Land Use and Runoff Uncertainty

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ABSTRACT

Data from about 160 neighborhoods in six Jefferson County, AL drainage areas were intensively investigated to determine the surface covers for each land use type. The data shows that the watersheds are highly impervious, with three of them having more than 50% of the watershed area composed of impervious cover. However, TR-55 (USDA 1986) guidance still shows that the impervious cover for all land uses investigated to be much greater than we observed for our area. It was also concluded that the variabilities of the surface covers within the different land uses for the investigated areas was small, especially for the impervious covers.
The percent of directly connected impervious cover (DCIA) was determined by direct field observations and was also estimated by empirical equations. Equations for determining DCIA developed as part of several different studies were use to predict DCIA for our data, but did not give good estimates especially when analyzed at land use level. There was a similarity between "highly connected basins" Sutherland equation and the fitted equation for our overall data. However, the residual analysis for the regression model failed, suggesting that the power equation is not the proper equation to be used for those six drainage areas. Consequently, equations for each existing land use were developed, concluding that a single equation cannot accurately estimate DCIA for all regions and land uses.

KEYWORDS: land use, land cover, imperviousness, impervious cover, runoff

INTRODUCTION

As part of a comprehensive stormwater management plan, an urban area inventory of watershed development conditions helps when understanding sources of pollutants and the magnitude of the runoff expected, and therefore assists in the selection of the most beneficial stormwater control practices. The type of urban development in an area can have a major impact on the local hydrology and water environment. This inventory is therefore valuable to support many decision making activities and to make local stormwater monitoring successful. Past studies (Schueler 1994; USEPA 1994; Arnold and Gibbons 1996; Booth and Jackson 1997) have demonstrated the importance of knowing the areas of the different land covers in each land use category and the storm drainage characteristics (grass swales, curb and gutters, and the roof drains). Increasing levels of impervious surfaces associated with urbanization result in higher volume of runoff with higher peak discharge, shorter travel time, and more severe pollutant loadings. Urban imperviousness is an important indicator for urban watersheds in measuring the impact of land development on drainage systems and aquatic life (Schueler 1994). However, there are many different types of impervious surfaces and their direct connectivity to the drainage system is an important attribute affecting stormwater runoff.

The purpose of this research was to provide more details on impervious surfaces for different land uses in the Southeast, because the literature assumptions on impervious cover are not very accurate when applied to local conditions. There are a lot of assumptions about impervious area characteristics for different types of land uses, but very little data has been available to support these assumptions. As part of this research, Little Shades Creek watershed (Jefferson County, near Birmingham, AL) and five highly urbanized drainage areas situated in Jefferson County, AL (in and near the city of Birmingham) were surveyed in detail to determine the actual development characteristics and their variability. Jefferson County is the largest county by population and fifth by size (NACO 2001) in the state of Alabama having as county seat the city of Birmingham, a heavily industrialized and urbanized area. Rainfall occurs year around, although is generally driest in the fall. About 55 inches of rainfall occurs in a normal year, but recent years have been marked by a significant drought. With the decreased rainfall, more attention is being placed on regional water resources, including stormwater.

To determine how land development variability affects the quantity and quality of runoff, different land surfaces (roofs, streets, landscaped areas, parking lots, etc.) for different land uses (residential, commercial, industrial, institutional, etc.) were directly measured. Surface cover of 125 neighborhoods located in the Little Shades Creek watershed and 40 neighborhoods located in the five of Jefferson County' highly urbanized drainage areas were analyzed to determine the actual development characteristics and their variabilities. The locally verified WinSLAMM model (Pitt and Voorhees 1995 and 2002) was then used to determine the sources of critical pollutants, and to predict their loads and concentrations. Statistical analyses were conducted at several levels to establish the quantitative and qualitative runoff sensitivity associated with variations of site characteristics.

ESTIMATION OF IMPERVIOUS AREA

Imperviousness is an important indicator for analyzing and measuring the impact of urbanization on drainage systems and aquatic life because the impervious cover is a variable that can be quantified for different types of land development (Schueler 1994; Arnold and Gibbons 1996; Booth and Jackson 1997).

