CSCE Annual Conference
Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)
June 12 - 15, 2019

DEVELOPING A HYDROLOGICAL-HYDRAULIC INDEX (HHI) FOR STRATEGIC ALLOCATION OF LOW IMPACT DEVELOPMENT: A CITY OF TORONTO CASE STUDY

Kaykhosravi, S.[1,3], Khan, U.T.[1], Jadidi, M.A.[2]
[1]Department of Civil Engineering, Lassonde School of Engineering, York University, Toronto, ON, Canada,
[2]Geomatics Engineering, Department of Earth & Space Science & Engineering, Lassonde School of Engineering, York University, Toronto, ON, Canada
[3]saherehk@yorku.ca

Abstract: Low Impact Development (LID) is a series of measures such as reducing the land slope, increasing perviousness, and providing storage volume to control stormwater runoff at the source and hence, reduce the risk of floods. However, among all factors, the degree of this control significantly depends on the location of the LIDs within a catchment. Identifying the sites that contribute the most in terms of flood generation is a spatiotemporal problem involving numerous spatial data. This identification helps water resources managers to allocate their limited resources to the sites that contribute the most to runoff generation and thus, to effectively retrofit downstream locations to limit runoff generation. Therefore, there is a need to develop a framework to help determine sites where there is a higher demand for LIDs. The focus of previous research has been limited to finding feasible sites for LIDs in the detailed design rather than in the strategic planning stage of the LID projects. In this research, we propose a spatiotemporal indexing model for strategic allocation of resources for LIDs using commonly available spatiotemporal data. This model uses a geospatial overlaying process that combines two developed indices to determine the LID priority map within the City of Toronto: (1) the hydrological index which represents the sites that contribute most to runoff generation, (2) the hydraulic index which represents the time of concentration of the catchments. Preliminary results show that the two indices prioritize several hotspots in the study region that have a high potential for flood risk and therefore require LID.

1 INTRODUCTION

Low Impact Development is an innovative flood management technique commonly known as LID (Mouritz 1992, Coffman et al. 1999, McCuen 2003, Heal et.al. 2004, Fletcher et al. 2015). LID allows for more sustainable development along with reducing the risk of flood through several non-structural and structural measures (Coffman 2002). This is done by including measures like reducing imperviousness, conserving natural resources and ecosystems, maintaining natural drainage courses, reducing the use of pipes and minimizing clearing and grading, in the development process. Green Infrastructure (GI) techniques such as bioretention cells, rain gardens, green roofs, and permeable pavements are employed as part of LIDs to increase infiltration of runoff, reduce the amount of runoff generated, while decreasing and delaying the peak flow (American Rivers et al. 2010, Prince George’s County 1999, Cheng et al. 2001, Khan et al. 2012, Khan et al. 2013).

There are several previous stormwater or LID geospatial or decision-making studies, in which the focus is primarily on the detailed design phase of a project and can be divided into three categories: The studies in the first category include the prioritization of different hydraulic scenarios (e.g., use of detention ponds, or other end-of-pipe methods) typically using stormwater models (SWM) in conjunction with a decision-making models to determine the most effective solution (e.g., Song and Chung 2017, Ahmed et al. 2017). In the second category, studies focus on finding feasible locations for implementing LIDs using geospatial analysis (e.g., Charlesworth et al. 2016). In the third category, studies prioritize feasible locations for LIDs using both geospatial analysis and SWM (e.g., Jato-Espino et al. 2016, Yang et al. 2015).

In addition to the aforementioned studies, limited research address prioritizing sites for LIDs in terms of hydrological and hydraulic parameters using methods not specifically developed for LID purposes. For example, Martin-Miklea et al. (2015) uses a spatial analysis to prioritize sites for LID in a catchment in central Oklahoma, U.S to identify hydrologically sensitive areas (HSA). HSA is a concept based on the probability of pollution transport risk used in a previous study (Martin-Miklea et al. 2015). However, the approach used was not developed specifically for LID purposes. Thus, the considered criteria and the developed HSA procedure does not match the physical processes that occur in LIDs, limiting its usefulness. The method does not consider the spatial or temporal distribution of rainfall, has mathematical limitations (e.g., can only handle non-zero values for some variables), and is overly sensitive to certain input parameters due to limitations in the overlaying technique used.

