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Elizabeth Brabec, Stacey Schulte and Paul L. Richards

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Impervious Surfaces and Water Quality: A Review of Current Literature and Its Implications for Watershed Planning

Elizabeth Brabec

Stacey Schulte

Paul L. Richards

Impervious surfaces have for many years been recognized as an indicator of the intensity of the urban environment and, with the advent of urban sprawl, they have become a key issue in habitat health. Although a considerable amount of research has been done to define impervious thresholds for water quality degradation, there are a number of flaws in the assumptions and methodologies used. Given refinement of the methodology, accurate and usable parameters for preventative watershed planning can be developed, which include impervious surface thresholds and a balance between pervious and impervious surfaces within a watershed.

For many years, impervious surfaces have been recognized as an indicator of the intensity of the urban environment (Espy et al. 1966; Stankowski 1972). With the advent of urban sprawl, impervious surfaces have also become a key issue in growth management and watershed planning due to their impact on habitat health (Arnold and Gibbons 1996). Increasing urbanization has resulted in increased amounts of impervious surfaces—roads, parking lots, roof tops, and so on—and a decrease in the amount of forested lands, wetlands, and other forms of open space that absorb and clean stormwater in the natural system (Leopold 1968; Carter 1961). This change in the impervious-pervious surface balance has caused significant changes to both the qual-

ELIZABETH BRABEC is an associate professor in the School of Natural Resources and Environment at the University of Michigan. Her research focuses on the interaction between people and the land and specifically on land conservation policy and practice. Previous to joining the faculty, she had fifteen years of experience in planning as president and founder of Land Ethics, Inc., a consulting firm that specializes in developing resource conservation strategies. Using her expertise as both a landscape architect and an attorney, she has developed award-winning approaches to land conservation for a variety of jurisdictions.

STACEY SCHULTE holds a Master's of Science in Resource Policy and Behavior from the University of Michigan's School of Natural Resources and Environment. She is currently completing a Master's of Urban and Regional Planning at the University of Colorado. Her primary research interests relate to open space and watershed planning. Her work includes projects on the economics, funding, and habitat quality of protected areas.

PAUL L. RICHARDS is an assistant research scientist in the School of Natural Resources and Environment at the University of Michigan who studies hydrological and geochemical processes of watersheds. His most recent activities have been in understanding the role that land development (especially imperviousness) has on runoff. Paul received his Ph.D. in geoscience from Pennsylvania State University in 1999. He teaches courses in Geographic Information Systems (GIS) and hydrology.

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ity and quantity of the stormwater runoff, leading to degraded stream and watershed systems: an increased quantity of stormwater for stream systems to absorb, sedimentation, and an increased pollutant load carried by the stormwater (Morisawa and LaFlure 1979; Arnold et al. 1982; Bannerman et al. 1993).

Although considerable study has been given to understanding the sources and fluxes of nutrients from individual watersheds (Schueler 1994) and the ratio of total imperviousness has been shown to be a key parameter in stormwater runoff models (Graham et al. 1974), comparatively little work has been undertaken to see how watersheds have changed in land cover over time and what effect these changes have had on the surface and subsurface watershed system (Richards and Host 1994; Osborne and Wiley 1988). In fact, the primary focus of watershed planning from the 1950s to the 1970s was on how to move the highest volume of water off the land in the shortest amount of time (Carter 1961).

Impervious cover is a relatively simple attribute for land planners to calculate and project. Land use planning and zoning are commonly carried out based on use and density categories that can provide specific indicators—through allowable lot coverage, road standards, and parking lot requirements—of the total impervious surface that will result at buildout. However, local planning departments do not typically perform these potential projections, nor existing land use analyses, to plan for water quality protection on a watershed basis.

Three previously published summaries of the relationship between imperviousness and water quality all indicated the importance of impervious surface to land use planning on a watershed basis. One review (Harbor 1994) focused on runoff volumes, defining a "simple analysis that a planner can use to address the question of the impact of land use change on long term volumes of stormwater runoff" (p. 96). A second summary (Schueler 1994) reviewed eleven studies (Booth 1991; Galli 1990; Jones and Clark 1987; Limburg and Schmidt 1990; Shaver et al. 1995; Schueler and Galli 1992; Klein 1979; Luchetti and Fuersteburg 1993; Steedman 1988; Steward 1983; Taylor 1993) published before 1995, citing the studies as evidence that stream quality declines at 10 to 15 percent imperviousness. The article also presented an initial framework to use this threshold in the planning process. A third reviewed the integration of the imperviousness variable into a geographic information system model, termed NEMO, to direct land use planning decisions (Arnold and Gibbons 1996).

Although the value of imperviousness as an indicator in water quality planning has had significant support in the literature, the implications and thresholds for land use decision making are much more complex than reliance on a specific impervious surface threshold. An analysis of the existing literature and its application to planning negate an attempt to define the impacts and potential mitigation of imperviousness this simplistically: (1) the determination of a single threshold of watershed imperviousness may not be the only or even the most important watershed variable; (2) mitigation efforts such as detention ponds and riparian buffers have limits to their effectiveness; (3) woodland cover and other pervious land uses are critical to the pervious/impervious equation; and, finally, perhaps the most comprehensive issue, (4) the location of impervious surfaces in a watershed can have significant impacts on water quality.

By reviewing and analyzing existing literature in the field, this article develops an understanding of the broader land use planning implications of the interaction of impervious and pervious surfaces and the spatial form those surfaces take in a watershed. In addition, the review illuminates the needs for changes in research methodology for the analysis of watershed imperviousness and associated land use patterns.

