Determination of Imperviousness in the Highland Creek Watershed

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The Highland Creek watershed, an area of about 100 square kilometres in the region of Toronto, was selected for this study. As a highly urbanized area, construction of roads and buildings has increased the region's imperviousness to watershed, which can cause severe impairment to both the quality and quantity of water. The imperviousness of this region therefore needed to be assessed to manage the watershed area effectively, and to improve future development projects. The task of assessing the watershed area was accomplished using digitized aerial photographs and Geographical Information Systems (GIS). Because GIS does not give detail total road area of land use, the difference between total area and impervious area was calculated and assigned as a total road area. The ratio between the impervious area and the total area was calculated to assess the impervious ratio of the watershed area, and was assigned a value of 0.533. Using this method, more than 120 subcategories can be selected within this watershed area, and the imperviousness can be calculated using land use subcategory ratios and averages ratios.

Non point source pollution has become an increasing threat to water systems because of urbanization. Among many reasons identified for water quality impairment, urbanization is found to be the major one in polluting the water ways and rivers.⁵ Stormwater runoff is increased because of the decreased infiltration resulting from impervious surfaces, which include roads, roof tops, buildings, paved floors, sidewalks and compacted soils. As an environmental indicator, Arnold and Gibbons have analyzed the effects of urbanization on water quality,² and have determined that as population density increases, the need to build the highways and other structures also increases, and ultimately results in a decreased pervious area.

Environmental impacts include; altered hydrologic cycle, fragmentation, increased runoff leading to flooding, increased stream sediments, decreased groundwater recharge - which all contribute to modify physical and ecological characteristics of the ecosystem.^{2, 4, 7} As an example, urbanization demands the removal of trees that would otherwise keep stream temperatures steady - because of fluctuations in temperature, the natural development of some fish species and other temperature sensitive living organisms is consequently hindered.⁵ In 2009, in the interest of maintaining the integrity of the Highland Creek Watershed (HCW) the *Toronto and Region Conservation Authority* (TRCA) focused its efforts on determining the threshold of the region's imperviousness.

The relationship existing between imperviousness and water quality has been studied to contribute to plans of land

use and watershed area. The findings from these studies were summarized by Brabec et.al, who found that watershed planning must be conducted based on runoff volumes and imperviousness, as water quality declines when imperviousness levels reach below 10-15%.³ From this work, integration of imperviousness into the Geographical Information System (GIS) was also determined to be very useful in watershed planning.^{3, 4}

While many studies are focused on imperviousness and its impact on watershed, few have explored actual calculations of imperviousness based on a surface area. Among them, Chabaeva et.al investigated several techniques by which an impervious area can be assessed, including a technique referred to as 'interpretive detection' where an image is interpreted by human analyst to gather data.⁴ Because this method is subject to visual errors, spectral pattern recognition is another method used, however, higher resolution information is required as it uses digital remote sensing images. A third technique, analyzed by Chabaeva et.al, is the statistical and mathematical modelling method, that utilizes the equations and coefficients in calculating the imperviousness.⁴ In their work, Chabaeva et.al suggest that selecting the appropriate technique for analysis will ultimately be based on availability of data, resource availability, and the accuracy level needed by the planning project.⁴

Based on the aforementioned factors, this paper presents a methodology for estimating the imperviousness of the HCW using aerial photographs and land use data.

METHODOLOGY

Study Area

The Highland Creek is the most developed (85% urbanized) watershed area in the Toronto and Region Conservation's Jurisdiction, where most of the watershed area lies within the City of Toronto, and a small portion lies in the Markham Township. According the 1996 census, the total population in this watershed area is 357,673,⁵ and has over 75 km of watercourses, draining a 102 square km area.⁵