Several gaps have been identified in previous research: none of the previous studies address the strategical planning phase of the LID projects (one phase prior to the detailed design phase) at which the optimized location for LIDs are identified; the scale of the studies is limited to small (i.e., neighbourhood) scale rather than a regional or city-scale approach; a geospatial framework is not used to find the sources of flood in previous research. To address these needs, the objective of this study is to develop a geospatial framework to identify the location of LID demand or priority areas, using a proposed hydrological-hydraulic index (HHI). To do this, based on physical principles, we identified the spatial variables representing the LID performance. Then, hydrological and hydraulic benefits of LID were geospatially indexed based on these variables. Combining these two indices an HHI map was generated, in which the sites within the study area are prioritized according to their potential in runoff generation and flood risk. The developed model was applied to an actual case study, City of Toronto.

The proposed framework is not limited by the scale of the study area, so modelling of a neighborhood to a megacity scale is feasible. The framework is developed based on the governing hydrological-hydraulic principles of LID and is conducted in geographical information systems (GIS) modelling environment (ArcGIS). This framework can be applied for development strategies for future flood risk reduction, urban planning, land use management, and sustainable development. This paper is organized as follows: section 2 presents the methodology, section 3 includes the results and discussion, followed by a conclusion in section 4.

2 METHODOLOGY

To identify the sites with the highest demand for LID, we developed a Hydrological-hydraulic index (HHI). HHI consists of two sub-indices as Hydrology Index and Hydraulic index. HHI ranks the areal units (e.g., pixels) based on their potential to generate a flood hazard. To do this, first the geospatial variables representing the hydrology and hydraulic process were identified based on the respective governing equations and physical principles. Then, two different indices were developed using the identified variables: the hydrological and hydraulic indices. Finally, the HHI was generated by overlaying these two indices and the index was applied to the City of Toronto as a case study.

2.1 Hydrological Index Development

The hydrological index is an index representing the hydrological impact of LID on flood generation. This index ranks the areal units based on their potential in generating the high volume of runoff. Meaning that the sites with the highest rank of hydrological index contribution the most in the flood generation in terms of runoff volume. To perform this ranking, linking the spatial characteristics of the sites and physical principles is required.

Implementing different types of LIDs in a catchment has an essential influence in decreasing the volume of runoff (e.g. pervious pavement or bioretention cell) (Kong et al. 2017, Ahiablameet al. 2013, Hu et al. 2017, Shah and Antuma 2016). The spatial variables with which this impact is represented are based on general theories of infiltration. In all common infiltration formulas (e.g. the Green-Ampt method (Mein and Larson 1973)), the amount of volume of runoff is a function of four main variable: (1) land cover (2) rainfall (3) soil properties (e.g. in Curve Number method (USDA Natural Resource Conservation Service 1986) the soil hydrological group, or in the Green-Ampt method, the soil hydraulic conductivity) (4) antecedent moisture of the soil.

In this research, we used the Green-Ampt approach to determine the spatial variable impacting the runoff volume. In this method, the antecedent soil moisture is considered to be saturated, and thus, the infiltration rate is equal to saturated hydraulic conductivity (K_s) (Mein and Larson 1973). Therefore, the amount of runoff generated is equal to the difference between the rainfall intensity (R) and K_s. However, in urban areas, K_s - derived from surficial geology – needs to be modified based on the impervious areas. To do this, land cover data (representing impervious areas) with impervious areal units were extracted, and their K_s value was set to zero.

The rainfall intensity, R, used was selected as maximum value of the intensity-duration-frequency (IDF) curve for the study region, which typically occurs in the first 5 minutes of a design rainfall event. In calculating the runoff volume, another critical variable is D, which is the minimum of depth to groundwater table and depth to the first impermeable soil layer. D indicates the soil capacity for containing runoff in depth direction. The soil capacity for containment of water is the porous volumes in the vertical direction so a coefficient of n (porosity) assumed to be 0.25 for the entire study area. We assumed this variable due to the lack of spatial data. Thus, a low value of either K_s or D decreases the amount of infiltration and therefore, increases the runoff volume.