AN ANALYSIS OF THE IMPLICATIONS FOR PLANNING

Many factors contribute to the quality of a stream and how it is affected by impervious surfaces. At a basic level, stream hydrology and function are dependent on five variables: climate, geology, soils, land use, and vegetation (Morisawa and LaFlure 1979). These "first-order" variables directly affect the "second-order" factors of discharge and sediment load, which in turn have an impact on the hydrology and morphology of the stream. Of these variables, land use and vegetation are the only variables over which man has direct control, underscoring their primary significance in the land use planning process. Indeed, Booth and Jackson (1997) identify changes in upland land use as critical in determining overall stream function, degradation, and rehabilitation potential, finding that even with best efforts at mitigation some downstream aquatic system damage is probably inevitable without limiting the extent of watershed development itself.

It is this change in the hydrologic system that is key in land use planning for watershed health. Although the primary tools available for assessing land use–related changes in watersheds are hydrologic models such as the USDA TR55 (U.S. Department of Agriculture 1986), EPA SWMM (Bedient and Huber 1992), U.S. Army Corps of Engineers STORM and HEC-1 (Harbor 1994), these models focus primarily on the changes to stream morphology caused by the second-order factor of discharge, the increasing quantity of water the system must absorb. In addition to the limitations of their focus, the hydrologic models are rarely used in the land use planning process due to their complexity and high cost of accumulating data (Harbor 1994).

To develop a broader understanding of the land use factors important in watershed planning, the following analysis will review (1) the issues of threshold parameters for watershed imperviousness, (2) the impacts of pervious land cover to the watershed system balance, (3) the effectiveness of development and imperviousness mitigation strategies, and (4) the impact that the location of impervious surfaces has on the water quality of the watershed.

The Issue of Threshold

Arnold and Gibbons (1996) defined four basic qualities of imperviousness that make it an important indicator of environmental quality: (1) although the impervious surface does not directly generate pollution, a clear link has been made between impervious surface and the hydrologic changes that degrade water quality; (2) an impervious surface is a characteristic of urbanization; (3) an impervious surface prevents natural pollutant processing in the soil by preventing percolation; and (4) impervious surfaces convey pollutants into the waterways, typically through the direct piping of stormwater.

From a planning perspective, the most important numerical quantification of the impact of imperviousness on stream quality is the threshold level at which water quality impacts occur. However, May et al. (1997) state that the "physical, chemical and biological characteristics of streams change with increasing urbanization in a continuous rather than threshold fashion" (p. 491). Booth and Jackson (1997) concur, stating that degradation begins at very low levels of urban development. However, after a certain level of degradation, there may not be much aquatic life that remains to be harmed, even if the increments of measurable destruction become larger in relation to the amount of additional impervious surface (Wang et al. forthcoming).

This focus on an initial threshold of degradation ignores the importance of planning within a watershed system that has streams at varying levels of water quality. Generally, it is not feasible for all streams in a watershed to be maintained at the highest biotic levels, therefore an understanding of the continuum of water quality impacts is critical to meeting the varying water quality goals of land use planners. Arnold and Gibbons (1996) define an average range of imperviousness (based on Schueler 1995), with a lower threshold at 10 percent "at which degradation first occurs" to 30 percent "at which degradation becomes so severe as to become almost unavoidable" (p. 246). This leads to a ranking of stream health "which can be roughly characterized as 'protected' (less than 10% impervious surface), 'impacted' (10%-30% impervious surface), and 'degraded' (over 30% impervious surface)."

To define a threshold of imperviousness or a continuum of water quality impacts, it is necessary to review the scientific findings that relate imperviousness to stream function and water quality. This is difficult due to the wide range of approaches and methodologies for defining both parameters in the equation: imperviousness and degradation. In defining the level of imperviousness a particular study correlates to a level of degradation, there are two major methodological flaws: (1) the methodology for defining the key determinant, percentage imperviousness per land use, varies between the studies, with percentage urbanization often equated to percentage imperviousness; and (2) most studies do not differentiate between total impervious area (TIA) and effective impervious area (EIA). In terms of the other half of the equation, degradation, the analyses use both biotic and abiotic measures to determine stream impacts, making a single threshold of degradation difficult to determine. These three issues—(1) the methodology for defining impervious surface, (2) TIA versus EIA, and (3) the measures of stream impacts—will be reviewed in the following three sections.

METHOD FOR DEFINING PERCENTAGE IMPERVIOUSNESS FOR VARYING LAND USES

The development of the scientific basis for the relationship between land use and the amount of impervious surface commonly found in association with that land use took place in the field of urban hydrology primarily during the 1970s. In the early research, imperviousness was evaluated in four ways: (1) identifying impervious areas on aerial photography and then using a planimeter to measure each area (Stafford et al. 1974; Graham et al. 1974), (2) overlaying a grid on an aerial photograph and counting the number of intersections that overlaid a variety of land uses or impervious features (Martens 1968; Gluck and McCuen 1975; Hammer 1972; Ragan and Jackson 1975), (3) supervised classification of remotely sensed images (Ragan and Jackson 1980, 1975), and (4) equating the percentage of urbanization in a region with the percentage of imperviousness (Morisawa and LaFlure 1979). The majority of current impervious surface studies rely on the methods of these original studies and subsequent studies that correlated percentage impervious surface to land use largely by using estimates of the proportion of imperviousness within each class (see Table 1).

Some past studies (Stankowski 1972; Graham et al. 1974; Gluck and McCuen 1975; Sullivan et al. 1978; Alley and Veenhuis 1983) have shown a significant correlation between some demographic variables and total imperviousness (Table 2), making it tempting to esti-

