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Overview of Methods Used to Estimate Imperviousness in a Drainage Basin

By Gregory E. Granato

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U.S. Geological Survey
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Foreword

The mission of the Federal Highway Administration (FHWA) is to continually improve the quality of our Nation's highway system and intermodal connections in a manner that protects and enhances the natural environment and communities affected by transportation. The FHWA must develop and disseminate research products that help FHWA and its partners implement surface transportation programs in a manner that protects and enhances the natural and human environment. More specifically, the Office of Office of Project Development and Environmental Review of the FHWA strives to develop and disseminate skills, tools, and information to redesign Federal environmental and transportation decisionmaking, and to ensure an integrated process at the Federal, State, tribal, and local levels. These tools, techniques and methods are designed to reduce direct and indirect adverse impacts of highways on water quality, habitat, and ecosystems to preserve and enhance human health, biological productivity, and ecological diversity.

This report, the associated computer applications, and data provide tools and techniques for developing planning-level estimates of stormflows at sites receiving highway runoff. This information is vital for assessing the potential for adverse effects of runoff on receiving waters throughout the Nation and it should provide transportation agencies with the tools and information to improve project delivery without compromising environmental protection.

Patricia Cazenas Highway Engineer
Office of Project Development and Environmental Review
Federal Highway Administration

Susan Jones Highway Engineer
Office of Project Development and Environmental Review
Federal Highway Administration

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Notice

Quality Assurance Statement

Contents

Figures

Tables

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Introduction

The stochastic empirical loading and dilution model (SELDM) uses regression equations that are based on the fraction of anthropogenic total impervious area (TIA; primarily pavement and roofs) to estimate runoff coefficient statistics. The average, standard deviation, and skew of volumetric runoff coefficients for a basin that is upstream of a highway outfall are used to generate a random population of stormflow volumes. Conceptually, this approach is based on the assumption that the highway and the upstream basin will be affected by the same storm, but that each will generate stormflows based on characteristics of the drainage area. Anthropogenic TIA was selected as the explanatory variable to predict runoff coefficients because TIA has a demonstrated effect on the mechanisms, magnitude and timing of storm runoff.

All commonly used methods for characterizing rainfall-runoff transformations implicitly or explicitly account for the degree of imperviousness within the drainage area. Imperviousness is an important explanatory variable for characterizing rainfall-runoff transformations because anthropogenic and natural impervious areas rapidly convey precipitation towards the channel network. Imperviousness also may convey runoff to adjacent pervious (or semi-pervious) areas at rates that may exceed the infiltration capacity of soils, which may lead to infiltration excess overland flows. Imperviousness is used as an explanatory variable in watershed-simulation models (for example, Alley and Smith, 1982; Linder-Lunsford and Ellis,1987; Shoemaker and others, 1997), runoff-volume regression-models (for example, Ellis and others, 1984; Driver and Tasker, 1990; Brezonik and Stadelmann, 2002), and runoff-coefficient regression-models (for example, Goforth and others, 1983; Schueler, 1987; Urbonas and Guo, 1989; Driscoll and others, 1990b; Granato and Cazenas, 2009). Imperviousness also is used for specifying NRCS curve numbers (Natural Resources Conservation Service, 1986). Imperviousness also has been identified as an important explanatory variable for water-quality characterization and for evaluating the effect of development on aquatic and riparian ecosystems (for example, Rimer and others, 1978; Krug and Goddard, 1986; Slonecker and others, 2001; Lee and Heaney, 2002; Coles and others, 2004; Xian and others, 2007; Cuffney and Falcone, 2009).

This appendix describes different methods for estimating imperviousness and includes the results of literature reviews and analysis of available data. Estimates of imperviousness are needed to estimate volumetric runoff-coefficient statistics for use with SELDM. The default SELDM runoff-coefficient regression equations are based on anthropogenic TIA. However, runoff coefficient statistics for different sites with similar anthropogenic TIA fractions can vary substantially. Methods for estimating directly connected impervious area (DCIA) are included because sites with a high proportion of DCIA may have larger runoff coefficients than similar sites with less DCIA. SELDM users can use information about DCIA to modify default runoff-coefficient statistics used in SELDM to reflect the proportion of DCIA in a stream basin upstream of a site of interest. Methods to identify natural impervious areas are included because these impervious features, such as bedrock outcrops and saturated soils, in riparian areas can contribute a substantial amount of runoff. As such, sites with a substantial amount of natural imperviousness may have runoff-coefficient statistics that resemble areas with a substantial amount of anthropogenic TIA. SELDM users also can use information about natural impervious areas to modify default runoff-coefficient statistics used in SELDM.

Estimating Anthropogenic Total Impervious Area

Different methods for estimating anthropogenic TIA (sometimes called mapped impervious area; MIA) by various measures are common in the literature (for example, Allen and Bejcek, 1979; Prych and Ebbert, 1986; Boyd and others, 1993; Ridd, 1995; Prisloe and others 2000; Cappiella, and Brown, 2001; Slonecker and others, 2001; Jennings and Jarnagin, 2002; Wu and Murray, 2003; Yang, Huang, and others 2003; Yang, Xian, and others, 2003; Homer, and others 2004; Slonecker and Tilley, 2004; Xian and Crane, 2005; Tilley and Slonecker, 2007; Homer, and others 2007). TIA can be estimated directly using maps, aerial photographs, or field surveys but this process is very labor intensive. As such, TIA is commonly estimated using land use maps, population density maps, or land-cover maps. Data describing the geographic distribution of land use, population, and land cover commonly are available in geographic information system (GIS) formats. Each method for deriving TIA estimates for a basin of interest, however, has advantages and limitations. Multiple methods can be used to refine or verify the uncertainty in a TIA estimate.

Land Use

TIA estimates by land use are made identifying land use categories for large blocks of land, summing the total area of each category, and multiplying each area by a characteristic TIA coefficient. Land use categories commonly are used to estimate TIA because areas with a common land use can be identified from field studies, from maps, from planning and zoning information, and from remote imagery. Land use coefficient methods commonly are used because planning and zoning maps that identify similar areas are, increasingly, available in GIS formats. Also, land use methods are selected to estimate potential effects of future development on TIA with planning maps that quantify projected changes in land use (Cappiella and Brown, 2001).

An initial estimate of TIA from land use can be made on the basis of the percent of developed area (PDA). The PDA can be estimated by identifying areas as developed or nondeveloped, summing the developed area, and using a regression equation to estimate the TIA. The Multi-Resolution Land

Characteristics Consortium (MRLCC) defines a developed area as being covered by at least 30 percent of constructed materials (U.S. Environmental Protection Agency, 2009b). Southard (1986) defined nondeveloped areas as natural, agricultural, or scattered residential development. Southard (1986) developed a regression equation to predict TIA using percent developed area (**table 6-1**). He developed his equation using logarithmic power function with data from 23 basins in Missouri. He noted that this method was advantageous because large basins could quickly be delineated and TIA estimated manually from available maps. For example, he indicated that drainage basins with areas less than 22 square miles could be delineated in less than 2 hours. GIS methods could substantially reduce this effort. Southard (1986) developed an accurate regression equation using to estimate TIA from the PDA.

A regression equation was derived for the SELDM study to facilitate rapid development of planning-level estimates of TIA from PDA. The regression equation was developed as a logarithmic power function using data from 262 stream basins in 10 metropolitan areas of the conterminous United States with drainage areas ranging from 0.35 to 216 square miles and PDA values ranging from 0.16 to 99.06 percent were used to develop the regression relation shown on **figure 6-1**. These data were developed as part of the U.S. Geological Survey's National Water Quality Assessment (NAWQA) effects of urbanization on stream ecosystems (EUSE) study (U.S. Geological Survey, 2008a; Cuffney and Falcone, 2009). The regression equation was developed using the line of organic correlation (Helsel and Hirsch, 2002). This equation has an r-squared value of about 0.92 and the nonparametric coefficient of efficiency (Legates and McCabe, 1999) indicates that this equation accounts for about 72 percent of the variation in TIA values for a measured PDA value. In comparison, Southard's equation has an (1986) r-squared value of about 0.99 but was developed with far fewer basins in urbanized areas of Missouri (**table 6-1;** Southard, 1986). Southard's equation accounts for about 44 percent of the variation in TIA values for a measured PDA value in the NAWQA data set.

Many TIA estimates in the literature and many of the TIA values used to describe rainfall-runoff monitoring sites in the database (SiteStorm.mdb) assembled for the SELDM project were developed using TIA values for different land use categories. The categories and associated values in **table 6-2** may be used with land use maps to calculate TIA estimates for an area of interest. The TIA values in the table are the range of mean or median values reported among the studies identified in the footnotes. Thus, the ranges of values presented in the table for each category do not represent the range of TIA values that may be reported within an individual study.

Table 6-1. Regression equations developed to estimate measures of imperviousness.

[CL, specific curb length, in feet per acre DCIA directly connected impervious area, in percent; $DCIA_m$ mapped directly connected impervious area, in percent; HD, housing density units per Acre; ILC Imperviouness by land cover category, in percent; ILU Imperviouness by land use category, in percent; N number in sample; NLCD92D 1992 national land-cover data set percent developed area; PD Population density, in persons per square mile; PDA Percentage of developed area, including nonrural areas delineated on 7.5 minute quadrangle maps; SD Street density, in miles per square mile; R2 fraction of variance explained by regression; TIA Total Impervious area, in percent; Equation users must examine the results over the range of anticipated values to ensure results are reasonable]

Reference	Predicted	Predictor	Type	Intercept	Slope	N	R^2	Equation
Allen and Bejcek, 1979	TIA	PD	Polynomial	3.54	--	15	0.984	$TIA = 3.54 + (6.71 * 10^{-3})PD - (2.0 * 10^{-7})PD^2$
	TIA	HD	Polynomial	4.11	--	15	0.984	$TIA = 4.11 + (2.05 * 10^{-2})HD - (6.1 * 10^{-7})HD^2$
	TIA	SD	Polynomial	4.68	--	15	0.981	$TIA = 4.68 + 3.17SD - (3.37 * 10^{-2})SD^2$
Alley and Veehuis, 1983	$DCIA_m$	TIA	Power	0.15	1.41	14	0.98	$DCIA_m = 0.15\ TIA^{1.41}$
Boyd and others, 1993	DCIA	TIA	Linear	0	0.75	38	0.86	DCIA = 0.75 TIA
	DCIA	$DCIA_m$	Linear	0	0.87	38	0.87	$DCIA = 0.87\ DCIA_m$
Dayaratne, 2000	DCIA	HD	Polynomial	-101.01	--	16	0.9	$DCIA = -5.1452HD^2 + 57.421HD - 101.01$
Graham and others, 1974	TIA	PD	Power	--	--	32	0.74	$TIA = 91.32 - 69.34 (0.9309^{PD/640})$
	TIA	HD	Power	--	--	32	0.81	$TIA = 90.76 - 64.74 (0.7928)^{HD}$
	CL	PD	Power	--	--	32	0.71	$CL=423.7 - 420.8 (0.8797)^{PD}$
	CL	HD	Power	--	--	32	0.69	$CL=427.4 - 388.1 (0.6899)^{HD}$
Greater Vancouver sewerage and drainage district, 1999	TIA	PD	Exponential	--	--	--	0.85	$TIA = 94 (1-e^{-0.00011\ PD})+1$
Hitt, 1994	HD	PD	Power	0.00661	1	8,556	--	HD = 0.00661 PD
Jennings and others, 2004	TIA	NLCD92D	Linear	0.3989	2.637	19	0.899	TIA = 2.6367 + 0.3989 NLCD92D
Moglen and Kim, 2007	ILU(TIA)	ILC(TIA)	Power	6.725	0.54	18,681	0.82	$ILU = 6.725\ ILC^{0.5402}$
	ILC(TIA)	ILU(TIA)	Power	0.0806	1.531	18,681	0.79	$ILC = 0.0806\ ILC^{1.5305}$
Moglen and Shivers, 2006	TIA	PD	Power	0.337	0.52	998	0.62	$TIA = 0.337\ PD^{0.5195}$
Prisloe and others, 2002	TIA	PD	Linear	10.447	0.004	16	0.85	TIA = 10.447 + 0.0043 PD
Roy and Shuster, 2009	DCIA	TIA	Linear	1.86	0.627	521	0.57	DCIA = -1.86 + 0.627 * TIA
Stankowski, 1972	TIA	PD	Polynomial	0.0218		21	--	$TIA = 0.0263\ PD^{1.247-0.108 \log10(PD)}$
Southard, 1986	TIA	PDA	Power	2.03	0.618	23	0.985	$TIA = 2.03\ PDA^{0.618}$
Sutherland, 1995	DCIA	TIA	Power	0.1	1.5	42	--	Average $DCIA = 0.1\ TIA^{1.5}$
	DCIA	TIA	Power	0.4	1.2		--	High $DCIA = 0.4\ TIA^{1.2}$
	DCIA	TIA	Power	0.04	1.7		--	Low $DCIA = 0.04\ TIA^{1.7}$
	DCIA	TIA	Power	0.01	2		--	Very Low $DCIA = 0.01\ TIA^{2.0}$
Taylor and others, 2004	DCIA	TIA	Linear	-3.11	1.038	16	0.985	DCIA = -3.11 + 1.038 TIA
Wenger and others, 2008	DCIA	TIA	Linear	-6.23	1.046	15	--	DCIA = -6.23 + 1.046 TIA