In this study to generate the hydrological index, we used mathematical operations to overlay the spatial data described above. The four variables (R, K_s, D, and n) were derived from raw data (collected from open data available at Government of Canada, Toronto and Region Conservation Authority (TRCA), Groundwater Information Network (GIN), and the City of Toronto) and overlaid in the ArcGIS environment to generate the hydrological index. Figure 1 presents the schematic of the process of developing the hydrological index including data sources, variables used and overlaying process.

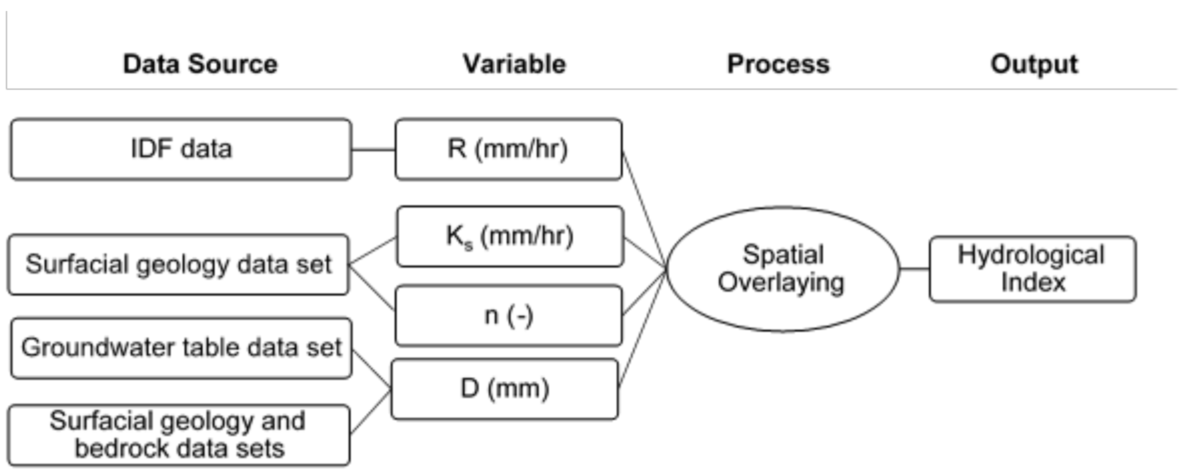

Figure 1: Schematic of the hydrological index development process including the data source, the variable of interest, the process and output of the model

2.2 Hydraulic Index Development

Unlike the hydrological index, the hydraulic index does not account for the volume of runoff. Instead, this index highlights the potential of areal units in generating short time of concentration. The sites with the same hydrologic index and different hydraulic index will generate the same volume of runoff but with different time of concentration (t_c) values.

In addition to runoff volume reduction, LID attenuates the peak flow and increases t_c (e.g. rain gardens) (Prince George's County 1999, Browne 2016). This is by providing detention volumes, decreasing the terrain slope (S) and increasing the surface roughness (Prince George's County 1999). The spatial variable representing this benefit of LID can also be represented with the time of concentration. The time of concentration, in all common formulae, is a nonlinear function of the area and slope of the catchment. Thus, in catchments with the same area (as is in this study, the areal units are pixels with the equal area), the difference in generating a shorter time of concentration is a function of the slope only. To determine the degree of the nonlinear relationship between the slope of the terrain and t_c, we used Kirpich's formula (Richard and Rawls 1984). In Kirpich's formula, t_c is a function of $S^{0.385}$. This nonlinear relationship was used in the slope layer as the variable representing the time of concentration.

2.3 Study Area

The study area is the administrative boundary of City of Toronto located in Southern Ontario, Canada with an area of 630.2 km^2. The extent of the study area is presented in Figure 2 (hatched with orange color). This city is a mixture of different land uses (e.g., residential, industrial, commercial, etc.). Eleven rivers pass through the city, which divides the city into eleven corresponding watersheds. Figure 2 presents the extent of the study area, each of the watersheds within Toronto, and their intersection with the administrative border of the City of Toronto.