TABLE 1. Measurements of Impervious Ratios for Land Uses in Various Studies

Measurement	TIA/EIA	Method	Number of Land Use Classes	Study
Direct measurement	TIA	Aerial photos and field survey	17	Hammer (1972)
			6	Alley and Veenhuis (1983)
			10	Rouge Program Office (1994)
	EIA	Measured from topographic maps	6	Krug and Goddard (1986)
		From aerials but no clear method stated	10	U.S. Department of Agriculture (1986)
		Field survey	10	Rouge Planning Office (1994)
Estimates	TIA	Typical impervious area ratios	Not indicated	Booth and Jackson (1994)
			27	Chin (1996)
			27	Taylor (1993)
		County land use maps and coefficients from Soil Conservation Service (1975) and Graham et al. (1974)	Not indicated	Klein (1979)
		Land use from digitized data and impervious estimates from U.S. Department of Agriculture (1986)	Not indicated	Maxted and Shaver (1998)
		Not clear, suggested use of graphic information systems (GIS) land use classification and impervious coefficients	Not indicated	May et al. (1997)
		GIS-derived land use intensity maps	9	Hicks and Larson (1997)
		Based on urbanization	Not indicated	Booth and Reinelt (1993)
		Urbanized areas from aerials and ratio of imperviousness of 30 to 50 percent from literature	Not indicated	Todd et al. (1989)
	TIA	Land use and ratio defined by Taylor (1993)	7	Wydzga (1997)
		Not indicated	8	Galli (1990)
			Not indicated	Griffin et al. (1980)
			Not indicated	Horner et al. (1997)
			Not indicated	Shaver et al. (1994)
	EIA	Land use and ratio of estimated imperviousness from previous study	5	Wang et al. (forthcoming)
Urbanization	% urbanization	U.S. Geological Survey land use classifications	Not indicated	Limberg and Schmidt (1990)
		Land use/land cover	Not indicated	Wang et al. (1997)
		Satellite imagery	Not indicated	Miltner (1997)
			Not indicated	Yoder et al. (n.d.)
		Unidentified	Not indicated	MacRae (1996)
Other measures	Housing density	Census data	Not indicated	Miltner (1997)
	Population densities	Census data	Not indicated	Jones and Clark (1987)

NOTE: TIA = total impervious area; EIA = effective impervious area.

TABLE 2. Functions Used to Evaluate Imperviousness from Census Data

Function	Variable	R^2	Reference
$I_{low} = 0.17D^{1.165 - 0.094 \log D}$ $I_{med} = 0.0218D^{1.206 - 0.100 \log D}$ $I_{high} = 0.0263D^{1.247 - 0.108 \log D}$	I_{low} : Minimum percentage imperviousness I_{med} : Mean percentage imperviousness I_{high} : Maximum percentage imperviousness D: Population density		Stankowski (1972)
$I = 90.76 - 64.74\ (0.7928)^H$ $I = 91.32 - 69.34\ (0.9309)^P$ $I = 87.06 - 52.06\ (0.7501)^E$	I: percentage imperviousness H: Households/acre P: Population/acre E: Employment/acre	81	Graham et al. (1974)
$I = 10.06 + 58.28$ $(0.000128P/1 + 0.000128P)$ $- 1.258\ (D - 10.6)$	P: Population/mi^2 D: Distance from center business district (mi)		Gluck and McCuen (1975)

TABLE 3. Percentage Imperviousness for Various Land Cover Classes as Calculated Directly from Aerial Photo and Map Analysis

Land Cover Class	Notes	Mean	Range	Reference
Single-family residential	< 0.25 acre lots	39	30-49	Alley and Veenhuis (1983)
	0.25-0.5 acre lots	26	22-31	Alley and Veenhuis (1983)
	0.5-1.0 acre lots	15	13-16	Alley and Veenhuis (1983)
	Includes multi-family residential	30	22-44	Sullivan et al. (1978)
Multiple-family residential		66	53-64	Alley and Veenhuis (1983)
Commercial		88	66-98	Alley and Veenhuis (1983)
		81	52-90	Sullivan et al. (1978)
Industrial		60	—	Alley and Veenhuis (1983)
		40	11-57	Sullivan et al. (1978)
Open		5	1-14	Sullivan et al. (1978)

mate imperviousness directly from widely available census data. Variables that have been shown to be useful in this regard include population density, number of households, employment, and distance from the central business district. However, some of these variables (employment, distance from the central business district) are not appropriate for all urban areas.

As a consequence of the results of early research, much of the effort in defining impervious ratios has been devoted to compiling the percentage of impervious area within specific land use classes (Tables 3 and 4). There are three major problems with this approach. First, the original data showed considerable variation of imperviousness within the same land cover class, indicating in many cases that the classes were too inclusive to provide accurate results when applying these ratios at the watershed level. Second, imperviousness has been shown to vary considerably with use density. Within a particular land use type, such as residential use, increasing lot and parcel size correlates with decreasing imperviousness at a site-specific level. However, although increasing parcel size results in decreased site-level imperviousness, imperviousness per capita increases, largely due to the additional roadway lengths necessary to access the larger lots. Third, the base studies from which the impervious-surface percentages are drawn for use in current studies focused primarily on urban areas at the East Coast during the seventies and early eighties, although demographic and land use patterns have changed considerably since that time. It is critical to the accuracy of impervious studies that local data are developed and field checked using a large number of classes, particularly in the residential category.

TIA VERSUS EIA

Many studies of urban hydrology (Cherkaver 1975; Beard and Chang 1979; Alley et al. 1980; Driver and Troutman 1989) show that TIA, although correlating with changes in runoff, does not affect runoff as much as EIA, the proportion of imperviousness that is directly connected to the stream network. The difference

TABLE 4. The Percentage Impervious Area Ascribed to Various Land Use Categories, Showing the Relationship of Total Impervious Area (TIA) to Effective Impervious Area (EIA) Used in Various Studies

