Imperviousness and Land-Use Policy: Toward an Effective Approach to Watershed Planning

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Abstract: Urban impacts to water quality and quantity have been a major focus of resource and ecosystem protection efforts since the early 1960s, focusing in the last decade on the impact of impervious thresholds. These are now commonly used as benchmarks of water quality planning and protection in local, watershed, and regional planning efforts. However, the relationship between urbanization and hydrologic impacts is much more complex than this cause-and-effect model would indicate, containing some weaknesses for effective growth management planning. This paper reviews the current literature to synthesize the development-related variables of hydrologic impairment, placing them in a context that is useful in growth management and development mitigation. Through this critical review of the literature, the paper focuses on an outstanding question in land planning: which best management practices, individually or in concert, are the most effective in dealing with the water quality impacts of urban growth and development? Research indicates two largely overlooked areas of potential improvement in water protection efforts: the location of impervious surfaces in the watershed, and the maintenance of adequate areas of forest stands and native vegetation.

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Introduction

Urban impacts to water quality and quantity have been a major focus of resource and ecosystem protection efforts since the early 1960s. Urbanization produces impervious cover at a fairly equivalent magnitude to the density of the development on the land. Intuitively, this makes some sense: as the movement of vehicles and people on the land increases, it is necessary to stabilize the surface. Since its link to development density and patterns is relatively direct and impervious cover is a relatively simple attribute for land planners to calculate and project, it has often been used as a proxy for development impacts.

As a result of this direct relationship, many studies that have sought to measure the impact of urbanization on surface water quality have focused on imperviousness as an indicator, and impervious thresholds are now commonly used as benchmarks in local, watershed, and regional planning efforts. However, since the relationship between urbanization (human development) and impacts on hydrologic systems is much more complex than this cause-and-effect model would indicate, this focus on imperviousness has had some drawbacks for effective growth management planning. This paper will review the current literature to synthesize the development-related variables in hydrologic impairment, and address an outstanding question in land planning: which tools and techniques, often termed best management practices, are the most effective in dealing with the water quality impacts of urban growth and development?

There is a considerable divergence in the literature regarding the definition of the term "best management practice." The literature tends to vacillate between defining a best management practice (BMP) as either any tool that can lead to improved watershed hydrology (Ellis and Marsalek 1996), or more commonly, limits its application to an engineered device that improves the quality or timing of storm-water flow (Center for Watershed Protection 1998; Strecker et al. 2000). This paper will use the comprehensive definition of the term: a device, practice, or method for removing, reducing, retarding, or preventing targeted storm-water runoff constituents, pollutants, and contaminants from reaching receiving waters and/or a device, practice, or method that maintains surface and subsurface flows as closely as possible to predevelopment levels. Therefore, this paper distinguishes between structural BMPs, which are either engineered and/or bio-engineered solutions for managing storm-water primarily on a site-specific basis, and nonstructural BMPs, which are primarily tools to guide the placement of development (Horner et al. 1997) or tools to modify actions.

Review of Impacts of Urbanization on Surface Water Systems

Since the early 1960s, numerous hydrologic studies have focused on the effects of urbanization on local hydrology (Carter 1961; Felton and Lull 1963; Antoine 1964; Espey et al. 1966; Leopold 1968; Martens 1968; Brater and Sangal 1969; Anderson 1970; Stall et al. 1970; Hammer 1972; Yucel 1974; Hollis 1975; Beard and Chang 1979; Klein 1979). In the early years, most of these studies focused on the increase in intensity of runoff in urban areas, and its impairment of water quality. To solve these problems, efforts at mitigation were focused on urban drainage, "with

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Table 1. Impacts and Stresses on Surface Water Caused by Urbanization

Category	Impact
Stream hydrology	Increased magnitude and frequency of floods
	Increased frequency of erosive bankfull floods
	More annual runoff volume as stormflow
	Less annual runoff volume as baseflow
	More rapid stream water velocities
Channel morphology	Channel widening and down cutting
	Greater streambank erosion
	Shifting bars of coarse-grained sediments
	Stream channelization and relocation
	Trash and debris jams
Water quality	Sediment pulse during construction
	Nutrient enrichment and algae growth
	Bacterial contamination
	Greater organic and hydrocarbon loads
	Higher trace metals levels
	Stream temperature
Ecology and habitat	Reduction in diversity of fish and aquatic insects
	Creation of linear barriers to fish migration
	Destruction of wetlands, riparian buffers, and springs

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" (Ellis and Marsalek 1996).