Urban imperviousness is site-specific and complicated to measure. There are several methods used to measure the actual and future impervious cover, some of which are more accurate than others. The most accepted techniques include direct measurement, estimation of impervious cover based on land use, estimation from road density (length of road per unit area), and estimation of impervious cover from population data, aerial photograph interpretation, and satellite remote sensing. Most common methods of determining directly connected impervious cover are field measurements and empirical equations. Several studies have dealt with imperviousness and its estimation (as reported by Heaney et al. 1977; Boyd et al. 1993 and 1994; Novotny and Olem 1994; Debo and Reese 1995). Table 1 shows some of the studies that estimate/measure impervious cover for a certain region/watershed. Booth and Jackson (1997) explained the limitations of using total impervious area (TIA) in urban hydrology and suggested using directly connected impervious area (DCIA) to describe urban development, but noted that its direct measurement is complicated. Consequently, empirical equations for determining DCIA have been developed as part of several different studies (Alley and Veenhuis 1983; Laenen 1983; Sutherland 2000).

Alley and Veenhuis (1983) developed an empirical equation that shows the relationship between the directly connected impervious area and the total impervious area for a highly urbanized area in Denver, CO.

$$DCIA = 0.15 * TIA^{1.41} \tag{1.1}$$

Sutherland (2000) developed an equation based on USGS work completed in Portland and Salem, OR that describes the relationship between effective impervious area (EIA or DCIA) and total impervious and has its general form as:

$$EIA = A\,(TIA)^{B} \tag{1.2}$$

This equation has the same form as used by Alley and Veenhuis (1983), where *A* and *B* are unique combination of numbers that satisfy the following criteria: TIA = 1 then EIA = 0% and TIA = 100 then EIA = 100%. This equation has several alternatives known as the “Sutherland Equations” (Sutherland 2000) developed to apply to various conditions of subbasins which might exist in a watershed.

Values of imperviousness can vary significantly according to the method used to estimate the impervious cover (Lee and Heaney 2003; Ackerman and Stein 2008). They concluded that the main focus should be on DCIA when examining the effects of urbanization on stormwater quantity and quality, because we know that impervious surfaces interrupt the hydrologic cycle. Reducing the DCIA by disconnecting the impervious surfaces (sidewalks, rooftops, parking areas, and streets) from the drainage system will not restore hydrologic function to pre-development levels, but will improve the base flows, lessen the frequency of bank erosion, and improve stream functions. From a hydrological point of view, road-related imperviousness usually exerts larger impacts than the rooftop-related imperviousness, because roadways are usually directly connected while roofs can be hydrologically disconnected (Schueler 1994).

FIELD DATA COLLECTION

For this study, a locally calibrated version of WinSLAMM was used to compute the runoff quantity and quality for Little Shades Creek watershed near Birmingham, AL and for five additional Jefferson County drainage basins.

The field data used for modeling was gathered manually as part of a cooperative study conducted by the University of Alabama at Birmingham, the Jefferson County office of the U.S. Natural Resources Conservation Service (NRCS), the U.S. Army Corps of Engineers, and other city and county governments. The field data collection effort for the five additional Jefferson County drainage basins reported in this paper was performed during the author’s master thesis research (Bochis 2007). Every impervious surface was checked to estimate its properties and connectivity. Streets were classified according to their drainage system: with curb and gutter (directly connected to the storm drainage system) or with swales (disconnected). Also, the pavement material of every street and parking lot was examined and classified.

