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Development of Techniques to Quantify Effective Impervious Cover

Ben Janke
John S. Gulliver

St. Anthony Falls Laboratory
Department of Civil Engineering

Bruce N. Wilson

Department of Bioproducts and Biosystems Engineering

University of Minnesota

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16. Abstract (Limit: 250 words)

Practitioners responsible for the design and implementation of stormwater management practices rely heavily on estimates of impervious area in a watershed. However, the most important parameter in determining actual urban runoff is the “effective” impervious area (EIA), or the portion of total impervious area that is directly connected to the storm sewer system. EIA, which is often considerably less than total impervious area and can vary with rainfall depth and intensity, is likely not determined with sufficient accuracy in current practice. A more accurate determination of EIA in a watershed would benefit a wide range of organizations involved in the design of stormwater management, pollution prevention, and transportation structures.

This study investigated two existing methods of estimating EIA in a watershed: (1) analysis of large rainfall-runoff data sets using the method of Boyd et al. (1994), and (2) overlay analysis of spatial (GIS) data, including land cover, elevation, and stormwater infrastructure, using the method of Han and Burian (2009). The latter method provides an estimate of connected pavement, but requires the user to input the value of connected rooftop to determine the actual EIA value, which is the sum of these two quantities. The two methods were applied to two urban catchments within the Capitol Region Watershed in St. Paul, MN. The results were used to evaluate the potential of each method and make recommendations for future studies.

In summary, the data analysis technique (Boyd et al., 1994) has the advantage of being quick and relatively simple to implement, as it did not require familiarity with specialized software tools (e.g. ArcGIS) and could be completed with any spreadsheet program with graphing capabilities (e.g. Excel). The EIA estimates from the data analysis are the most accurate, but the technique is unable to determine where in the watershed the EIA is located, and cannot be used if runoff discharge and local precipitation data is unavailable. By contrast, the GIS method (Han and Burian, 2009) has the advantage of being applicable to un-gauged watersheds, and also provides the location of EIA in the watershed. This latter feature makes it particularly attractive for honing the development and placement of BMP’s in a watershed. Unfortunately, the accuracy of the GIS method is completely dependent on the ability to faithfully represent the amount of roof connection in a watershed, a process that can add significant time and expense to the EIA estimate.

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Prepared by:

Ben Janke
John S. Gulliver

St. Anthony Falls Laboratory
Department of Civil Engineering

Bruce N. Wilson

Department of Bioproducts and Biosystems Engineering

University of Minnesota

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Executive Summary

Practitioners responsible for the design and implementation of stormwater management practices rely heavily on estimates of impervious area in a watershed. However, the most important parameter in determining actual urban runoff is the ‘effective’ impervious area (EIA), or the portion of total impervious area that is directly connected to the storm-sewer system. EIA, which is often considerably less than total impervious area and can vary with rainfall depth and intensity, is likely not determined with sufficient accuracy in current practice. A more accurate determination of EIA in a watershed would benefit a wide range of organizations involved in the design of stormwater management, pollution prevention, and transportation structures.

This study investigated two existing methods of estimating EIA in a watershed: (1) analysis of large rainfall-runoff data sets using the method of Boyd et al. (1994), and (2) overlay analysis of spatial (GIS) data, including land cover, elevation, and stormwater infrastructure, using the method of Han and Burian (2009). The latter method provides an estimate of connected pavement but requires the user to input the value of connected rooftop to determine the actual EIA value, which is the sum of these two quantities. The two methods were applied to two urban catchments within the Capitol Region Watershed in St. Paul, MN: one was a small (42-ac), relatively uniform residential neighborhood, and the other was a large (3400-ac), highly-urbanized catchment with a variety of land uses present. The results were used to evaluate the potential of each method and make recommendations for future studies.

In summary, the data analysis technique (Boyd et al., 1994) has the advantage of being quick and relatively simple to implement, as it did not require familiarity with specialized software tools (e.g. ArcGIS) and could be completed with any spreadsheet program with graphing capabilities (e.g. Excel). The EIA estimates from the data analysis are the most accurate, but the technique is unable to determine where in the watershed the EIA is located and cannot be used if runoff discharge and local precipitation data is unavailable. By contrast, the GIS method (Han and Burian, 2009) has the advantage of being applicable to un-gauged watersheds, and also provides the location of EIA in the watershed. This latter feature makes it particularly attractive for honing the development and placement of BMP’s in a watershed. Unfortunately, the accuracy of the GIS method is completely dependent on the ability to faithfully represent the amount of roof connection in a watershed, a process that can add significant time and expense to the EIA estimate.

Future work should be focused primarily on two general areas: (1) improving the GIS-based estimation technique, and (2) expanding the application of both techniques to additional sub-watersheds, with particular emphasis on newer development and on catchments with more homogenous land uses. The GIS method could be improved considerably by developing techniques to improve roof connectivity estimates, e.g. through the use of land use-specific site surveys or through some novel partitioning scheme based on age or type of rooftop. An improved method for handling canopy shading of impervious surfaces than that used herein could also be investigated. Insight on both of these areas of improvement could be supplied by application of both the data

analysis and the GIS-based techniques to additional watersheds. Furthermore, additional analyses could potentially allow EIA values to be correlated to land cover characteristics such as roof type, canopy shading, age of construction, lane-miles of road, BMP presence, etc. or even to rainfall characteristics such as intensity, duration, or antecedent rainfall depth. This type of generalized information would be valuable to practitioners in applications such as stormwater management, transportation design, or water quality protection.

1 Introduction

Stormwater management is an important issue in the construction of highways and in mitigating the impacts of transportation infrastructure on our water resources. Water management accounts for a significant portion of construction costs for roads and buildings, and impervious areas in general are of environmental concern because the degradation of urban waters is primarily caused or facilitated by urban runoff, the majority of which has its origin in roads, rooftops, and parking lots. Excess nutrients, sediment, and pollutants are rapidly washed from the landscape into receiving waters by efficient storm-sewer systems designed to prevent flooding.

Practitioners responsible for the design and implementation of stormwater management practices rely heavily on estimates of impervious area in a watershed. However, the most important parameter in determining actual urban runoff is the “effective” impervious area (EIA), or the portion of total impervious area that is directly connected to the storm-sewer system. EIA is often considerably less than total impervious area and can vary with rainfall depth and intensity.

Current and developing management techniques, such as rain gardens, infiltration basins, or pervious pavements, show awareness of the need to reduce EIA, or ‘disconnect’ impervious areas from the drainage system. However, there are no standard methods to assess the impact of these disconnection practices, partly because the connectedness of the existing watershed is not well known.

Currently, EIA can be estimated by analyzing rainfall-runoff data (e.g. Boyd et al., 1993; Lee and Heaney, 2003), using aircraft- or satellite-derived spatial data such as land cover and elevation (e.g. Alley and Veenhuis, 1983; Han and Burian, 2009), or by conducting field surveys of study sites (e.g. inspection of downspout connectivity, watershed delineation during rainfall events, etc.)

While the analysis of hydrologic data in a watershed of interest will produce the best results, these data can be expensive to collect and may not always be available or of sufficient quality or resolution for analysis. Field investigations similarly may be time-consuming and costly, and provide limited results. Thus the use of GIS-based tools to estimate EIA becomes particularly attractive due to its applicability to un-gauged watersheds, and to the increasing quality and availability of spatial data.

The GIS-based tool described in this report is based on the method of Han and Burian (2009), which estimates EIA from automated analysis of high resolution land cover and elevation GIS data derived from satellite and air-based imagery. Past efforts of the Minnesota Pollution Control Agency (MPCA) and others (e.g. Kilberg et al. 2011) have developed the necessary input data for the state of Minnesota, and in particular the Capitol Region Watershed (CRW) in St. Paul and surrounding communities. In addition, the Capitol Region Watershed District (CRWD) provided rainfall and runoff monitoring data for several sub-catchments in the CRW. The tool was applied to two of these catchments, and evaluated by comparing tool-based EIA estimates to EIA determined from rainfall-runoff observations using the method of Boyd et al. (1993). Modifications to the tool needed to improve the match between EIA estimates and observations will also be described.