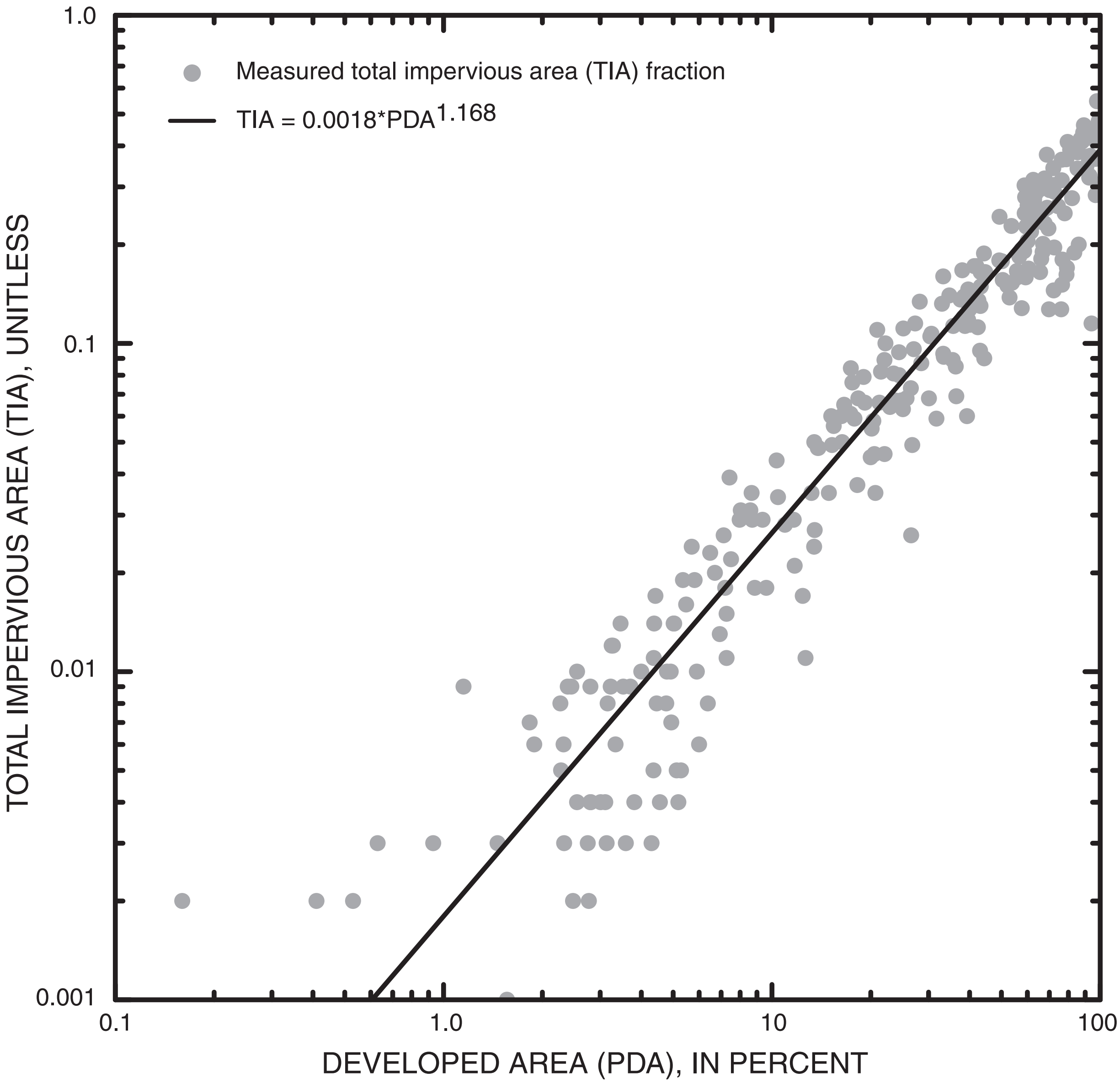

Figure 6-1. Graph showing a regression equation for estimating the fraction of total impervious area (TIA) from the percentage of developed area (PDA) in a drainage basin with for 262 stream basins in 10 metropolitan areas of the conterminous United States with drainage areas ranging from 0.35 to 216 square miles and PDA values ranging from 0.16 to 99.06 percent (Data from the U.S. Geological Survey's National Water-Quality Assessment effects of urbanization on stream ecosystems study; Cuffney and Falcone, 2009).

Table 6-2. Literature values for total impervious area (TIA) by land use, in percent.

Land use	Range of mean or median total impervious area, in percent	References
Impervious percentage: 0 to10		
Agriculture	0.75-5	6, 10, 12, 18
Agriculture buildings	10	18
Agriculture hay/pasture	2-7	8, 10, 14, 15, 16, 24
Agriculture row crops	2-8	8, 10, 14, 15, 24
Barren Land	1-10	8
Cemeteries	5-10	2, 6, 16
Forest, clear cut	6-9	17, 24
Forest, deciduous	1.3-5.5	8, 10, 14, 24
Forest, evergreen	1-9.4	8, 10, 14, 24
Forest, mixed	0-9	8, 10, 14, 18
Golf courses	5	6
Grassy areas	4-9	8, 10, 24
Open urban land	1-9	6, 10, 12, 14, 16, 18, 23, 27
Parks	1-10	15
Quarries/strip mines/gravel pits	6-10	13, 16
Residential, low density	7-10	8, 10, 12, 16, 27, 30
Residential, single family >1 Ac	6	4, 29
Rural, high activity	5	24
Rural, low activity	3	24
Utility rights-of-way	3	8
Water	0-1	8
Wetland, herbaceous	0-3	8, 10, 18
Wetland, woody	0-4	8, 10, 14, 18
Impervious percentage: greater than 10 to 20		
Agricultural/unclassified	15	21
Agriculture hay/pasture	11	13
Agriculture row crops	14	13
Barren Land	11-20	8
Commercial, low activity	12	24
Forest, deciduous	12	13
Forest, evergreen	15	13
Forest, mixed	11	13
Quarries/strip mines/gravel pits	14	13
Low-density built up	12-19	5, 8, 27
Low-impact industrial	15	21, 24
Open developed/urban land (grassy)	11-17	5, 8, 11, 15
Parks	13-15	3, 6, 16, 22
Residential, low density	10-20	13, 15, 16, 18, 20, 22, 23, 24, 25, 26, 27
Residential, single family > 0.5 Ac	15	1
Residential, single family 1 Ac	11-20	4, 6, 9, 21
Residential, single family 2 Ac	11-12	6, 21
Transportation, Rail Lines	15	15
Transportation, airport with adjoining land	15	9
Wetland, herbaceous	16-18	14, 24
Wetland, woody	20-21	13, 24

Table 6-2. Literature values for total impervious area (TIA) by land use, in percent. (continued).

Land use	Range of mean or median total impervious area, in percent	References
Impervious percentage: greater than 20 to 40		
Agriculture cultivated crops	24	8
Commercial	35-37	7, 18, 25
Commercial/Industrial/Transportation	35-62	13
Developed, low intensity	28	8
Developed, medium intensity	31	8
Exposed soil/construction	21	23
Industrial	30-39	22, 27
Institutional, church	40	6
Institutional, government	35	6
Institutional, school	30	6
Institutional, unspecified	34-36	6, 15, 27
Mixed, residential and commercial	30	23
Open urban land	21	13
Quarries/strip mines/gravel pits	45	13
Residential, low density	>20-31	15, 19, 26, 28
Residential, high density	30-40	11, 20, 26, 30
Residential, medium density	23-40	9, 15, 19, 23, 26, 30
Residential, single family 0.25-0.5 Ac	21-35	1, 2, 6, 7, 9, 20, 21
Residential, single family <0.25 Ac	33-39	1, 6, 7
Roads/highway	32-36	4, 14
Urban, low-density	30	28
Impervious percentage: greater than 40 to 60		
Agriculture, dairy or livestock	42	15
Commercial	54-59	7, 27
Commercial/Industrial	41-57	10, 24
Commercial/Industrial/Transportation	62	13
Construction	60	9
Developed, medium intensity	40-46	8
Developed, high-density	48-59	5, 8
Industrial	54-60	1, 22, 27
Infrastructure	59	5
Institutional	60	25
Institutional, college or university campus	47	15
Institutional, school	59	7
Power Plants	47	15
Quarries/mines/gravel	62	10
Residential	44-51	3, 16, 17
Residential, high density	45-52	8, 14, 15, 16, 23, 28
Residential, low density	42-50	10, 28
Residential, low-density trailer parks	42	15
Residential, multifamily	44-60	1, 6, 13, 16
Residential 1/8th Ac	40-65	2, 7, 19, 21
Residential, single family	43	12
Residential, townhome	40-55	6, 9, 10, 16
Transportation, Airport	45	15
Transportation, Highways	53-60	9, 15, 18
Urban, city center	42	5
Urban, medium density	50	28

Table 6-2. Literature values for total impervious area (TIA) by land use, in percent. (continued).

