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Unlocking Flow: An Investigation of topographical controls on Canadian river runoff

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Unlocking Flow: An Investigation of topographical controls on Canadian river runoff

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Abstract

Digital Elevation Models (DEMs) are a crucial tool for watershed analysis, offering valuable insights into landscape-scale hydrology. Traditional watershed delineations are derived by filling a DEM to force flow paths through topographic depressions, thus creating a continuous drainage network throughout the domain. However, this approach is challenged in landscapes characterized by abundant real-world depression storage, internally drained lake basins, and intermittently blocked stream channels such as the Canadian Shield (CS). The CS landscape is influenced by "fill-and-spill" surface water hydrology, with runoff flow paths controlled by bedrock sills and rocky cascades that are overtopped when water levels are high but cease flowing when water levels are low. To better represent this intermittently connected drainage pattern, we apply an alternative, less aggressive DEM filling model (Fill-Spill-Merge or FSM) to a continental-scale DEM (MERIT) for all of Canada. To ensure adequate filling of DEM errors while also preserving real-world topographic depressions, we propose a climatic method to initialize a key FSM parameter ("runoff depth") that optimizes observed discharges from 1690 Environment and Climate Change Canada (ECCC) active gauging stations with climate model data. Our application of FSM to all 1690 gaugues identifies 255 topographical control points that can influence the actively flowing area of the watershed. Extending the approach to ungauged areas of the CS identifies 583 control points. This research demonstrates how CS watersheds are affected by fill-and-spill hydrology, emphasizing the critical role of accurrate terrain modeling for delineating surface water flow paths in depressional landscapes.

Keywords: Watershed delineation, surface water hydrology, terrain analysis, Canadian Shield

Introduction

Extraction of drainage patterns from Digital Elevation Models (DEMs) constitutes a fundamental step in watershed analysis, providing invaluable insights into landscape hydrology[1–4]. Traditional watershed analysis methods have been established for this purpose, relying on algorithms designed to fill topographic depressions to create continuous drainage networks[5,6]. These methods have earned widespread recognition for their effectiveness in characterizing watershed flow paths and runoff behavior [7–10]. The fundamental principle behind these techniques involves treating depressions (also called "pits") in the DEM as artifacts, which are systematically filled to facilitate unimpeded water flow, but also eliminating any water storage in these depressions. This approach effectively removes all topographic barriers to flow, ensuring a consistent flow direction for each cell in the derived raster and a coherent, well-integrated drainage pattern[11–14].

Traditional drainage pattern analysis has known challenges in landscapes having abundant depression storage (i.e. internally drained basins, swales, wetlands, and lakes). These depressions are real-world topographical elements on the landscape that interrupt the regional drainage pattern and should not be removed as artifacts. There are many such places in the world [15–17]. One such place is the Canadian Shield (CS), dominated by glaciated bedrock with numerous topographical depressions (Figure 1). Previous studies have identified "fill-and-spill" hydrological processes on the CS[18,19], which intermittently connect topographic depressions on the landscape causing watershed source areas to expand or contract [4, 8–10]. During wet conditions, topographic depressions and/or lake basins fill and overtop bedrock sills and/or ephemeral channels, connecting to a down-elevation surface drainage network. This effect can increase downstream river discharge [20,21], recharge other lake basins, and mobilize the transport of sediment and nutrients across the landscape [22–25]. Controlling bedrock sills, low-gradient ephemeral channels, and waterfalls (rocky cascades) thus create topographical gateways or "control points" that shut off upstream drainage areas during low flow [26] but switch on during high flow. Depending on regional water balance, these control points can release or withhold flow to a downstream drainage network, producing erratic behavior in river hydrographs. Such control points are not identified with traditional DEM filling approaches, because they overfill most depressions to remove all topographic barriers to flow.

To mitigate DEM over-filling in depressional and/or poorly drained landscapes, new alternative algorithms that preserve topographic depressions and associated fill-and-spill processes have been developed. The contour tree method [27] constructs depression hierarchies by connecting local minima and maxima of a DEM-generated contour map. While accurate and straightforward, it is computationally intensive so is suboptimal for large geographical areas. A rainfall-based sequential depression-filling algorithm [28] fills low-lying areas sequentially based on their retention capacity and contributing area. However, since rainfall often occurs simultaneously over large geographical areas, this algorithm is not suitable for large study domains. The Fill-Spill-Merge (FSM) algorithm by Barnes et al [29], however, uses a "depression hierarchy" concept to enable high computational efficiency. Larger depressions can contain smaller ones, forming a hierarchy. FSM leverages this hierarchy to fill, overtop, and merge depressions at low computational cost as it does not treat each cell in the DEM to identify and process depressions. Instead, it utilizes the information about the hierarchical relationships between depressions to make decisions about filling and merging. This approach significantly speeds up the process of handling depressions in DEMs and unlike traditional methods, fills a DEM more realistically by preserving many real-world depressions. This, in turn, should enable detection of topographical control points likely to influence watershed source area(s) and drainage pattern.