	Percentage TIA								Percentage EIA				
Land Use Category	Cooper (1996)[a]	Taylor (1993)[b]	Alley and Veenhuis (1983)[c]	City of Olympia (1995)[d]	Stankowski (1972)[e]	Griffin et al. (1980)[f]	USDA (1986)[g]	Rouge Program Office (1994)[h]	Cooper (1996)	Taylor (1993)	Alley and Veenhuis (1983)	Krug and Goddard (1986)[i]	Rouge Program Office (1994)
Agricultural land/ open space	5	2-5	—	—	0	—	—	1.9-2.0	0	0-1.5	—	2	0.1-1.1
Public and quasi-public	—	—	—	—	50-75	—	—	—	—	—	—	—	—
Parks	5	5	—	—	0	—	—	10.9	0	1.5	—	—	4.2
Golf courses	5	20	—	—	—	—	—	—	0	10	—	—	—
Low-density single-family residential	10	< 15 (< 1 u/ac.)		—	12	14-19 (0-2 u/ac.)	12 (1 u/2 ac.)	18.8	5	4 (< 1 u/ac.)	—	18	2.4
Medium-density single-family residential	35	20 (1-3 u/ac.)	13-16 (1-2 u/ac.)	—	25	34-42 (2-8 u/ac.)	20 (1 u/ac.)	37.8	24	10 (1-3 u/ac.)	7-10 (1-2 u/ac.)	22	16.6
"Suburban" density 4 u/ac.	—	—	22-31 (2-4 u/ac.)	—	—	—	25	—	—	—	11-19 (2-4 u/ac.)	—	—
High-density single-family residential	60	40 (3-7 u/ac.)	30-49 (> 4 u/ac.)	40 (3-7 u/ac.)	40	25-48 (8-22 u/ac.)	30 (3 u/ac.) 38 (4 u/ac.)	51.4	53	25 (3-7 u/ac.)	18-32 (> 4 u/ac.)	25	30.3
Mobile homes	—	70	—	—	—	—	—	—	—	60	—	—	—
Multifamily	—	80 (> 7 u/ac.)	53-64	48 (7-30 u/ac.)	60-80	47-65 (> 22 u/ac.)	65 (8 u/ac.)	—	—	72 (> 7 u/ac.)	33-52	—	—
Commercial	90	60-90	66-98	86	80-100	89-96	85	56.2	86	48-85	51-98	35-40	43.9
Industrial	—	—	60	—	40-90	—	72	75.9	—	—	46	—	61.9
Highways	100	100	—	—	—	—	—	52.9	100	90	—	—	22.7
Construction site	—	50	—	—	—	0	77	—	—	37	—	—	—

NOTE: The number of land use classes varies considerably between studies. USDA = U.S. Department of Agriculture.

a. Abstracted from Alley and Veenhuis (1983), Pyrch and Ebbert (1996), Taylor (1993), Beyerlein (1996).

b. From King County Surface Water Management Division (1990), Department of Public Works, and PEI/Barrett Consulting Group (1990), Snoqualmie Ridge Draft Master Drainage Plan.

c. Based on direct measurement from aerial photos and field inspection from nineteen basins in the Denver area.

d. Total and effective impervious area percentages compiled from County Surface Water Management (1990); PEI/Barrett Consulting Group (1990), Snoqualmie Ridge Draft Master Drainage Plan; Alley and Veenhuis (1983); and for the open land/agricultural land category, estimated based on similar land uses.

e. No discussion of methodology for determining impervious figures.

f. The source for the percentage imperviousness figures is not indicated in the report.

g. Based on general field observations and studies by Carter (1961), Felton and Lull (1963), Antoine (1964), and Stall et al. (1970). These reference studies are not New Jersey specific.

h. Measured from aerial photographs and a field survey of three sample areas per land use category in each watershed.

i. Measured from topographic maps.

between the two lies in the direct connection to the stream system: total imperviousness includes roofs, roads, parking lots, and other noninfiltrating surfaces, whereas effective imperviousness includes only those impervious areas that drain into a piped storm sewer and discharge into a surface-water body. The reason for this distinction in urban runoff is the fact that for EIA, virtually 100 percent of the stormwater will reach the surface-water body. TIA, on the other hand, includes both EIA and "noneffective impervious area" or those impervious surfaces that drain to pervious ground (such as a driveway into a lawn) (Alley and Veenhuis 1983). The noneffective impervious areas will infiltrate all or a portion of the stormwater, depending on soil, slope, and ground cover characteristics (Alley and Veenhuis 1983).

> Historically, urban drainage was designed with a single objective in mind—to provide hydraulically and economically effective transport of surface runoff from urban areas into local receiving waters and thereby to protect urban dwellers against flooding and provide for their convenience by controlling runoff ponding in urban areas. (Ellis and Marsalek 1996, 724)

As discussed in the previous section, TIA is generally estimated based on land use type, and estimations for each land use are then weighted in proportion to the amount of that land use in the watershed to determine total percentage impervious area for the watershed. EIA, those surfaces directly draining to surface-water bodies can be measured through an overlay of the stormwater system on the watershed. However, all of the studies reviewed except two (Krug and Goddard 1986; Rouge Program Office 1994) estimated the EIA based on TIA percentages (Table 4).

The majority of the studies reviewed for this article do not distinguish between EIAs and TIAs in their threshold analyses. Although the methods of quantifying impervious areas vary, the water quality results converge rather consistently. This may be attributed to the accuracy of the estimations; however, it is more likely the result of the similarity and error in methods for estimating both EIA and TIA. Although the methods for estimating both TIA and EIA have been difficult in the past (Booth and Jackson 1997), the problem of direct measurement can be largely resolved with the prevalence of Geographic Information Systems (GIS) in planning use and the increasing availability of digital mapping of both land use, orthophoto aerials, and digitized storm sewer systems. Using TIA instead of EIA or not distinguishing between the two in hydrologic models that assess impervious threshold cause a series of problems in the analysis of the results: (1) runoff volumes and peak flows may be largely overestimated, (2) the simulated changes in runoff due to increasing intensity of land use may be smaller if TIA is used, and (3) infiltration rates are likely to be overestimated (Alley and Veenhuis, 1983).

MEASURES OF THE EFFECTS OF IMPERVIOUS SURFACE ON STREAM QUALITY

Because stream quality is a combination of the physical, chemical, and biological health of a stream, it stands to reason that there are a variety of measures for stream quality. These generally fall into two categories: biotic and abiotic measures. Many of the studies reviewed for this article define a percentage of impervious surface at which a factor of stream quality is measurably degraded. However, these differ in their criteria for the designation of a healthy versus an impacted stream, making it difficult to define a single standard threshold for watersheds beyond which the system will be degraded (Table 5).