Figure 2 The extent of the study area, the 11 main rivers (Carruthers, Don, Duffins, Etobicoke, Frenchmans Bay, Highland, Humber, Mimico, Petticoat, Rouge) and corresponding watersheds

2.4 Spatial Data

In this study, publicly available data were used. The spatial data used for this study included:

- Bedrock layer
- Digital elevation model (DEM)
- Groundwater table
- Land cover
- Soil saturated hydraulic conductivity
- Toronto precipitation data

All required variables were derived from the attributes of the raw data, then, converted to raster format with the ground resolution of 5 m x 5 m (which is the resolution of the DEM data).

3 RESULTS AND DISCUSSION

3.1 Identifying Sites with High Demand for LID using HHI

To generate the HHI, firstly, the four variables (R, D, K_s, n) of the hydrological index, were spatially overlaid. Then, the hydraulic index was generated using the slope variable. Finally, the hydrological and hydraulic indices were spatially combined.

The terrain slope (S) was derived from DEM data using the slope tool. Hydraulic conductivity (K_s) was derived from surficial soil characteristics. However, in urban areas soil is a partial type of land cover and a vast range of lands are impervious surfaces, whose K_s is zero. Thus, to set the K_s of impervious land covers (e.g. road pavements, parking lots and buildings) equal to zero, K_s layer is integrated into the land cover layer by a minimum operation. To do this, in the land cover layer the impervious layer was extracted and reclassified to zero.

The raster layer of depth to the groundwater table was generated using the inverse distance weighted (IDW) tool, using the point data of the groundwater well information. The raster layer of depth to restrictive strata, however, was generated from the polygon bedrock data. Depth to restrictive layer (D), was calculated from minimum operation between depth to groundwater table and depth to restrictive strata.

The rainfall layer (R) was derived from the Intensity-Duration-Frequency tables of three meteorological stations including Oshawa WPCP, Oakville southeast WPCP, and Toronto Buttonville (A) within the City of Toronto. the raster rainfall data for the study area were generated by an IDW tool. The value of R (in mm/hr) was selected as the 5 min rainfall intensity from the IDF graph for the 100-year return period. We assumed that an acute rainfall intensity represents an actual extreme event for the R value. Finally, the effect of existing LIDs was needed to be incorporated into the result. To do this, the HHI map was masked by existing LIDs or other GI locations, so existing LIDs were eliminated by converting the corresponding areal units to "NoData".Figure *3* illustrates the map of each of the hydrological variables (R, K_s, D), the hydraulic variable (S), and existing GI and the HHI produced. The HHI ranges from139 to 436 which was normalized linearly between 0 and 1, and is presented in Figure 4.

3.2 Discussion

The generated HHI map indicates that within the Don watershed the highest HHI are primarily located in the eastern branch of Don River. High HHI regions of the western branch are mostly concentrated in the central parts of the city. Similar to the Don, the eastern branch of the Humber River, Black Creek and Albion Creek shows to be a higher source of flood generation as compared to the western branch. Another notable area with high HHI is the northern part of the Highland watershed, upstream of three main rivers (the Malvern, Markham and Bendale branches of the Highland River), which can cause flooding at the intersection of these three branches or at any depression point along the rivers. In addition, the eastern part of Waterfront watershed located near Lake Ontario encloses a large area with high HHI. The last evident source of floods is located in Rouge watershed, located in the center of the catchment. In all these high HHI areas, the HHI value is due to a combination of low hydraulic conductivity, high precipitation, low depths to restrictive layers and high slopes of this area (Figure 3). Unlike these areas, the eastern part of the Humber River, Mimico, Etobicoke, Petticoat, Frenchmans Bay, and western part of Waterfront watersheds have relatively lower values of HHI.

The HHI index generated in this study is by considering the size of areal units to be 5 m by 5 m meaning that study area is segmented into 17.9 million areal units. The mean HHI for all areal units is 0.4 with a standard deviation of 0.079. The histogram of HHI versus normalized count of areal units for the entire

