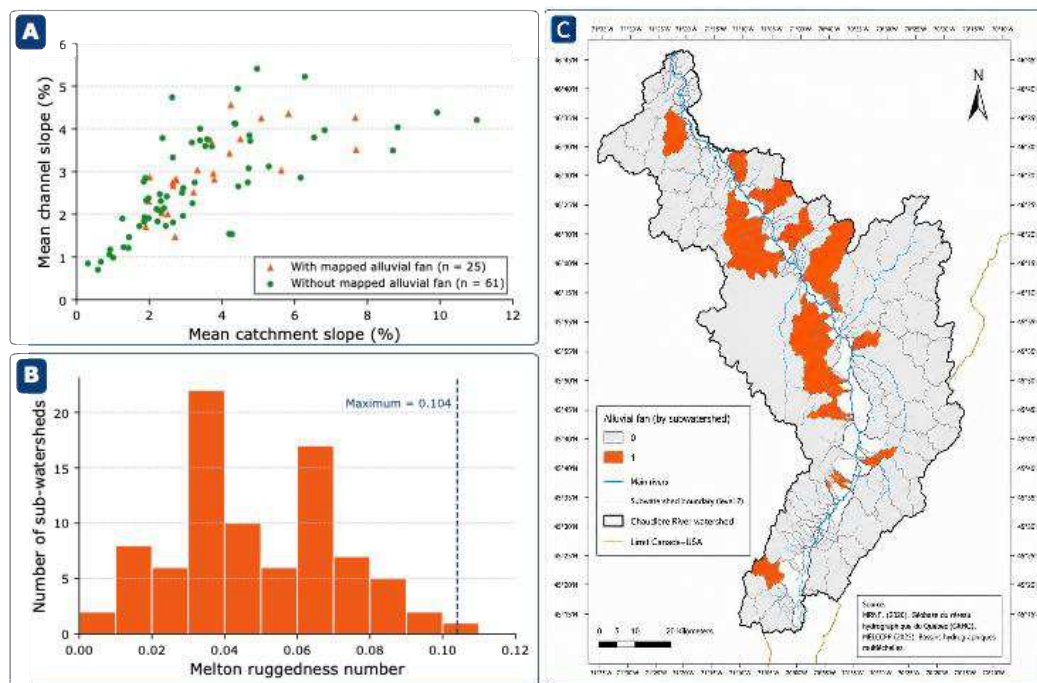


Fig. 6 Morphometric characteristics of the analyzed sub-watersheds: a) relationship between mean sub-watershed slope and mean channel slope, distinguishing watersheds with and without alluvial fans; b) Melton ruggedness number for

569 the analyzed level-2 units; c) spatial distribution of level-2 sub-watersheds containing alluvial fans at their outlets
570 within the Chaudière River watershed.
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573 **Table 2.** Hydrogeomorphological characteristics of the 11 level-2 sub-watersheds with at least three documented flood occurrences.

Sub-watershed	Area (km ²)	Flood occurrences	Catchment slope (Mean, %)	Channel slope (Mean, %)	Drainage density (km km ²)	Gravelius coefficient	Melton ruggedness	Alluvial fan
Bras Saint-Victor	733.07	27	1.85	2.76	1.21	1.89	0.018	No
Des Fermes	64.64	12	3.32	3.04	1.43	1.69	0.061	Yes
Beaurivage	718.89	10	1.44	1.47	2.10	2.01	0.021	No
Morency	34.06	8	3.40	3.73	1.36	1.46	0.073	No
Famine	712.58	8	1.26	1.90	0.97	1.86	0.015	No
Nadeau	39.64	6	7.69	3.52	1.21	1.48	0.066	Yes
Savoie	22.93	4	5.83	4.36	1.37	1.34	0.061	Yes
Bélair	44.47	4	2.66	2.67	1.18	1.46	0.040	Yes
Chassé	77.34	3	2.75	2.80	1.37	1.45	0.028	Yes
Ardoise	22.71	3	2.65	1.81	1.02	1.56	0.043	No
Cantin	19.93	3	1.43	1.21	1.77	1.35	0.015	No