In the studies reviewed, the threshold of biotic degradation is defined by various means: standard indexes, the researcher's own criteria, and governmental standards. The most common standard index is the Index of Biotic Integrity (IBI) (Karr 1987). The IBI is used in various studies to measure aquatic species' richness and composition, local indicator species, trophic composition, fish abundance, and fish diversity (Steedman 1988; Miltner 1997; Wang et al. forthcoming; Horner et al. 1997; Shaver et al. 1994; Wydzga 1997). Two of the studies did not define their criteria for the threshold of degradation (May et al. 1997; Horner et al. 1997), and four defined their own criteria for degradation (Booth and Reinelt 1993; Booth and Jackson 1997, 1994; May et al. 1997; Tennant 1975).

The threshold for many abiotic parameters is typically defined by individual variables—chemical or physical—such as increased water volumes, sedimentation and solids (Wydzga 1997; Griffin et al. 1980; May et al. 1997; Horner et al. 1997), channelization and streambank erosion (Booth and Jackson 1997; May et al. 1997), habitat (Horner et al. 1997; Booth and Reinelt 1993), temperature (Galli 1990), volume of base flow (Tennant 1975), dissolved oxygen (May et al. 1997), nutrients (Griffin et al. 1980; May et al. 1997), and heavy metals (Horner et al. 1997). Abiotic parameters do not measure overall biotic health but rather response by biota to increasing or decreasing concentrations of the variable.

The most notable trend in the data of the studies reviewed is the difference in the impact thresholds for biotic and abiotic measurements. Impact thresholds for biotic measurements, including fish and macro invertebrate diversity and abundance, ranged from 3.6 to 15

TABLE 5. Summary of Degradation Measures and Their Associated Threshold Findings

	Impact Measurement	Percentage Impervious Threshold for Degradation	Study
Parameter type	Parameter		
Biotic	Benthic invertebrates	< 10 humans per hectare	Jones and Clark (1987)
		8	Horner et al. (1997)
		15	Klein (1979)
	Fish diversity	10 urbanized	Limberg and Schmidt (1990)
		12	Klein (1979)
		8	Miltner (1997)
		3.6	Booth and Jackson (1994)
		10	Wang et al. (forthcoming)
	IBI	8 urban land use	Yoder et al. (n.d.)
	Macroinvertebrate diversity	8 to 15	Shaver et al. (1994)
		8	Miltner (1997)
	Species diversity	10 to 15	Booth and Reinelt (1993)
Abiotic and biotic	IBI, habitat quality	10 to 20 urban land use	Wang et al. (1997)
	Mean event water-level fluctuation/ indicator species	10 TIA, 14 EIA	Taylor (1993)
	Variation of water depth and indicator species	15 to 21	Chin (1996)
Abiotic—physical	Temperature for cold-water biota	12	Galli (1990)
	Base flow	45	Klein (1979)
	Stream flow	> 21	Horner et al. (1997)
		Not defined	Krug and Goddard (1986)
	Peak flows	4.6	Booth and Jackson (1994)
	Channel enlargement and streambank erosion	Not given	Hammer (1972)
		34 urbanization	MacRae (1997)
		8 to 10	Booth and Reinelt (1993)
		30	May et al. (1997)
		10	Booth and Jackson (1994)
	Habitat assessment	4 to 9 impervious surface and 30 to 50 forest	Hicks and Larson (1997)
	Large woody debris	9	Horner et al. (1997)
	Sediment	20	Wydzga (1997)
		50	Horner et al. (1997)
		Not defined	Krug and Goddard (1986)
		43	Griffin et al. (1980)
		45	May et al. (1997)
Abiotic—chemical	Nutrients	42	Griffin et al. (1980)
	Phosphorous	45	May et al. (1997)
	Threshold of eutrophication based on TSS and TP	30	Todd et al. (1989)
	Chemical water quality	45	May et al. (1997)
	Oxygen	10	May et al. (1997)
		7.5 urbanized	Limburg and Schmidt (1990)
		43	Griffin (1980)
	Metals	50	Horner et al. (1997)
	Zinc	40	Horner et al. (1997)

NOTE: IBI = Index of Biotic Integrity; TIA = total impervious area; EIA = effective impervious area; TSS = total suspended solids; TP = total phosphorus.

percent impervious surface. The threshold for fish population health ranged from 3.6 to 12 percent, whereas macro invertebrate health declined above a range of 8 to 15 percent. In comparison, abiotic measurements, including water quality and habitat characteristics, ranged from 4 to 50 percent impervious surface. Chemical water quality tended to higher impact levels, with thresholds ranging from 7.5 percent for oxygen to 30 to 50 percent for other measures. However, physical variable measurements were much more variable, ranging from 4.6 to 50 percent, with little consistency (see Table 5).

The different thresholds for each measurement may be attributed to a number of factors. First, biota are affected by a combination of both physical and chemical water quality influences, reflecting the impact of a combination of abiotic changes. Therefore, biotic diversity and abundance degradation may be more accurate measures of stream quality. Second, biota reflect the long-term health of the stream and not chemical changes that may be shorter-lived (Shaver et al. 1995). Third, biota appear to be more affected by habitat destruction than water quality. Therefore, aquatic communities change at a level of impervious surface much lower than that which affects water quality measures.

Several studies have combined abiotic and biotic measurements to arrive at an overall percentage of impervious surface that a watershed can sustain (Booth and Reinelt 1993; Booth and Jackson 1997, 1994), defining these measures in terms of their effect on structure (physical) and function (biotic) of the system, to provide the "best aggregate measures of 'quality' or 'degradation.'" Using habitat characteristics and biological integrity as stream health indicators, May et al. (1997) determined that at 5 to 10 percent TIA, stream quality declined rapidly. After studying the channel morphology, mitigation barriers, base flow, temperature, and water quality of twenty-seven small watersheds in Maryland, Klein (1979) estimated that stream impairment could be avoided at TIA less than 15 percent. However, both of these studies used an estimated TIA figure for their analyses, leaving the potential for significant error in these thresholds.