Here we proposed a climatic method to estimate a key parameter for ensuring the right filling of the DEM which removes DEM error but preserves the depressional storage. The key parameter in runoff depth is the sum of minimum filling depth and inundation depth. That parameter was used as the starting runoff depth value to identify those control points. Manual checking and validation were done to filter out artificial control points. After this analysis, we produced a novel dataset of 255 control points which can be cascades, lake overflows, or drypaths. These control points can impact the environment by affecting the flow of water, sediment, and nutrients. Mapping them is crucial for understanding and mitigating the environmental impact of human activities, such as dam construction or land development.

Figure 1: Aerial photo of CS region. This photo was taken at NASA AVoBE field campaign 2017 captured by Sarah Cooley

Materials and Methods

Data Used

The Multi-Error-Removed Improved-Terrain (MERIT) DEM was used for digital terrain analysis of Canada's drainage pattern. The MERIT DEM was developed by removing multiple error components (absolute bias, stripe noise, speckle noise, and tree height bias) from two existing satellite-derived DEMs (SRTM3 v2.1 and AW3D-30m v1) [30]. It represents terrain elevations at 3 arc sec resolution (~90m at the equator) and covers land areas between 90N-60S, referenced to EGM96 geoid. The absolute vertical accuracy of this DEM is less than 2m and horizontal accuracy is less than 17m. MERIT DEM's removal of noise and other errors from its underlying satellite data products from the make it well-suited for drainage network extractions[31,32].

To estimate an initial value for a critical FSM parameter ("runoff depth", see section Methodology) we compared Coupled Model Intercomparison Project Phase 6 (CMIP6) [33] Precipitation (P) – Evapotraspiration (ET) data with Environment and Climate Change Canada (ECCC) Water Survey of Canada (WSC) observations of river discharge for 1,690 active gauging stations throughout Canada. CMIP6 datasets (https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cmip6?tab=form) were used for this purpose instead of climate reanalysis or weather station datasets to enable future projections and uniform coverage over low-population areas, respectively. The 30-year mean of annual hydrologic year (1992 - 2022) runoff (P-ET) from the historical CMIP6 CanESM5 model for Canada was intersected with the watershed areas of all 1,690 active river gauges to retrieve 30-year mean CMIP6 modeled discharge for each basin. Similarly, Monthly discharge observations for all 1,690 active river gauges for 30 water year were downloaded from the Hydrometric Database (HYDAT), available form the ECCC WSC National Water Data Archive (https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity/monitoring/survey/data-products-services/national-archive-hydat.html). Yearly average was calculated from those discharge data. The watershed area was also obtained from HYDAT as well. The information about those basins, their name, area, station ID can be found on the supplementary files.

Potential control points identified from FSM terrain analysis were validated visually through inspection of high-resolution map and satellite image products. An initial visual assessment for each control point was conducted using ArcGIS base map, a high-resolution cartographic and satellite image product derived by Esri using DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community. If visual inspection of ArcGIS base map was inclusive, a second visual validation was performed using mulit-temporal Planet smallsat imagery (https://www.planet.com/products/planet-imagery/). Planet provides a Data API that allows users to search for specific imagery based on metadata criteria such as cloud cover percentage. Planet scenes acquiring during high flow and low flow conditions were used to determine if a DEM-flagged location appeared to be a lake basin sill, river cascade, intermittent stream, or similar topographic impediment surface water flow.

Methods

Fill-Spill-Merge algorithm

This study applies the recently developed Fill-Spill-Merge (FSM) algorithm [34] to delineate Canadian surface drainage patterns from the MERIT DEM. FSM employs a two-step process as follows. First, the algorithm identifies all DEM depressions by finding lower cells than their neighboring cells. It then creates a depression hierarchy, a tree-like structure representing all depressions in the DEM. Conceptually, an ocean is the tree's root, and individual depressions the tree's leaves. Next, the algorithm applies a user-specified runoff depth parameter (e.g., 0.5 m) of water uniformly across the DEM and routes it through the depression hierarchy, filling and merging them according to the underlying topography (Figure 2). Starting from the tree's root, the algorithm checks if each node is a depression. If yes, it fills it with water; if not, it moves up to the next node. Since water is distributed through the depression hierarchy rather than each individual DEM cell, the FSM algorithm can handle the large MERIT DEM at a continental scale.

Choice of the FSM runoff depth parameter – in essence a small, uniform DEM filling depth that is then redistributed across the landscape according to topography - is a key decision [35]. From this single parameter the algorithm calculates the total volume of water than will be used to (lightly) fill DEM depressions. The amount of water diverted into each will depend on the shape of the depression and the area of its local catchment. To initialize our study, MERIT DEM was filled using FSM with various 10 runoff depths ranging from 0.2 to 2 m, producing 10 corresponding flow direction and flow accumulation maps for Canada.

(a)

(b)

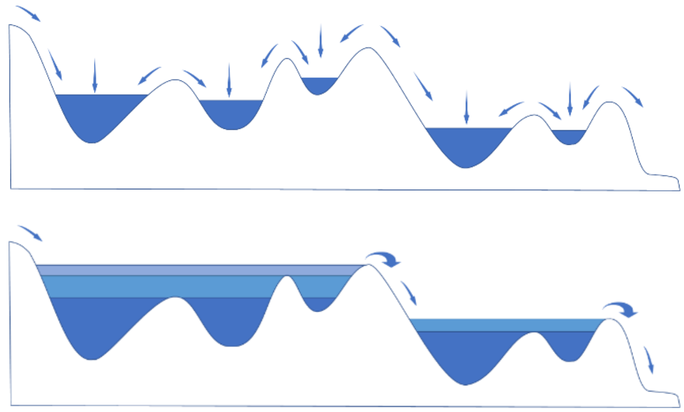

Figure 2: FSM process showing filling, merging, and overflowing process in DEM.