Land use	Range of mean or median total impervious area, in percent	References
Impervious percentage: greater than 60 to 80		
Agriculture, poultry	62	15
Commercial	66-79	2, 6, 16, 22, 23
Commercial, downtown	75-83	7, 15, 25, 28
Institutional	65-75	2, 16
Institutional, medical facilities	74	15
Industrial	70-75	3, 12, 19, 21, 26
Residential, high density	62-80	2, 11, 15, 17, 28
Residential, multifamily	70	25
Residential, townhome	80	11
Transportation, major roads	75	6
Transportation	75	18
Urban, high-density	60-72	8, 28
Impervious percentage: greater than 80 to 90		
Commercial	82-90	1, 12, 16, 19, 21
Commercial/Industrial/Transportation	90	8
Commercial, recreation	86-90	15
Industrial	82-90	2, 5, 15, 26
Institutional	82-90	11, 16
Institutional, religious facilities	82	15
Institutional, schools	82-90	15
Residential, multistory apartments/condominiums	86-90	15
Transportation	90	11
Urban, unspecified	85	18
Impervious percentage: greater than 90		
Agriculture, storage and processing facilities	96	15
Commercial	98-100	2, 13, 17, 30
Commercial, hotel and multistory office buildings	91-96	15
Commercial, retail shopping	95-97	15
Flood control waterways	100	15
Industrial	91-96	15
Institutional, government, police, fire	91	15
Residential, trailer parks	91	15
Transportation, bus, truck, and harbor terminals	91-100	15
Transportation, major roads	91	15
Transportation, railroads terminals and storage	91	15
Wastewater treatment facilities	96	15
Water bodies	100	15

Table 6-2. Literature values for total impervious area (TIA) by land use, in percent. (continued).

References
1. Alley and Veenhuis, 1983
2. Antoine, 1964
3. Baldys and others, 1996
4. Burns and others, 2001
5. Canters and others, 2006
6. Cappiella and Brown, 2001
7. Carter and Jackson, 2007
8. Chabaeva and others, 2009
9. Dinicola, 2001
10. Dougherty and others, 2004
11. Exum and others, 2005
12. Greater Vancouver sewerage and drainage district, 1999
13. Guay and Smith, 1988
14. Jennings and others, 2004
15. Kluitenberg, 1994
16. Los Angeles County Department of Public Works, 2006
17. Miller, 1985
18. Milheim, Lesley, 2009, U.S. Geological Survey, written comun.
19. Moglen and Kim, 2007
20. Morse and others, 2003
21. National Rescource Conservation Service, 1986
22. Niehus, 1997
23. Parcher, 2106
24. Prisloe and others, 2000
25. Rimer and others, 1978
26. Stankowski, 1972
27. Wenger and Roskie, 2008
28. Wu and Murray, 2003
29. Xian and Crane, 2005
30. Zarriello, 1999

Land use category coefficients are commonly used, but there are limitations to the application of the land use classification method for estimating TIA. Uncertainty in estimates of TIA by land use increase with increasing spatial resolution of land use areas (Carter and Jackson, 2007). Estimates of TIA made using the land use categories are affected by different definitions of similar land use patterns and variation in imperviousness within a land use area (Canters and others, 2006). The range of TIA values in **table 6-2** indicates that there are many land use classifications within the literature and that there is a substantial range of average TIA values for similar land use categories. This indicates that nationally consistent categories for classifying land use areas are needed (Hitt, 1994; Lu and Weng, 2006). Consistent TIA estimates made using land use categories may be difficult if drainage-basin boundaries cross political boundaries and different classification systems or mapping units are used in each area.

The range of TIA values in **table 6-2** indicates that there may be substantial differences in actual and estimated TIA estimates from different studies in the literature. Terms like low density and high density may differ in different areas (Hitt, 1994). A residential density of one-half acre per house may be classified as high density in a rural area, medium density in a suburban area, and low density in an urban area. For example, the low-density residential land use category is associated with impervious fractions raging from about 6 to 50 percent in different studies (**table 6-2**). The presence of open areas such as parks, cemeteries, and gardens in developed areas also may add ambiguity to TIA estimates. These types of open areas are associated with TIA values that range from 1 to 21 percent in different studies (**table 6-2**). Furthermore, such open areas commonly are included in other land use categories, which may reduce TIA in those areas (Boyd and others, 1993). Although there are many land use categories listed in the literature, TIA values for each category may not represent specific areas. For example, land use categories for industry commonly do not distinguish between different types of facilities (Parcher, 2006). For example, an old manufacturing facility may have high impervious fractions, a high proportion of DCIA, and a lack of flow-control BMPs. In contrast, a newer software-development facility may have more pervious landscaping, less DCIA, and more effective flow-control BMPs than an older manufacturing facility. The U.S. National Land Cover Database (NLCD) land use schema may provide a consistent national land use standard for future work (Parcher, 2006; U.S. Environmental Protection Agency, 2009b), but there will continue to be variations in TIA within categories in different areas.

Bias in TIA coefficients for different land uses can have a substantial effect on estimated imperviousness and therefore on calculated runoff-coefficient statistics. For example, Moglen and Kim (2007) indicated that TIA estimates made using the Natural Resources Conservation Service (1986) land use coefficients may be substantially higher than land-cover based TIA estimates if TIA is less than 55 percent of land area. They developed regression equations to estimate each measure of TIA (land use or land cover) using the other with about 19,000 GIS grid cells in Northeastern Maryland (**table 6-1**). Moglen and Kim (2007) indicate that the land use estimates may be 1.5 to 2 times higher than land-cover estimates.

If GIS files are not available for an area manual methods for identifying and quantifying land use areas are slow, labor intensive, and rely heavily on skills of interpreter (Yang, Xian, and others, 2003). Various methods have been developed to help facilitate and standardize the process for estimating TIA. For example, Morse and others (2003) reduce the effort for estimating TIA from land use and reduce variations in TIA fractions among land uses by quantifying large impervious areas (such as transportation and commercial areas) and estimating imperviousness using different residential categories for remaining areas.

Population Density

TIA fractions also are estimated from population density data by estimating the population in an area of interest and using regression equations to calculate the associated TIA (Stankowski, 1972; Graham and others, 1974; Gluck and McCuen, 1975; Allen and Bejcek, 1979; Greater Vancouver Sewerage and Drainage District, 1999; Chabaeva and others, 2004; Moglen and Shivers, 2006; Parcher, 2006). Population-density data are used because nationally consistent census-block data are available in GIS formats for the entire United States. Population-density methods also can be used for predicting potential effects of future development (Greater Vancouver Sewerage and Drainage District, 1999; Moglen and Shivers, 2006). Population-density equations for estimating TIA and housing density are provided in **table 6-1.** Although there may be substantial variation in relations between population density and TIA the accuracy of such estimates tend to improve with increasing drainage area as local variations are averaged out (Greater Vancouver Sewerage and Drainage District, 1999).

A three-segment regression equation was derived for the SELDM study to estimate the TIA fraction from population density (**figure 6-2)**. The regression equation was developed as a logarithmic power function using the basin characteristics data from the U.S. Geological Survey's EUSE study (U.S. Geological Survey, 2008; Falcone and Pearson, 2006; Falcone and others, 2007; Falcone and others, 2010). The population density in the 6,255 stream basins used to develop the regression equation ranged from about 0.01 to about 5,171 persons per square mile and impervious fractions range from 0.0001 to 0.63. This three-segment regression equation was developed using the Kendall-Theil robust line (Granato, 2006). The data in **figure 6-2** indicate a non-linear relation between the logarithms of population density and TIA. However, the three-segment model characterizes the relation in the different population-density ranges. The first segment, which represents about 37.5 percent of the data, includes the stream basins with a population density below 16 persons per square mile (with an associated TIA fraction of 0.00). The second segment, which represents about 62 percent of the data, includes stream basins with a population density from 16 to 5,332 persons per square mile (with an associated TIA fraction of 0.37). The third segment includes population densities between 5,332 and 13,392 persons per square mile (with an associated TIA fraction of 0.54). The lower slope of the third segment probably indicates an increasing fraction of industrial, commercial, or transportation land uses in highly impervious basins. The regression model based on population-density has a nonparametric coefficient of efficiency (Legates and McCabe, 1999) of 0.485, which indicates that it accounts for almost half of the variation in TIA for these stream basins throughout the United States.

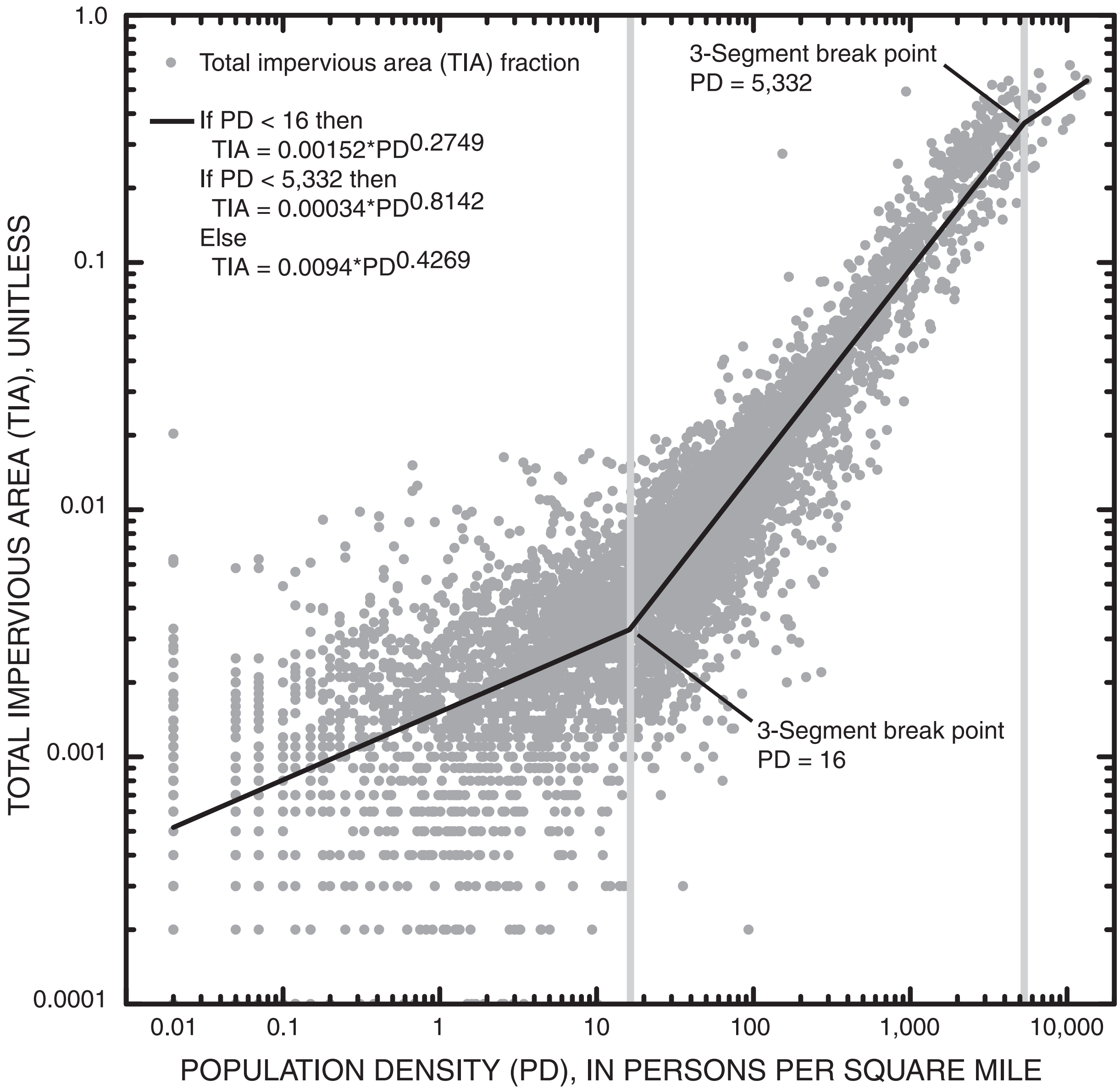

Figure 6-2. Graph showing a 3-segment regression equation for estimating the fraction of total impervious area (TIA) from Population Density (PD) for 6,255 stream basins in the United States with drainage areas ranging from 0.62 to 19,229 square miles. (Data from Falcone and others, 2010).

