ASSESSING DOWNSTREAM GEOMORPHIC IMPLICATIONS OF LOW-IMPACT DEVELOPMENT (LID) PROJECTS IN THE SPENCER CREEK WATERSHED

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TITLE: Assessing downstream geomorphic implications of low-impact development (LID) projects in the Spencer Creek watershed

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1. Introduction

Urbanization and land use change are primary factors impacting natural ecosystems globally. In particular, hydrologic networks are especially sensitive to the cumulative effects of land transformation and fragmentation (Ghunowa et al., 2021). These impacts are colloquially known as the “urban stream syndrome”, which refers to the changes caused by the physical, chemical, and ecological processes of a river. There are broad implications of geomorphology on hydrologic networks, as the field is largely related to geological structures based on principles of mechanics and fluid dynamics. Changes in the physical features of the Earth can impact hydrological systems as they physically change sediment quality and river channel networks (Gurnell et al., 2007). Despite the urgency of this matter, there are many challenges associated with anticipating susceptible areas along a river network. The response of streams can vary depending on the biophysical conditions of the watershed and the resiliency of the stream system’s properties (Weil et al., 2018). Although there have been various management strategies developed to address the urbanization effects on stream integrity, relatively few studies have focused on the relationship between improving pervious cover through low-impact development (LID) projects, which serve as an opportunity to reduce the impact of urbanization on geomorphic processes.

Impervious cover is understood as any surface that prevents the percolation of water, most commonly seen as roads, sidewalks, and parking lots in the city. During the process of urban development, activities such as increasing the surface area of road networks can result in decreased capacity to infiltrate precipitation. The loss of pervious surfaces subsequently increases the production of runoff and reduces the rate at which groundwater recharge occurs. In response to urbanization, many cities will implement artificial drainage systems to replace natural pathways, which further disrupts the hydrological response of an area to rainfall (Miller et al., 2014). To better understand the hydrological impacts of urbanization, it is important to consider the relationship between impervious surfaces and their effect on the distribution of surface runoff. When rain falls onto the surface in a natural water cycle, a portion of it evaporates, some of it infiltrates into the ground, and the remainder flows downhill overland until it reaches a body of water. With an increase in impervious surfaces, the portion of rainfall that can infiltrate the ground decreases, instead becoming surface runoff. In densely urbanized regions, this creates shorter lag times between the onset of rainfall, higher peak runoffs, and increases the total volume of runoff (Shuster et al., 2005). Furthermore, urbanization processes may often remove or narrow the floodplains of smaller river channels to maximize the space for development (Papangelakis et al., 2025). These construction choices, in conjunction with increased surface runoff, result in a higher frequency of floods, increased discharge, and flashy hydrographs. Fluvial systems have, ultimately, been found to be especially sensitive to land use change and can have major implications on the overall health of a watershed.

1.1 Stormwater Management Practices

In light of existing erosion and water quality concerns, city planning, globally, has developed increasingly novel sustainability practices. In recent years, there has been an increased focus on LIDs. Although there are various terms that refer to similar design principles, such as green infrastructure (GI) or best management practices (BMP), many LIDs have also been referred to by differing terms based on the geographical location (Senior et al., 2017). For instance, European city designers refer to these measures as sustainable urban drainage systems, and

Australia, as water-sensitive urban design (Liu et al., 2021). In early literature, stormwater management practices were most commonly known as BMPs. The past few decades have seen an increase in research that has evolved the discipline to include a cumulative mix of BMP policies and GI systems design. However, for the purpose of this study, these practices will be hereafter referred to as LID.

Traditional stormwater management systems were typically designed to transport flows from singular, large-scale storm events, which occur once every 2-100 years. Due to these infrastructures, existing systems often fail to properly account for frequent storm events, leading to issues with water quality and flooding (Senior et al., 2017). LID practices recognize the possibility of more frequent events, such as 6 months to 2 years, and ultimately design stormwater infrastructure in ways that can preserve both system and stream integrity (Grover & Krantzberg, 2012). These innovative approaches to stormwater management can also preserve ecosystem integrity in highly urbanized regions. Common goals of LID practices are to reduce stormwater runoff, improve water quality, and reduce costs in infrastructure operation and maintenance (Liu et al., 2021). As such, measures will often combine both land-use planning and system design engineering to create informed infrastructure management processes. One of the primary principles followed by LID measures is to retain the natural hydrologic conditions of an environment after urban development (Grover & Krantzberg, 2012). LIDs aim to incorporate a range of exit points, unlike conventional stormwater systems, which tend to transport surface runoff from impervious surfaces towards low points in the topography, into large end-of-pipe stormwater facilities (Grover & Krantzberg, 2012). With the integrated approach of LIDs, natural features in the urban environment can help distribute runoff. This form of system design ultimately offers greater flexibility for future planning, accounting for the possibility of urban retrofits or redevelopment projects. In practice, various types of infrastructure fall under the LID umbrella. Some of the most common infrastructures are bioretention cells, roadside swales, and permeable pavements. The following table lists a summary of common LID practices and their related descriptions (Table 1) (Grover & Krantzberg, 2012).

Table 1: A non-exhaustive list of common LID practices

LID Infrastructure	Description
Bioretention cells	A designated treatment area consisting of a vegetated shallow depression and soil media that temporarily stores, treats, and infiltrates runoff.
Dry/grass swales	A linear bioretention or enhanced grass swale that incorporates an engineered soil bed and optional perforated pipe underdrain. Shallow, broad, open channels are used to convey, filter, and attenuate stormwater runoff.
Green roofs	A thin layer of vegetation is installed on top of a conventional roof and stores rainwater until it is evaporated, evapotranspired by the plants, or drained away.
Infiltration trenches and chambers, soakaways	Underground linear ditches collect rainwater until it infiltrates nearby soil.
Permeable pavement	Pavements that allow stormwater to drain through them and into a reservoir, where it is temporarily stored or infiltrated into the underlying soil.
Rainwater harvesting	Infrastructure built to intercept, convey, and store rainwater for future use, typically for landscaping or non-potable uses.

1.2 Stream Power Analysis

LIDs have the potential to play a crucial role in reducing the impacts of urban development on geomorphic processes in a watershed. In recent literature, stream power has been growing in popularity as a metric to assess the impacts of urbanization on river morphology. Stream power-based analysis is therefore a widely used discipline to identify morphologic changes and channel instability. Although best defined as the rate of expenditure of potential energy in a river, in simpler terms, stream power measures the energy of a stream channel (Papangelakis et al., 2022). This variable is critical in understanding a water network's ability to transport sediment and its impact on erosional processes. Additionally, it has broad applications in geomorphology research due to its use as a metric for the cumulative effects on urban rivers.

Stream power can be affected by other variables, including peak discharge and channel gradient. These variables are particularly sensitive to changes in runoff caused by urbanization, and in turn, stream power as it controls sediment transport. This quality allows the use of stream power as a strong proxy for erosion, or the rate of urban stream degradation. Stream power analysis can also account for other factors in urbanization, such as percent impervious cover, which is a metric that integrates various types of human development activities in catchments (Stanfield & Kilgour, 2006). In 1968, Aldo Leopold recognized that the transformation of natural forest cover to agricultural and urban land caused an increase in impervious cover. This resulted in decreased infiltration of precipitation into solid ground and increased overland flow. The effect of increased impervious cover has also been demonstrated across various studies as a biological and physical stressor, particularly in stream environments.