This early concern for flooding and pollutants led to a focus on surface waters, particularly their quality and morphological changes (Table 1), almost to the exclusion of subsurface hydrology. Various researchers found that runoff from sites of intensive human use was often heavily polluted with nutrients (Weibel 1969; Omernik 1977), oxygen-demanding organics (Weibel et al. 1964; Keefer et al. 1979), suspended solids (Fusillo et al. 1977; Manning et al. 1977), and petroleum products, or other toxicants (Bryan 1974; McConnell 1980; Scott et al. 1986). Other researchers focused on the physical impacts of "flashy" runoff on streams, particularly after high levels of urbanization (MacRae 1997; Yoder et al. 1999) resulting in downcutting and loss of large woody debris (Booth 1991).

The focus on stream hydrology, morphology, and water quality led to the identification of impervious surface in the urbanizing watershed as a key variable in, and indicator of, watershed health (Espey et al. 1966; Stankowski 1972). However, early research identified two sides to the impervious surface equation: increasing urbanization resulted in increased amounts of impervious surfaces—roads, parking lots, roof tops, etc.—and a decrease in the amount of forested lands, wetlands, and other forms of open space which absorb and clean storm-water in the natural system (Leopold 1968; Carter 1961). Change in the impervious-pervious surface balance was understood to cause significant changes to both the quality and quantity of the storm-water runoff, leading to degraded stream and watershed systems (Morisawa and LaFlure 1979; Arnold et al. 1982; Bannerman et al. 1993). Subsequent research focused on the importance of impervious surface largely to the exclusion of pervious areas and their impacts on the hydrologic system (Griffin et al. 1980; Harbor 1994; Arnold and Gibbons 1996).

Although many studies cited the link between imperviousness and water quality, the most widely cited report that linked the amount of impervious surface to levels of water quality degradation was completed in 1995 (Schueler 1995). That report compiled the results of 11 previous studies (Klein 1979; Steward 1983; Jones and Clark 1987; Steedman 1988; Galli 1990; Limburg and Schmidt 1990; Booth 1991; Schueler and Galli 1992; Luchetti and Fuersteburg 1993; Taylor 1993; Shaver et al. 1995), citing them as evidence that stream quality declined at 10–15% imperviousness. The primary drawback of both the compiling summary and the underlying studies is that they often equated urbanization with imperviousness. In doing so, they do not make a clear distinction between the area of urbanization as a whole and the actual amount of impervious surface that a particular type of urban land cover creates (Brabec et al. 2002).

The critical error lies in how the original studies were developed, and then a subsequent lack of critical analysis of the methodology. The ratios for the relationship between land use and the amount of impervious surface it creates were developed in the 1970s, and have changed little in the studies in the intervening years. In the early research, imperviousness was evaluated four ways: (1) direct measurement (Graham et al. 1974; Stafford et al. 1974); (2) sampling (Martens 1968; Hammer 1972; Gluck and McCuen 1975; Ragan and Jackson 1975); (3) estimating the impervious area of land-use classes in remotely sensed images (Ragan and Jackson 1975, 1980); and (4) using urbanization as a proxy for imperviousness (Morisawa and LaFlure 1979).

Currently, the majority of studies correlate impervious surface to the area covered by a series of land-use classes (see Brabec et al. 2002 for a full review of these studies). The ratio or percent of impervious surface of each land use is most often determined through a reliance on impervious estimates published in past studies. Even when directly measured, there are four 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 of varying development densities (Table 2). Second, imperviousness varies considerably with lot size. Within a particular land-use type, such as residential, increasing lot size correlates with decreasing imperviousness on a site specific level. Third, residential land-use density has an impact on per capita calculations creating an inherent flaw: while lower land-use densities correlate with decreasing imperviousness on a site level, percent imperviousness per capita at the regional level increases due to the increased road length required to access each site. Fourth, the base studies from which the impervious surface percentages were calculated were developed in east coast urban areas during the 1970s and early 1980s: demographic and land-use patterns have changed considerably since that time, with both homes and driveways of single family homes in new suburbs increasing significantly in size. Therefore, while impervious surface is without a doubt a critical factor in hydrologic impairment, the impact thresholds that are commonly used in the planning field are based on findings of questionable accuracy. To rectify the bias, local data should be developed and field checked using a large number of land-use classes, particularly in the residential category.