While beyond the scope of the current project, a more mature version of the tool would benefit a wide range of organizations involved in the design of stormwater management, pollution prevention, and transportation structures by improving the accuracy of hydrologic simulations used in the design process, and providing a means to assess the impact of disconnection on discharge from a watershed of interest. These outcomes should result in more effective and properly designed stormwater management practices, with potential improvements in water quality and cost savings for practitioners.

2 Methods

2.1 GIS-Based Tool

The tool used in this work is based on the two-step method developed by Han and Burian (2009) for estimation of EIA from automated analysis of fine-scale GIS data layers for land cover, elevation, and stormwater collection infrastructure (e.g. gutters, catch basins, or open channels). The tool is a script written in Visual Basic for Applications (VBA), and relies on the ESRI ArcGIS software package. The first step in this method involves deriving a land cover map for a watershed from multi-spectral satellite imagery. Pixels in the land cover map were classified into four cover types: rooftop, paved (asphalt/concrete), water, and vegetation. In the second step of the method, a script is used to perform geospatial analysis by overlaying the land cover, digital elevation model (DEM), and collection layer files (rasters). For each paved cell in the land cover raster, the flow path is traced by following the direction of maximum slope along adjacent paved surfaces. The original cell is then classified as 'connected' pavement if it eventually drains into a stormwater collection cell, or as 'disconnected' pavement if it drains onto a pervious cell or a local depression.

Effective (Total connected) impervious area (or EIA) is the sum of connected pavement and connected rooftop area. However, the method does not determine roof connectivity, as it can generally only be determined from field inspection, thus it is left as a user-specified parameter. Han and Burian (2009) note that in previous studies, anywhere between 2.8% and ~100% of rooftop area was effectively connected.

Our tool modifies the Han and Burian (2009) method slightly. First, the initial step to classify land cover was unnecessary, as detailed land cover data was available for the CRW. This data set had been prepared by the Forestry Department of the University of Minnesota as part of a project to classify canopy coverage in St. Paul, MN (Kilberg et al., 2011). It was derived from a combination of multi-spectral imagery (pan-sharpened to 0.6-m horizontal resolution) and LIDAR-based elevation data (horizontal resolution finer than 1.0 m). The resulting land cover map consisted of 0.6 m-square pixels, classified into six cover types: (1) tree canopy, (2) grass/shrubs, (3) bare soil, (4) water, (5) rooftop, and (6) pavement (asphalt/concrete).

A second modification of the Han and Burian (2009) method was related to the capabilities of the ESRI ArcMap software used to process the GIS data. In the original tool, smoothing of the elevation data had to be performed to remove local sinks or peaks in the drainage network, and the flow direction for each cell had to be computed by the tool. ArcMap can perform both of these operations in the version used for our study (10.0). Therefore our version of the tool had an additional input layer, the flow direction raster derived from the smoothed elevation raster. Our tool was also written in Python, as ESRI had discontinued support for VBA in favor of Python as of the 10.0 version of ArcMap.

2.2 Rainfall-Runoff Analysis

Rainfall-runoff data for the study catchments were analyzed using the method of Boyd et al. (1993). In this method, the runoff depth (runoff volume normalized by total watershed area) is plotted versus rainfall depth for each storm in the record. A regression line is then fit to this data; the slope of the line is the percentage of total watershed area contributing water to the outlet. If all events are assumed to involve impervious runoff only, then this slope is the EIA percent.

Naturally, some points plot well above the regression line, and thus involve a greater contributing area, perhaps from pervious or previously-disconnected impervious surfaces. Boyd et al. (1993) recommend discarding points that are more than 1 mm above the line and recalculating the regression line. This process is repeated until all points are within 1 mm of runoff depth of the line, at which point the slope is assumed to reflect the connected (effective) impervious area only. The x-intercept of the line, while usually very small, represents the surface abstraction of the impervious area (i.e. the depth of water stored on the surface prior to the onset of runoff).

The slope of a regression line fit to the excluded points approximates the contributing area of the combined impervious and pervious areas; therefore the difference in slope between this line and the regression line for the connected impervious gives the percent of the watershed that is ‘connected’ pervious. Significant scatter in these excluded points is generally an indication that the contributing area outside of the effective impervious area is not consistent, instead depending on factors like antecedent rainfall, rainfall intensity, and rainfall duration (Boyd et al., 1993).

3 Results

3.1 Site Descriptions and Data Acquisition

Both the GIS-based method and the rainfall-runoff data analysis were applied to two gauged sub-catchments in the Capitol Region Watershed, a 41-square-mile, highly urbanized watershed comprised by a majority of St. Paul and parts of Roseville, Maplewood, Lauderdale, and Falcon Heights. The storm-sewer system of the CRW outlets at several points to the Mississippi River, and is therefore crucial to the river's water quality.

CRW was an ideal watershed for application of the GIS tool due to the availability in of necessary data: land cover classification and elevation (courtesy of the University of Minnesota), and a layer for the impervious surfaces in the watershed (courtesy of the Capitol Region Watershed District (CRWD)). CRWD also provided runoff volume data recorded at long-term monitoring sites in several sub-watersheds. These data were recorded in storm sewers at the outlets of the sub-watersheds using an area-velocity probe connected to an ISCO automatic sampler.

The first catchment chosen for application of the two EIA estimation techniques was a small, 42-acre watershed located near Como Lake that drains to an underground stormwater vault being monitored by CRWD (Figure 1). This watershed, also known as Arlington-Hamline, is primarily old residential, with significant tree cover (29%) and alleys instead of driveways, thus the EIA was expected to be low relative to industrial or newer residential development. This catchment was chosen because its small size and relatively homogenous land use made it ideal for a first application of the GIS tool and allowed a more detailed analysis to be completed than for the second catchment. Monitoring data for this site, furnished by CRWD, was available for the seasonal sampling period (generally April through November) of 2007 to 2010. This included a total of 165 rainfall-runoff events.