1.3 The Spencer Creek Watershed

The Spencer Creek watershed is the largest region managed by the Hamilton Conservation Authority (HCA), consisting of a complex network of rivers and streams that collect surface runoff throughout the region (Figure 1). At approximately 279 km^2, the watershed is comprised of 15 sub-watersheds and outlets directly into Cootes Paradise Marsh. There are various land uses contained within the area, including wetlands, idle farmlands, forests, escarpments, rural land use in the upper portion of the watershed, and urban development in the lower portion (Ahmed & Tsanis, 2016; Overy, 2010). The Spencer Creek River itself is a 6th-order stream whose flow is controlled periodically by two reservoirs, the Valens and the Christie Reservoir (Sultana & Coulibaly, 2011).

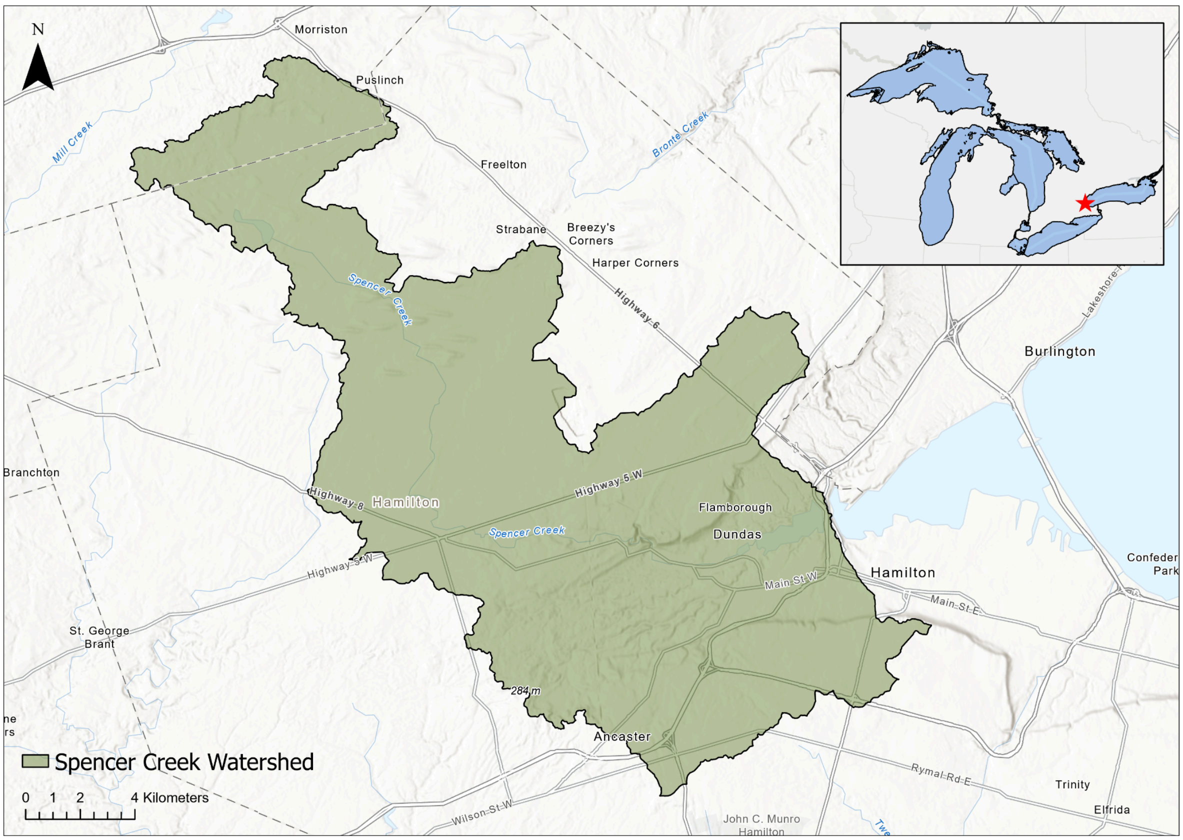

Figure 1: Location of the Spencer Creek watershed in Hamilton, Ontario.

In terms of natural features, the most significant of the region is the Niagara Escarpment and Dundas Valley. Due to the escarpment, the watershed has elevations ranging from 100-340 m, however, it has relatively flat topography (Grillakis et al., 2011). Among the 15 sub-watersheds, Spring, Sulphur, and Lower Spencer Creek were identified as priority watersheds due to their geographically urban location and direct impacts on the Cootes Paradise Marsh. The proximity of the Spencer Creek watershed to Cootes Paradise Marsh also causes the region's ecosystems to have higher sensitivity to urbanization (Wei & Chow-Fraser, 2005). In particular, the Lower Spencer Creek subwatershed is a vital marsh and open-water habitat that provides homes to warm-water fish communities and migratory birds (Hamilton Conservation Authority, 2010).

As the land use class of this region is predominantly urban, surface runoff is often a particular concern. Stormwater and surface runoff in the region are typically captured by storm sewers and processed at the Dundas Water Pollution Control Plant, where it is then discharged into Cootes Paradise. As of 2010, it is estimated that the subwatershed consists of 68% impervious surfacing (Hamilton Conservation Authority, 2010). Other major stressors noted from environmental assessments were storm sewer outfalls, abandoned groundwater wells, habitat fragmentation, and encroachment. However, due to a relatively large portion of the natural lands being owned by environmental organizations and protective legislation, greenfield development is not yet a major concern.

1.4 Results of Previous Studies

Previous studies have assessed the Spencer Creek network for areas that are geomorphically sensitive using stream power-based approaches, such as comparing spatial patterns of total stream power (Ramharrack-Maharaj & Papangelakis, 2025). Areas along the network that have high specific stream power values suggest a higher likelihood of geomorphic change. Specifically, the Dundas Valley and the lower southern portion of the watershed were identified to contain higher stream power ratio values, suggesting there were more pronounced changes to the hydrological system in these regions. Using these results, this study focuses on the Dundas Valley, an area directly below the Niagara Escarpment, and the urbanized neighbourhood of Ancaster (Figure 2). These regions are likely more geomorphically sensitive due to a combination of high flood discharges, steeper channel slopes, and intense urbanization. It is particularly important to continue researching these regions as the City of Hamilton has identified them as high-density flooding hotspots, with Dundas and Ancaster containing 161 and 114 hotspots, respectively (The Hamilton Spectator, 2012).