The Impacts of Pervious Cover

Although the data indicate that impervious surface is the dominant determinant of stream quality, various types of previous cover can also have considerable impacts. The increase of impervious area in a watershed, or conversely, the loss of wooded land area, reduces evaporation and infiltration and is directly related to a loss of vegetative storage and decreased transpiration (Lazaro 1979). Several studies show how pervious cover affects peak flows, water quality, and other stream characteristics.

Ross and Dillaha (1993) compared runoff, nutrient, and sediment concentrations from six different pervious surfaces in a simulated rainfall event (Table 6). The results showed a great difference in the runoff characteristics among different types of pervious surfaces. Whereas a mulched landscape produced no runoff, a gravel driveway and bare soil acted very much like an impervious surface, although they would not normally be included in the calculations.

TABLE 6. Comparison of Runoff Characteristics for a Variety of Pervious Surfaces (after Schueler 1995)

Surface	RV (Runoff)	Nitrate	Soluble P	TSS
Gravel driveway	0.51	0.03	0.06	692
Bare soil	0.33	0.32	0.79	1,935
Cold-season grass, sodded	0.05	0.31	1.12	29
Warm-season turf	0.03	0.44	0.33	43
Mulched landscape	0.00	None	None	None
Meadow	0.00	None	None	None

NOTE: RV = runoff volume; P = phosphorus; TSS = total suspended solids.

This difference in the runoff characteristics for various pervious surfaces is critical to land use planning, because land uses vary widely in their ability to absorb or shed rainfall. Even those areas that are typically considered completely pervious such as grassed lawn, meadows, and fields do not absorb the amount of rainfall absorbed by a mature forest stand. Because construction activity yields soil compaction and changes in soil profiles, more intense development equals more impacted land area that is at best only partially pervious (Booth and Jackson 1997). The issue of forested vegetation is complicated by evapotranspiration. Forested areas simultaneously allow for a high level of infiltration and varying levels of evapotranspiration. Urban imperviousness causes two simultaneous impacts to low flows in streams: precipitation is deflected from infiltration by the impervious surface, and advective enhancement of evapotranspiration exacerbates the loss of groundwater, due to the increase in heat from surrounding surfaces (Ferguson and Suckling 1990).

Based on the importance of forest stands in the hydrologic system, it is critical to use mature forest stands as a baseline for planning watershed quality. Several studies have found that forest stands in a watershed are vital for mediating other land use impacts on stream habitats (Richards et al. 1996; Steedman 1988; Osborne and Kovacic 1993). Whereas some water quality parameters can be modified by local riparian conditions (Osborne and Kovacic 1993), dominant water quality trends of streams among catchments are more strongly related to catchment-wide land use and geology (Richards et al. 1996). Although the threshold of forest cover needed has not been firmly established, Taylor (1993) found that at least 15 percent forested cover should be protected to reduce event water-level fluctuations.

Studies of the effects of forested areas in a watershed have illustrated their potential mitigating effects for other land uses. For example, the domain of degradation for Toronto area streams ranged from 75 percent removal of riparian forest at 0 percent urbanization to 0 percent removal of riparian forest at 55 percent urbanization (Steedman 1988). However, whole catchments may be as important as buffers around streams for determining several components of stream habitat. Variables related to hydraulic regime, such as channel dimensions, are influenced more by catchment area and composition than factors specific to stream ecotones (Hynes 1975, quoted in Richards et al. 1996). Steedman (1988) found a higher correlation between the proportion of basin in forest and water quality than the proportion of the channel with riparian forest. Hicks and Larson (1997) concurred in their analysis of forests, finding no discernible human impact on water quality at 4 percent impervious watershed surface, more than 50 percent forested land area, and more than 80 percent of the stream with a riparian buffer of 200 feet; a low level of impact at 9 percent impervious surface, 30 to 50 percent forest stand, and 50 to 80 percent riparian buffer; a moderate level of impact with 10 to 15 percent impervious surface, 10 to 29 percent forest stand, and 20 to 49 percent riparian buffer; and a high level of impact with 15 percent impervious surface, 10 percent forest stand, and less than 20 percent riparian buffer.

Forest stands, particularly riparian forests, directly affect the abiotic factors of stream quality, particularly woody debris and channel enlargement. The amount of forested land cover is often positively related to the quantity and types of detrital and woody debris in streams (Bisson et al. 1987; Richards and Host 1994) and mitigates channel enlargement due to a higher level of stormwater absorption (Table 7).

The location of wetlands also influenced several habitat features such as woody debris and some aspects of channel dimensions. When positioned in stream networks, wetlands also mitigate hydraulically driven variables including sediment, nutrients, temperature, and disturbance (Richards et al. 1996). Other studies have indicated that the spatial position of wetlands within the watershed influences their ability to modify inputs to streams (Johnston et al. 1990, quoted in Richards et al. 1996).

Although agricultural land has lower levels of runoff than impervious land cover, it contributes the most nutrients of any pervious or impervious land use. However, nutrient levels are less critical to IBI scores than runoff volume. In a study of 103 streams in Wisconsin, only 10 to 20 percent of urban land use was needed to put IBI scores in the poor range. Nonetheless, more than 50 percent agricultural land was required to reduce IBI scores, and IBI scores increased steadily with increasing forest cover (Wang et al. 1997). In a study comparing three watersheds dominated by forest, agricultural land, and urban land, Crawford and Lenat (1989) found that streams in an agricultural watershed had the most nutrients, but the urban streams had the highest temperature and concentration of metals.