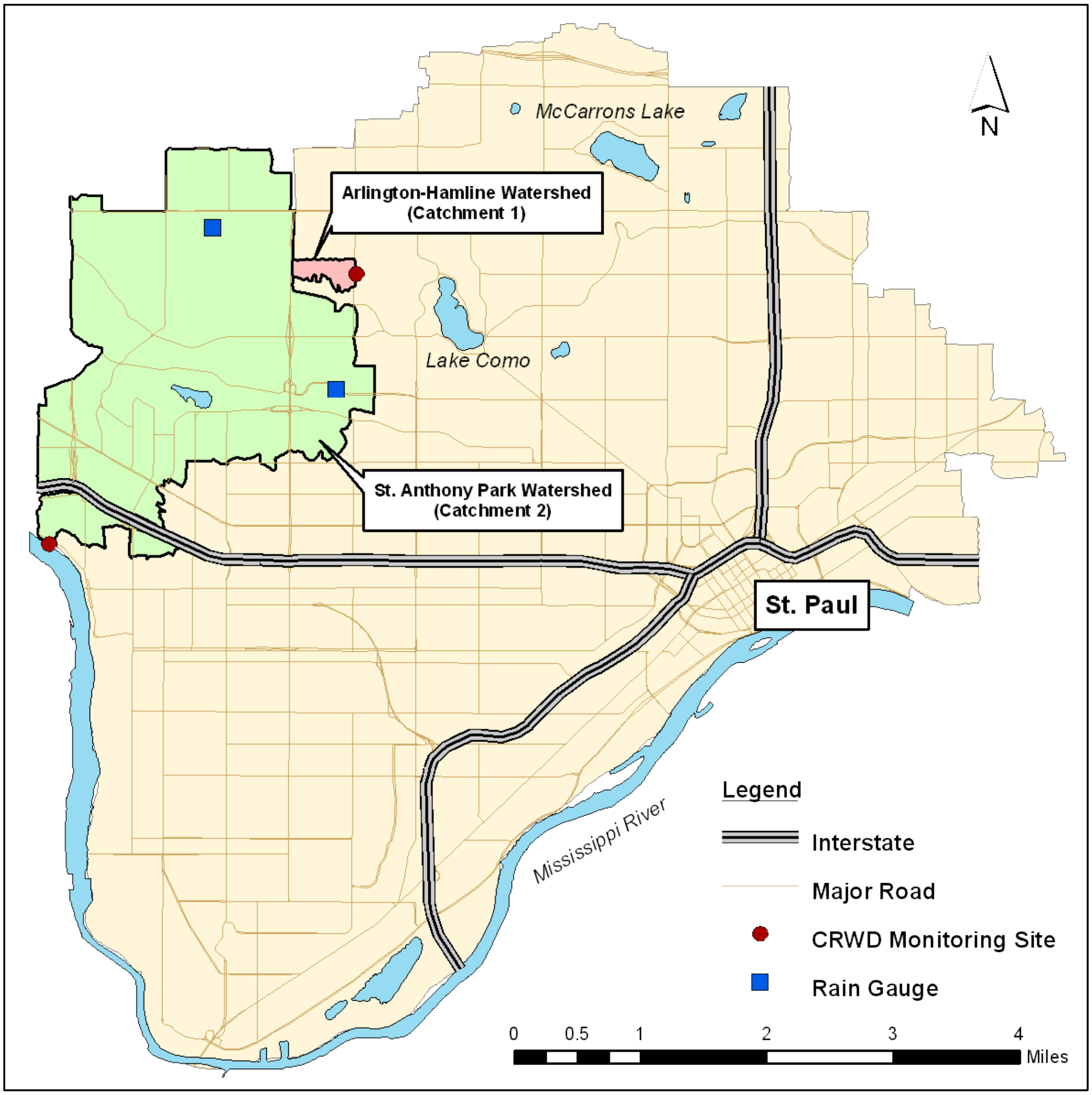


Figure 1. Map of the Capitol Region watershed, St. Paul, MN. The sub-watersheds of the two study sites (Arlington-Hamline and St. Anthony Park) are shown, along with the locations of the CRWD's monitoring sites and the two rain gauges used in the analysis.

EIA was also estimated with the two techniques for a second, larger catchment in the CRW (Figure 1). This 3400-acre watershed, known as the St. Anthony Park watershed, drains directly to the Mississippi River and is comprised of a variety of land uses, including old residential, parks, golf courses, the state fairgrounds, industrial, and institutional (primarily the St. Paul campus of the University of Minnesota). The watershed also contains several large stormwater ponds and some wetland area. Its large size and varied land use presented some challenges in application of the GIS tool in particular, and therefore the analysis is not as in-depth as for Catchment 1. Monitoring data was available at this site over the same period as Catchment 1 (2007-2010), but involved fewer rainfall events (125) due to the larger rainfall required to cause a measureable flow at the watershed outlet.

Rainfall data, also provided by CRWD, were taken from an automatic rain gauge located on the St. Paul campus of the University of Minnesota, located at the northern end of the St. Anthony Park watershed (Catchment 2) and within a mile of the first application site. Data from a manual rain gauge located near the eastern border of St. Anthony Park provided a second rainfall measurement for this watershed's rainfall-runoff analysis; an arithmetic mean of the two rainfall measurements was used.

3.2 EIA Estimates for Catchment 1 (Arlington-Hamline)

3.2.1 EIA from Rainfall-Runoff Data Analysis

A plot of runoff depth vs. rainfall depth for the entire sampling record (2007 – 2010) at the Arlington-Hamline site is shown in Figure 2. Rainfall data is from the University of Minnesota rain gauge. The successive regression technique of Boyd et al. (1993) was applied., and the regression line fit to the impervious-only points (145 of 165 rainfall events) has a slope of 0.148, thus 14.8% of the watershed is directly connected to the outlet, i.e. is EIA. The abstraction depth indicated by the x-intercept of this line is roughly 0.5 mm, which is an acceptable value for impervious surfaces (Boyd et al., 1993). The slope of the regression line fit to the rest of the points (20 rainfall events) is 19.5%, so the 'pervious' contributing area is roughly 4.7% of the total watershed area.

As is apparent from the plot, the larger rainfall events tend to produce runoff from more than just the directly connected impervious area. Rainfall intensity also plays a role; the mean rainfall intensity of the impervious-only events is 4.5 mm/h, while for the pervious events it is 10.0 mm/h. These are logical results given that large or high-intensity rainfall events can exceed the infiltration capacity of pervious surfaces (in this case, lawns) or cause certain portions of alleys or parking lots to overflow into guttered streets (a trend also observed by Boyd et al. (1993) in a study of three urban catchments).

In this particular watershed, nearly 88% of the rainfall events produced runoff from the effective impervious areas only; likewise, roughly 88% of the total runoff volume over the 2007 – 2010 period came from these surfaces. This suggests that any management practices in the watershed aimed at reducing runoff volumes would primarily need to target disconnection of the impervious surface areas. In reality, this watershed already has several sub-street infiltration trenches and rain gardens which serve to disconnect a significant portion (16 ac, or 28%) of the original 58-acre drainage area (CRWD, 2010).

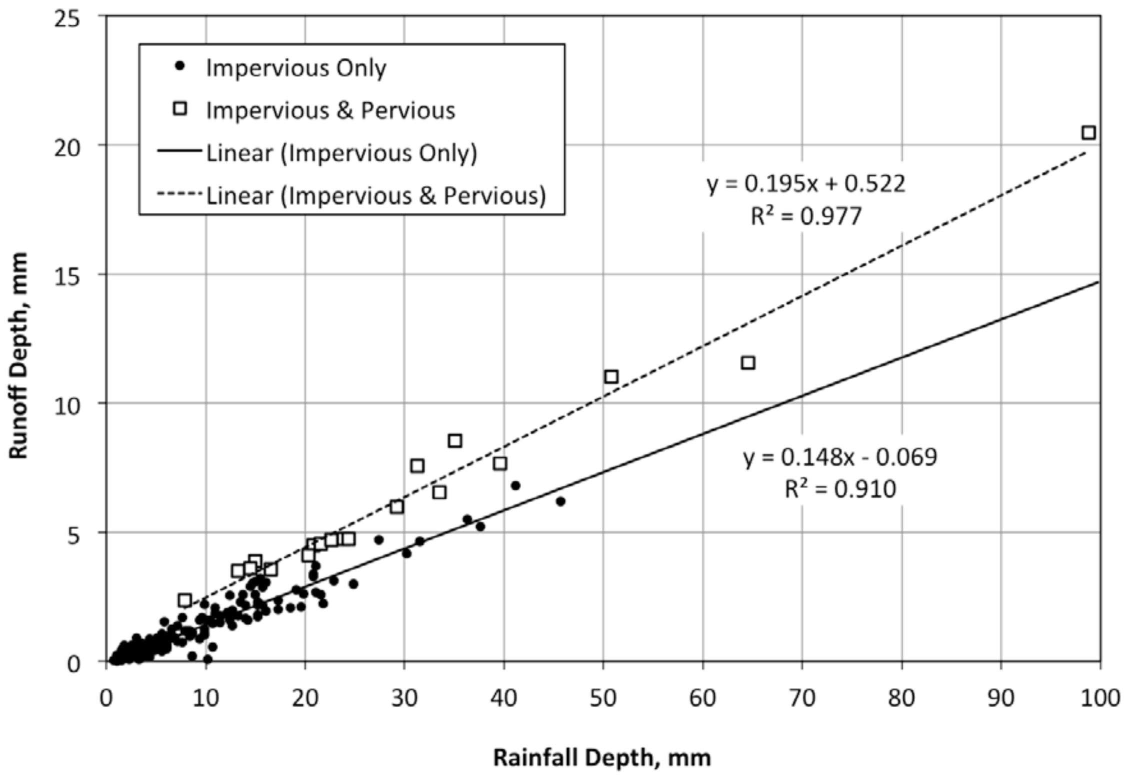


Figure 2. Runoff depth (mm) vs. rainfall depth (mm) for 165 rainfall events during the 2007 – 2010 monitoring period at Catchment 1 (Arlington-Hamline). Regression lines have been fit to sub-sets of the data according to the analysis technique of Boyd et al. (1993). Rainfall data is from the University of Minnesota rain gauge.