Empirical method for runoff depth

To determine an optimal minimum runoff depth parameter – large enough to smooth and fill most DEM artifacts, but small enough to preserve real-world topographic depressions – we correlated climate model P-ET with observed mean annual discharge for all 1,1690 WSC gauging stations assuming a range of plausible runoff depth parameter values (0.2 – 2.0 m). A smaller runoff depth yields a smaller, more fragmented drainage pattern while a higher runoff depth yields a large, more integrated drainage pattern. In principle, the runoff depth value that best correlates P-ET with observed discharge is optimal because its produce the most physically realistic watershed (under the assumptions that 1) mean annual P-ET ~ mean annual discharge; and 2) both climate model P-ET and gauging station observations are reasonably accurate). For each iteration of the runoff depth parameter, the upstream watersheds for all 1,690 gauges were delineated and their respective mean annual runoff correlated with corresponding CMIP6 P-ET for 30 water years (1992-2022). Maximum correlation between these two datasets (R2 = 0.67) was observed for a runoff depth of 0.6 m (Figure 3). Therefore, 0.6 m was selected as an initial minimum runoff depth parameter for topographic control-point detection.

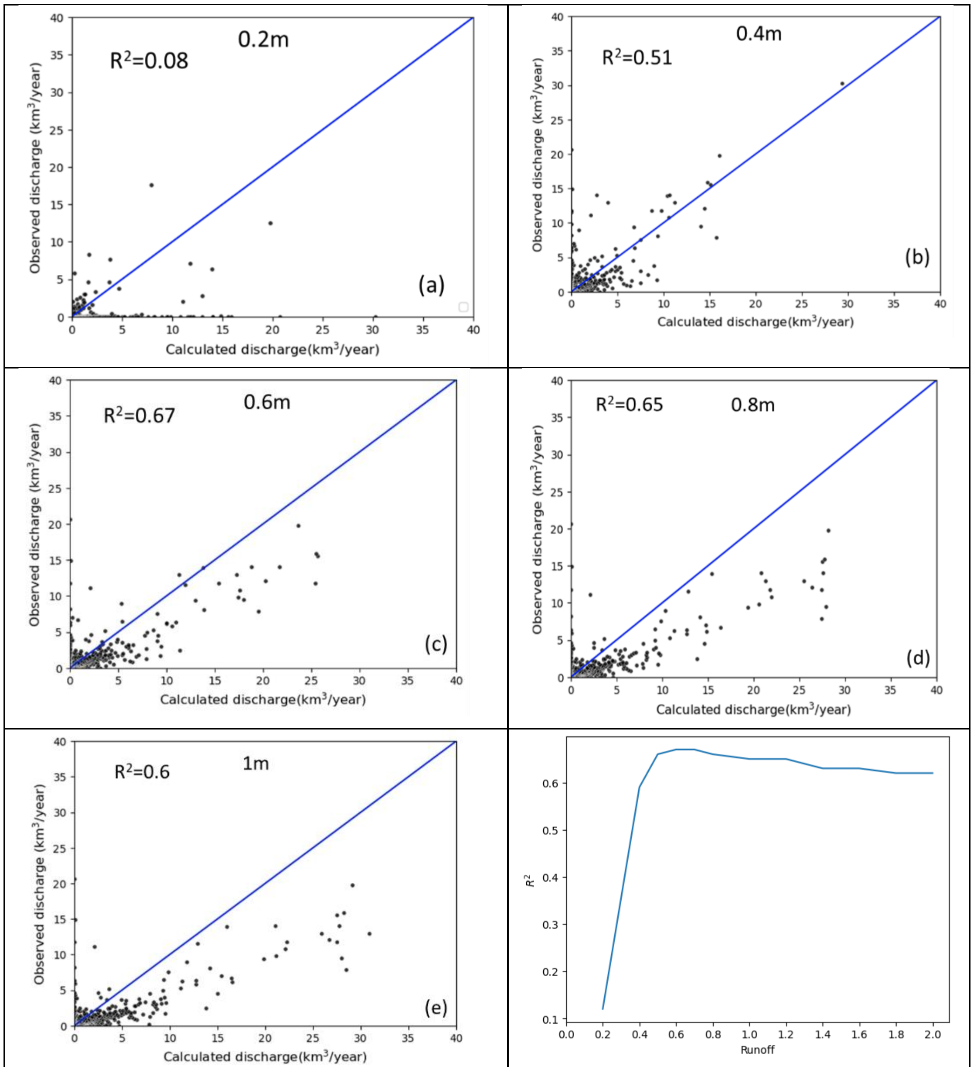

Figure 3: Climate correlation of calculated discharge and observed discharge for different runoff depths: (a) 0.2m; (b)0.4m; (c) 0.6m; (d) 0.8m; (e) 1m; (f) R^2 values for different runoff depth shows that 0.6m runoff depth is best right filling parameter which just removes noise but does not remove real depressions.