TABLE 7. Channel Enlargement Effects of Land Uses in a 1-Square-Mile Basin[a]

Land Use	Magnitude of Effect
Wooded land	0.75
Open land	0.90
Nonimpervious developed land plus impervious area less than four years old and unsewered streets and houses	1.08
Land in cultivation	1.29
Land in golf courses	2.54
Area of houses more than four years old fronting on sewered streets	2.19
Area of sewered streets more than four years old	5.95
Other impervious area more than four years old	6.79

a. See Hammer (1972).

The Effectiveness of Mitigation Strategies

Riparian buffers and best management practices (BMPs) are often used to mitigate the impact of impervious surfaces. In studies of stream quality, these measures have varying degrees of effectiveness. There seems to be no conclusive answer to the question, "At what percentage impervious surface can stream quality impacts not be mitigated?" After studying BMPs in Delaware, Maxted and Shaver (1998) found that BMPs could not mitigate the impacts of urbanization once the watershed reached 20 percent impervious cover. Galli (1990) found that none of the four BMPs he studied in Maryland prevented temperature standard violations in areas of impervious surface ranging from 12 to 30 percent.

Looking at it from another perspective, various studies have assessed the pollutant removal ability of various mitigation strategies. Because allowing for runoff to sit before reentering the hydrologic system is the key to accomplishing removal (Horner et al. 1997), detention ponds are key to the cleansing process and are statutorily required in many jurisdictions. In fact, two jurisdictions with very different hydrologic regimes, Beaufort County, South Carolina, and Bellevue, Wash-

TABLE 8. Comparison of Findings of Phosphorous Removal Capability by Detention Ponds

Study	Location	Total Phosphorous	Soluble Reactive Phosphorous
Comings et al. (2000)	Bellevue, Washington	19%-46%	3%-62%
Kantrowitz and Woodham (1995)	Pinellas County, Florida	13%-66%	Median 40%
Gain (1996)	Florida	21%-30%	—
Wu et al. (1996)	North Carolina	36%-45%	—
Stanley (1996)	—	—	–12%-26%
Maristany (1993)	—	64%	–50%

SOURCE: Adapted from Comings et al. (2000).

TABLE 9. Comparison of the Ability of Detention Ponds to Clean Various Contaminants from Stormwater

Contaminant	Maristany (1993)	Stanley (1996)	USEPA (1983)	Kantrowtiz and Woodham (1995)
Total suspended solids	95.4	71	93	7
Turbidity	86.6	—	—	—
Total chromium	77.5	—	—	25
Total copper	72	26	64	52
Total lead	91.3	55	84	>60
Total nickel	68	—	—	—
Total zinc	84.9	26	51	48
Total organic carbon	24.3	10	—	—
Chemical oxygen demand	14	—	44	16
Biochemical oxygen demand	20.3	—	51	49
Total nitrogen	31.3	26	—	—
Ammonia	54.5	9	—	40
Total Kjeldahl nitrogen	28.8	—	38	—
Nitrate	60	–2	44	—
Total phosphorus	64	14	64	40
Orthophosphate	–50	26	—	52

NOTE: USEPA = U. S. Environmental Protection Agency.

ington (Comings et al. 2000), statutorily require removal of 50 percent of the pollutant loads. However, as noted in Comings et al. (2000), studies for both total phosphorous and soluble reactive phosphorous removal by detention ponds are highly variable but generally fall below 50 percent (see Tables 8 and 9).

The findings of various studies concur that detention ponds can provide a certain mitigation of stormwater impacts; however, they are limited in their effectiveness, and more widespread use of stormwater infiltration ponds is impeded by such problems as concerns about groundwater contamination, lack of design guidance, and concerns about maintenance and longevity of infiltration systems (Ellis and Marsalek 1996).

Riparian forests also have limits to their effectiveness. Riparian buffers are key mitigants of the loss of large woody debris and leaf litter that enters the aquatic food chain (Booth and Jackson 1997), and temperature increases (Galli 1990). When streamside vegetation is cleared, less wood enters the channel that functions to protect the streambed and banks from erosion (Booth and Jackson 1997; Booth et al. 1996).

> If corridor clearing is proportional to basinwide urban land uses, stream conditions can be no better than "fair" once the basin achieves about 30% urban land use. At typical suburban densities, this corresponds to about 7 to 10% impervious area. Even with virtually complete retention of streamside buffers (i.e., "percentage riparian forest" equals 100%), impervious area coverage much beyond this range will lead to nearly certain, measurable degradation. (Booth and Reinelt 1993, 549)

After watershed imperviousness reached 45 percent in Seattle area watersheds, riparian buffers ceased to effectively protect biological integrity (Horner et al. 1997). Steedman (1988) also found that the amount of riparian cover that can be removed while sustaining biological integrity is inversely proportional to the amount of impervious surface: with 0 percent urbanization, 75 percent of the riparian forest could be removed, and with 55 percent urbanization, 0 percent could be removed. Even complete retention of streamside buffers could not prevent "measurable degradation" after approximately 7 to 10 percent impervious area (Booth and Reinelt 1993). In addition, significant changes in instream nutrient concentrations were identified if land cover changes occurred within 150 meters of the stream channel, whereas insignificant changes in nutrient concentrations resulted if the land use change occurred at more than 150 meters from the channels (Tufford et al. 1998). This finding suggests that basin land use planning aimed at reducing nonpoint sources of nutrient loading should be especially concerned with near-channel land uses.

The issues of using BMPs can be summarized as follows (Ellis and Marsalek 1996):

1. No single BMP offers a universal solution to stormwater pollution.
2. BMPs should be considered as part of the treatment train, which starts in the catchment, continues in the collection system and a series of complementary BMPs, and ends with in-stream measures.
3. The success and sustainability of BMPs has to be ensured through proper design, operation, and maintenance to meet specific objectives and cannot be manipulated in real time.
4. Even though well-designed BMPs provide stormwater quantity and quality control, visual amenities, and wildlife habitat, they must be recognized as wastewater treatment facilities that may affect wildlife and cause contaminant entry into the food chain.