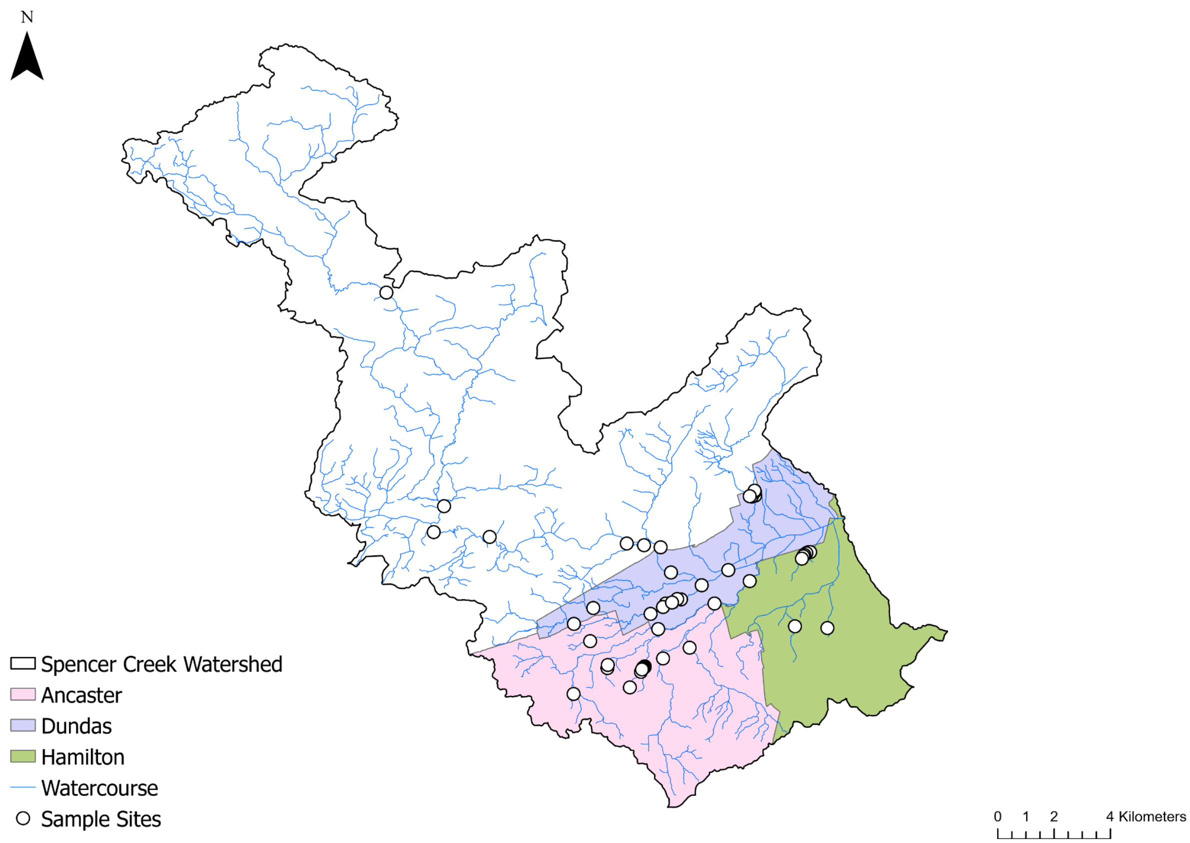

Figure 2: Location of the Dundas, Ancaster, and Hamilton regions within the Spencer Creek watershed, with sites sampled for bankfull widths for this study.

1.5 Objectives

The primary purpose of this study is to investigate the downstream effects of land use change and potential LID systems on Spencer Creek, an urbanizing watershed in Hamilton, Ontario. Specific objectives were to: (1) identify possible LID infrastructure for at-risk regions in Spencer Creek, (2) generate land use scenarios to assess the implications of LIDs on Spencer Creek's geomorphic sensitivity, and (3) sample and contribute field values to the Spencer Creek dataset to support future analyses. The results of this study aim to enhance the accuracy of the Stream Power Index for Networks (SPIN) tool for the Spencer Creek watershed and demonstrate its effectiveness in guiding future water management plans.

2. Methodology

2.1 SPIN Tool

To conduct a stream power-based analysis, the SPIN tool was used to assess the existing and potential areas at risk for stream erosion. The SPIN tool is a Python script that applies simple user inputs to calculate a variety of metrics involving stream power and its relationship to land-use conditions. The basis of this study's methodology uses the 2-year return discharge (Q_2) to represent the change in hydrologic systems caused by urbanization. For the purpose of erosion risk assessment, Q_2 is used to approximate bankfull discharge, which has been found to perform the most geomorphic work in fluvial environments (Wolman & Miller, 1960; Emmett & Wolman, 2001). In SPIN, the discharge is calculated at each segment of the river network in relation to a parameter of drainage area, generating an undeveloped, rural watershed condition (Q_{2r}). This relationship follows the form of Equation 1, where A represents the drainage area, and a and b are empirical coefficients developed from regression data (Phillips & Desloges, 2014).

For the estimation of Spencer Creek scenarios, coefficients of a = 0.248 and b = 0.910 were used, which were derived from regression data by Phillips & Desloges (2014), using 210 watersheds in Southern Ontario.

$$Q_{2r} = aA^b \tag{1}$$

SPIN assesses three primary user inputs and produces outputs that can be visually assessed in GIS tools. The first input is a digital elevation model (DEM) of the study site, most commonly a watershed. The results of SPIN are highly influenced by the use of DEMs, which are layers of raster data wherein each pixel is representative of a square unit of area and a numerical elevation value. The use of a hydrologically enforced DEM (eDEM) layer allows for the delineation of a water network in the watershed of interest. This study obtained a 30 m resolution eDEM from the Ontario Ministry of Natural Resources and Forestry (Ontario Ministry of Natural Resources, 2019). The result is a network separated into a set of longitudinal stream segments. The second input is a land-use shapefile, which indicates the existing types of land-use classes as polygons (Figure 3). SPIN uses land use polygons to determine the fraction of a segment's drainage area that is covered by impervious surfaces and to assess the increase in stream power. This study used a 2018 land use map obtained from the City of Hamilton (CHDITS, 2018).