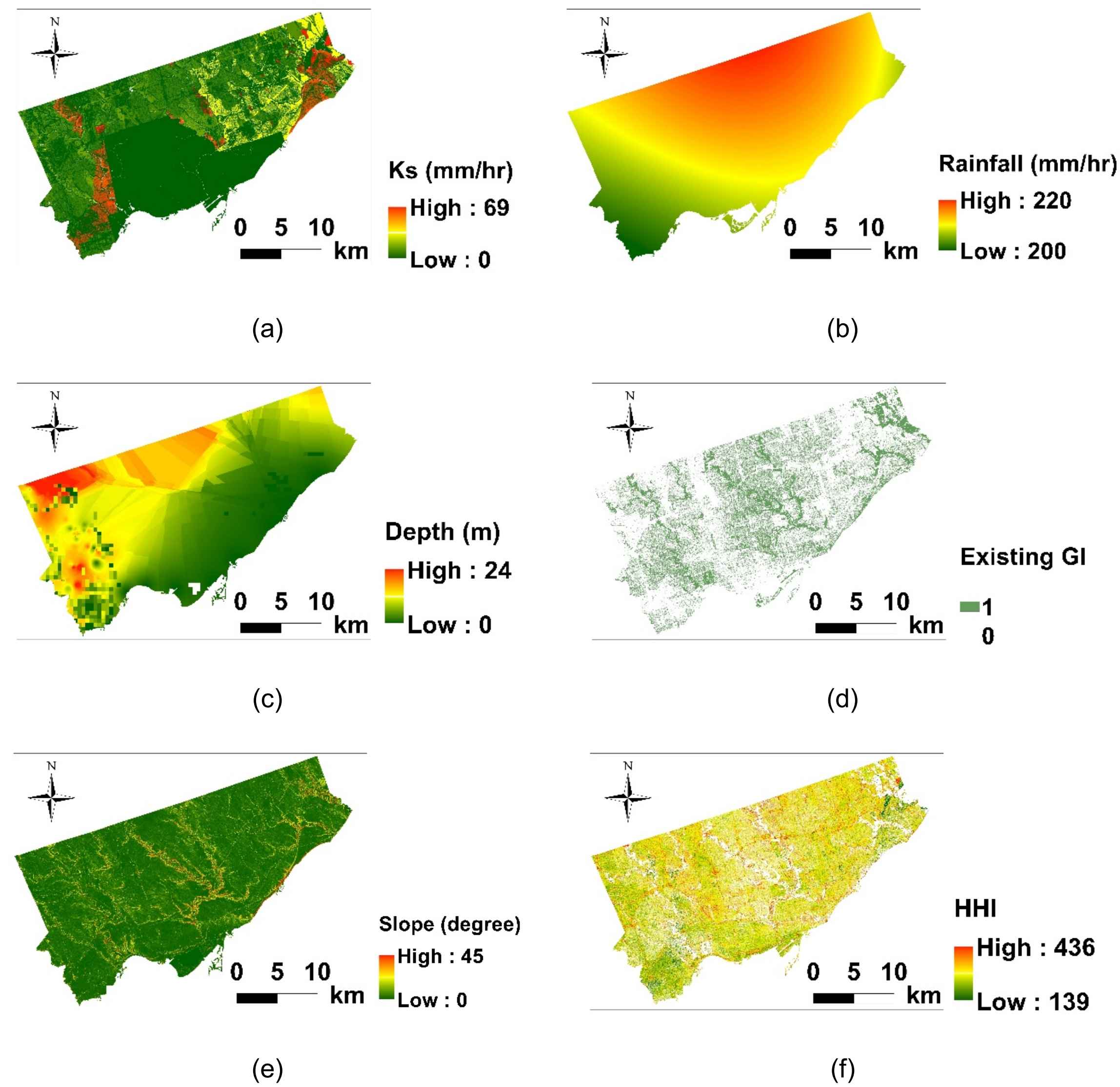

Figure 3: Hydrological variables (a) Hydraulic conductivity, (b) Rainfall intensity, (c) Depth to restrictive layer, (d) existing GI, (e) hydraulic variable terrain slope, and (f) Generated Hydrological-Hydraulic index

study area is presented in Figure 5. The non-symmetrical distribution of HHI is skewed to the right, highlighting a small portion of areas that have higher HHI than the mean.