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5.4 Land-use changes and regional hydrogeomorphological susceptibility

Analysis of land-cover evolution between 2000 and 2020 revealed changes in mapped class areas at the scale of the entire Chaudière River watershed (Figure 7a). Forest remained the dominant mapped class, occupying slightly more than 5,000 km² in 2020, followed by cropland at approximately 1,000 km². Both classes showed a slight decline over the study period, whereas settlement surfaces increased to approximately 400 km².

The reported relative increase in settlement area between 2000 and 2020 was approximately 40%, while grassland area declined by approximately 20% (Figure 7b). The remaining mapped classes also showed negative changes over this interval. Catchment-level change mapping was available only for settlement surfaces (Figure 7c); the analysis did not provide equivalent sub-watershed maps of forest or wetland losses.

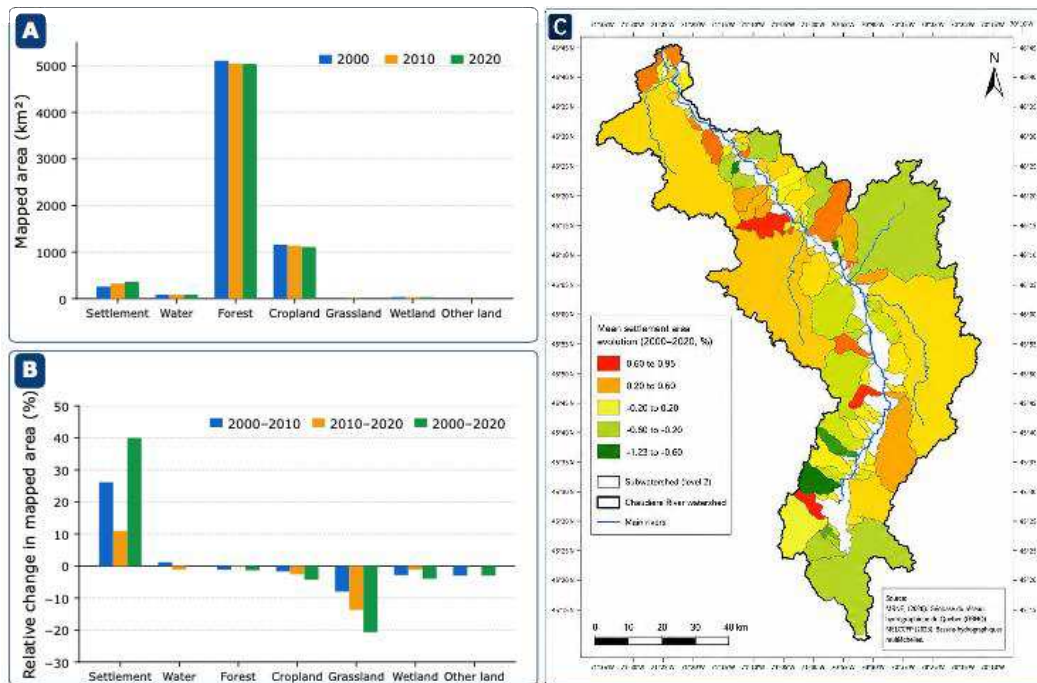


Fig. 7 Land-use dynamics in the Chaudière River watershed between 2000 and 2020: a) area (km²) of major land-use categories in 2000, 2010, and 2020; b) relative change (%) in land-use categories for the periods 2000–2010, 2010–2020, and 2000–2020; c) spatial distribution of the settlement-change metric summarized at the level-2 sub-watershed scale between 2000 and 2020.