Population-density estimates also may be refined with other geographic data. For example, Hitt (1994) developed equations for population density and housing density using the line of organic correlation; as such the equation in **table 6-1** can be inverted to estimate population density from housing density; either of which may be used to estimate TIA. For example, the equations developed by Hitt (1994) may be used to estimate TIA in conjunction with the other population-density equations in **table 6-1** or with housing-density-based land use coefficients listed in **table 6-2**.

There are, however, limitations to the application of the population-density methods for estimating TIA. Exum and others (2005) examined population-based TIA estimates and determined that available equations were limited within different population ranges. Population-based estimates substantially under predict TIA in areas dominated by commercial, industrial, mining and quarrying land uses, and in areas with urban parks (Greater Vancouver Sewerage and Drainage District, 1999; Exum and others, 2005). The accuracy of population-density methods also are limited by the frequency and format of census data. Population-density based TIA estimates may be uncertain in developing areas because census data are collected each decade and released once the data are processed. The population-density data are georeferenced as point data at the centroid of each census block and the geometry of the census blocks are provided in a separate file format (Hitt, 1994). Census blocks with areas outside the basin must be clipped to the basin boundaries if the boundaries may not correspond to so the census blocks. The population within a census block may not be evenly distributed, but the population in clipped blocks must be proportioned evenly.

Land Cover

Land-cover data also are used to estimate TIA with information about the size and location of individual impervious features (such as roads, roofs, and parking lots) that are identified and tabulated using various methods (Prych and Ebbert, 1986; Knutilla, and Veenhuis, 1994; Ridd, 1995; Vogelmann and others, 1998; Cappiella and Brown, 2001; Slonecker and others, 2001; Jennings and Jarnagin, 2002; Lee and Heaney, 2003; Wu and Murray, 2003; Yang, Huang, and others, 2003; Yang, Xian, and others, 2003; Jennings and Jarnagin, 2004; Slonecker and Tilley, 2004; Xian and Crane, 2005; Lu and Weng, 2006; Parcher, 2006; Tilley and Slonecker, 2007; Homer and others, 2007; Moglen and Kim, 2007). Land-cover based TIA estimates are considered to be more accurate than other methods because fine-scale site-specific characteristics of the area of interest are characterized. Land-cover estimates can be used to quantify TIA coefficients for different land use classes if it is necessary to estimate potential effects of future development (Prisloe and others, 2000; Wissmar and others, 2004).

Land-cover TIA estimates may be derived from intensive field data collection efforts (Alley and Veenhuis, 1983; Prych and Ebbert, 1986; Knutilla and Veenhuis, 1994; Sleavin and others, 2000; Lee and Heaney, 2003; Roy and Schuster, 2009) manual or automatic aerial-photograph processing (Jennings and Jarnagin, 2002; Dougherty and others, 2004; Slonecker and Tilley, 2004; Lee and Heaney, 2003; Canters and others, 2006; Lu and Weng, 2006) or satellite-image processing (Ridd, 1995; Prisloe and others, 2000; Dougherty and others, 2004; Jennings and others, 2004; Canters and others, 2006; Lu and Weng, 2006; Homer and others, 2007; Moglen and Kim, 2007). Field data collection efforts provide detailed characterization of TIA, DCIA, and related drainage features (for example, Prych and Ebbert, 1986; Lee and Heaney, 2003; Roy and Schuster, 2009). However, field data collection is expensive, time consuming, and not feasible for large areas (Sleavin and others, 2000; Lee and Heaney, 2003). For example, Lee and Heaney (2003) determined that manual inspection of impervious areas and drainage structures in the field required 155 times the effort necessary for simple map-based land use estimates. Digitizing aerial photographs manually to determine TIA also is expensive, time consuming (Sleavin, and others, 2000; Lee and Heaney, 2003; Wu and others, 2003). Lee and Heaney (2003) determined that manual image digitizing required about 97 times the effort necessary for simple map-based land use estimates. Slonecker and others (2001) indicate that manual image processing requires about 23 times the effort required for automated delineation of impervious land cover. Sampling methods can be used for greater efficiency in manual image processing efforts. For example, Jennings and Jarnagin (2002) delineated a sample of residential roofs and applied the average value to all roofs in the study area.

Land-cover based TIA estimates also may provide valuable information for characterizing different types of imperviousness within a drainage basin. For example, Lee and Heaney (2003) characterized impervious surfaces in a medium-density single-family residential area in Colorado with a TIA value of about 26 percent. They did field surveys of impervious areas and found that buildings, streets, driveways and sidewalks accounted for 36, 36, 21, and 7 percent of the impervious area in the neighborhood, respectively. Slonecker and Tilley (2004) examined different methods for determining TIA. They examined estimates for 11 watersheds in 5 areas of the country with drainage areas ranging from 8 to 58 mi^2 and TIA values ranging from about 9 to 45 percent of the drainage area. They found that, on average, TIA consists of buildings (29 percent), roads (28 percent), parking lots (25 percent), driveways (9 percent), sidewalks (3 percent), and other anthropogenic impervious surfaces (3 percent of TIA). On average, airports were about 4 percent of TIA, but this value was calculated on the basis of one airport, which was about 30 percent of the TIA in that basin. Slonecker and Tilley (2004) also determined that roads were about 35 percent of TIA in the basin where TIA was 10 percent of the basin area and the percentage of roads decreases to 25 of TIA in the basin where TIA was 45 percent of the basin area. Similarly, Roy and Shuster (2009) estimated that about 28 percent of TIA was buildings, 25 percent was driveways, 23 percent was streets, 12 percent was parking areas 6 percent was sidewalks and about 6 percent was other anthropogenic impervious surfaces. Roy and Shuster (2009) characterized these impervious surfaces in a residential and agricultural stream basin with 20 percent TIA by using land-cover maps and field surveys.

Land-cover based TIA estimates do have some limitations and different methods may give different results (Cappiella and Brown, 2001; Hoffman and Crawford, 2001; Slonecker and others, 2001; Jennings and Jarnagin, 2002; Wu and others, 2003; Yang and others, 2003; Dougherty and others, 2004; Lu and Weng, 2006). Small features such as sidewalks and driveways may not be included in land-cover estimates (Cappiella and Brown, 2001; Hoffman and Crawford, 2001; Dougherty and others, 2004), but these areas can be about 15 to 37 percent of TIA (Slonecker and Tilley, 2004; Roy and

Shuster, 2009). However, errors in land-cover based TIA estimates can be reduced with various techniques. Roy and Schuster (2009) adjusted TIA estimates from land-cover maps by using field surveys. Jennings and others (2004) developed estimates for average residential driveway size in different areas and multiplied the average value times the number of residences in the study area to estimate driveway-related TIA. Land-cover based TIA estimates tend to overestimate actual TIA in low-density areas and underestimate TIA in high density areas (Wu and others, 2003; Yang, Huang, and others 2003; Lu and Weng, 2006). However, uncertainty in TIA estimates for different areas tend to decrease with increasing TIA. For example Dougherty and others (2004) indicate that, as imperviousness increases from 2 to 70 percent of the land area, variations in TIA estimates decrease exponentially from about 100 percent of the TIA value to about 30 percent of the TIA value.

National Land Cover Impervious Surface Data

The U.S. NLCD impervious surface data set may provide a high-quality nationally-consistent land cover data set in a GIS-ready format that can be used to estimate TIA values for use with SELDM (Vogelmann and others, 1998; Yang, Huang, and others 2003; Homer, and others 2004; Homer, and others 2007). The NLCD consistently quantifies the percent anthropogenic TIA for the NLCD at a 30-meter (a 900 m^2) pixel resolution throughout the Nation. Within the data set, each pixel is quantified as having a TIA value that ranges from 0 to 100 percent. The NLCD was developed by the MRLCC, which includes the Bureau of Land Management, the National Atmospheric and Space Administration, the National Oceanic and Atmospheric Administration, the National Resources Conservation Service, the Office of Surface Mining, the U.S. Fish and Wildlife Service, the U.S. Forest Service, the USEPA, and the USGS (U.S. Geological Survey, 2007a). Agencies within the MRLCC are using this data to support research, planning, and decision-making efforts. The MRLCC has developed standard methods for classifying and identifying land-cover categories (Homer, and others 2004; Homer, and others 2007). The MRLCC provides the NLCD data in GIS-ready formats with metadata and source documentation. As such, the NLCD can be used with other GIS data sets to rapidly develop consistent and defensible TIA estimates.

TIA estimates made with the NLCD impervious surface data set represent an aggregated TIA value for each pixel rather than a TIA value for an individual impervious feature. For example, a two lane road in a grassy field has a TIA value of 100 percent, but the pixel containing the road would have a TIA value of 26 percent. If the road (equally) straddles the boundary of two pixels, each pixel would have a TIA value of 13 percent. The Data-quality analysis of the NLCD 2001 data set with manually delimited TIA sample areas indicates that the average error of predicted versus actual TIA may range from 8.8 to 11.4 percent (Homer, and others 2007).

Several studies (Falcone and Pearson, 2006; Chabeva and others, 2009; Jones and Jarnagin, 2009; Brandt and Steeves, 2009) indicate that the NLCD 2001 TIA data set may have systematic bias in different TIA ranges. Falcone and Pearson (2006) compared a sample of 235 impervious values from the NLCD 2001 TIA data set with impervious fractions that were manually digitized from high-resolution (1-foot) color orthophotoimagery for 150 meter by 150 meter plots in 3 metropolitan areas. Falcone and Pearson (2006) found that, on average, NLCD values were less than the manually digitized values in two areas (Atlanta, GA and Raleigh, NC) and were equivalent to the manually digitized values in Portland OR. Chabeva and others, (2009) examined lumped impervious values for 53 towns in New York and Connecticut and indicate that NLCD TIA values generally are biased greater than manually delineated impervious values with a root mean square error of about 8 percent. Jones and others (2009) compared NLCD impervious values to manually delineated impervious values for 240 sample regions (about 0.1 square mile) in the Piedmont and Coastal Plain ecoregions in the mid-Atlantic region. They found that 49 of the 240 cells had TIA errors (NLCD TIA - manually delineated TIA) greater than 10 percent TIA. They removed 14 cells with differences caused by land-cover changes between data collection dates. After removing these problem cells, mean error was about -4 percent TIA and ranged from -26 to 37 percent TIA. They found that mean error was greater in the Piedmont ecoregion (-5.83 percent TIA) than in the Coastal Plain ecoregion (-1.53 percent TIA). The attributed ecoregion differences to the more complex terrain, mixed land uses, and mixed tree canopies in the Piedmont ecoregion. They conclude that NLCD TIA values under predict manually delineated impervious values for the 0.1 square-mile cells, but the differences are generally small. Brandt and Steeves (2009) developed TIA estimates for stream basins in Massachusetts and developed a logarithmic regression equation to compare NLCD 2001TIA estimates with a $1m^2$ cell TIA coverage provided by the Massachusetts Office of Geographic and Environmental Information (MassGIS). Their equation indicates that NLCD values are less than MassGIS values for TIA percentages less than 16.75 percent and are higher than MassGIS values above this threshold.