When comparing results of HHI generation for each watershed within the study area, the results (shown in Figure 6) show that the Don has the greatest mean HHI of 0.427, whereas Mimico has the minimum mean HHI of 0.382 (10.5% less than the Don). The mean HHI values for the Waterfront, Humber, Highland, and Rouge watersheds are 8.9, 4.4, 2.8 and 2.6% less, respectively than the Don watershed. Comparing on a watershed basis can help prioritise each watershed on the need or demand of LID in each area. The results clearly demonstrate that the Don has the highest rank in terms of flood or runoff generation, whereas the Rouge has the lowest rank. Obviously, the hydraulic capacity status of the existing stormwater collection network and river is needed to be incorporated into these results to finalize the demand of LID within each of the watersheds. However, the distribution of HHI across the study area provides us with a knowledge of estimating the potential flood vulnerable areas.

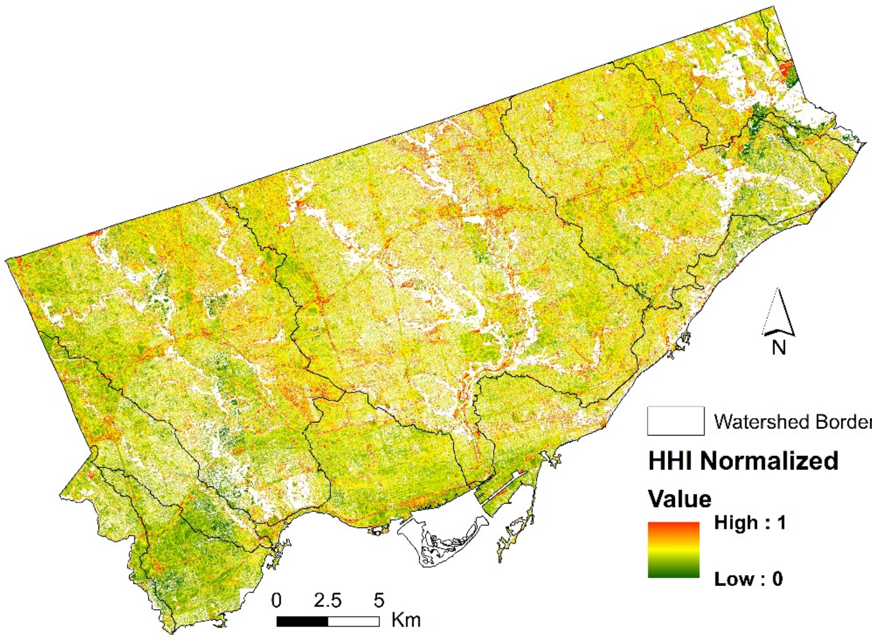

Figure 4: The normalized HHI map showing the Toronto watershed borders; areas in red represent areas with higher HHI and vice versa for green

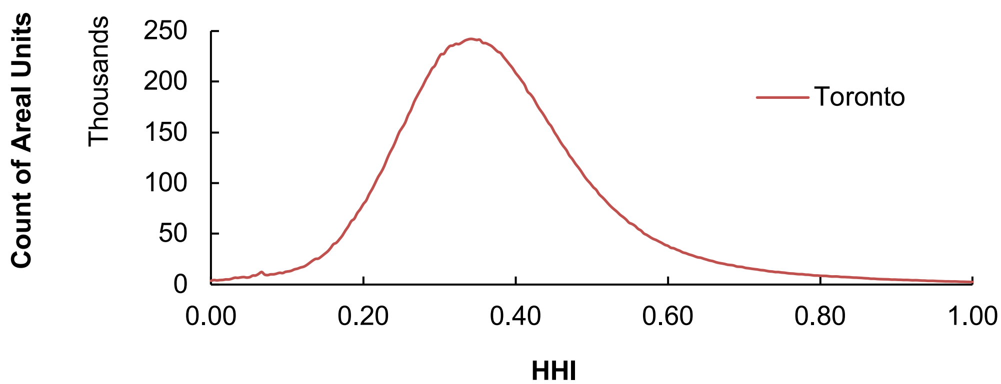

Figure 5: The frequency of the HHI for the entire study area (City of Toronto)

This estimates of HHI produced in this research provides an insight into the hydrological-hydraulic status of sub-catchments at a micro scale of 25 m^2 (the size of each areal unit). This allows us to highlight the upstream areal units within the study area which contributes the most in runoff or floods to the downstream flood-prone locations. Targeting these areas for implementing LID enhances the effectiveness of LID for stormwater management. Studying the effect of HHI on the downstream flood occurrence is suggested to be performed for independent watersheds individually. This allows us to investigate the effect of HHI on flood generation across each watershed.