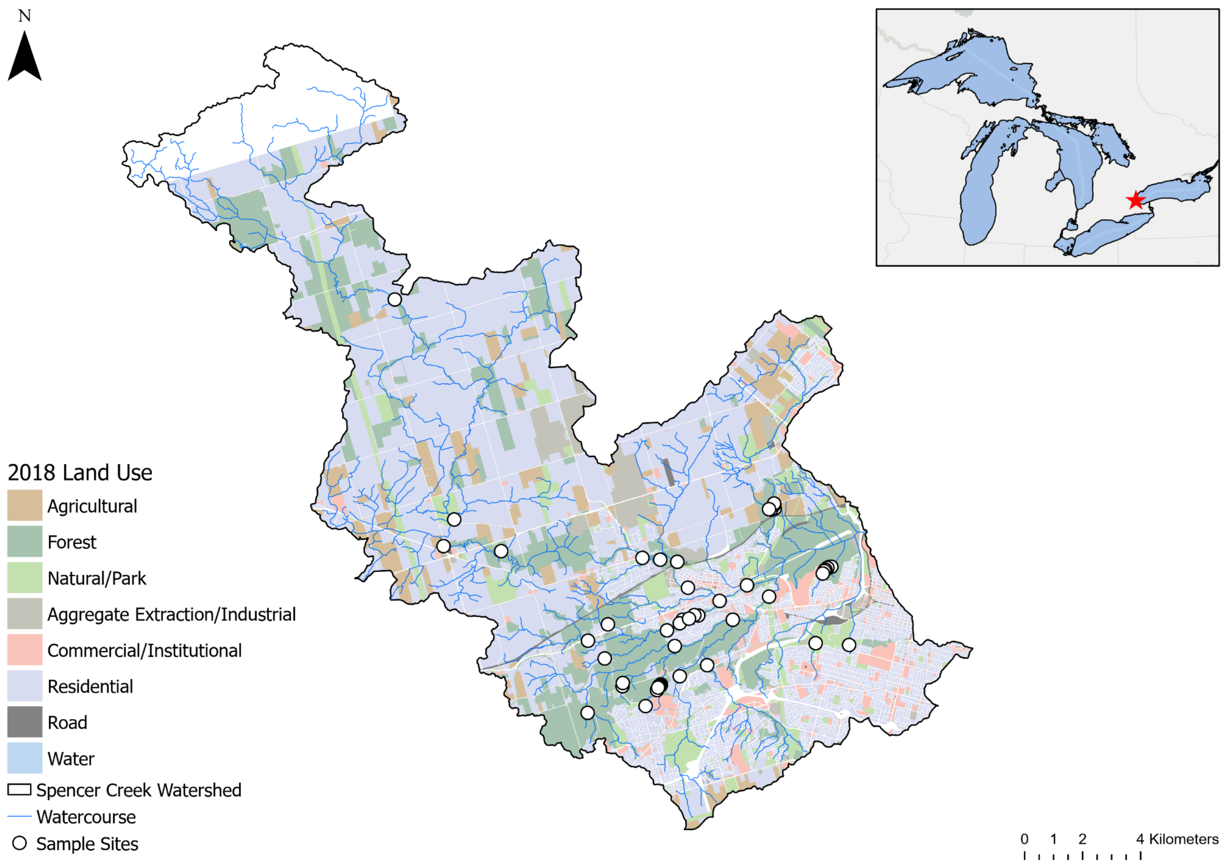

Figure 3: Land use maps of the Spencer Creek watershed for 2018, showing the watercourse and sites sampled for bankfull widths for this study.

The third input is an impervious cover file, which dictates the impervious cover percentages associated with each land use polygon. The original values for this input were sourced from standardized values set by the Toronto Region Conservation Authority (TRCA) and can be found in Appendix A. These values are then used to calculate the percent impervious cover of a drainage area (I) and ultimately an urban scenario (Q_{2u}) as represented by Equation 2, where A represents the drainage area, I represents the impervious percentage, and d and e are empirical coefficients developed from regression data (Bledsoe & Watson, 2001).

$$Q_{2u} = cA^{d}I^{e} \tag{2}$$

2.2 Percent Impervious Cover

To assess the geomorphic implications of LID strategies, this study altered the third input of SPIN, the impervious percentage file, by applying literature values from previous studies which have analyzed similar projects. By following previous literature values, this study used the variable of peak runoff as a proxy to implement hypothetical LIDs throughout the Spencer Creek watershed. If a linear relationship between peak runoff reduction and imperviousness is assumed, the former can be used as an indicator of LID strategy effectiveness. The value of this type of analysis lies in its ability to produce simple outputs with low data requirements. This study aims to complete a preliminary assessment of the Dundas and Ancaster region to better inform Hamilton stormwater management strategies. Using literature values from previous studies, this study associated new percent imperviousness values with each land use polygon to replicate the implementation of specific LID infrastructure. The following table summarizes the averaged percentages of reduction in peak runoff for the associated LID practice (Table 2). The papers used to synthesize these values can be found in Appendix B. All adjustments made to the imperviousness value file were derived from averaged literature values as referenced.

Table 2: Average percentage of reduction in peak runoff by LID type

Type of LID infrastructure	Percentage of reduction in peak runoff	Average percentage of reduction in peak runoff
Vegetative swales	7.5 *Naeini, Tabesh, and Soltaninia (2024)*	7.55
	7.6 *Sui and van de Ven (2023)*	
Permeable pavements	9.12 *Naeini, Tabesh, and Soltaninia (2024)*	14.87

Type of LID infrastructure	Percentage of reduction in peak runoff	Average percentage of reduction in peak runoff
	9.5 *Sui and van de Ven (2023)*	
	26 *Arjenaki et al. (2020)*	
Bioretention cells	8.8 *Naeini, Tabesh, and Soltaninia (2024)*	12.3
	15.8 *Sui and van de Ven (2023)*	
Green roofs, Permeable pavements	13.9 *Sui and van de Ven (2023)*	24.56
	13.5 *Bae and Lee (2020)*	
	25.9 *Palermo, Talarico and Turco (2020)*	
	45 *Palla and Gnecco (2015)*	
Bioretention cell, vegetative swales	17.44 *Naeini, Tabesh, and Soltaninia (2024)*	16.92
	16.4 *Sui and van de Ven (2023)*	

In this study, scenarios were separated based on three criteria: the type of land use that would be targeted, the type of LID system that would be implemented, and the percentage of implementation capacity. The first criterion consisted of the range of land uses that occur within the Dundas and Ancaster regions, including low- to medium-density residential, high-density residential, commercial, and industrial. Due to a general lack of industrial and high-density residential land uses in Ancaster, these scenarios were not run for the study site. The second criteria established the type of potential LID infrastructure, which consisted of four sub-scenarios, (1) permeable pavements as an individual system, (2) permeable pavements and green roofs as a binary system, (3) bioretention cells including dry swales as an individual system, and (4) an idealized combination of all the previously mentioned. Lastly, the percentage of implementation consisted of 50% and 100%, which tested whether the effectiveness of a LID solution is reliant on the capacity at which it is implemented. For instance, a 50% scenario would indicate that only half of the target land use is altered with the LID infrastructure.

2.3 Assessing Geomorphic Sensitivity

After modelling various scenarios, two indices calculated by SPIN, the total stream power and stream power ratio (SPR), were used to assess the impacts of LIDs on Spencer Creek's geomorphic sensitivity. According to previous studies in the Etobicoke Creek watershed of Toronto, the SPR index has been found to be representative of the change in total energy in the channel, or the total potential for erosion (Papangelakis et al., 2022). As such, SPR can be used to compare pre-urbanization and post-urbanization conditions in a watershed. For the purpose of this study, the SPR outputs by SPIN was processed using ArcGIS Pro and split into five bins, spanning the range of the total values for better visualization. The cutoff values for SPR bins follow those used by Papangelakis et al. (2022) in Etobicoke Creek, who found that regions of the water network with SPR values of equal to or greater than 2 are typically where ground observations of erosion hazards can be recognized. SPR values of 3 or more can then be considered erosion sites in very poor condition. Therefore, to assess the effects of different LID solution combinations, each scenario's total length of network with an SPR value of equal to or greater than 3 was calculated. The network lengths of different scenarios were then compared with one another, where a shorter length ultimately represented a more effective solution.

3. Results

For ease of results interpretation, the nomenclature of a few scenarios will first be established. A control scenario refers to one with no changes made to any land use type's impervious values and defines the existing network conditions of the Spencer Creek watershed (Figure 4). This scenario produced a total network length of 54.00 km. The total network length of Spencer Creek is approximately 353.64 km, which suggests that 15% of the watershed is currently at greater risk for erosion and is more geomorphically sensitive to urbanization. In this scenario, the segments of the network with SPR values equal to or greater than 3 had an average slope of 0.02. These segments also generally had a shorter length, 35.98 m, in comparison to the rest of the watershed, which had an average length of 36.74 m.