3.2.2 Connected Pavement Estimate from the GIS Tool

EIA was next estimated for the Arlington-Hamline site using the GIS-based technique of Han and Burian (2009). The original land cover map and the distribution of each cover type are shown in Figure 3a and Table 1, respectively. Roughly 38% of the catchment is classified as impervious (22% rooftop and 16% paved), with the rest classified as either lawn or trees. Note the significant amount of tree cover that overhangs roads and rooftops in this original land cover map.

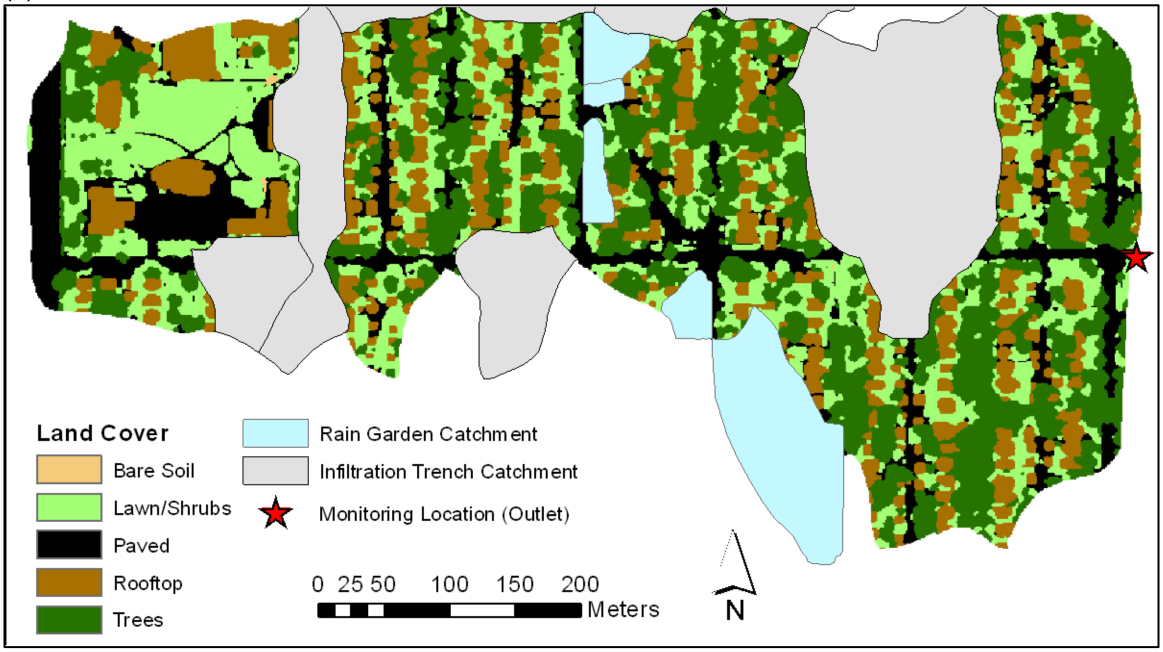
A first pass of the GIS tool using this data produced a connected pavement area of 8.0% (Figure 3b and Table 2), or roughly 50% of the total paved area. To match the observed EIA of 14.8%, approximately 30% of the rooftop would have to be directly connected to the drainage system. In this particular watershed, this estimate of roof connectivity seems rather high, as very few homes had driveways (a primary means of connecting rooftop to street), and the one parking lot appeared to be mostly disconnected from the street (southwest corner of Figure 3b).

The discrepancy between the data analysis and GIS tool estimates of EIA likely results from a limitation of the GIS tool for highly shaded watersheds. Tree canopy obscures a significant portion of paved area (roads especially) that is almost certainly connected to the drainage network, with the result that the tool produces ‘pockets’ of disconnected road (Figure 3b).

To improve the GIS estimate of connected pavement, the land cover layer was modified to ‘un-shade’ the roads and alleys by removing tree cover that obscured these surfaces and re-classifying the cells as ‘paved’. This process significantly changed the distribution of land cover classification for the watershed (Figure 4a and Table 1); total impervious area increased to 46% (22% rooftop and 24% paved).

A second pass of the GIS tool using this modified land cover map produced a pavement connectivity of 14.9% (Figure 4b and Table 2), or approximately 63% of the total paved area. Assuming zero rooftop connectivity, this produces an EIA value that matches the data-derived value of EIA (14.8%) almost exactly. However, the assumption of zero rooftop connectivity, even in this watershed, is an unlikely scenario. The over-estimate of connected pavement likely comes from classifying much of the alley surface as connected. While some of the alleys are certainly connected to the street, many alleys typical of this type of this age of construction are poorly maintained; some are gravel rather than pavement, and significant cracks and even vegetation may be present in the alleys, serving to disconnect some portion of the area. Therefore the actual value of connected pavement is likely somewhere between the two estimates (8.0% and 14.9%). A more accurate measure of rooftop connectivity would help fix this value of pavement connectivity with more certainty.

(a)



(b)

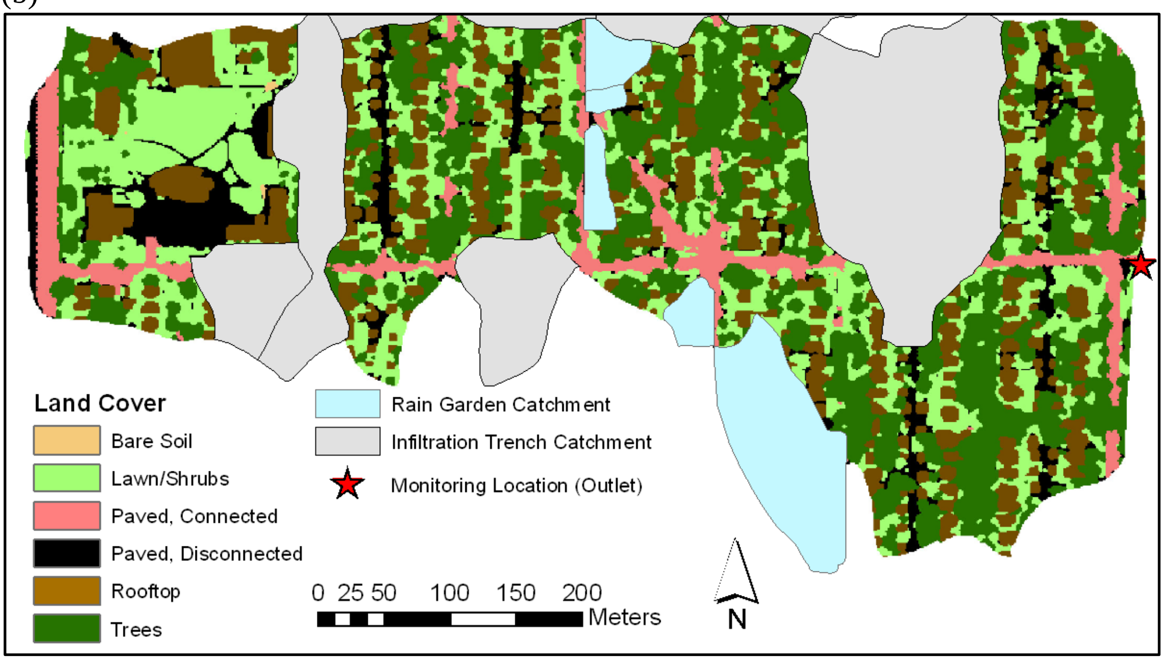
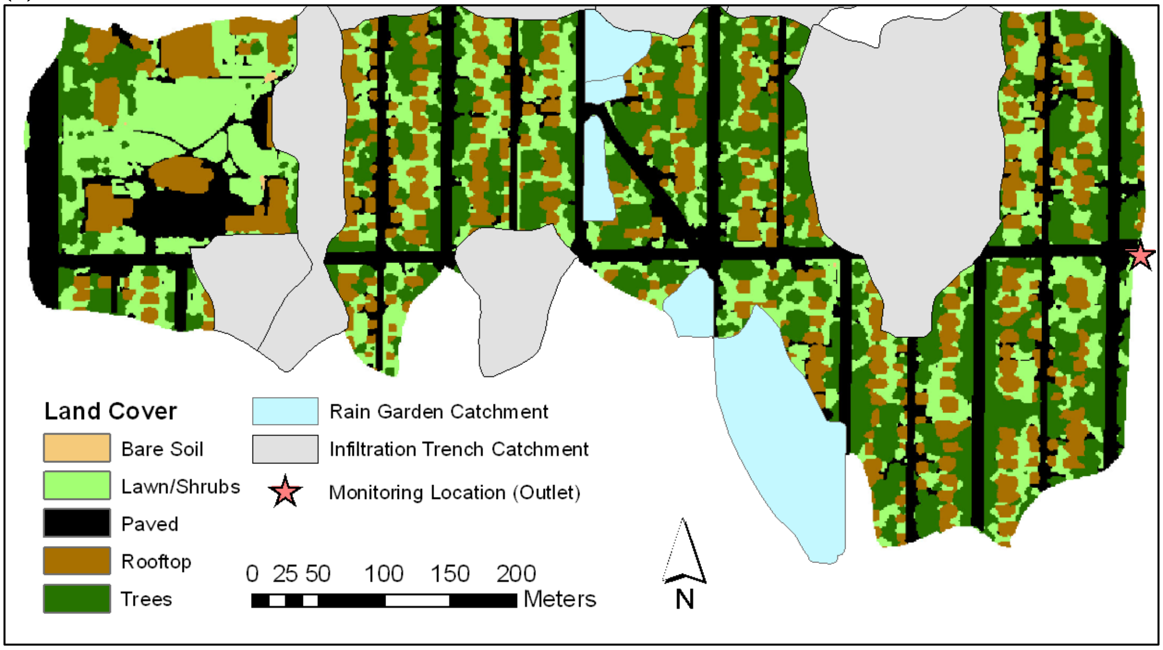