The torrential flood susceptibility assessment revealed spatial contrasts among the three component scores and their weighted combination (Figure 8). Higher slope scores occurred mainly in the Upper Chaudière and parts of the Middle Chaudière. In contrast, higher land-cover scores occurred principally in the Middle

and Lower Chaudière. Elevated substrate-based runoff-potential scores were reported for several Middle Chaudière catchments and parts of the downstream lowlands.

At the raster scale, higher composite values were concentrated in the Middle Chaudière and along several tributary corridors. Lower values generally characterized the Lower Chaudière, although some downstream sub-watersheds exhibited higher scores. The Upper Chaudière displayed contrasting values rather than uniformly high susceptibility.

The highest reported catchment-mean TFSI values were 0.54 for both Savoie and Carter. Numerous Middle Chaudière sub-watersheds had mean values above 0.40, whereas values below 0.40 predominated in the Lower Chaudière. These values describe the relative distribution of the weighted index; 0.40 was not established as an independently calibrated flood-occurrence threshold.

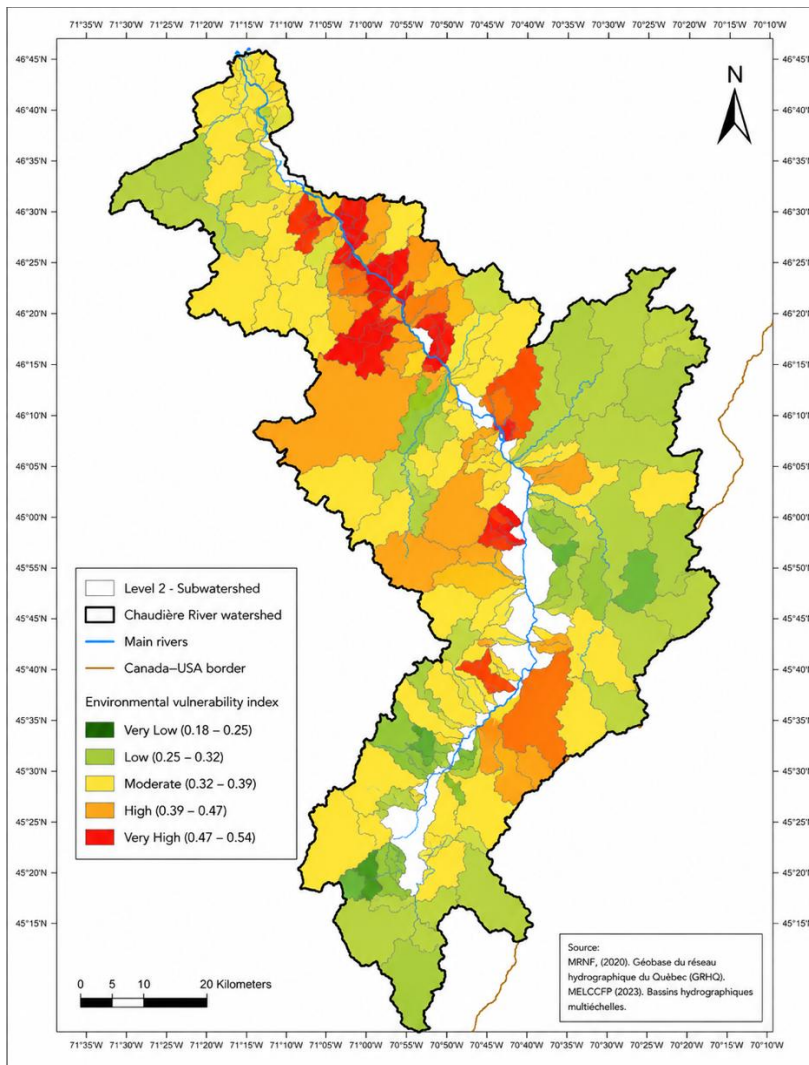


Fig. 8 Torrential Flood Susceptibility Index for the Chaudière River watershed, calculated from weighted slope, land-cover, and substrate-based runoff-potential scores and summarized by level-2 sub-watershed.