Detection of topographic control points

Flow control points be any topographic control or obstruction which causes a sharp increase (decrease) in upstream drainage area when overtopped (exposed) by high (low) water. Their overall effect is to connect to a downstream flow network during wet (high water level) conditions and detach during dry (low water level) conditions. Waterfalls, rapids, dry overspills, lake sills, dams, and road embankments are all examples of potential control points. In this study, potential control points throughout Canada with identified using the FSM algorithm, by applying the FSM algorithm to MERIT DEM with an initial runoff depth of 0.6m and progressively increasing it to 2.0 m. For each 0.2 m increase in runoff depth, grid cells experiencing a +20% and/or +5,000 km^2 increase in upstream watershed area were considered sufficiently "abrupt" to be flagged as a potential control point. In total, some 2519 of locations satisfying these criteria were identified within the known watersheds of the 1,690 WSC gauges across Canada. Control points outside of the ECCC watershed were also detected by finding the location of new flow path formation all over CS.

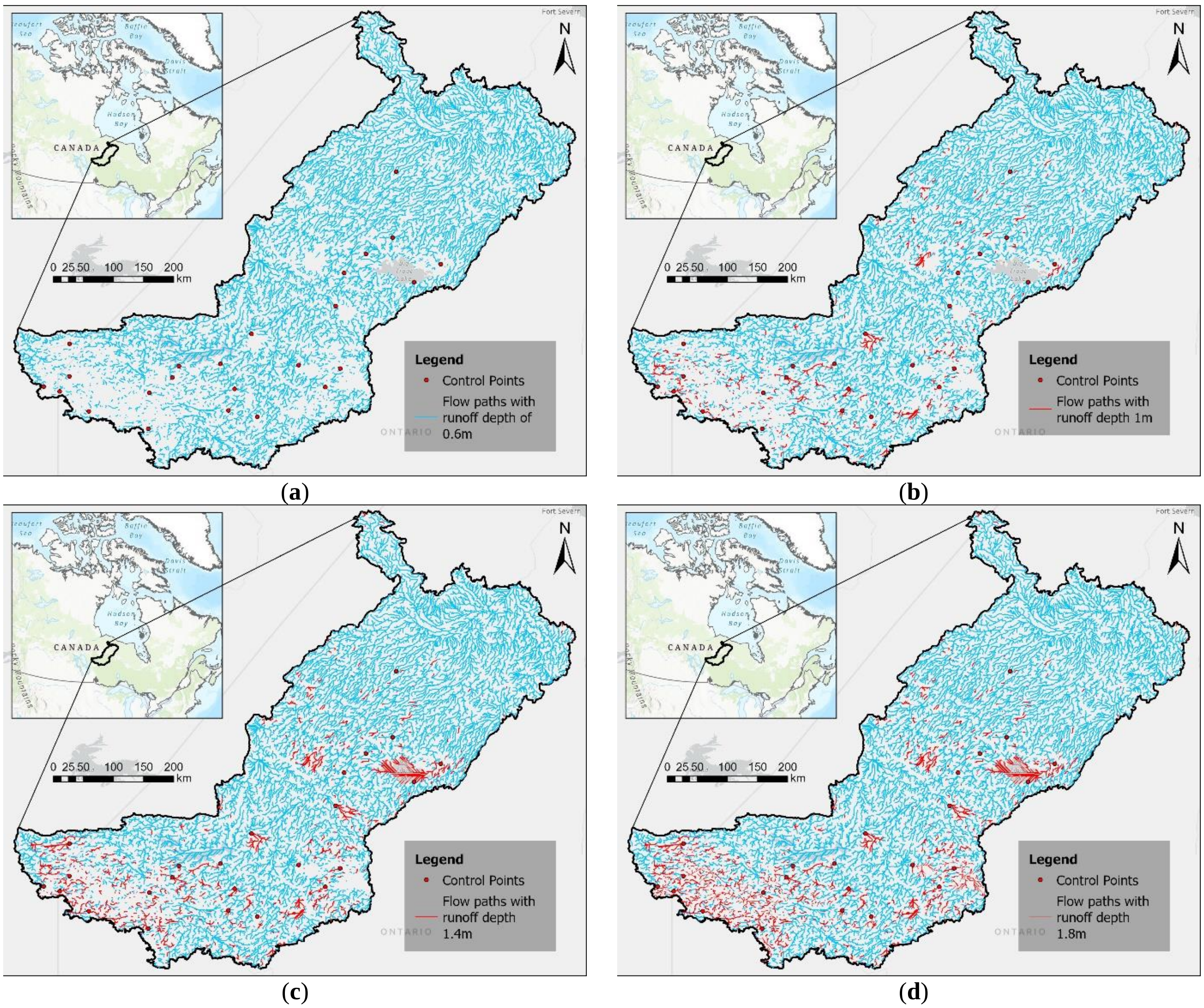

Figure 4: Increasing drainage pattern and control points in Severn River watershed of CS on increasing runoff depth: (a) 0.6m; (b) 1m; (c) 1.4m (d) 1.8m.