A multisegment nonparametric regression model using the comparative TIA values described by Falcone and Pearson (2006) was developed for the SELDM study using the using the KTRLine software (Granato, 2006). The regression line (**figure 6-3**) was developed to adjust NLCD impervious values to the measured impervious values. The regression line was developed using the TIA fraction rather than the TIA percentage because the TIA fraction is the predictor variable for estimating runoff coefficient statistics in SELDM. A two-segment regression model was developed because the relation between the NLCD imperviousness and the manually delineated imperiousness (for the Atlanta, GA and Raleigh, NC data) changes with increasing impervious fraction. **Figure 6-3** is plotted using logarithmic scales because the impervious fractions vary by more than two orders of magnitude. This graph shows the paired data for each study area, the two segment regression line, the equations for the regression line, the break point between segments of the best fit model (0.32), and a line indicating a 1:1 relationship between data values. Most of the points plot above the 1:1 line indicating that the NLCD 2001 estimates may under predict actual imperviousness in some areas, especially if the TIA value is less than about 0.3. About 94 percent of the conterminous United States falls into this TIA category (Table 6-1).

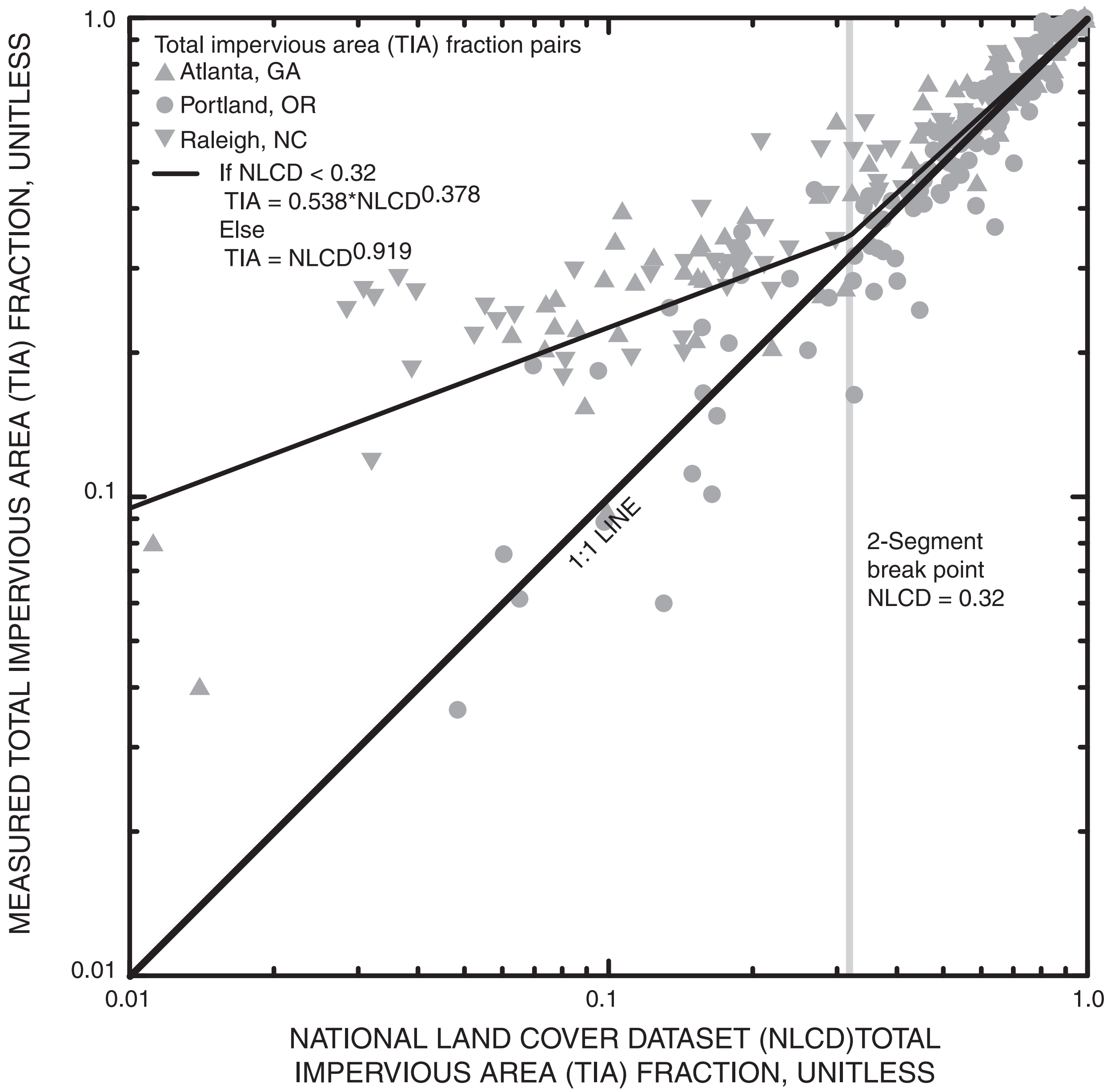

Figure 6-3. Graph showing a two-segment regression relation between total impervious area (TIA) estimates using the 2001 National Land Cover Dataset and the National Water-Quality Assessment Program (NAWQA), Effects of Urbanization on Stream Ecosystems (EUSE) impervious surface data set for 235 selected plots in three urban areas (Data from Falcone, 2009, written commun.).

A multisegment nonparametric regression model using the stream basin TIA values generated by Brandt and Steeves (2009) was developed for the SELDM study using the using the KTRLine software (Granato, 2006). The regression line (**figure 6-4**) was developed to adjust NLCD impervious values for stream basin values developed using the MassGIS values assuming that the 1 m^2 cell TIA coverage was more representative than the 900 m^2 cell coverage. An adjustment equation is needed because the high-resolution MassGIS data set is not available for basins (or parts of basins) outside of MA (Brandt and Steeves, 2009). The regression line was developed using the TIA fraction rather than the TIA percentage because the TIA fraction is the predictor variable for estimating runoff-coefficient statistics in SELDM. A two-segment regression model was developed because 71 percent of the stream basins within MA have impervious fractions less than 0.1and the equation developed by Brandt and Steeves (2009) systematically overestimates impervious fractions greater than 0.32. **Figure 6-4** is plotted using logarithmic scales because the impervious fractions vary by more than three orders of magnitude and 71 percent of the sites have TIA fractions below 0.1. This graph shows the paired data, the two segment regression line, the equations for the regression line, the break point between segments of the best-fit model, a line indicating a 1:1 relationship between data values, and the point of equivalence. The graph shows that the two segment model is unbiased above and below the impervious fraction breakpoint of 0.234. The point of equivalence (an impervious fraction of 0.173) indicates the point on the regression line where NLCD estimates equal the MassGIS TIA. This value is similar to the point of equivalence (a TIA fraction of 0.1675) determined by Brandt and Steeves (2009) and indicates the TIA fraction at which the NLCD estimate transitions from being biased low to being biased high in comparison to the MassGIS TIA values. The bias in NLCD values may exceed 36 percent for NLCD fractions less than 0.1. The adjustment factor may be important (assuming that the MassGIS TIA values represent true imperviousness and the regression equations on **figure 6-4** are transferable to other areas) because 86 percent of the conterminous United States has an impervious fraction less than 0.1 (Homer and others, 2007). Differences between the NAWQA EUSE data and the MassGIS data may reflect the fact that the NAWQA data are manually delimited for small samples and the MassGIS data are a derivative state-wide data set.

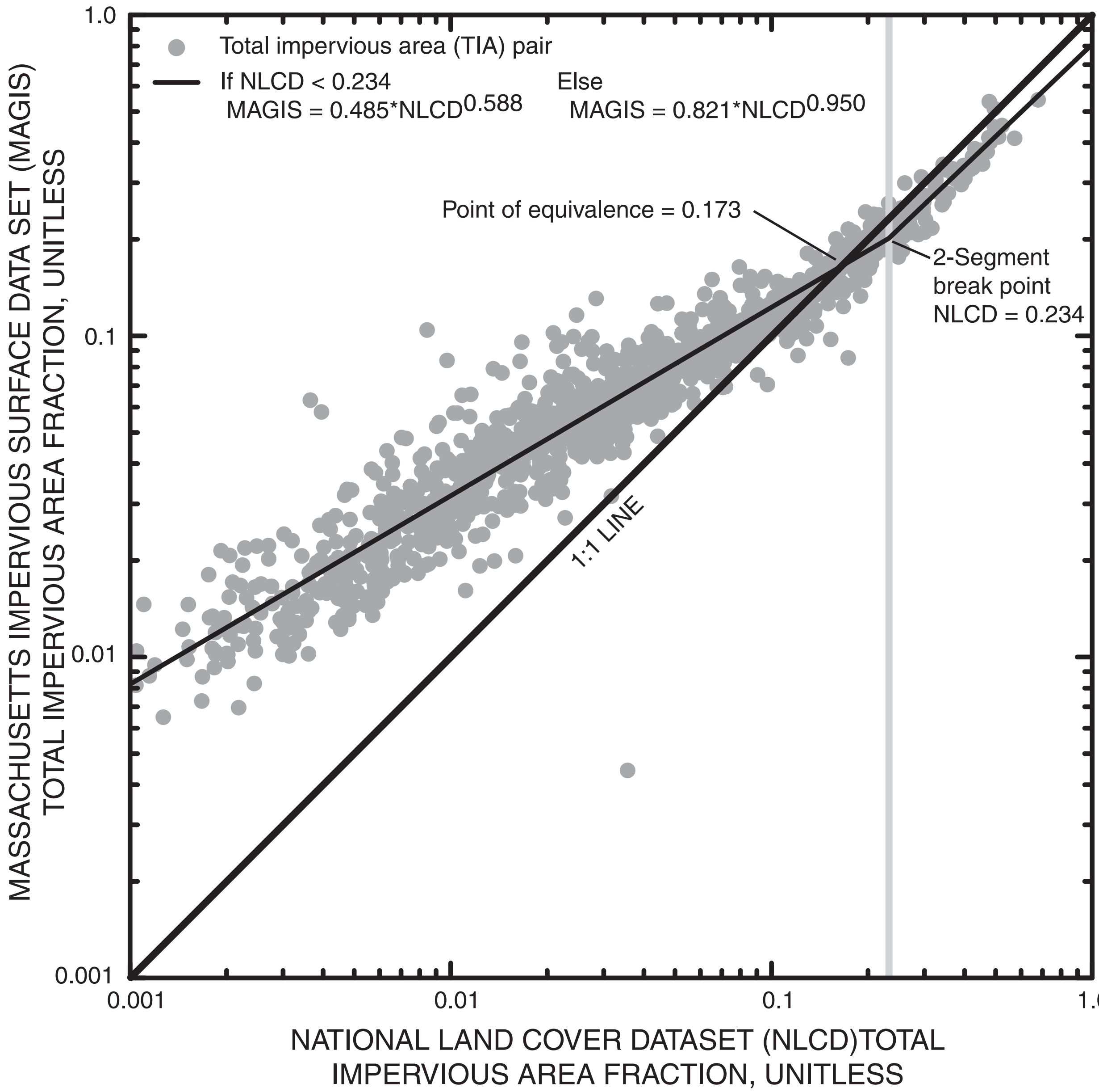

Figure 6-4. Graph showing a two-segment regression relation between total impervious area (TIA) estimates using the National Land Cover Dataset and the Massachusetts impervious surface data set delineated for 1,281 stream basins in Massachusetts. The intersection of the regression line and a line delimiting equal values indicates that the point of equivalence for the two TIA estimates is about 0.173 (Data from Brandt and Steeves, 2009).