5.5 Comparison with historical flood occurrence

Comparison between the historical occurrence counts and the torrential flood susceptibility assessment showed variable correspondence rather than a uniform ranking (Figure 9). For the ten recurrently affected sub-watersheds for which a catchment-mean TFSI value could be verified, values ranged from 0.34 to 0.54. Bras Saint-Victor had the largest recorded occurrence count (27) and a mean TFSI of 0.47. Des Fermes had 12 occurrences and a value of 0.44. Morency and Famine each had eight occurrences, but their index values differed: 0.48 and 0.34, respectively. Conversely, Savoie had the highest index value within this comparison group (0.54) but four recorded occurrences. Chassé had three occurrences and an index value of 0.49.

These comparisons show that higher historical counts did not consistently correspond to higher mean susceptibility scores. Repeated flooding was documented across sub-watersheds with differing index values and morphometric characteristics. The comparison does not establish whether recurrently affected units collectively differ from the remaining sub-watersheds, because no full-sample statistical comparison or inferential test is reported.

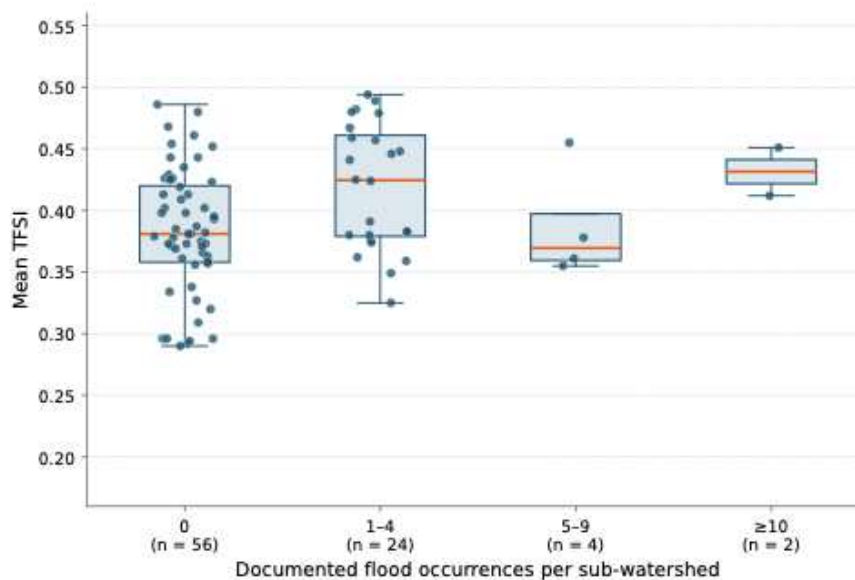


Fig. 9 Distribution of mean Torrential Flood Susceptibility Index (TFSI) values according to the number of documented flood occurrences across the 86 level-2 sub-watersheds. Points represent individual sub-watersheds; boxes indicate the interquartile range, and horizontal orange lines indicate median values. Sample sizes are reported below each

occurrence class. TFSI values were provisionally reconstructed from the mapped results; the comparison is descriptive and does not constitute predictive validation.

6. Discussion

6.1 Flood-dominated torrential systems: evidence and limits of process identification

The historical reconstruction documents repeated flooding with reported torrential characteristics in the Chaudière River watershed. Accounts of rapid tributary responses, erosion, sediment transport, and damage to crossings establish that damaging rainfall-driven floods are not restricted to the main river. These observations support examining tributary hazards alongside the mainstem flooding that features prominently in the regional documentary record. However, the inventory includes both types of occurrences and should not be interpreted as 53 uniformly verified tributary flash floods.