Figure 3. Land cover classification for Catchment 1 (Arlington-Hamline): (a) original land cover map, and (b) land cover map showing location of connected pavement after applying the GIS method. Drainage areas for BMP's in the watershed are also shown. Land cover distributions are given in Table 1.

(a)



(b)

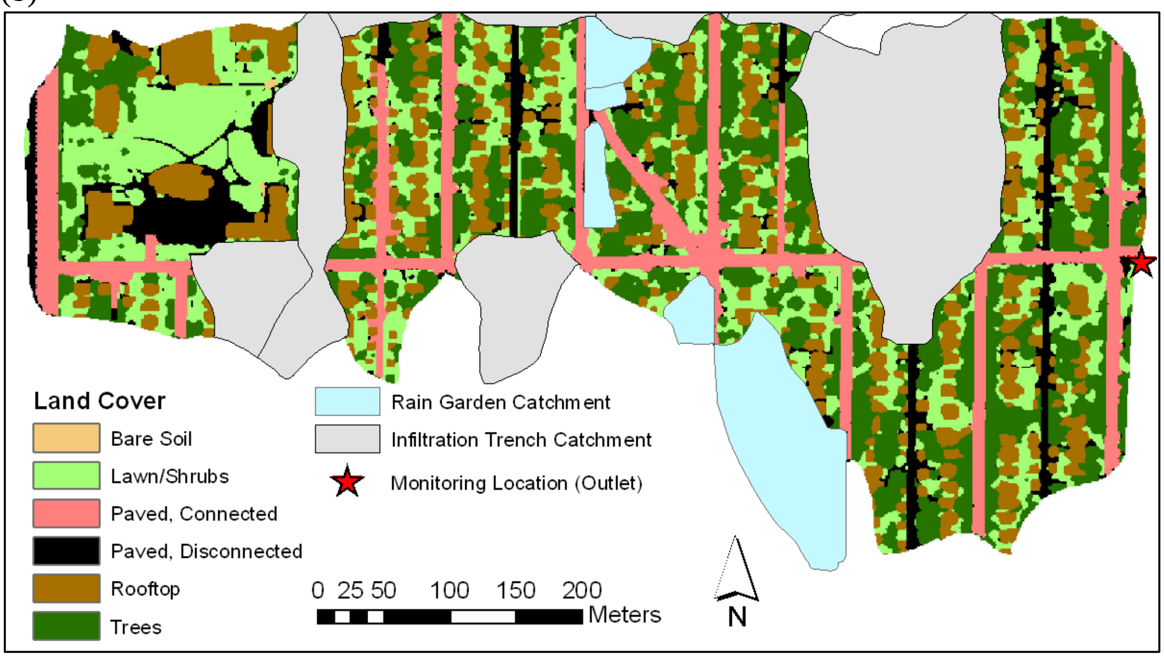


Figure 4. Land cover classification for Catchment 1 (Arlington-Hamline): (a) land cover map modified to 'un-shade' roads and alleys, and (b) land cover map following application of the GIS method to determine connected pavement area. Drainage areas for BMP's in the watershed are also shown. Land cover distributions are given in Table 2.

Table 1. Distribution of land cover classes within Catchment 1 (Arlington-Hamline). Values are shown for the original land cover map, and for the modified land cover map in which all roads and alleys were 'un-shaded' (i.e. cleared of overhanging canopy).

Land Cover Type	Original Land Cover Map		'Un-shaded' Roads and Alleys	
	Area *ac*	%	Area *ac*	%
Trees	14.47	34.1	12.37	29.2
Grass/Shrubs	11.53	27.2	10.66	25.1
Bare Soil	0.02	0.1	0.02	0.1
Water	0.00	0.0	0.00	0.0
Roof	9.47	22.3	9.32	22.0
Paved	6.92	16.3	10.04	23.7

Table 2. Distribution of land cover classes within Catchment 1 (Arlington-Hamline) after application of the GIS method for estimation of pavement connectivity. Values are shown for the original land cover map, and for the modified land cover map in which all roads and alleys were 'un-shaded' (i.e. cleared of overhanging canopy).

Land Cover Type	Original Land Cover Map		'Un-shaded' Roads and Alleys	
	Area *ac*	%	Area *ac*	%
Trees	*14.47*	*34.1*	*12.37*	*29.2*
Grass/Shrubs	*11.53*	*27.2*	*10.66*	*25.1*
Bare Soil	*0.02*	*0.1*	*0.02*	*0.1*
Water	*0.00*	*0.0*	*0.00*	*0.0*
Roof	*9.47*	*22.3*	*9.32*	*22.0*
Paved, Disconnected	3.58	8.3	3.74	8.8
Paved, Connected	3.41	8.0	6.30	14.9

3.3 EIA Estimates for Catchment 2 (St. Anthony Park Watershed)

3.3.1 EIA from Rainfall-Runoff Data Analysis

Runoff depth vs. rainfall depth for the 125 events in the 2007 – 2010 record at the St. Anthony Park monitoring site are shown in Figure 5 with the successive regression technique of Boyd et al. (1993) applied. The slope of the regression line for the impervious-only events (108 of 125 events) indicates an EIA of 18.3% for the watershed, with an abstraction depth (x-intercept) of 0.1 mm. The EIA estimate is slightly higher than that of the Arlington-Hamline site, which is expected given that the watershed has a higher proportion of impervious area (50% vs. 38%, using original land cover data).

The regression line fit to the remaining points (15 events) has a slope of 23.6%, indicating that the connected 'pervious' area in this watershed is roughly 5.3%, very similar to Arlington-Hamline. Unlike Arlington-Hamline, however, there is a lot more scatter in these remaining points; several plot far above the regression line. For these particular events, significant rainfall had occurred in the previous 24 hours, which reduces infiltration capacity of the watershed and increases its contributing area. Boyd et al. (1993) noted a similar trend for their study watersheds, and used parameters such as 1-day and 5-day antecedent rainfall as potential parameters for runoff volume prediction in a multiple linear regression analysis. Antecedent rainfall may not have been as significant for the much smaller Arlington-Hamline watershed since nearly all (89%) of the runoff volume was being contributed by the paved surfaces, indicating a large abstraction capacity for the vegetated surfaces.