Estimating Anthropogenic Directly Connected Impervious Area

DCIA is considered to be a better explanatory variable for predicting runoff volumes from precipitation volumes than is TIA because directly connected impervious areas effectively transmit rainfall to the stream channel with minimal interception, storage, and resistance to flow. A few studies have published results of detailed field surveys that were conducted to quantify fractions of TIA and DCIA in different areas (for example: Metzker and others, 1993; Mustard and others, 1987; Boyd and others, 1993; Kluitenberg, 1994; Knutilla and others, 1994; Wigmosta and others, 1994; Trommer and others, 1996a;b; Waschbusch, 1996; U.S. Environmental Protection Agency, 2001b; Lee and Heaney, 2003; Peters and others, 2003, Hatt and others, 2004; Taylor and others, 2004; Selbig and Bannerman, 2007, 2008; Roy and Shuster, 2009). However, the time and cost requirements for mapping the connection of impervious surfaces to drainage systems and waterways commonly are prohibitive, even for small drainage areas (Lee and Heaney, 2003). As such, the DCIA fraction commonly is estimated using many of the same methods that are used to estimate TIA.

Some studies have developed land use based estimates of DCIA (**table 6-3**). Land use DCIA coefficients can vary substantially for the same nominal land use categories. For example, average DCIA coefficients in the literature vary from 3 to 36 percent for single-family residential land uses, from 36 to 76 for multifamily residential land uses, and from 35 to 100 percent for commercial land uses. These ranges probably represent real variations in DCIA from site to site, but it may be difficult to select a meaningful value without prior knowledge of the degree of connection for different areas within a stream basin. As with TIA estimates, land use areas within a drainage basin are delimited on a map and the impervious fraction for each land use is multiplied by the total area of each land use in the basin.

DCIA commonly is estimated from the slope of rainfall-runoff regression lines from streamflow data (Miller, 1985; Guay and Smith, 1988; Trommer and others, 1996b; Boyd and others 1993; Zarriello and Barlow, 2002). Site specific rainfall and runoff data are needed to develop these regression lines. These regression lines commonly are developed with selected storms, which may not represent the full range of field conditions. Differences in base flow separation techniques have a direct affect on estimated DCIA values because the regression equations are based on estimated runoff rather than total storm flow. These regression equations also are based on the assumption that all runoff is generated as infiltration excess overland flow from impervious areas. Furthermore, these DCIA estimates are formulated with the assumption that runoff from pervious areas and unconnected impervious areas is limited or negligible in many storms. If direct precipitation or saturation overland flow (**appendix 4**) supplies a substantial proportion of runoff, these regression methods will over predict the amount of anthropogenic impervious area that is contributing to runoff.

Table 6-3. Literature values for directly connected impervious area (DCIA) by land use, in percent.

[Ac Acres; DCIA directly connected impervious area; > greater than; < less than]

Land use	Range of mean/median DCIA, in percent	References
Directly connected impervious percentage: 0 to10		
Agricultural	1-2	5, 6
Forest/Rural Open	2	5
Residential	5-6	2, 7
Residential, low density 2-5 Ac	3-4	3, 5
Residential, medium density 1 Ac	6-10	1, 3
Urban Open	5	5
Directly connected impervious percentage: greater than 10 to 20		
Highway	18	7
Institutional	16	5
Residential, single family 0.2-0.5 Ac	15-19	1, 4, 6, 8
Residential, medium density	18	5
Wetlands	18	5
Directly connected impervious percentage: greater than 20 to 40		
Commercial	35	6
Highway	22	5
Industrial	40	6
Residential, high density	25-33	5, 6
Residential, multifamily	36	4
Residential, single family 0.125-0.2 Ac	22	6
Residential, single family 0.25 Ac	23-33	3, 8
Directly connected impervious percentage: greater than 40 to 60		
Commercial	86	8
Industrial	46	1
Residential, multifamily	42-48	1, 3, 7
Directly connected impervious percentage: greater than 60 to 80		
Commercial	70-86	1, 5, 8
Industrial	65	5
Residential, multifamily	63-76	8
Directly connected impervious percentage: greater than 80 to 90		
Commercial/Industrial/Transportation	86	3
Directly connected impervious percentage: greater than 90		
Commercial	98-100	4, 7
Lakes/Reservoirs, Streams	100	5

1. Alley and Veenhuis, 1983
2. Burns and others, 2005
3. Dinicola, 1990
4. Guay and Smith, 1988
5. Kluitenberg, 1994
6. Krug and Goddard, 1986
7. Miller, 1985
8. Zarriello and Barlow, 2002

DCIA also is estimated as part of rainfall-runoff model calibration efforts (For example, Dawdy and others, 1978, Laenen, 1980; Alley and Smith, 1982; Guay and Smith, 1988; Dinicola, 2001; Canters and others, 2006). DCIA and other factors are adjusted until simulated streamflow records are calibrated to measured streamflow records. Long-term streamgage records are commonly used for calibration so these models can only be calibrated on a (sub)basin scale. In many cases individual basins have many land use areas. As such, DCIA estimates commonly are based on lumped parameters rather than site specific data. Also many rainfall-runoff models are the assumption that all runoff is generated as infiltration excess overland flow from impervious areas, rather than as direct precipitation or saturation overland flow. The calibrated DCIA estimates from such models may best reproduce streamflow records in the model area, but may not be transferable to other basins and may not be indicative of actual impervious connections within the modeled basin.

Several studies (Alley and Veenhuis, 1983; Boyd and others, 1993; Sutherland, 1995; Taylor and others, 2004; Wenger and others, 2008; Roy and Shuster, 2009) have used measured DCIA values to develop equations for estimating DCIA from TIA (**table 6-1**). These DCIA regression models were developed because of the extensive amount of effort required to accurately map DCIA. Four of the studies use linear regression models and two use power function regression models (linear regression models calculated with the logarithms of TIA and DCIA). Three of the four linear regression models produce a negative DCIA value for some nonzero TIA values, which are identified by the authors of these equations as TIA ranges with zero DCIA values. However, power function regression models yield DCIA values that exponentially approach zero as TIA approaches zero. The different equations produce different DCIA estimates and available equations are based on small or geographically limited sample sets.

A data set of paired TIA and DCIA measurements was assembled to help estimate runoff coefficient statistics for use with SELDM (**fig. 6-5**). This data set includes measured TIA and DCIA values at 477 sites from 15 studies (Metzker and others, 1983; Mustard and others, 1987; Boyd and others, 1993; Kluitenberg, 1994; Knutilla and others, 1994; Wigmosta and others, 1994; Trommer and others, 1996a; Waschbusch, 1996; U.S. Environmental Protection Agency, 2001a;b; Lee and Heaney, 2003; Hatt and others, 2004; Taylor and others, 2004; Selbig and Bannerman, 2007, 2008; Roy and Shuster, 2009). Figure 6-4 shows these values as impervious area fractions (0-1). The data indicate that there is substantial variation in DCIA values over the entire range of TIA. For example, the points along the x-axis indicate that 127 sites with TIA fractions ranging from 0 to 0.6 were identifies as having no DCIA. At the other extreme DCIA values equal the TIA values at 97 sites with TIA fractions ranging from 0.16 to 1and 58 sites with TIA fractions ranging from 0 to 0.6. The DCIA values generally increase exponentially with increasing TIA, but the zero values preclude use of a power-function regression model. The pattern of paired values over the range of TIA indicates that there is not one meaningful regression relation between TIA and DCIA. Sutherland (1995) addressed the problem by developing regression models for qualitative DCIA categories. Sutherland (1995) identified sites as having no connection, very low connection, low connection, average connection, high connection and complete connection. He calculated regression equations for sites assigned to the very, low, average, and high degrees of connection. These regression models provide a quantitative relation between TIA and DCIA but they require a detailed knowledge of the degree of connection.

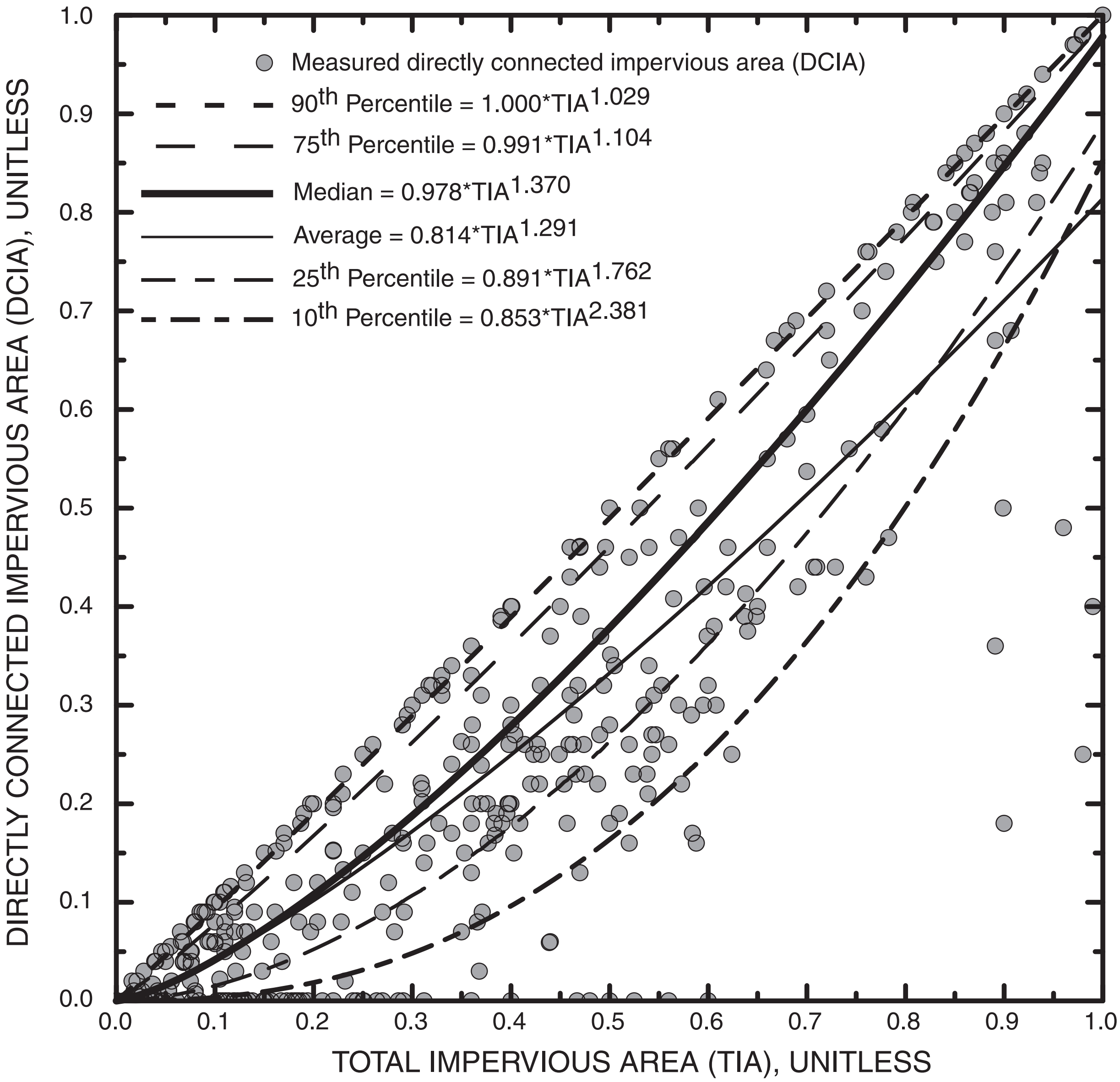

Figure 6-5. Graph showing measured values of the total impervious area (TIA) and directly connected impervious area (DCIA) at 477 sites with estimated regression-equation values for the 10th, 25th, 75th and 90th percentiles, the median, and the average DCIA using the median TIA value within 21 evenly spaced TIA-value bins. (Data from Metzker and others, 1983; Mustard and others, 1987; Boyd and others, 1993; Kluitenberg, 1994; Knutilla and others, 1994; Wigmosta and others, 1994; Trommer and others, 1996b; Waschbusch, 1996; U.S. Environmental Protection Agency, 2001b; Lee and Heaney, 2003; Hatt and others, 2004; Taylor and others, 2004; Selbig and Bannerman, 2007, 2008; Roy and Shuster, 2009).