The available evidence is consistent with flood-dominated torrential activity, but the strength of this interpretation differs among sources. Historical descriptions provide qualitative information about water-level changes, erosion, and sediment deposition, whereas the low Melton values characterize catchment-scale relief relative to area. Neither source directly establishes sediment concentration or flow rheology during individual events. This distinction is important because water floods, debris floods, and debris flows may produce partly overlapping impacts while differing substantially in sediment concentration, bed mobility, and flow mechanics (Church and Jakob 2020; Jakob et al. 2022). The morphometric classification of Wilford et al. (2004) therefore provides supporting evidence rather than definitive identification of historical flow processes. Recent morphometric studies similarly show that process domains overlap and that indicators such as the Melton ruggedness number should be treated as screening variables rather than deterministic thresholds (Ilinca 2021).

Alluvial-fan occurrence adds a longer-term geomorphological perspective by documenting sediment delivery and deposition at tributary outlets. Nevertheless, fan presence does not establish contemporary activity, the frequency of deposition, or a unique formative process. The coexistence of low catchment-scale Melton values and mapped fans is compatible with flood-driven sediment transfer, but it does not exclude sediment-rich flows within smaller tributaries or during events absent from the documentary record. Moreover, the geomorphic effects of a torrential flood depend on channel gradient, bed and bank materials, sediment availability, flow duration, and the hydraulic stresses reached during the event; properties that cannot be inferred from catchment morphometry alone (Church and Jakob 2020; Jakob et al. 2022; Rączkowska et al. 2024).

The term “flood-dominated torrential systems” is consequently useful as a working interpretation of the available evidence, not as a newly demonstrated process category or a permanent catchment state. The

contribution of this study lies in bringing together historical and spatial evidence from a humid Appalachian watershed, rather than establishing that its tributaries occupy a distinct position outside the recognized spectrum of torrential processes. Process attribution should therefore remain open to revision where field evidence, sedimentological observations, or event-scale hydraulic data become available.

6.2 Catchment heterogeneity and the scale of historical flood occurrence

The results do not identify a uniform morphometric signature shared by all recurrently affected sub-watersheds. Historical occurrences were recorded in both relatively steep units, such as Nadeau and Savoie, and larger catchments with lower mean slopes, including Bras Saint-Victor and Famine. Drainage density and compactness also varied within the recurrently affected group. These contrasts do not negate the relevance of catchment morphology to runoff concentration, but they prevent the present analysis from establishing steep slopes, compact geometry, or high drainage density as independently demonstrated controls on historical occurrence. Instead, they suggest that similar documented impacts may arise from different combinations of rainfall forcing, catchment configuration, channel conditions, and local exposure.

Recent hydrosedimentary investigations provide independent support for the mechanisms underlying this interpretation. Bérubé et al. (2026) identified high structural connectivity in several steep tributary catchments of the Chaudière watershed, particularly where permanent drainage pathways intersect agricultural and forested areas. This finding supports the role of slope and drainage organization in facilitating water and sediment transfer, without demonstrating that these characteristics independently explain the historical distribution of floods. Structural connectivity describes potential transfer pathways, whereas their activation remains dependent on hydroclimatic forcing and antecedent catchment conditions (Bracken et al. 2015; Heckmann et al. 2018).

A central issue is the difference between the spatial scale of the mapped units and that of the processes documented in the archives. A large level-2 sub-watershed can contain steep headwater tributaries, lower-gradient receiving channels, and several affected municipalities. Its mean slope may therefore poorly represent the location responsible for a damaging flood response. Likewise, a high occurrence count can reflect reports from several nested tributaries or settlements rather than repeated flooding at a single outlet. This spatial averaging is especially important for the Famine and Bras Saint-Victor catchments, where catchment-wide morphometric values may conceal highly reactive tributaries. Analyses conducted at smaller nested scales would probably provide a more direct representation of the contributing areas responsible for rapid runoff and sediment delivery.