The Impacts of Impervious Surface Location within a Watershed

The placement of impervious surface within the watershed appears to be of some importance to stream quality, although few quantitative relationships have been made between percentage impervious surface, placement, and stream quality. The placement of impervious surface determines a number of changes in stream functioning, including speed with which flow enters the stream and possible absorption by pervious surfaces.

The placement of impervious surface along the stream course may contribute most to stream health. In general, upstream impacts will create disturbances over more stream miles, whereas downstream disturbances will create more concentrated impacts (Maxted and Shaver 1998). Booth (1990) concluded that increased sediment from streambank erosion occurs especially when the upper watershed is paved.

The organization of impervious surface is of some importance to stream quality as well, although again its significance may well change if impervious areas are sewered or not. Roth et al. (1996) found that "local riparian vegetation was a weak secondary predictor of stream integrity," whereas regional land use was the primary determinant of stream conditions, even "able to overwhelm the ability of local site vegetation to support high-quality habitat and biotic communities" (p. 141). When analyzing the effects of dispersed impervious surface compared to clustered development, higher sediment yields were measured in areas with dispersed impervious surface; however, the spatial characteristics of the impervious area did not affect runoff volumes, only flow rates and associated sediment loads (Corbet et al. 1997). Conversely, Yoder and Rankin (1997) found that biological performance was good even with urbanization as high as 15 percent if the site was developed with estate-type residences.

The distance between impervious cover and the stream channel appears to be one of the most important factors regarding placement, particularly for areas in which runoff is not piped directly to the stream. Impervious cover further away from the stream resulted in less channel enlargement in watersheds near Philadelphia (Hammer 1972). Tufford et al. (1998) found that nutrient concentrations changed significantly in relation to land use within 150 meters of streams in South Carolina; however, beyond this point, land use change did not significantly affect nutrient concentrations. In his assessment of Ontario area streams, Steedman (1988) also found that land uses 10 to 100 km^2 above the site of interest are more important to biotic integrity than the land uses within the entire basin. These findings correlate well with the buffer findings discussed earlier, because imperviousness placed further from the stream will have less impact simply by virtue of not destroying the buffer.

CONCLUSIONS

In a search for effective indicators of the impacts of urbanization on streams, most literature to date in the area of watershed planning has focused on impervious surface, with the resulting quantity and quality of runoff and the related effects on stream channels of variations in stream flow. This is largely due to the focus on stream-flow modeling of the 1970s and 1980s and the fact that changes in stream flow and water quality data are relatively easily obtained. However, given this direction and impetus for the research, the result has been that parameters and models for preventative planning measures are in their infancy.

As this review of the current literature has shown, there are a number of indicators that can and should be used to determine watershed impacts. Any indicator is merely a proxy for the complex set of actions and events that affect water quality, such as the construction practices that cause erosion and sedimentation, the changes in habitat as natural vegetation is removed, and the changes in stream hydrology. However, this complexity argues for a variety of interrelated indicators that will most clearly approximate the actual conditions on the ground.

To date, jurisdictions have begun to focus on impervious surface thresholds as a parameter of long-term land use planning. Jurisdictions as diverse as Brunswick, Maine, Broward County, Florida, and the state of Maryland in its Chesapeake Bay Critical Area have all used impervious surface thresholds and limits as a way to minimize the impact of development within their watersheds. However, the use of these thresholds has a number of shortcomings that need to be resolved before their use will be effective in a planning context.

As a first step, the methodological issues in calculating impervious surface must be resolved. The accuracy of the calculation of impervious surface area can be improved by sampling directly from aerial photographs, by distinguishing between effective and total impervious area, by using a detailed series of land use classes, and by tailoring those classes to the land use patterns of the region. The breakdown of land use classes is key to accurate future planning projections, because a difference in density between, for example, 1-acre and 2-acre residential lots will change considerably the impervious levels at the lot scale and at the regional scale. Residential land use classes should recognize, at a minimum, the predominant subdivision parcel sizes (e.g., 1/8th acre, 1/4 acre, 1 acre, etc.) to provide a clear baseline for analysis of existing impervious area calculations. To ensure that regional variations in development patterns are accounted for, sampling of the various land use classes should, whenever possible, occur in the jurisdiction in question or at a minimum be borrowed from a closely analogous, neighboring jurisdiction.

The second issue that must be resolved is that of defining accurate thresholds for a continuum of impervious surface impacts. Using a historical analysis of degraded streams in a region, the future result if other watersheds are similarly developed can be predicted. However, to set thresholds for impacts and clearly determine appropriate thresholds for impervious surface areas within watersheds, the measures of stream impacts must be standardized before the planning profession can use the scientific findings to achieve parameters for preventative planning.

As watershed planning and modeling move into a new age with the aid of geographic information systems, the definition, application, and use of a variety of indicator thresholds in watersheds will become even more critical. With the advent of graphic information systems, watershed modeling has become more accurate and effective, giving planners and hydrologists the ability to study watershed systems in greater detail through models. However, at least for the foreseeable future, indicators will be a necessity for many jurisdictions who cannot afford to invest in the development or application of watershed models. Particularly in the measurement of TIA and EIA, the increasing availability of digital mapping has provided the ability to improve the accuracy and reliability of threshold indicators.

In addition to the focus on impervious thresholds, there is preliminary evidence in the scientific literature that the new model for watershed-based water quality planning requires an equal focus on threshold amounts of forest cover in the watershed that can act to mitigate the impervious areas within the system. In fact, the literature argues for the development of a continuum model, in which the varying percentages and placement of land uses from totally impervious to almost totally pervious (mature forest stands) can be balanced in any given watershed to achieve the desired level of water quality at watershed buildout. As stated by Booth and Jackson (1997),

> The changes imposed on the natural system are a continuum, and so, defining a strict "threshold" in this context would be naive; but our perception of and our tolerance for those changes appears to undergo a far more abrupt transition, one which suggests a basis for discrete levels of both impact evaluation and management response. (P. 1084)

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