Table1. Reported Percent Impervious Cover for Various Land Uses

<table>
<tr><th rowspan="2">Land Use</th><th rowspan="2">Density (units/ac)</th><th colspan="10">Source</th></tr>
<tr><th>Northern Virginia (NVPDC, 1980)</th><th>TR-55 NRCS (USDA, 1986)</th><th>Puget Sound, WA (Aqua Terra, 1994)</th><th>Rouge River, MI (Kluitenberg, 1994)</th><th>Olympia, WA (COPWD, 1995)</th><th>Holliston, MA (CRWA, 1999)</th><th>Connecticut (Prisloe, 2000)</th><th>Chesapeake Bay (CWP, 2000)</th><th>Birmingham, AL (Bochis, 2007)</th><th>Simple Method Default</th></tr>
<tr><td>Forest</td><td>-</td><td>1</td><td>-</td><td>-</td><td>2</td><td>-</td><td>1</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Agriculture</td><td>-</td><td>1</td><td>-</td><td>-</td><td>2</td><td>-</td><td>1</td><td>-</td><td>2</td><td>-</td><td>-</td></tr>
<tr><td>Urban Open Land</td><td>-</td><td>-</td><td>-</td><td>-</td><td>11</td><td>-</td><td>7-23</td><td>-</td><td>9</td><td>13</td><td>-</td></tr>
<tr><td>Water/ Wetlands</td><td>-</td><td>-</td><td>0</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">Low Density Residential</td><td><0.5</td><td>2-6</td><td>-</td><td rowspan="3">10</td><td rowspan="3">19</td><td rowspan="3">-</td><td rowspan="3">12</td><td rowspan="3">7-10</td><td>-</td><td>-</td><td rowspan="3">10</td></tr>
<tr><td>0.5</td><td>9</td><td>12</td><td>11</td><td>-</td></tr>
<tr><td>1</td><td>12</td><td>20</td><td>14</td><td>18</td></tr>
<tr><td rowspan="3">Medium Density Residential</td><td>2</td><td>18</td><td>25</td><td>-</td><td rowspan="3">19</td><td>-</td><td rowspan="3">14</td><td rowspan="3">14-21</td><td>21</td><td rowspan="3">22</td><td rowspan="3">30</td></tr>
<tr><td>3</td><td>20</td><td>30</td><td rowspan="2">40</td><td rowspan="2">40</td><td>-</td></tr>
<tr><td>4</td><td>25</td><td>38</td><td>28</td></tr>
<tr><td>High Density Residential</td><td>5-7</td><td>35</td><td>65</td><td>40</td><td>38</td><td>40</td><td>19</td><td>28</td><td>33</td><td>30</td><td>40</td></tr>
<tr><td rowspan="3">Multifamily all >7 units/acre</td><td>Townhouse</td><td>40</td><td rowspan="2">65</td><td rowspan="2">60</td><td rowspan="2">51</td><td rowspan="2">48</td><td rowspan="2">47</td><td rowspan="2">39</td><td>41</td><td>35</td><td>60</td></tr>
<tr><td>Apartments</td><td>50</td><td>44</td><td>42</td><td>-</td></tr>
<tr><td>High Rise</td><td>60-75</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Industrial</td><td>-</td><td>60-80</td><td>72</td><td>90</td><td>76</td><td>86</td><td>60</td><td>53</td><td>53</td><td>59</td><td>75</td></tr>
<tr><td>Commercial</td><td>-</td><td>90-95</td><td>85</td><td>90</td><td>56</td><td>86</td><td>45</td><td>54</td><td>72</td><td>73</td><td>85</td></tr>
<tr><td>Roadway</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>58</td><td>80</td></tr>
</table>

DESCRIPTION OF STUDY AREAS

The Little Shades Creek watershed has an area of about 8 square miles and was about 70% developed at the time of these surveys (mid 1990s). It lies under the jurisdiction of several municipal governments as well as the county government, which made land development highly variable and uncoordinated. Many types of land development are represented, even though the residential areas, mostly as single family residential units, are predominant. Sixteen land use categories belonging to major land uses such as residential, commercial, institutional, industrial, and open space were surveyed by investigating about 10 neighborhoods for each land use. The predominant land use in the watershed was residential land, subdivided according to the density type, and age (Table 2).

A large fraction of imperviousness was found in the five Jefferson County drainage basins (Table 2). The stormwater drainage system was predominantly formed of curbs and gutters in good or fair condition with very little use of grass swales. Most of the roofs (pitched in residential and institutional areas and flat in rest) were found to be directly connected to the drainage system. The streets and most of the commercial parking lots had asphalt pavement, but industrial parking lots and residential sidewalks/driveways had smooth concrete as their predominate surface cover. As expected, the most imperviousness was found in commercial, followed by industrial, freeway and institutional land uses.