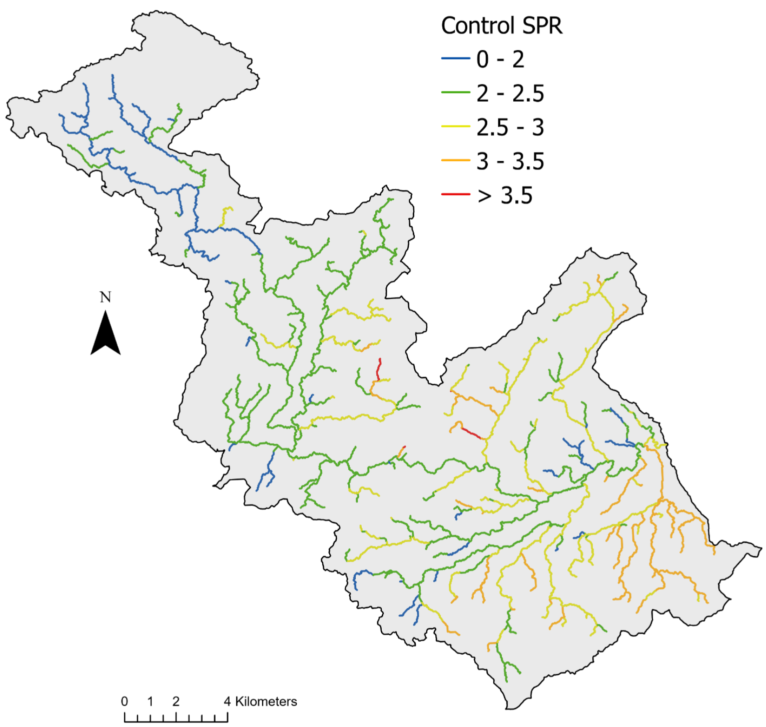

Figure 4: SPIN tool outputs showing the total SPR values calculated for control 2018 land-use scenarios in the Spencer Creek watershed. Network segments with values equal to or greater than 3 are considered at high risk for erosion and geomorphic sensitivity.

Secondly, an ideal LID system scenario refers to scenarios that use a combination of all LID infrastructure discussed, including permeable pavements, green roofs, and bioretention cells. A binary LID system refers to the combination of permeable pavements and green roofs. Lastly, an ideal land use scenario targets all existing land uses, including low- to medium-density residential, high-density residential, commercial, and industrial. A full table of the scenarios run for this study can be found in Appendix C.

3.1 Dundas-specific Scenarios

Preliminary results of various Dundas scenarios generated the same network length, which suggests that these combinations of solutions should be of a lower priority for the City of

Hamilton. The shared quality between these solutions was the targeting of commercial and industrial land uses. Furthermore, the use of individual systems (permeable pavements) and binary systems (green roofs and permeable pavements) did not appear to affect the overall network length at a high sensitivity. These results suggest implementing such solutions would provide minimal benefits for the city's stormwater management, as they do not appear to greatly affect downstream geomorphic conditions.

The binary system of green roofs and permeable pavements, which has also been supported by previous studies, appeared to be an overall effective strategy across all scenarios (Joksimovic & Alam, 2014). When combined with a 100% target of low- to medium-residential land use, a total network length of 52.94 km was produced. The most effective scenario was the ideal solution where all LID types were implemented at 100% capacity. This resulted in a total network length of 52.61 km (Figure 5). It should be noted that the difference in total network length between this ideal scenario is still quite similar to scenarios that solely targeted residential land uses, suggesting that lower percentages of LID implementation can be equally as effective in Dundas, provided that an appropriate land use is altered. To further support this conclusion, a 50% implementation of the ideal scenario produced a total network length of 52.94 km, which is the same output as various low- to medium-residential scenarios. This suggests Dundas can either place a stronger focus and implementation intensity on the residential land uses within its boundaries or spread out its LID infrastructure across the region at a lower implementation intensity. A full table of the scenarios run for Dundas-specific scenarios can be found in Table 5 of Appendix C.

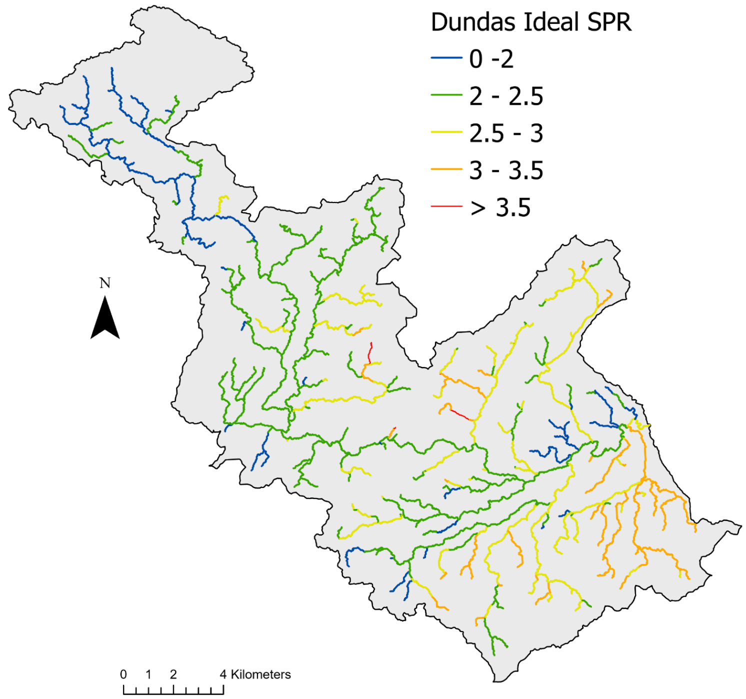

Figure 5: SPIN tool outputs showing the total SPR values for an ideal Dundas solution, which comprises implementing permeable pavements, green roofs, and bioretention cells across all land use types at 100% implementation capacity.

3.2 Ancaster-specific Scenarios

When analyzing the overall land use types in Ancaster, high-residential and industrial scenarios were not considered due to the low value of records. This study focused on the low- to medium-residential land uses, which consisted of 8956 records. Following the success of the binary system with green roofs and permeable pavements in Dundas, this solution was implemented at 100% of low- to medium-residential land uses in Ancaster, producing a total network length of 46.82 km. This scenario suggests 13% of the watershed would be more geomorphically sensitive to urbanization. Similarly, when applying the binary system to other land use types, the results produced are within the range of 44-46 km. The shortest total network length for Ancaster scenarios was produced by the ideal solution, where all LID types were implemented at 100% capacity, generating a length of 44.70 km (Figure 6). In this scenario, channel segments with SPR values of equal to or greater than 3 had an average slope of 0.08 and an average length of 36.20 m.