This scale mismatch also helps frame the relationship between historical records and alluvial fans. Five of the eleven recurrently affected sub-watersheds contained a mapped fan, indicating that fan occurrence and

documented flooding identify overlapping but non-equivalent aspects of catchment behaviour. Fans record sediment deposition under particular geomorphological conditions, whereas archives preferentially record events that attracted attention through damage or disruption. Their incomplete correspondence is therefore not, by itself, evidence against the relevance of either source.

The concentration of records near major municipalities must similarly be interpreted as the combined expression of flood occurrence, exposure, and documentary visibility. It cannot be attributed exclusively to physical predisposition. Geo-historical studies in other mountain watersheds have similarly shown that apparent temporal and spatial concentrations of flood impacts may reflect changes in source availability, settlement, infrastructure, and exposure as well as changes in the underlying hazard (Boisson et al. 2022). Resolving these alternatives would require more precise event locations and comparisons that account for catchment area, settlement distribution, and the spatial footprint of rainfall. Accordingly, the 185 event-locality records should be interpreted as documented manifestations of flooding rather than as a spatially homogeneous sample of hydrological events.

6.3 Land-use change as a potential modifier of runoff-generating conditions

The mapped increase in settlement surfaces between 2000 and 2020 identifies a contemporary landscape change that may influence hydrological response. Urbanization can alter infiltration, surface storage, and drainage connectivity, but its effects depend on the location and configuration of development and the characteristics of the drainage network (Bronstert et al. 2002). The present analysis documents land-cover change rather than measuring these hydrological mechanisms. In particular, settlement area is not equivalent to impervious area, and its expansion cannot be directly converted into an increase in flood discharge.

The spatial organization of developed surfaces may be as important as their total extent. Impervious surfaces located close to channels or efficiently connected to stormwater networks can produce stronger and faster runoff responses than similarly sized but hydrologically disconnected areas (Dell’Aira and Meier 2025; Lim and Welty 2017; Roodsari and Chandler 2017). This reinforces the need to distinguish generalized settlement cover from effective or connected imperviousness.

The spatial scope of the land-use results further constrains interpretation. Forest, cropland, grassland, and wetland changes were assessed at the whole-watershed scale, whereas only settlement changes were mapped by sub-watershed. The results therefore do not establish where forest or wetland losses coincided with recurrent tributary flooding. Nor can changes over 2000–2020 explain the full historical inventory, which extends well beyond the period represented by the land-cover datasets. Differences among the land-

cover datasets, including classification accuracy and minimum mapping units, may also contribute to some of the measured changes, particularly for spatially limited classes such as wetlands and other land.

The 2000–2020 analysis also represents only the recent portion of a longer anthropogenic trajectory. Channel straightening, agricultural drainage, forest-road development, sediment extraction, and direct modification of several tributaries were already widespread during the twentieth century, particularly between the 1960s and 1980s (Bérubé et al. 2026; TecSult inc. 1994). These inherited modifications may continue to influence runoff efficiency and hydrosedimentary connectivity even where recent land-cover changes appear limited. Present-day land-cover conditions should therefore be interpreted partly as the cumulative outcome of earlier landscape transformations rather than as an independent control on recent flooding.

Land-cover change is thus best treated as a plausible modifier of existing catchment conditions and a target for further investigation. Demonstrating its contribution would require spatially explicit change metrics linked to rainfall and discharge observations, or hydrological simulations comparing alternative land-cover conditions. The current evidence does not support attributing the recent increase in documented flood events to urban expansion. Such an attribution would additionally require separating changes in hydrological response from increased exposure, improved reporting, and temporal variations in extreme rainfall.

6.4 Interpreting the multicriteria susceptibility assessment

The multicriteria index summarizes selected environmental conditions into a regional measure of relative physical predisposition. Its value lies in making the scoring and weighting of slope, land cover, and substrate-based runoff potential explicit. The resulting map complements the historical inventory by describing environmental contrasts, including in catchments with few or no documented events. The four susceptibility classes shown in Figure 8 facilitate regional interpretation but remain descriptive classes rather than probability-based hazard categories.