Total Impervious Area (TIA) versus Effective Impervious Area (EIA)

One attempt to refine imperviousness as a causal mechanism was proposed by Alley and Veenhuis (1983), who classified anthropogenic imperviousness features into two kinds of imperviousness: *directly connected* and *unconnected*. *Directly connected* imperviousness, also called effective imperviousness (EIA) is impervi-

Table 2. Percent Imperviousness for Various Land Cover Classes as Calculated Directly from Aerial Photo and Map Analysis

Land cover class	Notes	Percent imperviousness (%)		Reference
		Mean	Range	
Single family	<0.25 acre lots	39	30–49	Alley and Veenhuis (1983)
Residential	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 multifamily 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)

ousness that is hydrologically connected to anthropogenic features (storm sewers, gutters, ditches, etc.) which drain directly into streams. This type of imperviousness moves large quantities of runoff rapidly to the stream, reducing the opportunity for infiltration and evaporation. *Unconnected* impervious areas are patches of imperviousness that are adjacent to pervious areas where runoff may infiltrate into the ground. Most watershed studies lump unconnected impervious areas together with connected areas under a term called total impervious area (TIA) (Brabec et al. 2002).

Many studies of urban hydrology (Cherkaver 1975; Beard and Chang 1979; Alley et al. 1980; Driver and Troutman 1989) show that TIA, while correlating with changes in runoff, does not impact runoff to the extent of EIA. The direct connections of EIA allow the flow of pollutants into surface water systems with little to no cleansing of the runoff. Using TIA instead of EIA, or not distinguishing between the two in hydrologic models that assess impervious threshold results in analytical bias: (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).

Although directly connected imperviousness has significant impacts, the effects of unconnected impervious areas may be equally severe, affecting how water infiltrates. Due to the passive design of most infiltration zones, the majority of infiltration will occur along narrow linear zones on the boundaries of imperviousness features. For example, in the case of runoff from roof gutters and down spouts, water delivery and therefore infiltration is focused into very small zones at the end of the down spouts. As the proportion of imperviousness to perviousness increases in the watershed, the effective size of the precipitation event increases, and rainwater is forced to infiltrate over a smaller area. This could lead to an increase in surface water body recharge if the flux of water into these areas exceeds the available water-holding capacity.

Infiltration and Evapotranspiration

While urbanization increased storm-water runoff and decreased the lag time of storm-water discharge, there was a resulting lack of infiltration and reduction in evapotranspiration that is an essential part of any vegetative ecosystem. The alteration of these essential exchange processes (Brunke and Gonser 1997) in the hydrologic system can be severe. "After precipitation has been deflected from infiltration and recharge by impervious surfaces, and infiltrated water in the subsurface reduced by evapotranspiration, there is no possible amelioration of declining low flows; the water to support base flows is no longer available in the watershed (Ferguson and Suckling 1990)." Equally important is the presence of moisture in the upper 2 ft of soil that is available for plant uptake and evapotranspiration. If absent, and evapotranspiration is decreased, the result could be a troubling trend of increasing desertification.

A study in Nassau County found that base flow was reduced "to about 20% of total stream flow by (1) sanitary sewerage and the discharge of the resulting treated effluent to tidewater; (2) the routing of storm-water runoff directly to streams through storm sewers; and (3) the decrease in infiltration of precipitation as a result of the reduction in permeable area. In an adjacent urbanized but unsewered area, base flow has been reduced to about 84% of total stream flow by storm sewerage, reduced permeable area, and the effects of lowered groundwater levels in the adjacent sewered area" (Simmons and Reynolds 1982).

A recent study conducted in the Rouge River Basin of Michigan (Richards and Brabec 2003) focused on the link between connected and unconnected imperviousness in a watershed that was rural in 1950 and highly urbanized by 1999. The results of this study indicated that all roads, driveways, and commercial and industrial imperviousness features were directly connected to surface water bodies, even within internally drained portions of the watershed. This emphasizes the importance of focusing on the transportation network in designing environmentally friendly development. Between 1950 and 1990, directly connected imperviousness was found to have risen in the watershed from 1.8 to 14.2%, while unconnected imperviousness increased from 0.4 to 7.5%. The results also confirmed that storm sewers increased the effective size of the watershed under study, crossing subwatershed boundaries.