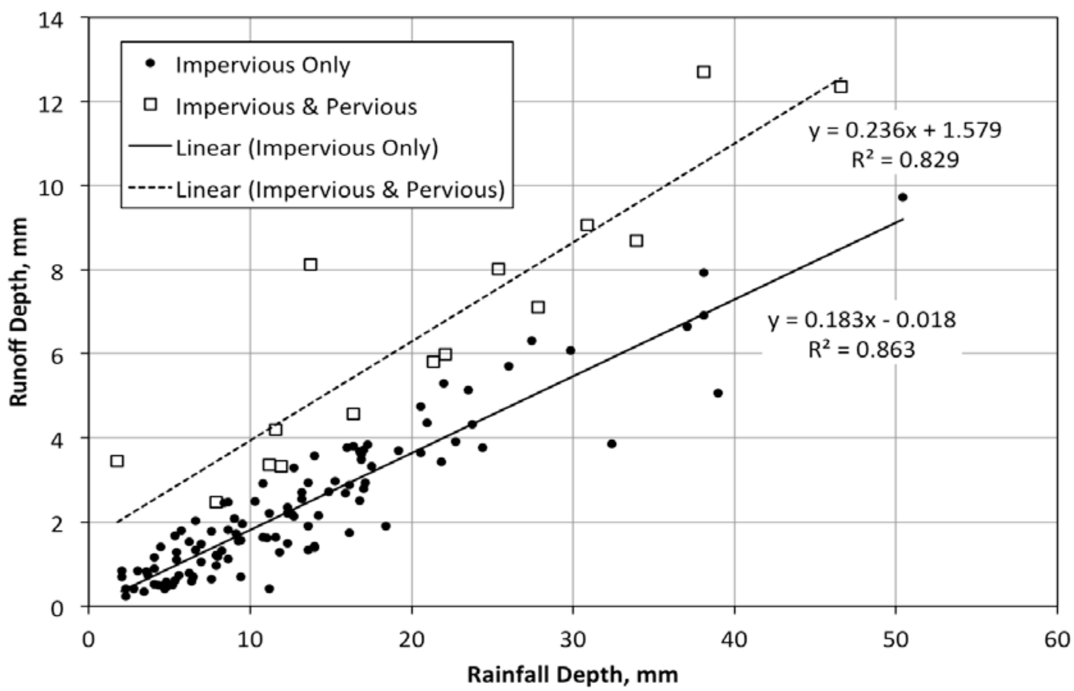


Figure 5. Runoff depth (mm) vs. rainfall depth (mm) for 125 rainfall events during the 2007 – 2010 monitoring period at Catchment 2 (St. Anthony Park). Regression lines have been fit to sub-sets of the data according to the analysis technique of Boyd et al. (1993). Rainfall depths are the mean of observations at the two rain gauges in this watershed (see Figure 1).

It should be noted that the two largest events in the record, with rainfall totals of 3.89 in and 2.65 in, had to be discarded due to an apparently malfunctioning flow gage. The runoff volumes were far too low for the amount of rainfall, and closer inspection of the data revealed that in both cases, the loggers had quit recording flow an hour into each storm. Both events would undoubtedly have produced pervious runoff and improved the estimate of connected pervious area in the watershed.

The difference in mean rainfall intensity between the 'impervious' and 'pervious' rainfall-runoff events was also present for this watershed: 4.5 mm/h for the impervious events, and 10.5 mm/h for the pervious events (including the two excluded events). This is very similar to the Arlington-Hamline watershed, a logical result given that both analyses relied on the same rainfall data set from the University of Minnesota rain gauge. A second rain gauge was incorporated into the analysis of the St. Anthony Park data, but in general these rainfall data were not much different than the measurements taken from the University of Minnesota.

Also similar to the Arlington-Hamline watershed, nearly all (86%) of the rainfall events produced runoff from the effective impervious areas only, with 88% of the total runoff volume estimated to be coming from directly-connected impervious areas only. It is expected that this percentage would be slightly lower if the true runoff volumes from the two very largest rainfall events were known.

3.3.2 Connected Pavement Estimate from the GIS Tool

The GIS tool was also applied to the St. Anthony Park watershed. However, given that the results using the modified land cover map had provided a convenient upper bound for the connected pavement area in the Arlington-Hamline watershed, the modified land cover map (i.e. with roads and alleys un-shaded) was used in the analysis rather than the original land cover map,.

The original land cover map and distribution of land cover classes for St. Anthony Park are shown in Figure 6 and Table 3. As mentioned previously, this watershed was more diverse than the much smaller Arlington-Hamline watershed: 50% of the area is impervious (17% rooftop and 33% paved), with nearly 1% open water present in the form of a few ponds and wetlands. Un-shading the roads and alleys (Table 2b) further increased the amount of area classified as impervious to 56% (16% rooftop and 40% paved).

The GIS tool produced a connected pavement value of 15.8% (Figure 7 and Table 3), which would require a rooftop connection of only 16.2% to match the EIA estimate from the data analysis (18.3%). This seems like a low value of roof connectivity for the watershed, given the significant amount of commercial and industrial rooftop in this watershed (43% of total roof area, based on CRWD's impervious surface layer). Both of these types of rooftops will have high connectivity, as they are often directly piped to storm sewers via roof drains. Furthermore, in this type of watershed, old age and compactness of the infrastructure prevents the installation of on-site detention ponds or infiltration practices designed to keep roof runoff from reaching the storm sewer. Thus the implication is that the tool has over-estimated the amount of connected paved area, which was also likely the case in the Arlington-Hamline watershed.

A closer look at the resulting land cover map (Figure 7) reveals an interesting discrepancy: almost all of the impervious area on the University of Minnesota campus and the Minnesota Fairgrounds (near the middle top of the watershed) are designated as 'disconnected' impervious, despite the presence of guttered streets and catch basins. This is because road/catch basin data did not exist for this part of the watershed, and therefore it was impossible for the tool to trace any flow paths to a collection point. In reality, much of the University's campus drains to a wetland system where the residence time of runoff is increased significantly, and a large portion of the fairgrounds drains to a series of retention ponds and infiltration basins; thus most of this area is effectively disconnected anyway. However, the tool would have erroneously classified much of it as 'connected' pavement had the campus and fairgrounds roads been included in the collection layer. This illustrates the importance of adapting a future version of our tool to incorporate knowledge of the location of stormwater management practices in the watershed, and in particular, which ones are connected to the drainage system. Han and Burian (2009) included such a feature in their version of the tool.