Table 2. Imperviousness Percentage based on Land Cover in Birmingham, AL Area (Bochis 2007)

Land Use	Total Impervious Area (%)	Directly Connected Impervious Area (%)	Pervious Area (%)
High Density Residential	30	19	70
Medium Density Residential	22	13	78
Low Density Residential	18	9	83
High Rise Res/Apartments	42	17	58
Multi Family	35	27	65
Commercial	73	72	27
Institutional	46	41	54
Industrial	59	50	41
Open Space	13	9	87
Freeways	58	0	42

RESULTS AND DISSCUSIONS

Impervious Cover Variability

Regardless of the method used to estimate imperviousness, some type of field verification is necessary, not to be mentioned that field verification is the only truthful way to estimate the directly connected portion of the impervious area (Gregory, et al. 2005). Therefore, in addition to field surveys, aerial photographs and satellite images were used to assist in the measurement of the actual coverage of each type of surface in each neighborhood studied, and were used to supplement the field collection information. Table 2 shows the percentage impervious and pervious cover for the land uses found in Birmingham, AL area. Table 3 shows the existing land uses with their average DCIA and the corresponding coefficient of variation.

Table 3. Directly Connected Impervious Areas in Birmingham, AL Area (Bochis 2007)

Land Use	Directly Connected Impervious Area (%) Local Conditions	COV	TR-55 Estimates (using interpolation)
High Density Residential	19	0.48	52
Medium Density Residential	13	0.68	39
Low Density Residential	***9***	***1.03***	23
High Rise Res/Apartments	17	0.97	65
Multi Family	27	0.53	-
Commercial	***72***	***0.29***	85
Institutional	41	0.61	-
Industrial	50	0.66	72
Open Space	***9***	***1.21***	-

Those drainage basins have the most of the impervious surfaces directly connected to the drainage system, exception being the low density residential and open space land uses which have the lowest connectivity and the greatest coefficient of variation, meaning that there is a high variability within the land use. The other extreme case is the commercial land use, which has almost all impervious cover connected and little variability.
Following the empirical equations for determining DCIA from TIA suggested by the literature, a power equation was fitted to the data. The plot shown in Figure 1 relates the percent directly connected impervious areas to the total impervious areas for all of the individual homogeneous land use sites investigated (Bochis 2008).

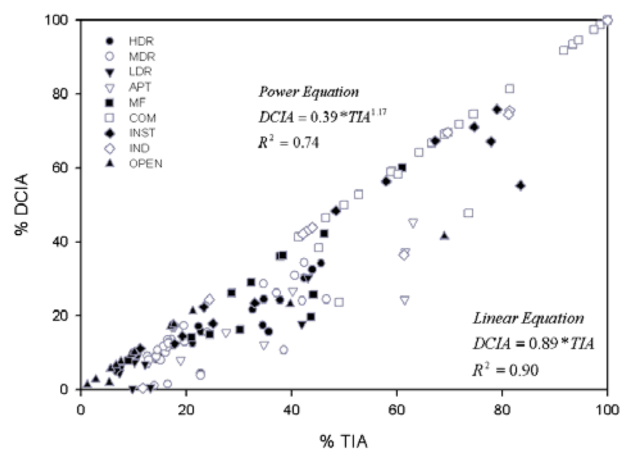

Figure 1. Empirical Estimation of DCIA based on TIA for Birmingham, AL Study Areas (Bochis 2008)

This figure shows that the study areas' DCIA might be a power function of TIA, as previously shown by Sutherland (highly connected basin, 2000), and Alley and Veenhuis (1983). In fact, for these drainage basins, most of the impervious surfaces are directly connected to the drainage system. The fitted equation for the entire study areas is comparable to one of the Sutherland equations used for highly connected basins where drainage collector is storm sewer with curb and gutters, roofs are connected, and there are no infiltration devices. The power equation is fitted separately for each individual land use existent in the study areas. The *A* and *B* equation coefficients, along with their coefficient of determination and residual P-values are presented in Table 4. This data shows that DCIA of each land use is not always a power function of TIA, suggesting that power fitting cannot be successfully applied on Alabama's local condition. We found that the linear equations better fits our data (Table 4).