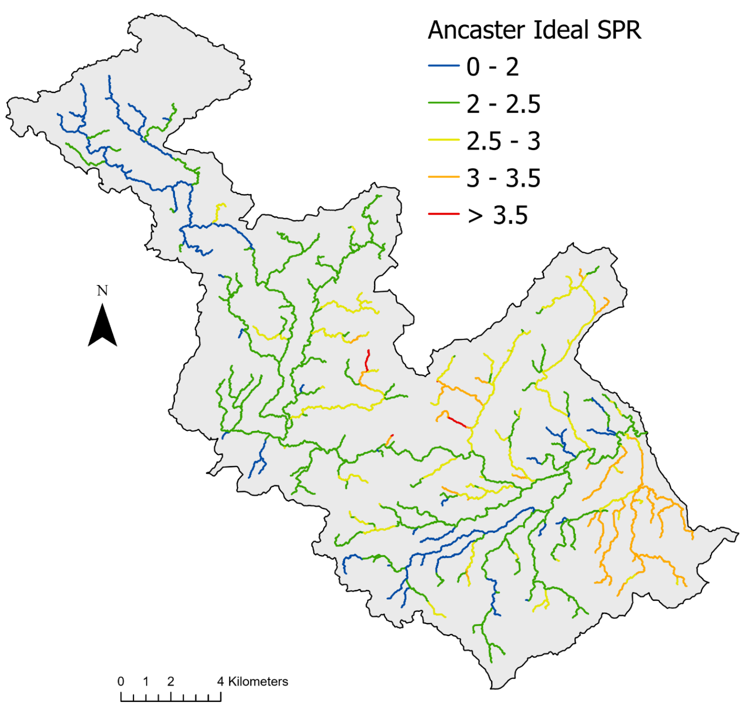

Figure 6: SPIN tool outputs showing the total SPR values for an ideal Ancaster solution, which comprises implementing permeable pavements, green roofs, and bioretention cells across all land use types at 100% implementation capacity.

Comparing the scenarios generated for Ancaster, it appears that the addition of bioretention cells to the binary system solution produces marginal differences in the outcome. For instance, the binary system implemented at 100% of all land use types produced the same total network length as the ideal LID system implemented at 50% of all land use types. This supports the conclusion that less intensive implementation of LIDs in Ancaster can largely reduce downstream geomorphic effects. A full table of the scenarios run for Ancaster-specific scenarios can be found in Table 6 of Appendix C.

3.3 Combination Scenarios

To assess the cumulative impacts of Dundas and Ancaster on Spencer Creek's network sensitivity, scenarios where LIDs were implemented across both regions were considered. An ideal scenario using all discussed LID infrastructure, targeting 100% of all land uses, produced a total network length of 43.31 km, which is the shortest length among all scenarios run in this study (Figure 7).

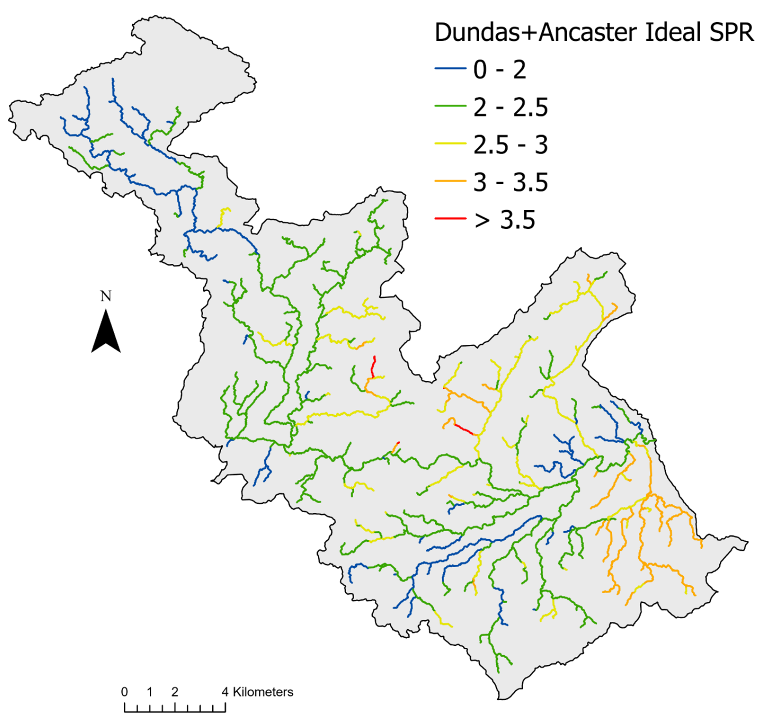

Figure 7: SPIN tool outputs showing the total SPR values for a combined ideal Dundas and Ancaster solution, which comprises implementing permeable pavements, green roofs, and bioretention cells across all land use types at 100% implementation capacity.

Furthermore, the same ideal scenario implemented at 50% produced a length of 45.82 km. The similarity of this scenario with Ancaster-specific scenarios' range of 44-46 km suggests that Ancaster affects the network quality at a much greater capacity than Dundas. When comparing the lengths of the channel segments with SPR values of equal to or greater than 3, this combination scenario produced an average length of 36.21 m, which is strikingly similar to the ideal Ancaster scenario's value of 36.20 m. A full table of the scenarios run for Dundas-specific scenarios can be found in Table 7 of Appendix C.

4. Discussion

By comparing Dundas-specific, Ancaster-specific, and combination scenarios, it can be concluded that incorporating Dundas into the solution has minimal impact on the total network length. This result is likely due to the geology and topography of the Spencer Creek watershed. Geographically, Ancaster is located right along a natural break in the Niagara Escarpment and the Ancaster Creek, scarp-facing stream (Gentilcore, 1963; Hamilton Public Library, 2025). Considering the natural flow of water in this region, the chief tributary of the Niagara River is the Welland River, which begins in the sandy moraine of Ancaster (Jackson, 1997; Kennedy, 1955). It then meanders east across steep gradients into the Niagara River at Chippawa, Ontario. Based on the geographical locations of Ancaster and Dundas, water would flow from Ancaster over the edge of Dundas Valley as waterfalls before continuing east (Hamilton Conservation Authority, 2008). The elevation of Ancaster also ranges from 80-250 masl, creating an average channel slope of 0.02. However, as seen in the Ancaster-specific scenarios, the channel segments with SPR values of equal to or greater than 3 had an overall higher average slope of 0.08, confirming that steeper slopes create more geomorphically sensitive networks. Moreover, along the exposed lithological units near Ancaster, the upper Lockport group consists of the Ancaster Member of the Goat Island Formation and the Gasport Formation. The Ancaster member has a particularly fractured and highly unstable nature, causing it to be more sensitive to physical weathering processes and escarpment erosion (Ellis, 2022). Overall, the combination of these factors can explain why the Spencer Creek network appears to be more greatly affected by land use changes in Ancaster.

4.1 Recommendations

When implementing LIDs in a practical sense, many considerations can affect the construction and effectiveness of infrastructure. Selecting the location for implementation is a critical step in the process and typically requires manual siting. Given limited financial resources in city planning, there is a need to identify regions of concern by prioritizing where to spend resources and maximize the value of LIDs. SPIN can address this challenge by producing informative data with a low resource requirement. Overall, results from this study recommend that the city of Hamilton focus on the Ancaster region, with a stronger emphasis on the green roofs and permeable pavements solution across low- to medium-density residential areas. The binary system solution is best suited for this region as owners of single-family homes may not be interested in maintaining green roofs, allowing them to pivot to permeable pavements, which can be implemented across driveways (Joksimovic & Alam, 2014). Furthermore, since dust and particulate matter emitted from automobiles can reduce permeability over time, it can be more suitable to implement permeable pavement as driveways, compared to commercial parking lots, as traffic volume is low, and maintenance can be reduced (Brattebo & Booth, 2003).