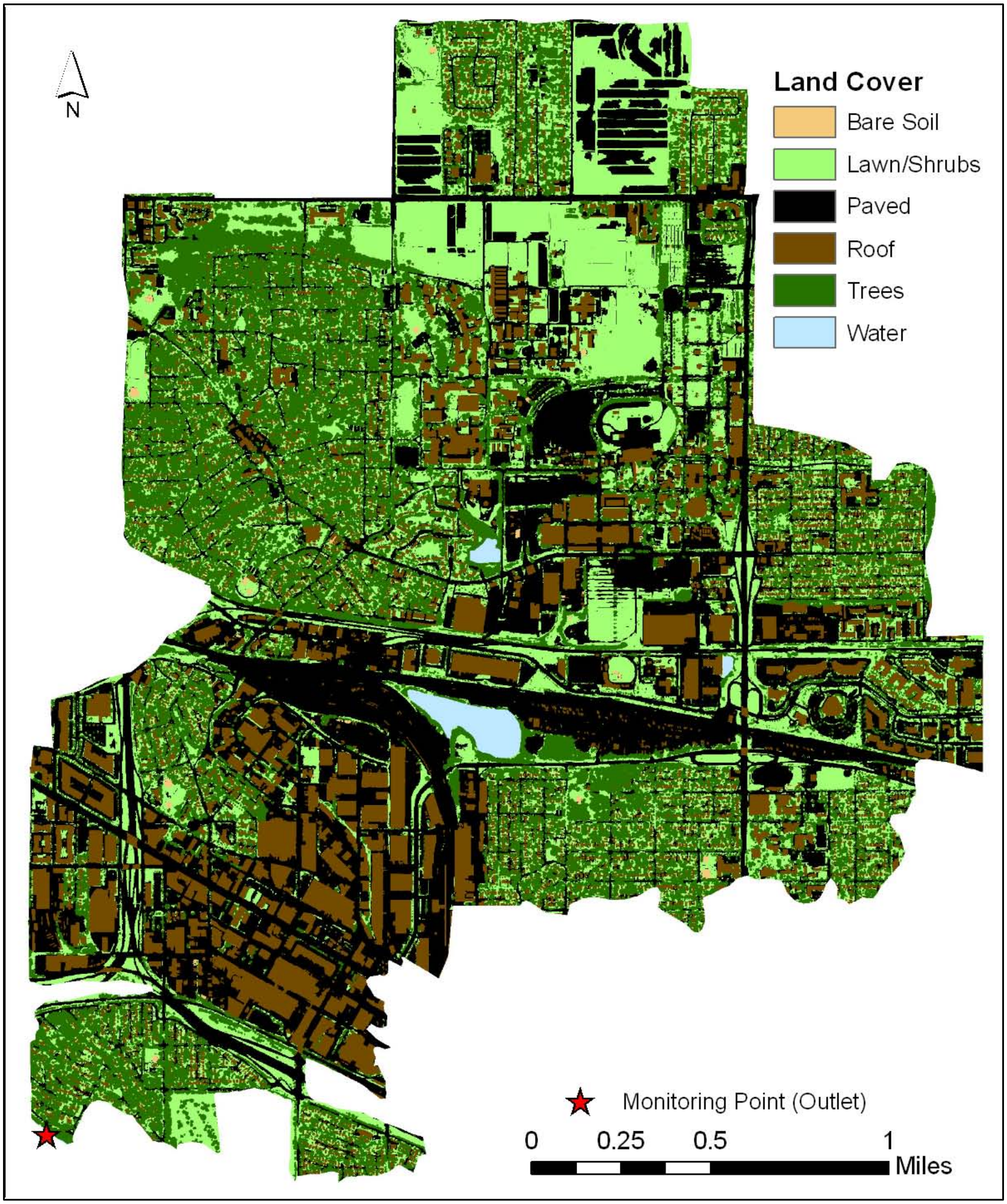


Figure 6. Land cover classification for Catchment 2 (St. Anthony Park), with modification for 'un-shading' of roads and alleys. Land cover distributions are given in Table 3.

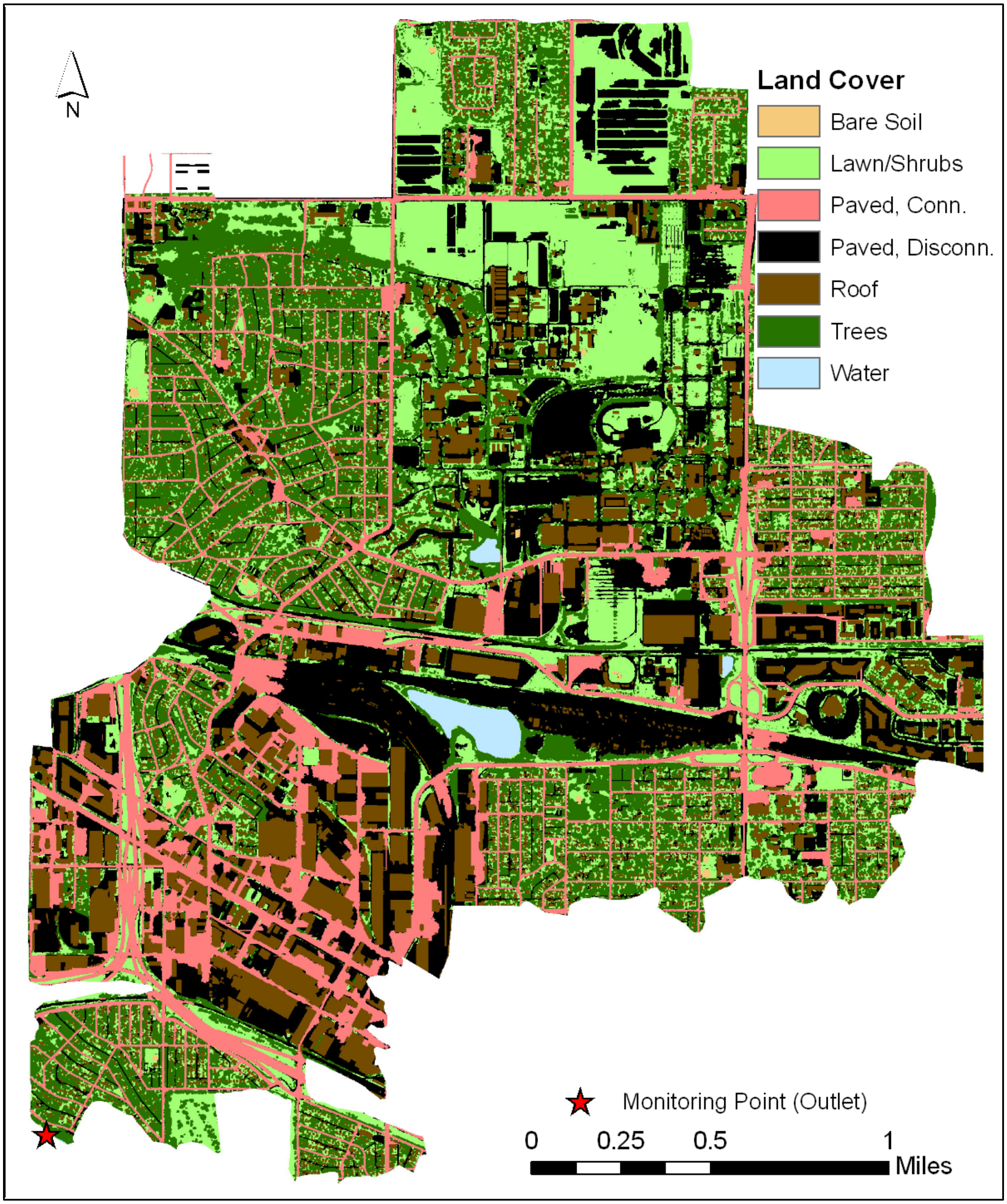


Figure 7. Land cover classification for Catchment 2 (St. Anthony Park), after application of GIS method for determination of connected pavement using the modified land cover map (Figure 6). Land cover distributions are given in Table 3.

Table 3. Distribution of land cover classes within Catchment 2 (St. Anthony Park), (a) before and (b) after application of the GIS method for estimation of pavement connectivity. The modified land cover map in which all roads and alleys were 'un-shaded' (i.e. cleared of overhanging canopy) was used in this analysis.

(a)

Land Cover Type	'Un-shaded' Roads and Alleys	
	Area *ac*	%
Trees	796	23.4
Grass/Shrubs	703	20.6
Bare Soil	5	0.1
Water	22	0.6
Roof	535	15.7
Paved (all)	1,346	39.5

(b)

Land Cover Type	'Un-shaded' Roads and Alleys	
	Area *ac*	%
Trees	796	23.4
Grass/Shrubs	703	20.6
Bare Soil	5	0.1
Water	22	0.6
Roof	535	15.7
Paved, Disconnected	809	23.7
Paved, Connected	537	15.8

4 Discussion

4.1 Conclusions

While the analyses completed in this study were not exhaustive, the results suggest that the GIS analysis technique needs refinement before it can match the accuracy of the data analysis technique. In particular, the lack of a method for accurately determining roof connectivity limits the applicability of the results of the GIS method. Other issues, such as how to address canopy shading of impervious surfaces, also contribute uncertainty to the results.

In general, the GIS technique predicted lower values of effective impervious area in the test watersheds than what was determined from the data analysis. For Arlington-Hamline, predicted EIA was 8.0% (using the original land cover classification and assuming 0% roof connection) while actual EIA was 14.8%. Using the modified land cover data (i.e. with roads and alleys 'un-shaded'), the GIS-derived EIA for Arlington-Hamline matched the data-derived value, but in St. Anthony Park, predicted EIA (15.8%) was still lower than actual EIA (18.3%). Han and Burian (2009) encountered similar results in their application to a single watershed; the tool predicted 15.9% EIA, while 21.8% EIA was observed from application of the Environmental Protection Agency's SWMM (Storm Water Management Model) to the same watershed and calibrating it to 6 years of stream flow data. As in our case, this is with the assumption of 0% roof connection, which should lead to an under-prediction of EIA by the tool as long as some roof connection is present in reality.