Table 4. Equation Coefficients for Each Land Use Existent in Birmingham, AL Study Area (Bochis 2008)

	Power Equation				Linear Equation		
Land Use	**A coeff.**	**B coeff.**	**R^2 value**	**Residuals p-value**	**A coeff.**	**R^2 value**	**Residuals p-value**
High Density Residential	0.34	1.16	0.64	**0.008**	0.64	0.78	0.061
Medium Density Residential	0.42	1.09	0.36	**<0.005**	0.63	0.65	0.061
Low Density Residential	0.22	1.16	0.27	0.415	0.55	0.78	0.292
High Rise Res/Apartments	0.22	1.22	0.83	0.823	0.56	0.74	0.943
Multi Family	0.74	1.00	0.77	0.714	0.80	0.72	0.527
Commercial	0.49	1.16	0.82	**<0.005**	0.98	0.90	0.048
Institutional	0.75	1.04	0.97	0.106	0.88	0.93	0.153
Industrial	0.04	1.78	0.75	0.068	0.95	0.94	0.382
Open Space	1.05	0.92	0.91	**<0.005**	0.67	0.87	0.373

There are some other reported literature values on impervious cover are not very accurate when applied to local conditions. The TR-55 (USDA 1986) (Table 1) method overestimate the impervious cover for all land uses investigated, because the model assumes that all impervious area are directly connected to the drainage system. Table 2, Table 3 and Figure 2 show that impervious area in the six Jefferson County watersheds are almost entirely directly connected, and that there is a large variability among and within land uses. In the case of residential land uses (high, medium and low density), the predominant land use in the study area, the TR-55 method gave values of impervious cover which are about three times higher than the observed values. This overestimation will lead to overestimation in runoff volume.

We used a Pearson correlation matrix to relate the magnitude of the relationships between the field measurements and predicted concentrations for those highly urbanized drainage areas. The matrix shows that runoff volume can be mostly predicted by using DCIA, TIA, and parking lot areas. Also, there are high correlations between several pairs of parameters, showing that some pollutants concentrations (COD and phosphorus) are directly related to the particulate solids concentrations.

Expected Biological Conditions as a Function of Impervious Area

Table 5 is a summary of the existing land uses that were monitored as part of this research. The data shows that three watersheds are highly impervious, with more than 50% of watershed being composed of impervious cover. The expected biological conditions of the receiving waters were calculated by WinSLAMM to be "poor" for the base conditions having no stormwater controls. The highly impervious watersheds (ALJC001 and ALJC012), which have mainly industrial and commercial land uses respectively, have higher values of Rv (about 0.6) but lower values of TSS concentrations, compared to the watersheds dominated by residential land uses (ALJC009, ALJC010, and Little Shades Creek).

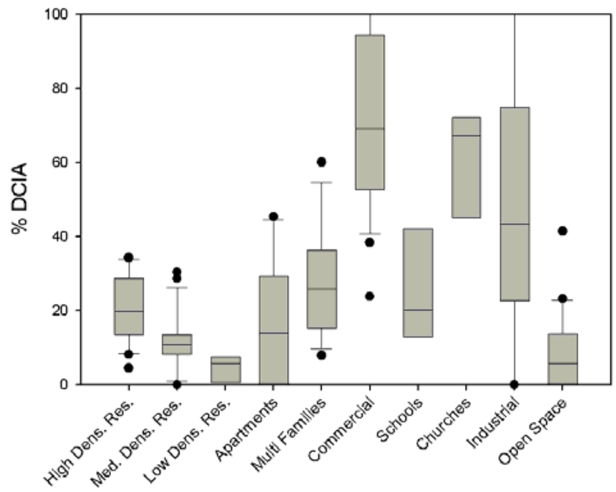

Figure 2. Percent of Directly Connected Impervious Area by Land Use for Little Shades Creek and Jefferson County, AL Watersheds (Bochis 2007)

The residential watersheds are closer to the threshold between fair and poor biological conditions (an Rv of about 0.25) than the industrial and commercial watersheds, as expected. WinSLAMM was used to investigate the relationship between watershed and runoff characteristics for each of the individual 160 neighborhoods investigated. An example evaluation of the relationships between the directly connected impervious area percentages (DCIA %) and the calculated volumetric runoff coefficients (Rv) for each land use category (using the average land use characteristics) in the Little Shades Creek watershed, based on 43 years of local rain data showed that there is a strong relationship between these parameters for both sandy and clayey soil conditions.