Validation

Validation of the 362 identified potential control points was performed visually using ArcGIS base map imagery and Planet imagery. Most of the identified control points (~91%) were located in rocky cascades, lake sills, moist swales, intermittent streams, dams, road embankments, beaver dams and other visually evident features of intermittent and/or controlled water flow (Figure 7). An initial visual inspection of each location was done in ArcGIS basemap. Based on this inspection each point was either assigned to a respective descriptive category (Rocky Cascade, Dry path, Sills, dam, beaver dam, farm land, bridge, narrow stream total = 342 locations). Others were narrow rivers and streams erroneously detected as control points owing to the limitations of the 90m resolution of MERIT DEM and were removed from the dataset (total = 20 locations). Control points that could not be positively in ArcGIS basemap were verified using multi-temporal Planet imagery, by examining images during both high- and low-flow conditions. A total of 362 control points were detected between 0.6m and 0.8m runoff depth.

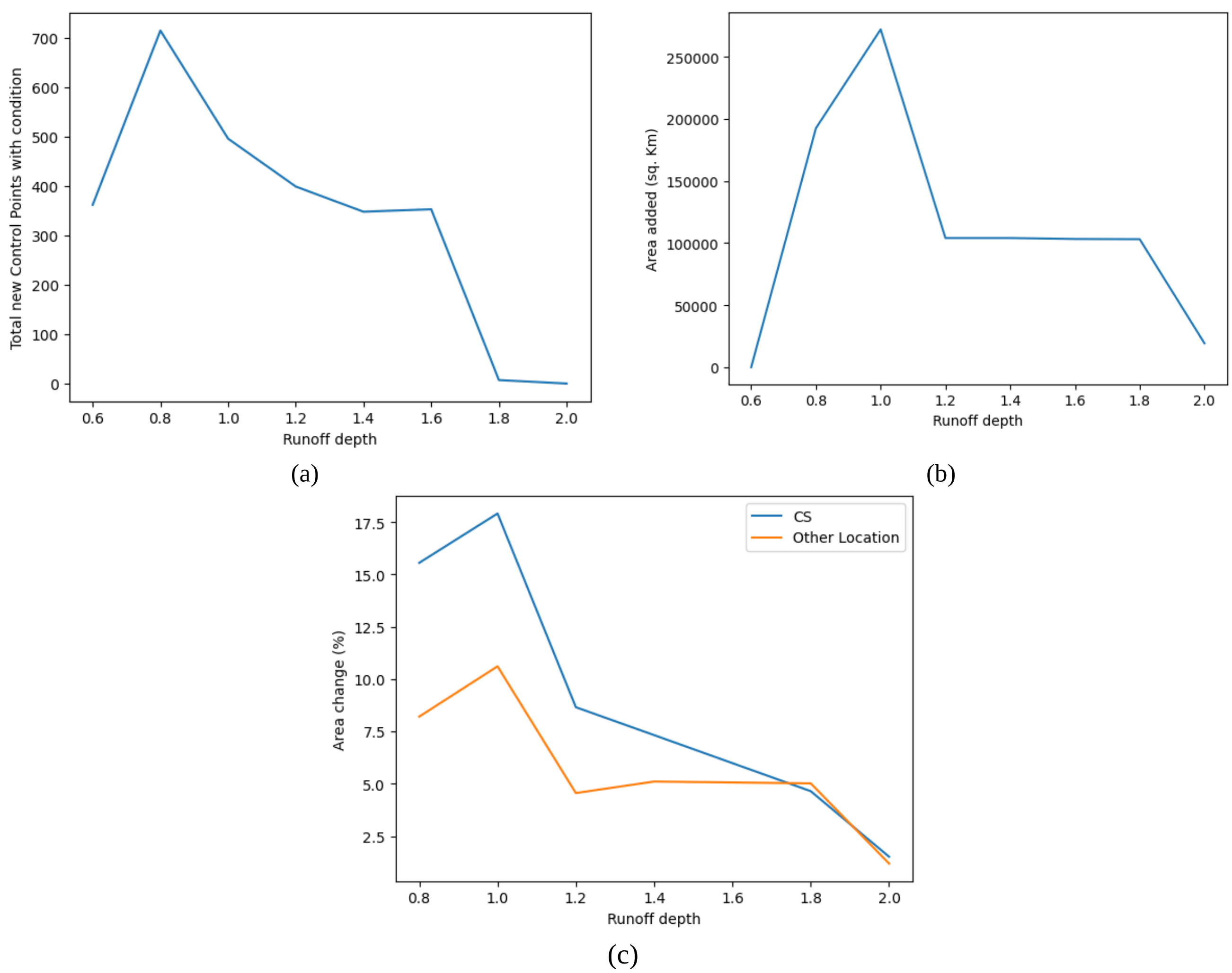

Figure 5: Number of control points detected and watershed area increase with progressive increase of runoff depth starting from 0.6m up to 2m: (a) New control points formed in various runoff depths when we applied the condition of more than 20% or 5000 sq. km; (b) The percentage of watershed area increasing with increasing runoff depth for different places of Canada shows there is a huge increase in runoff depth in CS (20 % in 0.8-1.0m) and less in other parts of Canada; (c) watershed area added with increasing runoff depth.