For the use of permeable pavements, studies have found that the infrastructure can function adequately at slopes greater than the recommended 5%. However, there has been caution in implementing this solution in climates that experience freeze-thaw cycles (Henderson, 2012; Lucke et al., 2012). Additionally, few studies have identified a concern for implementing LIDs that promote infiltration in regions with high pre-existing groundwater levels, which can cause higher risk of groundwater flooding and pollution (Bhaskar et al., 2018; Zhang & Chui, 2018). Land uses such as industrial and commercial regions should avoid the use of pervious pavement as they can create surface runoff with greater levels of contamination. High-risk activities such as the storage of hazardous materials and onsite fueling stations can also increase the risk of groundwater contamination (Ministry of the Environment, Conservation and Parks, 2022). The results of this study suggest the combined use of green roofs and permeable pavements, which allows for greater flexibility in regards to the LID infrastructure used in commercial and industrial regions. Considering the concerns of groundwater contamination, it is suggested that Hamilton focuses on green roofs as a solution for its industrial and commercial land use.

Despite the various benefits of LIDs, societal and structural barriers exist to implementing this infrastructure. Many of the societal challenges are centred around an overall lack of understanding of the discipline. For instance, the Credit River watershed, located within the city of Mississauga and managed by the Credit Valley Conservation (CVC) authority, had an interest in addressing LID obstacles. In 2012, the CVC completed an analysis of the perceived barriers, noting that one of the primary barriers was the lack of public awareness about LID measures (Grover & Krantzberg, 2012). This challenge can limit property owners' acceptance and willingness to invest in LID features, such as green roofs. Similarly, Hamilton has hosted several workshops and engagement sessions in 2024 to deliberate on the future of the city's stormwater management strategies. Interested parties mentioned a concern about perceived implementation difficulties. The greatest barrier to green roofs would be their cost, approximating $15-25 per square foot compared to a conventional roof of $8 per square foot (Davis, 2011). Due to the necessary materials for upkeep, an intensive green roof can reach upwards of $40, depending on the aesthetic features implemented.

There is additionally a lack of LID knowledge among design professionals. As water management system designs have historically fallen under the engineering discipline, the implementation of LIDs would require collaboration with various fields, including planners and architects. These issues are further exacerbated by a lack of standards and bylaws, which delays the process of planning. When accompanied by a lack of up-to-date watershed studies, it becomes increasingly difficult to determine the current state of water management infrastructure and create the appropriate plans to incorporate LID principles (Grover & Krantzberg, 2012). Ultimately, this study highlights the need for greater advocacy for the use of LIDs in Hamilton city planning. The lack of understanding of LIDs' processes can cause perceived skepticism regarding the efficacy of this infrastructure. Despite green roofs and permeable pavements demonstrating their advantages in this study, decision makers in Southern Ontario remain hesitant to implement these solutions.

4.2 Existing Applications of LIDs in Southern Ontario

There are some cases of studies within Southern Ontario where LIDs have been implemented in road reconstruction projects. Dundas Street is a major arterial roadway that runs parallel to the shore of Lake Ontario from the City of Hamilton to Toronto. In 2013, a section of Dundas Street under Halton Region jurisdiction was proposed to undergo reconstruction after completion of environmental assessments (Senior et al., 2017). Initial reports determined that challenges regarding the implementation of LID infrastructure were primarily due to limited space on the four-lane roadway, the highly urbanized nature of the site, and the underlying soil composition. However, with the region's interest in promoting LID in future road reconstruction projects, expert feedback suggested LID measures in the form of modified catchbasin units with pre-fabricated soil reinforcement grids. Firstly, roadway catch basins will direct low flow into planter units beside the road. High flows are allowed to bypass the planter units, leaving directly into conventional storm sewers. The modified soil reinforcement structures will aim to provide structural reinforcement as well as allow for the use of less compacted soils below pavement. Ultimately, this creates greater void space and stormwater uptake by the nearby natural vegetation. As part of a larger Dundas Street Corridor improvement project, the construction for this particular design was planned for 2017, and completion is anticipated for 2027 (Halton Region, 2025; Senior et al., 2017).

An example more specific to Hamilton is the 2018 bump-out project. This project involved the design and construction of a rain garden at a selected pilot bumpout site. The exact location of the infrastructure was planned for the intersection of Bay Street North and Simcoe Street (ICLEI, 2018). The LID bumpout was proposed in response to increasing challenges associated with heavy rainstorms. As the city progressed with green infrastructure designs, the LID was meant to control stormwater runoff and improve infiltration. Furthermore, since the bumpout project was proposed along with Hamilton's North End Traffic Management Plan, the infrastructure was also incorporated into overall traffic system designs by a third-party consulting firm, the IBI Group.

In terms of the design process, the LID included a rain garden to direct stormwater away from paved surfaces. A variety of mulch and plants that absorb water and nutrients would be planted in the garden. In plant-based LIDs, the selection of plants plays a large role in the efficacy of the system. Plants selected for this project included a mixture of perennials and grasses designed to attract pollinators and tolerate city challenges like spring flooding, summer drought, and winter salt (ICLEI, 2018). More specifically, native species such as Blue Flag Iris, Heavy Metal Switch Grass, and Purple Dome Aster were used. After the collection of runoff into the gain, water can be filtered through layers of sand and organic materials before arriving at a gravel layer. At this point in the system, the runoff is filtered and cleansed before it is allowed to be reintroduced into the ground. These case studies suggest that LIDs have potential in Southern Ontario and should be promoted as novel stormwater management practices.

4.3 Limitations of Study

Despite the multi-faceted uses of SPIN, there are certain limitations to the model. Firstly, the results of the generated model are highly dependent on the quality of the DEM used. Higher-resolution DEMs can generate results with a greater level of detail for slope variation. By nature of how DEMs are created, the raw elevation data collected from LIDAR or similar technology must be preprocessed and burned before it is used to delineate channels in SPIN. This process can cause errors in the DEM product and lead to inaccurate results (Ghunowa et al., 2021). Secondly, river channels can be influenced by an assortment of natural factors, such as in-channel wood or bedrock outcrops. These external factors are not captured by the SPIN model, but can potentially increase the storage of sediment and reduce the effectiveness of the channel. Therefore, the results calculated by the model can have an overestimation of flow rates, affecting the accuracy of the stream power index.

Another limitation of this study is the method used to assess the potential implications of LID solutions. SPIN is a highly flexible tool which, despite its empirical-based approach, allows for input from popular water resource databases such as the U.S. Army Corps of Engineers Hydrologic Engineering Center’s River Analysis System (Papangelakis et al., 2022). However, as SPIN is a stream power-based approach, it is difficult to produce a model of the hydrologic dynamics that accounts for all possible factors. Although a linear relationship was assumed between the reduction of surface runoff and the impact of LID, in application, other variables, including slope, soil type, and underlying geology, can also affect this relationship. Despite this limitation, SPIN produces straightforward outputs with minimal input data, making it a useful first step for decision-makers to assess areas of potential geomorphic sensitivity. Furthermore, additional analysis can be completed for at-risk regions identified by SPIN, reducing the need for repeated high-resource costs.