Table 5. Runoff Quantity and Source Area Drainage Connections by Land Use for Birmingham, AL Sites (Bochis 2007)

Watershed ID	**Major Land Use**	**Area (ac)**	**Pervious Areas (%)**	**Directly Connected Impervious Areas (%)**	**Disconnected Impervious Areas (%) (draining to pervious areas)**	**Volumetric Runoff Coefficient (Rv)**	**Expected Biological Conditions of Receiving Waters**
ALJC 001	Industrial	341	25	72	2.8	0.67	Poor
ALJC 002	Industrial	721	40	53	7.3	0.51	Poor
ALJC 009	Residential High Density	102	54	34	12	0.37	Poor
ALJC 010	Residential Medium Density	133	64	28	7.9	0.30	Poor
ALJC 012	Commercial	228	36	61	3.4	0.61	Poor
Little Shades Creek	Residential	5120	67	21	12	0.29	Poor

The fitted exponential equations are (Bochis and Pitt 2005):

$$\text{Sandy soils:} \quad R_v = 0.062e^{0.031*DCIA} \; (R^2 = 0.83)$$

$$\text{Clayey soils:} \quad R_v = 0.15e^{0.017*DCIA} \; (R^2 = 0.72)$$

It is interesting to note that the Rv is relatively constant until the 10 to 15% directly connected impervious cover values are reached (at Rv values of about 0.07 for sandy soil areas and 0.16 for clayey soil areas), the point where receiving water degradation typically is observed to start. The 25 to 30% directly connected impervious levels (where significant degradation is observed), is associated with Rv values of about 0.14 for sandy soil areas and 0.25 for clayey soil areas, and is where the curves start to greatly increase in slope.

DISCUSSION AND CONCLUSION

The data collected for the Jefferson County watersheds show that this area in Birmingham, AL, has an average impervious cover of about 39%, of which about 25% is directly connected to the drainage system and 14% drains to pervious areas (Tables 2). Table 5 is a summary of the discharge conditions for the study drainage areas and shows that three urban areas are highly impervious, with more than 60% of the watershed areas being composed of impervious covers. It also shows the expected conditions in the local receiving waters due to the measured amounts of impervious cover from these local land uses. The stream quality is damaged to severely damage, a fact confirmed by in-stream investigations by the Storm Water Management Authority Inc. biologists. As expected, the land use with the least impervious cover is open space (parks, cemeteries, golf course), and the land uses with the largest impervious covers are commercial areas, followed by industrial areas. It can be concluded that impervious areas in Little Shades Creek and Jefferson County watersheds are almost entirely directly connected, and that there is a large variability between the land use categories. It was found that for a typical high density residential land use located in the Birmingham area, the total amount of impervious area does not vary much. There is an apparent variability in front landscaped vs. back landscaped areas, the reason being the position of the house on the lot, but in fact, the total amount of landscaped areas has a low variability for residential land use areas.

Urbanization radically transforms natural watershed conditions and introduces impervious surfaces into the previously natural landscape. Total impervious areas are mostly composed of rooftop and transportation related components that can be either directly connected or disconnected to the drainage system. The impervious areas that are directly connected to the storm drainage system are the greatest contributor of runoff and stormwater pollutant mass discharges under most conditions. The amount of impervious cover has become recognized as a tool for evaluating the health of a watershed and serves as an indicator of urban stream quality. Knowledge about the impervious surfaces, and how they can be managed, is an effective stormwater management tool and can be used to help reduce the impacts of developments within watersheds.

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