In Han and Burian's application, roof connection was determined to be 69% in order to match the observed EIA of 21.8%, which was higher than expected but deemed reasonable by the authors for the test watershed. By contrast, Arlington-Hamline required 30% rooftop connection (original land cover case) and St. Anthony Park 16% rooftop connection (modified land cover case) in order to match data-derived EIA values. In the former case this value may have been a bit high, in the latter case it was likely too low given that commercial and industrial rooftop, which generally have nearly complete connectivity, made up roughly 43% of total rooftop area.

The amount of rooftop connection required to match data-derived EIA appears to be related to the land cover map used in the GIS analysis. The original land cover classification used in our study, which was derived from summer photography and intended to show the extent of canopy coverage in the watershed, included a significant amount of paved area (roads, alleys, lots) obscured by vegetation. In the Arlington-Hamline catchment, roughly 7% of the total watershed area (31% of total paved area) was 'shaded pavement'; in the St. Anthony Park catchment, shaded pavement comprises 6.5% of total watershed area (16% of total watershed area). 'Un-shading' this paved area, i.e. reclassifying it as 'paved' in the land cover map, resulted in more connected pavement area in both test watersheds, and therefore a lower required roof connection to match the actual EIA.

This inflated value of pavement connectivity may not reflect reality. It is possible that canopy cover may effectively disconnect underlying paved areas for low-intensity or small rainfall events, particularly in the case of large, mature trees that can intercept a significant amount of rainfall (e.g. 5 – 15 mm (Endreny, 2005)). Removing this shading from the land cover map may have resulted in an over-estimation of connected pavement. In addition, using the modified land cover map resulted in a significant amount of alley being classified as 'connected.' This also may not reflect reality due to the typically poor maintenance of alleys, which may have large cracks, vegetation growth, or local depressions that serve to disconnect much of the area. Therefore, in the GIS method, the two land cover classifications could potentially be used to bracket the actual amount of connected pavement: the original land cover map could be used to define the lower bound, and the modified land cover map could provide the upper bound.

The amount of time required to implement each technique was comparable, although the data analysis technique was potentially much quicker depending on the availability and format of necessary data. With the exception of the run time for the script itself on the larger watershed, which took over 10 hours to complete, the most time-consuming aspect of the GIS method was organizing and formatting the input data to be run by the script. Familiarity with the ArcGIS software would speed up the pre-processing steps in the GIS method, and a separate script could be utilized to automate this process (Han and Burian (2009) included such a feature in their version of the tool). It is also likely that the analysis script would be able to work much faster with some optimization.

In summary, the runoff-precipitation technique (Boyd et al., 1993) has the advantage of being quick and relatively simple to implement, as it did not require familiarity with specialized software tools (e.g. ArcGIS) and could be completed with any spreadsheet program with graphing capabilities (e.g. Excel). The EIA estimates from the data analysis are the most accurate, but the technique is unable to determine where in the watershed the EIA is located, and obviously can't be used if accurate runoff discharge and precipitation data is unavailable. By contrast, the GIS method has the advantage of being applicable to un-gauged watersheds, and also provides the location of EIA in the watershed. This latter feature makes it particularly attractive for honing the development and placement of BMP's in a watershed. Unfortunately, the accuracy of the GIS method is completely dependent on the ability to faithfully represent the amount of roof connection in a watershed, a process that can add significant time and expense to the EIA estimate. One observation on these two watersheds is that the un-modified and the modified GIS methods seem to bracket the EIA of the watershed, indicating that it could be a watershed management tool for watersheds that do not have the data required for the runoff-precipitation technique.

4.2 Potential for Future Work

The analyses completed in this study were not exhaustive. While the results were encouraging and demonstrate the potential value of both EIA estimation techniques, the work could be extended and improved in several ways.

In general, the EIA analysis using both techniques needs to be applied to more watersheds. A small (42 ac), relatively homogenous residential catchment and a very large (3400 ac), diverse urban catchment were used in this study. Additional watersheds might include new, suburban-type residential and commercial development, as well as medium-sized catchments with more uniform land cover types. These watersheds might help generalize results for certain cover types by allowing EIA estimates to be correlated to land cover characteristics, such as roof type, canopy shading, age of construction, lane-miles of road, presence of BMPs, etc. Application of the GIS method in particular to newer construction might help isolate the influence of tree canopy on results, as these newer developments tend to have fewer and less mature trees than in older neighborhoods such as the Arlington-Hamline catchment.

The rainfall-runoff data analysis technique could be extended following the work of Boyd et al. (1993). In their study, runoff depth was correlated to several rainfall and antecedent characteristics, including rainfall intensity, rainfall duration, 24-hour antecedent rainfall, five-day antecedent rainfall, and number of dry days prior to rainfall. Logical trends emerged; impervious-only runoff was generated in cases of low-intensity storms for low antecedent wetness, while pervious runoff was generated for larger, high-intensity storms or in cases of significant antecedent rainfall. Boyd et al. (1993) also developed multiple linear regression models for prediction of runoff depth for small (< 40 mm) and large events separately. These regressions were incorporated into a more general equation for runoff prediction that includes factors for impervious fraction, pervious fraction, soil storage capacity, rainfall depth, and antecedent rainfall. Sufficient data exists for the Capitol Region Watershed that a similar analysis could be completed in future work, and the results could potentially be compared to those obtained by Boyd et al. (1993) for their study watersheds.

The most significant limitation of the GIS method is its inability to characterize the fraction of connected rooftop from GIS layers, an issue noted in the original work by Han and Burian (2009). A couple of methods could be employed to improve roof connectivity estimates. The first is the use of site surveys in the study watershed to determine the portion of each roof that is connected via downspouts or drains to the street or sewer. This estimate could be aided with the use of aerial photography, or a simple approach that partitions the total roof area based on the number of connected and disconnected downspouts per roof could be used (Lee and Heaney, 2003). Depending on the size of the watershed, this may or may not be a feasible approach, as it can significantly increase time required to provide an EIA estimate (Lee and Heaney, 2003). A second option for determining roof connectivity is to specify it by roof or cover type, and calculate a composite value for the watershed weighted by the areal distribution of each roof type (Han and Burian, 2009). This allows a distinction to be made between very different roof types, for example, between ‘old residential’, which would have a low roof connectivity (e.g. 15%), and ‘industrial’, which might have a value of 90% or higher. Site surveys could be used to characterize each roof type, if needed.

Additional work on the GIS method is needed to determine how to handle pavement that is shaded by canopy. Depending on the collection layer used, overhanging trees can completely isolate a portion of road from the drainage network in the land cover map, resulting in erroneous classification of small pockets of road as ‘disconnected.’ However, forcing the un-shading of roads and alleys appeared to produce an over-estimate of connected pavement. This suggests that trees themselves may provide a certain amount of disconnection, at least for small events, by intercepting rainfall that would otherwise fall on a road or driveway and routing it instead along leaves and branches to the trunk of the tree where it has a chance to infiltrate into the ground. Therefore the GIS method may need to be adapted to create a third pavement type: ‘shaded’ or ‘vegetated’ pavement. This pavement type would serve as a connection between any adjacent, un-shaded paved areas, but would not itself be included in the ‘connected’ paved area value. It could be tallied separately from the other pavement types, to be included in the total EIA value for rainfall events above a certain depth threshold.

As it pertains to this study, future work should concern the other gauged sub-catchments in the Minneapolis-St. Paul metropolitan area. The Capitol Region Watershed, for example, has extensive runoff data for 7 or 8 other sub-catchments ranging in size from roughly 450 to 5000 acres; but the limiting factor in future application may be the quality and availability of rainfall data in these other parts of the watershed. The data analysis method is highly dependent on an accurate measurement of rainfall within the study watershed, and significant spatial variation of rainfall depth can be present for a given storm. The GIS method results could be improved by using site surveys to determine roof connectedness, particularly in the relatively small Arlington-Hamline watershed. Selective surveys could be used to improve roof connectivity estimates for certain roof or development types (i.e. commercial or industrial) in larger watersheds, such as St. Anthony Park. Such surveys could be used to better quantify the accuracy of the GIS method.

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