However, the comparison across the 86 sub-watersheds in Figure 9 shows extensive overlap among the historical-occurrence groups rather than a monotonic increase in TFSI with event frequency. Some recurrently affected catchments have elevated scores, but others occupy moderate classes, while several catchments without documented events also present relatively high susceptibility. The small numbers of catchments in the highest occurrence categories further preclude strong statistical conclusions. The relationship should therefore be interpreted as partial spatial correspondence rather than predictive validation.

This result is not unexpected because historical occurrence and the TFSI represent different dimensions. The inventory records reported events and impacts over more than a century, whereas the index represents current catchment conditions derived from three spatial variables. Reviews of flood-susceptibility mapping emphasize that model outputs are strongly influenced by variable selection, classification, weighting, spatial resolution, and validation strategy (Kaya and Derin 2023).

The observed mismatch is also consistent with the distinction between structural connectivity and functional response. Bérubé et al. (2026), for example, mapped high potential connectivity in several Chaudière tributaries but found that their observed geomorphic activity varied substantially over time and among catchments. A catchment may therefore contain efficient transfer pathways without producing a documented flood during the archival period, whereas intense localized rainfall may generate flooding in a catchment with only moderate mapped susceptibility. Similar limitations apply to sediment-connectivity indices, which characterize potential pathways rather than observed fluxes or event probabilities (Heckmann et al. 2018; Hooke and Souza 2021).

Differences between the two sources should not automatically be attributed to incomplete archives. They may also reflect limitations of the index, including omitted rainfall variability, channel capacity, sediment availability, infrastructure effects, and the aggregation of spatially heterogeneous conditions. Both explanations remain possible and require independent evaluation. The weighting scheme introduces an additional interpretive constraint. Because slope receives half of the total weight, a strong topographic expression in the final map is partly prescribed by the model structure. It is not independent evidence that slope is the dominant control on observed flooding. Similarly, including contemporary land cover does not demonstrate that land-use change caused the mapped susceptibility pattern, because the index was not calculated as a controlled comparison between historical land-cover scenarios.

Further evaluation should therefore examine the sensitivity of catchment rankings to weights, score boundaries, normalization, and spatial aggregation. The substrate-based runoff indicator also requires particular attention because it represents an ordinal classification rather than an observed hydrological response. Alternative weighting scenarios—including equal weighting and data-driven weighting—would indicate whether the same priority catchments remain consistently classified as highly susceptible. Cross-validation against independently located events would be required before interpreting the index as a predictive model. These tests would establish how strongly the mapped priorities depend on analytical choices before the index is used beyond exploratory screening.

6.5 Implications for watershed management and further investigation

The combined approach supports a differentiated strategy for subsequent investigation. Catchments with both repeated documented impacts and elevated susceptibility warrant closer examination of local channels, crossings, and rainfall–runoff behaviour. Catchments with recurrent impacts but moderate mean scores require investigation of processes or local conditions that the regional index may overlook. Conversely, high-scoring catchments without historical records should be treated as priorities for verification, not as confirmed locations of unrecorded flooding.

This use preserves the distinction between susceptibility mapping and risk assessment. The index does not delineate inundation zones, estimate event probabilities, or quantify exposure and social vulnerability. It can help organize regional investigations, but it cannot independently determine development restrictions, engineering design criteria, or the expected benefits of preventive interventions. Those decisions require site-specific evidence and appropriate hydrological or hydraulic analyses. For steep tributaries, such investigations should also consider sediment transport, potential channel widening, bank erosion, woody debris, and the obstruction or failure of road crossings, because these processes can substantially modify flood pathways and impacts (Jakob et al. 2022).