Results

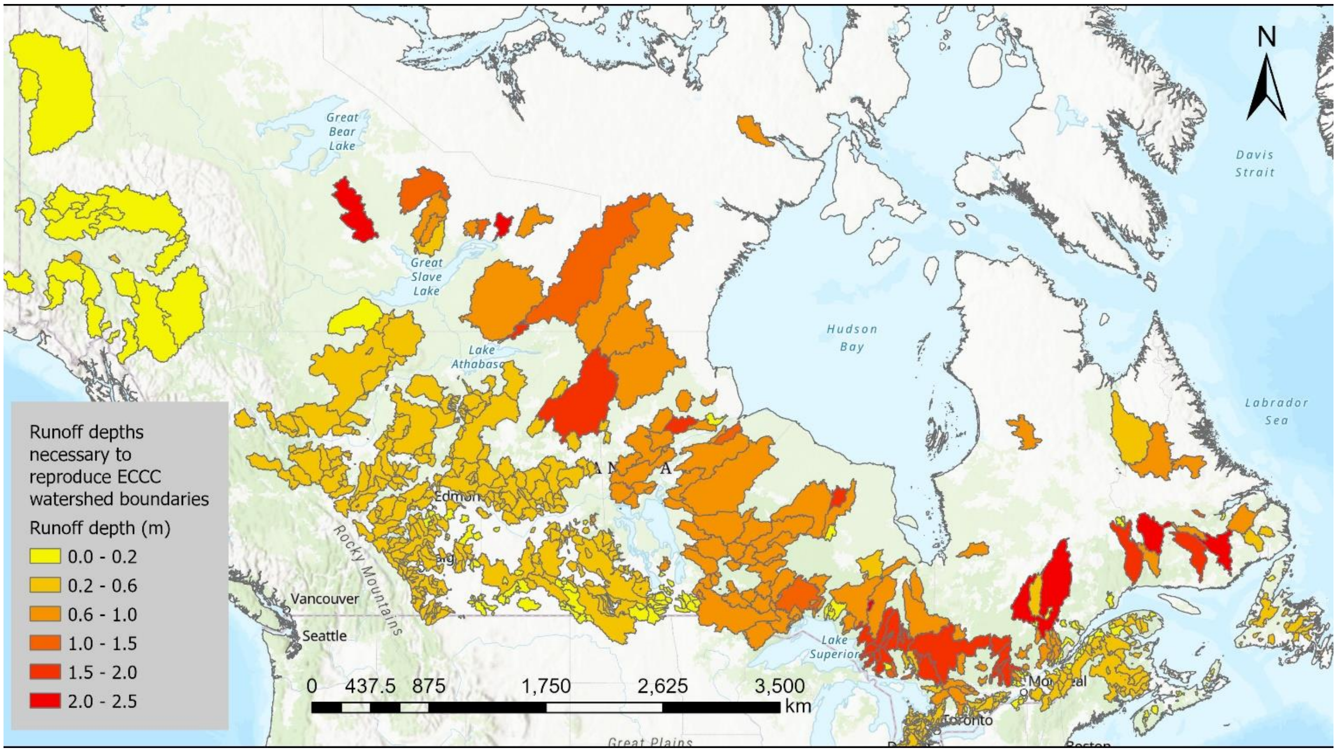

Figure 6: Different ECCC watershed has different depressional storage. This figure shows the runoff depth required to match up with the ECCC watershed area. From this, we can see CS needs more runoff depth because of fill-and-spill hydrology.

Progressive DEM filling with FSM identifies As anticipated derived drainage patterns expand as MERIT DEM is progressively infilled with runoff depths above 0.6 m (Figure 4), and sometimes abruptly in fill-and-spill landscapes (e.g. the Severn River watershed on the Canadian Shield, Figure 4). Control points influencing at least 20% or 5,000 km^2 of upstream watershed area were mostly found within 0.6m – 1.0m. Above 1.0 m, the number of new control points encountered decreases (Figure 5). Watershed area increases largely track the number control points (Figure 5b). Watershed area increases are nearly 20% for the CS, roughly double other parts of Canada (~10%). Most of these increases occur within the first 1 m of inundation, gradually declining out to 2 m (Figure 5c). As expected, the total depression storage varies stronlgy across Canada, with the greatest filling required in the CS (Figure 6, Figure 5c). This affirms the need to use a range of runoff depths to identify control points, as well as greatest depression storage within the CS physiographic region.