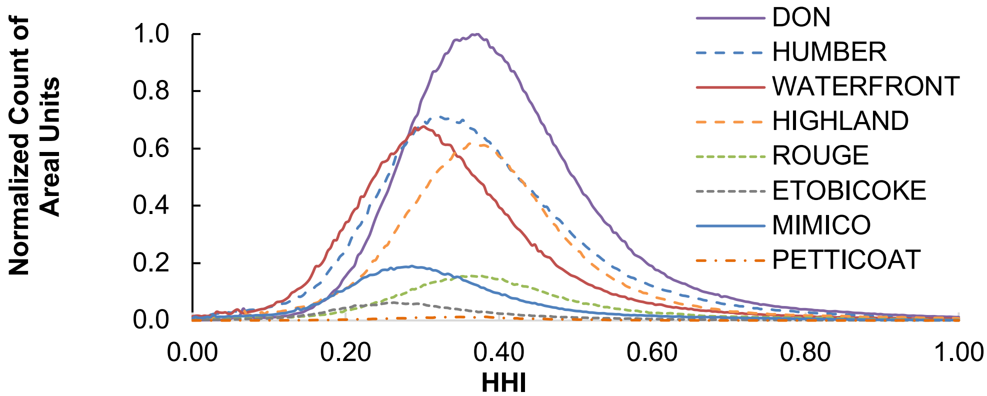

Figure 6 The normalized frequency of HHI for each watershed within the City of Toronto showing the distribution of the areal units for different HHI values

4 CONCLUSION

In this study a physical-based geospatial framework was generated to index, rank and highlight the study area sites based on their potential in flood hazard generation. The method applied was considering hydrological-hydraulic governing equations using publicly available spatial data. Two different indices were generated and combined to develop a LID HHI map for the City of Toronto. Results highlight regions with the highest potential to contribute to runoff and flood generation, and are thus, regions most suited to the installation of LIDs. The advantages of this framework include: a physical-based spatial approach in which publicly available data is used; it is applicable in either small or large-scale watersheds; using this method for stormwater management planning can enhances the effectiveness of implementing LIDs; addresses the lack of a systematic decision model in the strategic planning phase of the LID projects (Zhang and Chui 2018).

REFERENCES

Ahiablame, L. M., Engel, B. A. and Chaubey, I. 2013. Effectiveness of Low Impact Development Practices in Two Urbanized Watersheds: Retrofitting With Rain Barrel/Cistern and Porous Pavement. *Journal of Environmental Management*, **119**: 151–161.

Ahmed, K., Chung, E., Song, J. and Shahid, S. 2017. Effective Design and Planning Specification of Low Impact Development Practices Using Water Management Analysis Module (WMAM): Case of Malaysia. *Water*, **9**(3): 173–187.

American Rivers, Tetra Tech and Joyce Foundation. 2010. *Low Impact Development Manual for the Lower Maumee And Ottawa River Watersheds*. American Rivers, Beltsville, MA, USA.

Browne, F X. 2003. Using Low Impact Development Methods to Maintain Natural Site Hydrology. *World Water & Environmental Resources Congress,* ASCE, Philadelphia, PA, USA, 1–9.

Charlesworth, S., Warwick, F. and Lashford, C. 2016. Decision-Making and Sustainable Drainage: Design and Scale. *Sustainability,* **8**(8): 782–793.

Cheng, M.S., Coffman, L.S. and Clar, M.L. 2001. Low-Impact Development Hydrologic Analysis. *Specialty Symposium on Urban Drainage Modeling at the World Water and Environmental Resources Congress,* ASCE, Orlando, FL, USA, **1**: 659-681.

Coffman, L.S. 2002. Low Impact Development: Smart Technology for Clean Water – Definitions, Issues, Roadblocks, and Next Steps. *Ninth International Conference on Urban Drainage*, ASCE, Portland, OR, USA, 1–11.

Coffman, L.S., Goo, R. and Frederick, R. 1999. Low-Impact Development: An Innovative Alternative Approach to Stormwater Management. *29th Annual Water Resources Planning and Management Conference,* ASCE, Tempe, AZ, USA, 1–10.

Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, D., Semadeni-Davies, A., Bertrand-Krajewski, J., Mikkelsen, P.S., Rivard, G., Uhl, M., Dagenais, D. and

Viklander, M. 2015. SUDS, LID, BMPs, WSUD and More – The Evolution and Application of Terminology Surrounding Urban Drainage. *Urban Water Journal,* **12**(7): 525–542.
Heal, K., Mclean, N. and D'arcy, B. 2004. SUDS and Sustainability. *26th Meeting of the Standing Conference on Stormwater Source Control*, University of Edinburgh, Dunfermline, Fife, Scotland, 1–9.
Hu, M., Sayama, T., Zhang, X., Tanaka, K., Takara, K. and Yang, H. 2017. Evaluation of Low Impact Development Approach for Mitigating Flood Inundation at a Watershed Scale in China. *Journal of Environmental Management,* **193**: 430–438.
Jato-Espino, D., Sillanpää, N., Charlesworth, S.M. and Andrés-Doménech, I. 2016. Coupling GIS with Stormwater Modelling for the Location Prioritization and Hydrological Simulation of Permeable Pavements in Urban Catchments. *Water,* **8**(10): 451–468.
Khan, U.T., Valeo, C., Chu, A. and van Duin, B. 2012. Bioretention Cell Efficacy in Cold Climates: Part 2 - Water Quality Performance. *Canadian Journal of Civil Engineering,* **39**(11): 1222–1233.
Khan, U.T., Valeo, C., Chu, A. and He, J. 2013. A Data Driven Approach to Bioretention Cell Performance: Prediction and Design. *Water,* **5**(1): 13–28.
Kong, F., Ban, Y., Yin, H., James, P. and Dronova, I. 2017. Modeling Stormwater Management at the City District Level in Response to Changes in Land Use and Low Impact Development. *Environmental Modelling and Software,* **95**: 132–142.
Martin-Miklea, C.J., de Beurs, K.M., Julianb, J.P. and Mayer, P.M. 2015. Identifying Priority Sites for Low Impact Development (LID) in a Mixed-Use Watershed. *Landscape and Urban Planning*, **140**: 29–41.
McCuen, R.H. 2003. Smart Growth: Hydrologic Perspective. *Journal of Professional Issues in Engineering Education and Practice*, **129**(3): 151–154.
Mein, R.G. and Larson. C.L. 1973. Modeling Infiltration during a Steady Rain. *Water Resources Research,* **9**(2): 384–394.
Mouritz, J.M. 1996. *Sustainable Urban Water Systems; Policy & Professional Praxis*, PhD Thesis, Murdoch University, Perth, Australia.
Prince George's County. 1999. *Low-Impact Development Design Strategies: An Integrated Design Approach,* Department of Environmental Resource Programs and Planning Division, MD, USA.
McCuen, R.H., Wong, S. and Rawls, W.J. 1984. Estimating Urban Time of Concentration. *Journal of Hydraulic Engineering*, **110**(7): 887–904.
Shah, I. and Antuma, R. 2016. Conventional vs Low Impact Development Stormwater Management Case Studies. *2016 Annual Conference of the Canadian Society for Civil Engineering,* CSCE, London, ON, Canada, 985–987.
Song, J.Y. and Chung, E.S. 2017. A Multi-Criteria Decision Analysis System for Prioritizing Sites and Types of Low Impact Development Practices: Case of Korea. *Water*, **9**(4): 291-308.
United States Department of Agriculture (USDA), Natural Resources Conservation Service. 1986. *Urban Hydrology for Small Watersheds TR-55*. 2nd ed., USDA, USA.
Yang, J.S., Son, M.W., Chung, E.S. and Kim, I.H. 2015. Prioritizing Feasible Locations for Permeable Pavement Using MODFLOW and Multi-Criteria Decision Making Methods. *Water Resources Management*, **29**(12): 4539–4555.
Zhang, K. and Chui, T.F.M. 2018. A Comprehensive Review of Spatial Allocation of LID-BMP-GI Practices: Strategies and Optimization Tools. *Science of the Total Environment,* **621**: 915–929.