A set of regression equations relating DCIA to TIA were developed to help estimate runoff coefficient statistics for use with SELDM (**fig. 6-5**). These equations were developed to address the great uncertainty in DCIA values for a given value of TIA and to provide a more quantitative approach than Sutherland (1995). The paired values of TIA and DCIA were grouped by TIA value into 20 bins with equal TIA fraction widths of about 0.0495 and the TIA values of 1.0 were grouped in a 21st bin. The median TIA value and the average DCIA value and the 10th, 25th, 50th (median), 75th, and 90th percentile of the DCIA values in each bin were calculated. Regression relations were developed between the median TIA value and each DCIA statistic. The regression lines and associated equations on **figure 6-5** provide statistical estimates of DCIA populations that may occur for a given TIA value. The equations are more quantitative than the equations developed by Sutherland (1995) but the user still needs knowledge of the site and some professional judgment to produce a realistic estimate of DCIA.

Land-cover methods may better represent the location and extent of the DCIA fraction in a stream basin than land use, runoff-volume regression, rainfall-runoff model calibration, or TIA regression estimates. Land cover estimates also are based on DCIA coefficients, but the coefficients are applied to specific features in the basin and also may be adjusted to reflect the position of a land-cover area with respect to natural or man-made drainage systems. For example, Hoffman and Crawford (2001) indicate that about 80 percent of residential roof area and 100 percent of streets, commercial buildings and parking lots may be DCIA. Lee and Heaney (2003) indicate that transportation-related impervious areas (roads, parking areas and sidewalks) have a higher ratio of DCIA to TIA than other impervious areas such as building roofs. DCIA estimates by land-cover class may be used to estimate the proportion of TIA that is DCIA from the proportion of each land-cover class in the study area. For example, the land-cover percentages documented by Slonecker and Tilley (2004) may be used to estimate DCIA. Graham and others (1974) developed equations to estimate specific curb length from population density and housing density (**table 6-1**). The equations developed by Graham and others (1974) may be used to estimate DCIA in residential areas because curb and gutter streets have been identified as a principal component of DCIA.

Theoretically, DCIA may be a better explanatory variable for storm runoff than TIA, but DCIA is not formally used to estimate runoff-volume statistics for SELDM for several reasons. It is more difficult and costly to measure DCIA at a given site. There is more TIA data available and there are many accepted methods to estimate TIA. For example, there are three times as many sites and four times as many storms in the rainfall-runoff database (SiteStorm.mdb) assembled for the SELDM project. DCIA cannot be used with TIA to formulate a multiple-linear regression model because these two variables are highly correlated (with a Spearman's' Rho value of 0.87). However, DCIA estimates may be used (informally), to refine regression estimates of volumetric runoff-coefficient statistics if site conditions indicate a relatively high or relatively low proportion of DCIA in comparison to average site conditions for a TIA estimate (**fig. 6-5**).

Estimating Natural Impervious Areas

Natural impervious areas are defined herein as land covers that can contribute a substantial amount of stormflow during small and large storms, but commonly are classified as pervious areas. These areas are not commonly considered as an important source of stormflow in most highway and urban runoff-quality studies, but may produce a substantial amount of stormflow. These natural impervious areas may include open water, wetlands, rock outcrops, barren ground (natural soils with low imperviousness), and areas of compacted soils (Southard, 1986; Kluitenberg, 1994; Prisloe and others, 2000; Peters and others, 2003; Parcher, 2006; Los Angeles County Department of Public Works, 2006; Wenger and Roskie, 2008). In some areas, inclusion of natural imperviousness may substantially increase total TIA (Southard, 1986; Parcher, 2006). Natural impervious areas, depending on their nature and antecedent conditions, may produce stormflow from infiltration excess overland flow, saturation overland flow, or direct precipitation (**Appendix 4**). The effects of natural impervious areas on runoff generation are expected to be more important in areas with low TIA than in areas where infiltration excess overland flow from anthropogenic impervious surfaces dominate stormflows. Information about the prevalence of natural impervious areas in the upstream basin for a site of interest may be used to refine regression estimates of volumetric runoff-coefficient statistics

Natural impervious areas may have a substantial effect on runoff coefficient statistics. Variations in runoff coefficient statistics between different sites with similar TIA values may be caused by differences in contributions of natural impervious areas from site to site. For a given anthropogenic TIA value, the mean volumetric runoff coefficient may depend on the amount of natural impervious area in the basin. Variations in runoff coefficients from storm to storm at a given site may be attributable to variations in contributions from natural impervious areas. The variable nature of runoff from natural impervious areas may increase the standard deviation and skew of the volumetric runoff coefficients in comparison to different basin with the same anthropogenic TIA value.

Potential effects of natural impervious areas may be substantial at many sites of interest because a large proportion of the country is currently (2009) still undeveloped. For example, Sutton and others (2006) indicate that 84 percent of the conterminous United States is rural, 14.3 percent is low-density suburban, and only 1.7 percent is urban. Similarly, in a summary of the 2001 national land-cover database, Homer and others (2007) indicate that about 76 percent of the conterminous United States is classified as having less than 1 percent impervious cover, 11 percent as having an impervious cover of 1 to 10 percent, 4 percent of the nation as having an estimated impervious cover of 11 to 20 percent, 4.4 percent of the nation as having an estimated impervious cover of 21 to 40 percent, and about 4.4 percent of the nation as having an estimated impervious cover greater than 40 percent (**table 6-4**).

Table 6-4. Land-cover impervious estimates by category from the 2001 National Land Cover Database (modified from Homer and others, 2007).

[Note: 30-square-meter pixels are classified with integer values for imperviousness from 0 to 100 percent impervious. The total area of the conterminous United States is from Sutton and others, 2006]

Percent impervious category	Total area in square miles	Percent of total area within the category	Percent of total area within impervious categories
Less than 1	554,437	75.85	--
1-10	83,164	11.38	47.12
11-20	29,137	3.99	16.51
21-30	18,832	2.58	10.67
31-40	13,505	1.85	7.65
41-50	10,037	1.37	5.69
51-60	7,334	1.00	4.16
61-70	5,142	0.70	2.91
71-80	3,698	0.51	2.10
81-90	2,992	0.41	1.70
91-100	2,629	0.36	1.49
Sum of			
Total Area:	730,907	100.00	--
Impervious Categories:	176,470	24.15	100.00

There was a concerted effort to obtain data from sites that represent the full range of TIA values during development of in the rainfall-runoff database (SiteStorm.mdb) assembled for the SELDM project. The sites used to develop SELDM equations do include almost the full TIA fraction range (from 0.0001to 0.994), but the distribution of TIA among sites does not reflect the proportion of impervious cover represented in the NLCD. About 1 percent of the basins used to develop the SELDM regression equations have TIA fractions that are less than 0.01, 23 percent have fractions that are 0.01 to 0.1, 13 percent have fractions that are 0.11 to 0.2, 26 percent have fractions that are 0.21 to 0.4, and about 37 percent have TIA fractions that are greater than 0.40. The differences between the proportion of TIA coverage in the United States (table 6-4) and the proportion of TIA fractions in studies used to generate the SELDM runoff-coefficient regression equations probably reflects the prevalence of rainfall-runoff studies in more developed areas of the country.

The NLCD provides land-cover statistics (U.S. Geological Survey, 2007) that can be used as a qualitative measure of the prevalence of different land covers that may act as natural impervious areas. **Figure 6-6** is a boxplot of the percentage of each selected land-cover category in each state of the conterminous United States (U.S. Geological Survey, 2007). Four natural and land-cover categories (category 11 open water, category 91 woody wetlands, category 92 emergent herbaceous wetlands, and category 31 Bare Rock/Sand/Clay) that may act as natural impervious areas were selected. Category 85 Urban/Recreational Grasses was selected because this category may represent large areas of compacted soils. The developed categories (21: Low Intensity Residential, 22: High Intensity Residential, and 23: Commercial/Industrial/Transportation) were selected for comparison and because nominally pervious areas in these land cover classes may be counted as pervious but also may act as natural impervious areas because of compacted soils. Large variations in the percentage of each land cover are expected from basin to basin within each state (especially for states like Washington that include drastically different climates), but the statistics in **figure 6-6** may indicate the relative prevalence of the selected land covers.

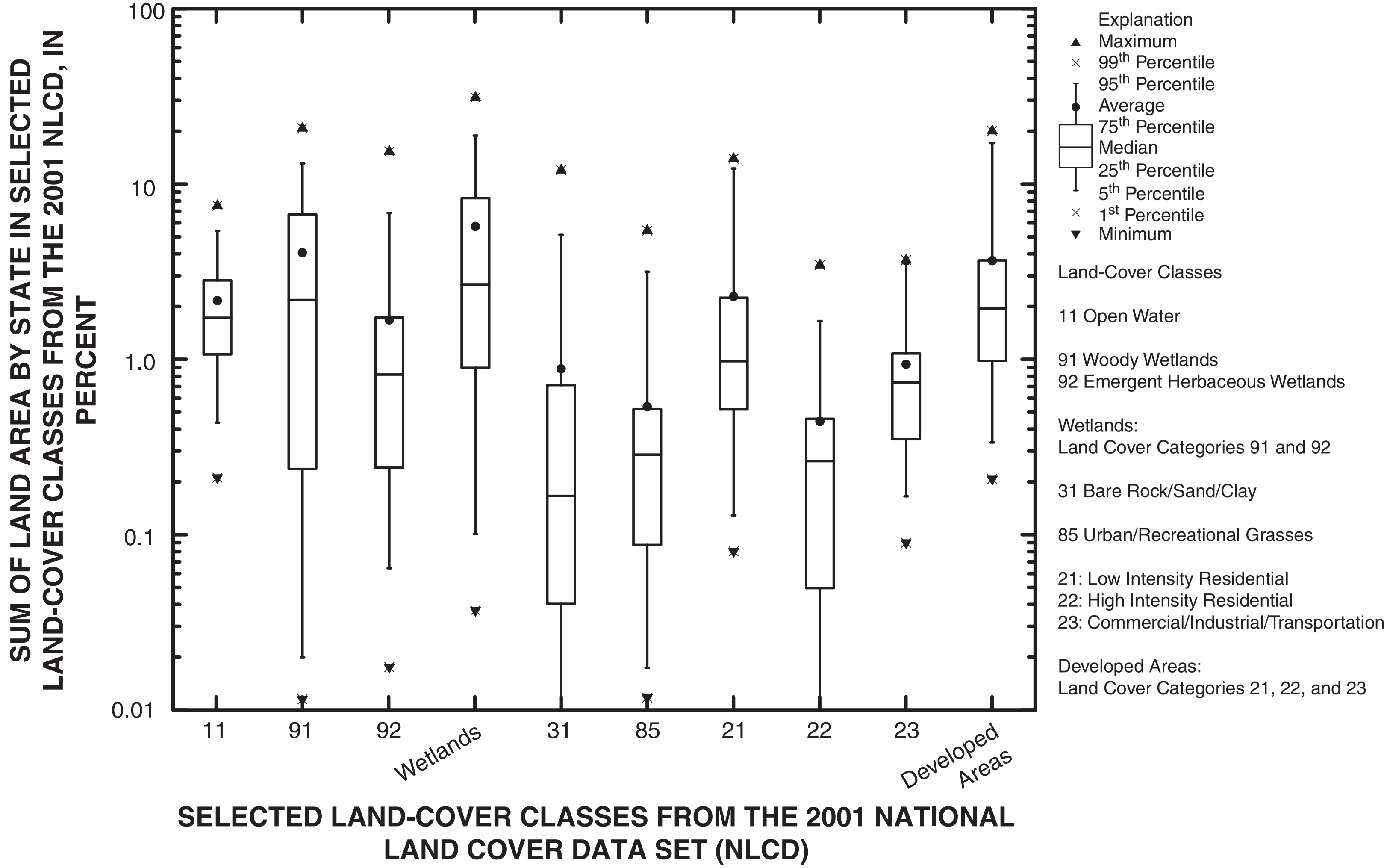

Figure 6-6. Boxplot of the percentage of each selected land-use category from the National Land Cover Data set in each state of the conterminous United States (Data from U.S. Geological Survey, 2007).