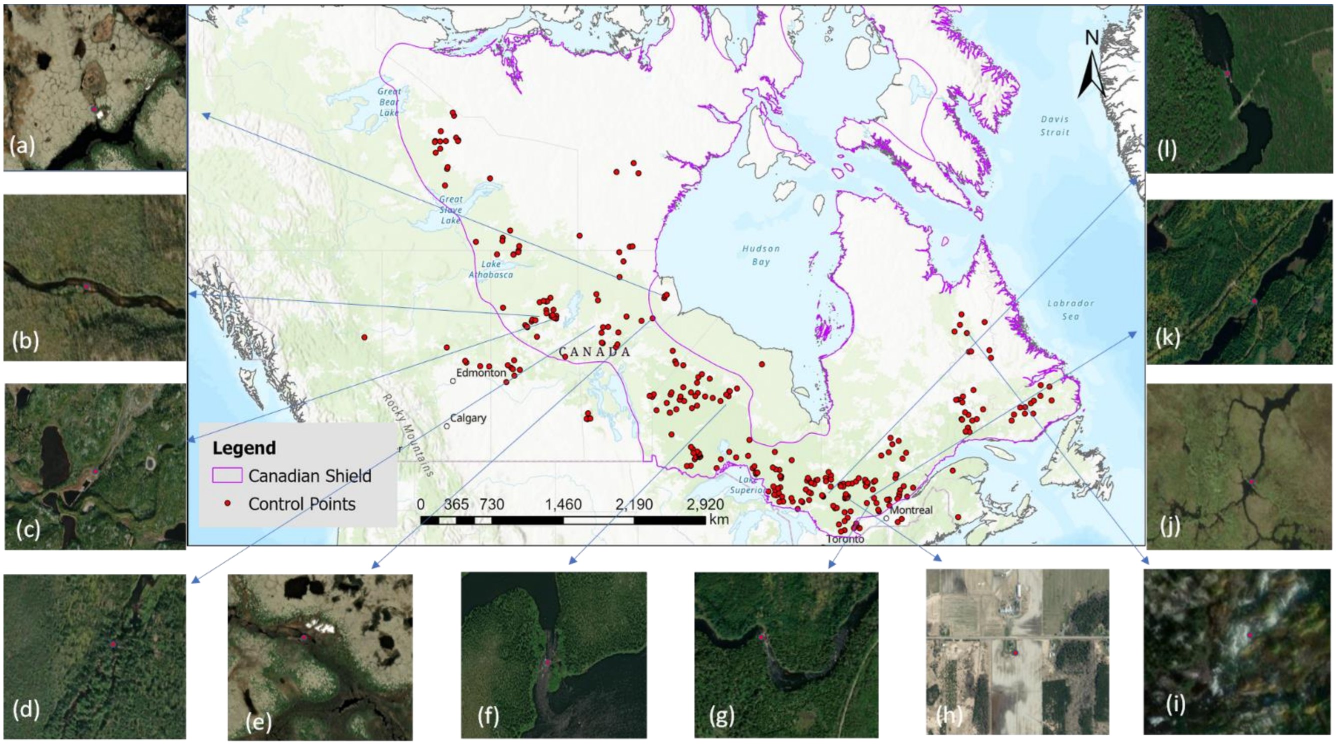

Figure 7: 326 control points of Canada detected using our algorithm when filling with increasing fill with 0.2 m starting from 0.6m: (a) A dry River; (b) Sill; (c) Dry Stream; (d) Sill; (e) River; (f) Cascade; (g) Cascade; (h) farm; (i) Cascade; (j) Beaver Dam; (k) Beaver Dam; (l) Bridge;

Out of 362 major control points identified throughout Canada, 290 (~80%) are in the CS and most of the rest are in topographically similar terrains resembling the CS (Figure 6). From the visual inspection of ArcGIS Basemap and satellite imagery, we removed those points that were in the river without any obstruction. We also removed Dams, Bridges, Beaver Dams, Farms, and Human intervention from the datasets. These types of obstruction are shown in Figure 5. After removing those we had 255 control points. Among the remaining control points, 147 are cascades (~56%), and 57 are protruded bedrock sills (29%) but not cascade. 32 are dry paths (12.54%) and the remaining are some points between lakes and intermittent streams.

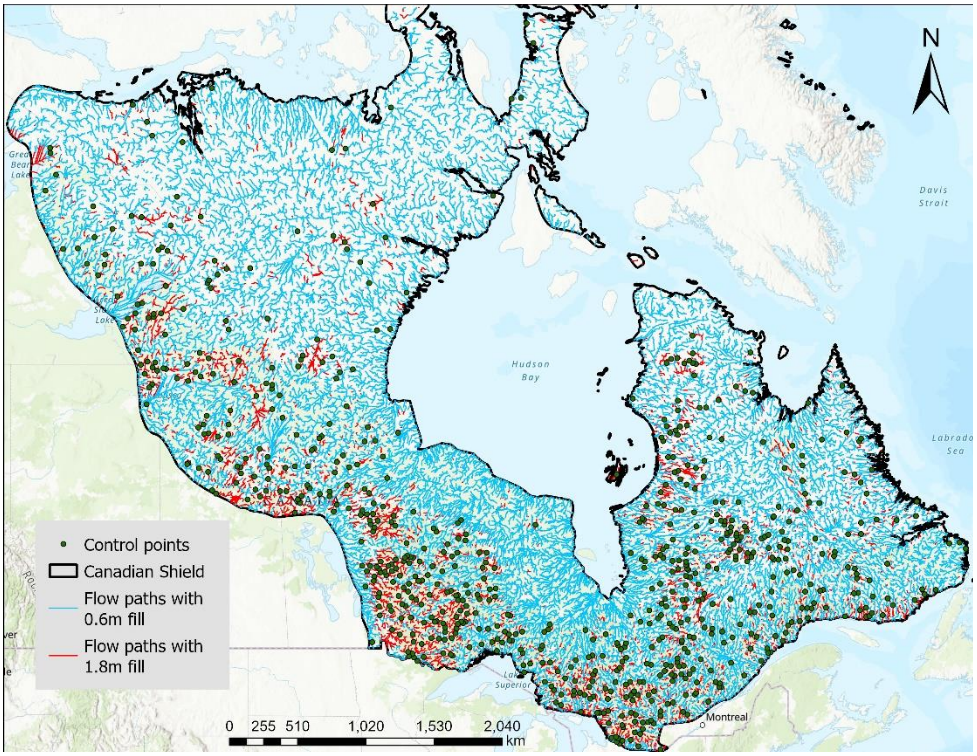

Figure 8: Control points in CS with flow path at 0.6m fill in blue and increased flow path in 1.8 m fill in blue. This shows fill-and-spill hydrology of CS