The historical inventory also provides a basis for identifying locations where rainfall, discharge, and geomorphic monitoring could improve understanding of tributary responses. More precise event attribution, targeted field assessment of fan and channel activity, and analysis at smaller nested catchment scales would directly address the principal uncertainties identified here. Priority monitoring could combine sub-hourly rainfall, water-level measurements, repeat channel surveys, and systematic post-event documentation in catchments representing the different combinations of historical occurrence and mapped susceptibility.

Climate-change scenarios could subsequently be incorporated to examine changes in rainfall forcing, but the present study does not project future flood frequency or magnitude. This distinction is important because changes in extreme rainfall do not translate uniformly into changes in flood magnitude; the response also depends on event duration, antecedent moisture, snow conditions, catchment storage, and spatial rainfall patterns (Wasko et al. 2024).

Overall, the integration of historical reconstruction and spatial susceptibility mapping is most useful when agreement and disagreement are both retained as informative outcomes. Their combination identifies documented impacts, environmental contrasts, and unresolved local conditions, providing a structured basis for further assessment rather than a completed validation of regional flood risk. The framework should therefore be viewed as a first-level regional screening approach that directs limited monitoring and modelling resources toward catchments where additional evidence would be most valuable.

7. Conclusion

This study combined historical reconstruction, catchment morphometry, land-use analysis, and multicriteria mapping to examine torrential flood susceptibility in the Chaudière River watershed. The documentary inventory identified 53 distinct event dates within the 1900–2023 search period, encompassing warm-season floods affecting tributaries and the main river. Historical descriptions of rapid runoff, erosion, sediment transport, and damage to crossings, considered together with the generally low catchment-scale Melton values, are consistent with predominantly flood-driven torrential activity. However, the available evidence does not exclude sediment-rich processes within smaller tributaries or during poorly documented events.

The analysis of 86 level-2 sub-watersheds revealed considerable physical heterogeneity rather than a uniform morphometric signature among recurrently affected catchments. Historical occurrence counts and catchment-mean susceptibility showed partial correspondence: repeated impacts were documented across a range of index values, while some sub-watersheds without documented events displayed relatively elevated susceptibility. These differences highlight the importance of spatial scale, documentary precision, rainfall variability, and local conditions not represented by the three-variable index. Land-use changes provide additional context, but their effects on flood response were not directly quantified and cannot be inferred from changes in settlement area alone.

The principal contribution is therefore a regional framework linking documented flood activity with mapped physical predisposition, rather than a validated prediction of flood occurrence. Its practical value lies in identifying catchments requiring closer investigation, including those where historical evidence and susceptibility scores diverge. The framework should consequently be used as a regional screening and prioritization tool, not as a substitute for event-scale hydrological, hydraulic, or sediment-transport modelling. Priorities for further work include refining event attribution, testing the sensitivity of the index to variable selection, weighting, classification thresholds, and spatial aggregation, and obtaining tributary-scale hydrological and geomorphological observations. Integrating exposure and social vulnerability would subsequently extend this susceptibility assessment toward a more comprehensive evaluation of flood risk. Such improvements would support more targeted monitoring, land-use planning, and preventive intervention in the tributary catchments of the Chaudière River watershed.

Supplementary Information

Online Resource 1. Historical flood inventory for the Chaudière River watershed, 1900–2023. The Excel workbook contains 185 event–locality records associated with 53 distinct event start dates, together with reported triggers, hydrogeomorphic effects, impacts, documentary sources, original excerpts, and a data dictionary.

Online Resource 2. Morphometric characteristics and mapped alluvial-fan occurrence for the 86 level-2 sub-watersheds analyzed in the Chaudière River watershed. The Excel workbook contains drainage area, mean catchment and channel slopes, drainage density, Gravelius compactness coefficient, Melton ruggedness number, alluvial-fan occurrence, and a data dictionary.

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1105 manuscript and figures. Generative AI was not used to generate, analyze, or modify the research data or
1106 results.

Supplementary Files

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- [OnlineResource2ChaudiereSubwatershedMorphometry.xlsx](#)