Hydrologic analysis indicated that the hydrologic efficiency of this watershed in both surface runoff and baseflow had increased over time. While the former is to be expected, the long-term increase in baseflow does not support the common notion that urban development reduces recharge. Reduction in evaporation caused by imperviousness may be partly responsible for this increase in baseflow, and increased base flow may be due, at least in part, to a leaky water supply. However, another cause of increase in the efficiency of groundwater recharge and baseflow may be the concentration in infiltration flow paths caused by the rerouting of water to the edge of unconnected impervious features, resulting in increased point-specific infiltration.

Table 3. Typical Pollutant Removal Efficiencies of Site-Level BMPs

Pollutant	Typical percent removal rates of site-level BMPs							
	Infiltration trench[a]	Modular treatment systems[b]	Porous pavement[c]	Bioretention[d]	Storm-water wetlands[e]	Wet detention ponds[f,g]		Vegetated swales[h]
Sediment	90	—	82–95	—	—	—	—	—
Total suspended solids	—	99	—	90	67	50–90	7–11	81
Total phosphorous	60	90	65	70–83	49	30–90	—	9
Total nitrogen	60	77	80–85	68–80	28	—	—	38 (nitrate)
Soluble Nutrients	—	—	—	—	—	40–80	2–52	—
Metals	90	—	—	93–98	—	—	25–60	—
Lead	—	77	—	—	62	70–80	—	67
Chromium	—	98	—	—	—	—	—	—
Zinc	—	90	—	—	45	40–50	—	71
Cadmium	—	—	—	—	36	—	—	42
Copper	—	—	—	—	41	—	—	51
Bacteria	90	—	—	90	77	—	—	—
Fecal coliform	—	97	—	—	—	—	—	—
Organics	90	—	—	90	—	—	—	—
Biochemical oxygen demand	70–80	82	—	—	—	20–40	16–49	67
Petroleum hydrocarbons	—	90	—	—	87	—	—	62

[a]Schueler and Galli (1992) in USEPA (1999b).
[b]StormTreat Systems, Inc. (1998) (USEPA 1999c).
[c]USEPA (1999d).
[d]USEPA (1999a).
[e]USEPA (1999e).
[f]USEPA (1999g).
[g]Kantrowitz and Woodham (1995).
[h]USEPA (1999f).

Structural and Nonstructural BMPs: Importance of Planning

The focus on the mitigation of degraded water quality and increased flashiness has led to an emphasis on engineering solutions to achieve those results (Federal Interagency Stream Restoration Working Group 1998; USEPA 1999a,b,c,d,e,f,g). Currently, federal, state, and nongovernmental organizations (NGO) educational efforts and local government planning responses discuss primarily traditional engineering and site-specific BMPs, and avoid the large-scale planning BMPs. Even in those documents which do cross the planning "line," efforts tend to focus on site level planning principles and avoid regional planning approaches to protecting water quality at the catchment or watershed level.

Paradoxically, discussions of catchment and watershed level planning are not new in the literature. Marsh (1983), in his textbook on *Landscape Planning*, addresses the importance of planning the entire catchment. However, this framework for planning misses an important distinction: as the zones of the catchment are defined in Marsh's work, only the riparian area and the immediate buffer zone surrounding the riparian area are targeted. As explored below, an analysis of the existing literature and its application to planning find the following:

1. While a threshold of watershed imperviousness is commonly applied to watershed planning, it is not the only or perhaps even the most important watershed variable;
2. Engineered and site-level 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 the balance of evapotranspiration, infiltration, and base flow, and finally, perhaps the most comprehensive issue; and
4. The location of impervious surfaces in a watershed can have significant impacts on water quality and the hydrological system.

Limits of BMP Efficiency

Although BMPs are used to mitigate the impact of development, in studies of stream quality these measures have been found to have varying degrees of effectiveness. In addition, there is no conclusive answer to the question, "At what percent impervious surface can stream-quality impacts not be mitigated?" Two studies have identified a limit at the lower end of the imperviousness spectrum: Maxted and Shaver (1998) found that BMPs could not mitigate the impacts of urbanization once the watershed reached 20% impervious cover; and Galli (1990) found no mitigation of temperature standard violations in areas of impervious surface ranging from 12 to 30%.