4.4 Future Steps

In the early stages, as a part of the third objective of this study, bankfull widths along various sites in Spencer Creek were sampled in an attempt to derive regionally defined empirical coefficients for the SPIN tool. These sample sites can be seen in Figures 2 and 3. The sites span across various sub-watersheds in Spencer Creek, with a focus on the Dundas and Ancaster regions. However, the regression generated from this data, in conjunction with previously-sampled summer 2022 site values, produced an irregular relationship between drainage area and channel width. As such, the coefficients were not used to generate SPIN scenarios in this study. Future studies should aim to complete more thorough sampling to find an appropriate relationship and generate empirical values that better represent the Spencer Creek region.

Furthermore, additional scenarios should be generated for the lower-southern portion of Spencer Creek, consisting of Hamilton. Various scenarios in this study indicated that regions of high SPR values included Ancaster and Hamilton. Future studies testing the Hamilton region can further support decision makers in their ability to implement efficient LIDs at the most optimal locations.

5. Conclusion

This study used stream power-based analyses to investigate the downstream effects of land use change and potential LID systems on Spencer Creek, an urbanizing watershed in Hamilton, Ontario. Literature values of percent imperviousness derived from LID studies were applied to existing Spencer Creek land use cover, replicating the implementation of LID infrastructure. Scenarios were run on Dundas and Ancaster, high-risk regions for geomorphic sensitivity, using various combinations of solutions. The ideal scenarios implemented in Ancaster were found to produce better water network quality than scenarios implemented in Dundas, highlighting the need for greater prioritization in this region. Among the LID infrastructure tested, binary systems proved more beneficial than individual systems, particularly the green roofs and permeable pavements combination. The additional implementation of bioretention cells produced minimal changes in water network quality, suggesting resources can be better allocated to alternate methods.

Technologies, such as SPIN, have great potential to be implemented into existing city planning strategies by becoming a preliminary site assessment tool. The overall motivation for developing SPIN was to aid decision-makers in improving water resource management. Due to its empirical approach, high-level and efficient results can be produced. Its ability to generate visual products allows for an ease of data interpretation, providing cities with invaluable qualitative patterns at the watershed scale. Decision-makers should ultimately consider the applications of SPIN and results of similar stream power analyses to develop more targeted watershed management plans for the Dundas and Ancaster regions, which experience a disproportionately greater percentage of flood events in Hamilton.

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Appendix A

Table 3: Total percent impervious (TIMP) standardized by the Toronto Region Conservation Authority (TRCA) (Toronto Region Conservation Authority & Tam, 2021)

TRCA Code	TIMP
Airport	45
Cemetery	35
Commercial	95
Conservation Lands	0
Estate Residential	40
Farm	0
Federal park	0
Golf Course	0
Hydro Corridor	10
Industrial	95
Institutional	80
Natural Cover	0
Open Space	0
Park	10
Recreational	20
Residential High	80
Residential LowMed	60
Road (ROW)	90
Rural Residential	20

Transportation	60
Water	100

Appendix B

Table 4: Studies on the efficacy of LID infrastructure in the reduction of peak runoff

Author & Year	Study area	Type of LID infrastructure	Percentage of reduction in peak runoff
Naeini et al., 2024	Tehran, Iran	Vegetative swales	7.5
		Permeable pavement	9.12
		Bioretention cells	15.8
		Vegetative swales, bioretention cell	17.44
Sui & van de Ven, 2023	San Antonio, Texas	Green roofs	4.4
		Vegetated swales	7.6
		Bioretention cells	8.8
		Permeable pavements	9.5
Arjenaki et al., 2021	Shahrekord City, Iran	Permeable pavement	26
		Rain barrel	25
Bae & Lee, 2020	Seoul, South Korea	Green roofs, Permeable pavement	13.5
Palermo et al., 2020	Paola, Italy	Green roofs, Permeable pavement	25.9
Eckart et al., 2018	Ontario, Canada	Bioretention cells, Permeable pavements, Infiltration trenches, Rain barrels	13
Palla & Gnecco, 2015	Genoa, Italy	Green roofs, Permeable pavement	45
Lee et al., 2013	Cheon-an, South	Infiltration trenches,	16

Author & Year	Study area	Type of LID infrastructure	Percentage of reduction in peak runoff
	Korea	Vegetation swales,	

Appendix C

The following codes will be used in the following tables, where:

RLM = Residential LowMed

RH = Residential High

C = Commercial

I = Industrial

GR = Green roofs

PP = Permeable pavements

BCVS = Bioretention cells, Vegetative swales

Table 5: Results of SPIN scenarios for the Dundas region

Code	Scenario		Impervious Value (%)	Sum of Length of Network (km)
Cont -rol	N/A			*Sample calculation:* *(30 * 779) = 23370* *(42.426407 * 722) = 30631.865761* *23370 + 30631.865 = 54,001.865 m* 54.00 km
1	RLM	100% GR + PP	*Sample calculation:* *60 (-24.56) =* 35	52.94

Code	Scenario		Impervious Value (%)	Sum of Length of Network (km)
2	RH		55	54.00
3a	RLM + RH		35 (RLM) 55 (RH)	52.94
3b		50% GR + PP		53.18
4	C	100% PP	80	54.00
5a	I			
5b		100% GR + PP	70	
6	C + I	100% PP	80	54.00
7a		50% PP		
7b		100% GR + PP	70	
7c		50% GR + PP		
7d		100% BCVS	78	53.18
7e		50% BCVS		54.00
8a	*(Ideal)* RLM + RH + C + I	100% GR + PP	35 (RLM) 55 (RH) 70 (C + I)	52.94
8b		50% GR + PP		53.18

Code	Scenario		Impervious Value (%)	Sum of Length of Network (km)
8c		*(Ideal)* 100% GR + PP + BCVS	18 (RLM) 38 (RH) 53 (C + I)	52.608
8d		*(Ideal)* 50% GR + PP + BCVS		52.94

Table 6: Results of SPIN scenarios for the Ancaster region

Code	Scenario		Impervious Value (%)	Sum of Length of Network (km)
Cont -rol	N/A			54.00 km
1	RLM	100% GR + PP	35	46.82
N/A	RH	Skipped due to low existence of LU (8 records)		
N/A	I	Skipped due to low existence of LU (15 records)		
2a	*(Ideal)* RLM + RH + C + I	100% GR + PP	35 (RLM) 55 (RH) 70 (C + I)	46.40
2b		50% GR + PP		49.51
2c		*(Ideal)* 100% GR + PP + BCVS	18 (RLM) 38 (RH) 53 (C + I)	44.70
2d		*(Ideal)* 50% GR + PP + BCVS		46.89

Table 7: Results of SPIN scenarios for combined the Dundas and Ancaster regions

Code	Scenario		Impervious Value (%)	Sum of Length of Network (km)
1a	*(Ideal)* RLM + RH + C + I	*(Ideal)* 100% GR + PP + BCVS	18 (RLM) 38 (RH) 53 (C + I)	43.31
1b		*(Ideal)* 50% GR + PP + BCVS		45.84