Because this area was developed before the instalment of adequate storm water management measures, poorly designed watercourses now feed degraded water into the Highland Creek, which eventually empty into Lake Ontario (**Figure 1**). Erosion prevention construction, including concrete or gabion baskets, lined water courses, have made the creeks and rivers an unfavourable habitat for terrestrial living organisms. Highland Creek also has more than 90 in-stream barriers, which include weirs and dams, that prevent the free movement of fish species. Furthermore, the watershed area has suffered extensive tree loss and is left with only 6.2% of surrounding forest untouched, which impacts the temperature of the Creek.⁵ Disadvantages of non point source pollution include a high nutrient (pollutant) load, high volume of runoff, and a constant threat to fish species such as trout, carp and bass.⁵

Method

City of Toronto land use maps were used to calculate the imperviousness of HCW area. The city has a comprehensive database of main land use categories, which include commercial (COM), Industrial (IND), Institutional (INS), Multifamily Residential (MFR) and the Single Family Residential (SFR) divisions, with each category containing many sub-categories based on each land parcel's actual use. As an example, SFR is divided into detached, semi detached, link homes, town houses etc. Digitized aerial photographs of the watershed, taken in 2005, were used to estimate impervious area of each land parcel using ArcGIS 9.2.⁷

The objective of this method was to select several land parcels randomly, as sample representations of overall imperviousness, ensuring spatial variability and variability among land use types. Five to six major sub-categories were selected within the major land use groups (COM, IND, INS, SFR and MFR), and impervious areas were digitized using ArcGIS according to aerial photographs. **Figure 2** illustrates the distribution of land parcels used for analysis under different land use group. Using GIS attribute tables, ratio imperviousness to total area for each parcel was calculated using *equation 1*:

$$\text{ImperviousnessRatio} = \frac{\text{ImperviousArea}}{\text{TotalArea}} \quad [1]$$

Once the percent imperviousness was estimated, an average value for each land use group (ie: COM) was determined by averaging the whole land use sub-categories under each main land use considered. These averages were assumed to represent the imperviousness of the appropriate land group throughout the watershed. That is, for all the other land use sub categories that were not estimated, values were assigned based on their main land use category. Rather than taking just one average, averages for more than one area were considered for accuracy. This task was accomplished by calculating several averages from each group, by averaging 2, 3, 4, 5 of the land use sub-categories, following with the rest of all subcategories. These five averages were then applied respectively for all the subcategories to calculate the impervious area and the percent imperviousness of HC watershed area. Since it is not possible to manually draw all the impervious area of all the sub categories in the watershed area, priority was given to the most common subcategories. Also, variation within the main land use is very minimal, and so the average values of the group (COM) that were calculated as explained before, were used for other subcategories within each main land use group (COM).

The task was to establish which average best suited the watershed imperviousness, thereby determining whether the method is valid or not. The number of subcategories used to calculate each average (2, 3, 4 etc) was added to plot against the percent imperviousness (calculated for the whole watershed area) using the different averages as described previously. We will now discuss the verifying method.

The aim of this verifying method was to determine whether the method used to calculate the percent imperviousness was valid. In this method, subcategories

Figure 1: Highland Creek watershed area showing the boundaries and the Creek (using ESRI maps, 2005)

Figure 3: Land parcels and areas selected for the study within the HC watershed area (using ESRI, 2005 maps)

were also used for percent imperviousness calculations. The difference however is that five, roughly one square kilometre area parcels, were randomly selected within the watershed to draw the impervious area in the digitized aerial photograph (**Figure 2**). To obtain land use details, selected square kilometre areas were matched and clipped with GIS files. Imperviousness of each sub-category and calculated averages of main land use categories were used to calculate the total impervious area of each area parcels using *equation 1*. Results obtained using the method and the verifying methods will be discussed in the results and discussion section.

In calculating the imperviousness of the watershed area, *equation 1* required total impervious area and total area of each area parcels selected for testing. Therefore in verifying the method, for each individual area parcels, the impervious area was obtained from the attributes table of the respective impervious shape file, and the total area from the attributes of the respective area clip file. The difference between these was therefore considered the road area. To assess the imperviousness of the roads, visual inspection was used and an impervious ratio of 0.75 was applied throughout the watershed area.