Open Water

Open water (land cover category 11) may act as a natural impervious area if direct precipitation is routed through the channel network and arrives as stormflow at the site of interest. Direct precipitation commonly is considered to be negligible (Mockus, 1972). However, direct precipitation may be a substantial proportion of storm flow for small storms in natural basins with on-stream lakes and riparian wetlands. For example, O'Brien (1980, indicated that storm water runoff from wetland basins under dry conditions may be entirely comprised of direct precipitation in surface-water channels. Similarly, Roulet (1991) studied a low-slope natural basin and found that runoff coefficients were proportional to the channel area, indicating the influence of precipitation falling directly on stream channels. Stream channels, natural lakes with surface-water outflows, and impoundments may be a source of stormflows from direct precipitation. These water features also may be a source of through flow if they are groundwater discharge areas. Natural lakes with a substantial storage capacity, however, may detain stormflows to the extent that outflows are interpreted as base flow recession rather than stormflow recession. Impounded lakes may retain stormflows for consumptive water uses or detain stormflows.

Open water area may be substantial in humid areas. On a state-by-state basis, the percentage of open-water cover ranges from 0.21 percent (in New Mexico) to 7.5 percent (in Louisiana) with a median of 1.7 percent (**fig. 6-6**). In comparison, the percentage of open-water land cover values in the NAWQA EUSE basins ranged from 0 to 8.2 percent with a median of 0.36 percent (U.S. Geological Survey, 2008). About 20 percent of these perennial stream basins have a nominal percentage of open-water land cover that is equal to zero (undetectable at a 900 m^2 grid size), which indicates that the percentage of open-water land cover values may underestimate areas that contributing direct precipitation. The percentage of impounded basin areas in the NAWQA EUSE basins ranged from 0 to 99.9 percent with a median of 0.0 percent, which indicates the potential effect of impoundments on stormflows (U.S. Geological Survey, 2008).

Wetlands

Wetlands (land cover categories 91 and 92) may act as a natural impervious area during storms when groundwater discharge and saturation overland flow are a substantial proportion of stormflow. Wetlands that are perennial groundwater discharge areas are expected to have less variability in storm-to-storm or season-to-season discharge than intermittent or ephemeral wetlands they are more consistently saturated than the non- perennial wetlands. For example, O'Brien (1980) studied the hydrology of adjacent basins and found that wetlands may absorb precipitation during dry times but act like impervious area with wet antecedent conditions because of saturation overland flows. Taylor (1982) showed that riparian wetlands acted as DCIA. The undeveloped basin in his study had an average runoff coefficient of 0.18, and runoff coefficients ranged from about 0.01, when the watershed was relatively dry, to as much as 0.6 when the watershed was very wet. Kirnbauer and Haas, P., (1998) reported that runoff coefficients ranged between 0.3 and 0.9 for a wetland in a small headwater basin. Burns and others (2001) indicated that runoff coefficients of a riparian wetland (about 17 percent of the drainage area) ranged from about 0.8 to 2.0 because of variations in groundwater discharge (including through flow) and saturation overland flow with antecedent conditions. On a state-by-state basis, the percentage of wetland cover ranges from 0.04 percent (in New Mexico) to 31 percent (in Florida) with a median of 2.6 percent (**fig. 6-6**). In comparison, the percentage of wetland land cover values in the NAWQA EUSE basins ranged from 0 (undetectable at a 900 m^2 grid size) to 39 percent with a median of 0.88 percent (U.S. Geological Survey, 2008a).

Barren Ground

Barren ground (land cover category 31) in riparian areas may act as a natural impervious area during storms because these areas are a source of infiltration excess overland flows. For example, Burns and others (2001) indicated that the runoff coefficient of a rock outcrop (about 30 percent of the drainage area) was about 0.7 in an undeveloped basin because it was adjacent to a forested wetland that generated saturation overland flows. In this case, a land use map would indicate a natural forested basin without any impervious cover. Land cover maps, soil maps, and aerial photographs, however, would indicate the presence of this large rock outcrop as a potential impervious area. Latron and Gallart (2007) determined that a bedrock outcrop and a natural impervious area provided almost 100 percent of runoff under dry conditions and a substantial amount of the total under wet conditions. On a state-by-state basis, the percentage of barren ground ranges from 0 percent (in Ohio) to 12 percent (in Utah) with a median of 0.17 percent (**fig. 6-6**). In comparison, the percentage of barren ground values in the NAWQA EUSE basins ranged from 0 (undetectable at a 900 m^2 grid size) to 13 percent with a median of 0.1 percent (U.S. Geological Survey, 2008a).

Compacted Soils

Seemingly pervious areas that have been affected by development activities may act as impervious areas and generate infiltration excess overland flows. These stormflows may occur even during storms that do not meet precipitation volume or intensity criteria to produce runoff based on nominal infiltration rates. Developed pervious areas may behave like impervious areas because development and subsequent use tends to compact soils and reduce infiltration rates. For example, Felton and Lull (1963) measured infiltration rates for forest soils and lawns to indicate a potential 80 percent reduction in infiltration as a result of development activities. Similarly, Taylor (1982) did infiltrometer tests in areas before and after suburban development and noted that topsoil alteration and compaction by construction activities reduced infiltration rates by more than 77 percent. Legg and others (1996) indicate that suburban lawns may be a substantial source of runoff and need to be considered in rainfall-runoff analyses. They also found that newer lawns (less than three years old) produce more runoff than older lawns, but the age of the older lawns was not a reliable predictor of runoff coefficients. Gregory and others (2006) did infiltration tests at different sites and found that construction activity reduced soil infiltration rates by 70 to 99 percent. Construction and landscaping also can reduce vegetation and natural plant litter, thereby reducing absorption and interception. Foot and vehicular traffic on a athletic fields, park areas, pathways and unpaved parking lots cause these areas to become more compacted, and therefore more impervious over time; surface bulk densities for these compacted soils approach values for impermeable concrete surfaces (Schueler, 2000). Pitt and others (2008) measured a 10 fold decrease in infiltration rates after compaction of sandy soils, clayey soils, and silty, loamy soils. Increased infiltration excess overland flow (and therefore, the imperviousness to subsequent storm precipitation) also may be increased by watering lawns and athletic fields during dry periods preceding a storm (Williams, 1980).

Compacted soil may be a substantial proportion of basin area. On a state-by-state basis, the percentage of urban recreational grasses (land cover category 31) ranges from 0.01 percent (in Nevada) to 5.4 percent (in Rhode Island) with a median of 0.3 percent (**fig. 6-6**). The percentage of low intensity residential (land cover category 21), which may have nominal pervious fractions ranging from about 0.5 to 0.93 (**table 6-2**), ranges from 0.08 percent (in Montana) to 13.9 percent (in New Jersey) with a median of 0.91 percent of the land area of each state (**fig. 6-6**). The percentage of high intensity residential (land cover category 22), which may have nominal pervious fractions ranging from about 0.09 to 0.7 (**table 6-2**), ranges from 0.0 percent (in Utah and Nebraska) to 3.4 percent (in New Jersey) with a median of 0.26 percent of the land area of each state (**fig. 6-6**). The percentage of commercial, industrial, and transportation (land cover category 23), which may have nominal pervious fractions ranging from about 0.0 to 0.88 (**table 6-2**), ranges from 0.1 percent (in Wyoming) to 3.7 percent (in Rhode Island) with a median of 0.26 percent of the land area of each state (**fig. 6-6**). Agricultural land covers (which cover more than 25 percent of the conterminous United States) also may have substantial areas of soils compacted by grazing livestock, and heavy farm machinery (Schueler, 2000).

Sources of Data and Information for Estimating Imperviousness

Impervious-area data are needed to estimate runoff-coefficient statistics for a stream basin of interest. Estimates of anthropogenic TIA are needed to use the volumetric runoff-coefficient regression-equation developed for use with SELDM. Estimates of DCIA and natural impervious area may be needed to refine regression-based estimates of volumetric runoff-coefficients. All 50 States and the District of Columbia have governmental organizations that provide GIS data (Trust, 2009). State and local GIS data sets may provide the most accurate and fine-scale data for estimating imperviousness (Chabaeva and others, 2009). For example, plot by plot land use data and storm sewer maps may be available at the local scale but these data sources may not span local or state political boundaries (Brandt and Steeves, 2009; Chabaeva and others, 2009). Examples of National geographic information system resources are listed in **table 6-5** to facilitate location and use of geographic data that can be used to estimate the location and extent of anthropogenic TIA, DCIA, and natural impervious areas in a stream basin of interest.

Table 6-5. Examples of National geographic information system resources that can be used to estimate anthropogenic total impervious area (TIA), anthropogenic directly connected impervious area (DCIA), and natural impervious area.

Reference	Primary data type(s)	Comment	Current (2009) Internet address
Bureau of Transportation Statistics, 2008	Transportation	Download site for all kinds of transportation-related data	http://www.bts.gov/publications/national_transportation_atlas_database/
Federal Highway Administration, 2008	Transportation	Provides links to GIS resources for Transportation	http://www.gis.fhwa.dot.gov/
Federal Office of Management and Budget, 2009	Integrated source	Public gateway for improving access to geospatial information	http://gos2.geodata.gov/
U.S. Census Bureau 2007	Population density	Location and population of census blocks	http://tiger.census.gov/
U.S. Fish and Wildlife Service, 2009	Wetlands	On-line wetlands mapper	http://www.fws.gov/wetlands/Data/Mapper.html
U.S. Environmental Protection Agency, 2009a	Drainage-Basin Delineation, watershed properties, weather	Basin properties for watershed modeling	http://www.epa.gov/waterscience/basins/
U.S. Geological Survey, 2008b	Land cover	On-line mapper for many types of data including hydrography, land cover, orthoimagry, and transportation	http://nationalmap.gov/landcover.html
U.S. Geological Survey, 2009c	Open water	Surface water component of the National Map defining the location and properties of open water	http://nhd.usgs.gov/
U.S. Geological Survey, 2009d	Drainage-basin delineation, basin properties and streamflow statistics	Provides detailed drainage basin delineation and selected basin characteristics	http://water.usgs.gov/osw/streamstats/
U.S. Multi-Resolution Land Characteristics Consortium, 2008	Anthropogenic impervious area, land cover, and tree-canopy (can be used to estimate	On-line mapper for land-cover data	http://www.mrlc.gov
U.S. Natural Resources Conservation Service, 2008	Natural impervious features based on soil properties	On-line mapper for soil properties	http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm
Verdin and Greenlee, 2005	Drainage-basin delineation and derived data products	On-line mapper for basin delineation and other derived data based on 900 square meter digital elevation models	http://edna.usgs.gov/Edna/new.asp

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