The CS is characterized by fill-and-spill hydrology, especially in Northwest Territories, Manitoba, and Saskatchewan (Figure 7). A total of 21% of ECCC gauged watersheds contain control points influencing at least 20% or 5000 sq. km particularly Geiki River, Seal River, Kazan River, and Tazin River. By applying FSM to the entire CS domain, we identify 763 control points (including 362 lying within ECCC watersheds) (Figure 8). These control points mostly lie in the rivers (e.g. rocky cascades). There are also numerous beaver dams, dams, and bridges that do not necessarily restrict streamflow on the CS.

Discussion and Conclusion

Depressional landscapes contain internally drained basins and topographic depressions that store water and fragrment regional drainage patterns. Traditional DEM-based watershed analysis approaches commonly override these features by overfilling DEMs to create continuous, well-integrated drainage patterns that may or may not reflect reality. FSM terrain modeling offers a novel approach for detecting topographic controls on regional and continental-scale drainage patterns, including bedrock sills, rocky cascades, and intermittent flow paths that can switch on or off depending on water levels. By applying FSM to the 90m MERIT DEM for all of Canada, we find that depressional landscapes are common in certain areas, most notably in the Canadian Shield and some topographically similar areas in northern Alberta, Manitoba, and Saskatchewan. This broad-scale analysis thus affirms previous studies reporting fill-and-spill hydrology in the CS [18,19,36–39], as well as heterogeneity in depression storage[40] and the importance of hydrological connectivity to runoff processes [41–43].

A classical challenge in watershed analysis is determination of a DEM filling parameter[44,45]. This filling parameter should sufficiently large to reduce DEM artifacts, pits, and error but not so large as to remove real-world topographic depressions. Our pairing of climate data with gauging station discharge records (Figure 3) offers a novel, physically-based rationale for estimating a plausible initial value of this critical parameter. Depending on project aims, modest increases (or decreases) in this parameter are likely owing to variable depression storage for different physiographic regions of Canada (Figure 6). Greatest filling is necessary in the CS, where depression storage of currently gauged watersheds is here estimated to be as high as 2.0m.

Our application of FSM across 1,690 gauged Canadian watersheds identifies 255 control points with the potential to influence the actively flowing area of the watershed. An estimated 323 of 1623 (~12%) of gauged watersheds contain one or more control points influencing at least 20% and/or 5,000 km^2 of the affected area. Such variable source areas may explain irregular river hydrograph behavior and/or unusual flood risk statistics downstream. Control points may also contribute to variable sediment and/or geochemical loads downstream. Based on our first analysis here, we suggest the Gieki, Snare, Kazan, and Seal rivers may be particularly affected as 20-25% of their watersheds are potentially impacted by flow control points.

Most of the flow control points identified in this study are activated with sub-meter increases in regional water balance (e.g., 0.6-0.8m, Figure 4). A total of 91 percent of (235 out of 255) control points identified in our dataset appear to be active or occasionally active today, even at runoff depths as high as 1.8m.

A primary limitation of our work is the 90m spatial resolution of MERIT DEM. Smaller channels, narrow connections between lakes and other fine-scale features are not well-resolved at this resolution so our analysis is necessarily regional/continental in scale. Similarly, topographical slope breaks in continuous river channels sometimes erroneously flagged as control points in MERIT DEM, because the channel was not resolved. While computational expense currently prohibits analysis of higher-resolution DEMs (e.g. ArcticDEM) at continental scales, future studies should consider using ArcticDEM or other high-resolution DEMs for local or regional studies.

In conclusion, we find that FSM improves drainage pattern delineations of Canadian watersheds, by striking an optimal balance between terrain smoothing vs. information loss in DEM analysis. Through a continental-scale analysis of the MERIT DEM, we identify at least 255 control points in currently gauged Canadian watersheds, and another 508 control points in other, ungauged areas of the Canadian Shield. These natural features likely connect intermittently to downstream flow networks, complicating their fluxes of water, sediment, and geochemical loads. While acknowledging the limitations of DEM analysis, our research highlights the value of nuanced, physically-based terrain modeling for understanding the surface water hydrology of poorly drained landscapes with abundant depression storage.

Author Contributions

Conceptualization: Nimisha Wagle; Laurence C. Smith

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Data curation: Nimisha Wagle

Formal analysis: Nimisha Wagle

Investigation: Nimisha Wagle, Laurence C. Smith

Methodology: Nimisha Wagle; Laurence C. Smith

Software: Nimisha Wagle

Supervision: Laurence C. Smith

Validation: Nimisha Wagle

Writing – original draft: Nimisha Wagle; Laurence C. Smith

Writing – review & editing: Nimisha Wagle, Laurence C. Smith

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Data Availability Statement

All data are available in USGS EarthExplore and EarthData. The data URL is provided in the Main text itself.

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Conflicts of Interest

The authors declare no conflict of interest.

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