Although there are two different ways in which the imperviousness can be calculated, using total impervious area (TIA) and the directly connected impervious area (DCIA), TIA was used in this study due to lack of data availability. Also, identified categorized land use types, such as buildings and streets, were used as per Roy and Shuster digitized aerial photographs.⁸ Interestingly, Roy and Shuster used publicly available geographic information system and the parcel scale field assessment data to obtain valuable results, that can now be used to plan the future DCIA within a defined land parcel. Although DCIA or effective

impervious area (EIA) is the more appropriate measure because storm water runoff is immediately directed to the creeks and rivers, it is time consuming to collect individual parcels scale field assessments.⁸

RESULTS AND DISCUSSION

Figure 3 represents the distribution of the statistical data of the HCW area. To start, the institutional group (INS) ranges between 0.2 and 0.85, indicating that more data is needed to better represent the watershed imperviousness. Similarly, in the commercial group (COM) because of its short range (0.8 to 0.95) we can determine that more data is needed to be conclusive with results. The Industrial group (IND) was next shortest in range because of the limited data set. The average imperviousness of particular land use, the range of imperviousness, and 10th and 90th percentile of the range were obtained from this plot. The variability order can therefore be listed in descending order starting from INS, MFR, SFR, IND and COM.

In **Figure 4**, the ratio imperviousness is almost steady throughout the number of land parcels used. Starting from 55 land parcels, the study considered 134 land parcels to calculate the average imperviousness. Although imperviousness was observed to be a little higher around the point closed to 80th land parcel, the trend was steady and remained at 0.533 imperviousness ratio (at 119th land parcel). This implies that the minimum land parcels that can be used to represent the imperviousness of the whole watershed area is 119 for a watershed of the same area as the HCW. The

Figure 2: Statistical representation of land use types and their imperviousness in the HCW area, with land use types and their ratio imperviousness spanning vertically

method used 134 subcategories for the study and determined

Figure 5: The plot to show the ratio imperviousness obtained

that the ratio imperviousness for the HCW area is 0.533. **Table 1** summarizes the results obtained from five land areas taken for imperviousness calculations.

In **Table 2**, imperviousness using the testing method and the direct method are presented. Imperviousness using the testing method for area 1 through 5 was calculated by calculating the impervious area and the imperviousness of the subcategories found within, if any other subcategories found within the area parcels, the calculated average for that particular main land use group was used.

Using the above described methods, ratio imperviousness was calculated, and using the testing method, validation of results was compared (**Figure 5**). With an R^2

Figure 4: Comparison of actual imperviousness using the direct method and the estimated imperviousness of the testing method. $y=x$ line represent the ideal situation

Table 2: Summarizes the impervious ratio from the HC watershed area

Number of land parcels	Impervious ratio
55	0.533
79	0.551
100	0.543
119	0.533
134	0.534

Table 2: Comparison between approaches for determining land use area

Area	Testing Method	Direct Method
Area 1	0.483	0.446
Area 2	0.468	0.435
Area 3	0.716	0.682
Area 4	0.597	0.577
Area 5	0.593	0.588

value is 0.98, the correlation between these two data sets can be well accepted, and from this, we can determine that the method is an accurate one. An ideal case line is shown for comparison, where $x = y$.

Having proved the method for imperviousness calculation (using the random selection of land use subcategories) this method is applied to the whole watershed area to calculate the imperviousness of the HCW area as described in the previous section, using imperviousness of subcategories and average values. For this purpose, Area 4 was taken as the best representation as it intersects with the actual vs. estimated imperviousness line (**Figure 5**).

CONCLUSION

To calculate percent imperviousness, total area and impervious area were needed using GIS tools and the digitized aerial photographs. According to the method used, percent imperviousness of the HCW area was calculated to be 53%. Interestingly, this value is consistent with studies conducted by Ackerman and Stein,¹ who determined that a high density and highly urbanized area (such as the HCW) should have the percent imperviousness falling within the range of 50- 80%.¹ Another conclusion we draw from this study is the ability to estimate the imperviousness of a watershed area of about 100 square kilometres, using a minimum of 120 land parcels (particularly commercial and industrial land uses) as these are features shared by the HCW.

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