While there has been considerable research on the efficiency of some types of BMPs, many of the nonstructural BMPs have not been adequately evaluated for their use and efficacy in a watershed. Typical pollutant removal efficiencies of some of the more common structural, site-level BMPs are presented in Table 3.

Retention and Detention Ponds

Detention ponds (Horner et al. 1997) are integral to the stormwater cleansing process and are statutorily required in many jurisdictions. In fact, two jurisdictions with very different

Table 4. Comparison of Ability of Detention Ponds to Clean Various Contaminants from Storm Water

Contaminant	Maristany (1993)	Stanley (1996)	NURP (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

hydrologic regimes, Beaufort County, South Carolina, and Bellevue, Wash. (Comings et al. 2000), require removal of 50% 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%. Utilizing 1–2% of the watershed area for the development of wet detention ponds could reduce pollutant loadings to meet targeted requirements of water quality improvements (Wu et al. 1996).

Although dry detention ponds are in use throughout the United States, pollutant removal efficiencies have been measured in only a handful of the ponds (Stanley 1996). The findings of various studies concur that detention ponds can provide a certain mitigation of storm-water impacts, however they are limited in their effectiveness (Table 4), and more widespread use of storm-water infiltration ponds is impeded by concerns about groundwater contamination, lack of design guidance, and concerns about maintenance and longevity of infiltration systems (Ellis and Marsalek 1996).

Modifications to storm-water retention basin designs (e.g., expanded capacity, constructed wetlands) could increase pollutant removal efficiency (Maxted and Shaver 1998). However, detention ponds are compromised in their ability to clean storm water and mitigate impacts by an explicit design limit for flows, after which the water will overtop or bypass the storage area. As a result of the hydrologic modeling that is used in the pond design, an excessive rate of release from the pond is created (Booth 1991). Wet detention ponds have been cited as one method to improve water quality efficiencies. The establishment of aquatic vegetation has the effect of increasing the efficiency of detention ponds in reducing loads of urban-runoff contaminants in storm water (Kantrowitz and Woodham 1995), but experience declining removal of organic matter (oxygen demand) if not properly maintained (Maristany 1993).

Riparian Buffers

Riparian buffers are a commonly accepted form of nonstructural BMP. However, since implementation is fairly straightforward and generally requires maintenance of existing site features rather than the conscious engineering of a constructed BMP, they are often imbued with powers far beyond their ability to impact the hydrologic system (Booth 1991). While the effectiveness of riparian forests is limited, riparian buffers are key mitigants of temperature increases (Galli 1990), and the loss of large woody debris and leaf litter that enters the aquatic food chain (Booth and Jackson 1997). When streamside vegetation is cleared, less wood enters the channel (Bisson et al. 1987; Richards and Host 1994) which functions to protect the streambed and banks from erosion (Booth et al. 1996; Booth and Jackson 1997).

There are several factors that can act to reduce the effectiveness of buffers (Booth 1991): (1) the effects of existing land use in the watershed; (2) stream crossings by roads and utilities; (3) human intrusion; (4) buffer alteration over time by individual property owners; and (5) channelized flow, or flow through buried culverts or pipes, through the buffer into the stream carrying pollutants and sediments, along with flow increases from impervious surfaces.

Several studies reinforce the limits of buffer protection. After watershed imperviousness reached 45% 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% urbanization, 75% of the riparian forest could be removed, and with 55% urbanization, 0% could be removed. Even complete retention of streamside buffers could not prevent "measurable degradation" after approximately 7–10% impervious area (Booth and Reinelt 1993). In addition, significant changes in instream nutrient concentrations were identified if land cover changes occurred within 150 m of the stream channel, while insignificant changes in nutrient concentrations resulted if the land-use change occurred at more than 150 m 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. In particular, nutrient levels were found to be alleviated only temporarily by forested buffer strips (Omernik et al. 1981). One study found "stream buffers (100 m) were more important than whole catchment data for predicting sediment-related habitat variables (Richards et al. 1996) and riparian forest within about 1 km of a station was the most important in predicting maximum stream temperature and trout distribution in southern Ontario (Barton et al. 1985). One hundred ft buffers are generally accepted in planning practice since benefits of wood recruitment, aquatic food supply and shading appear to decline much beyond 100 ft (Murphy et al. 1986; Budd et al. 1987; Booth 1991).

Pervious-Impervious Balance: Importance of Mature Forest

While 100% imperviousness is an absolute measure, are all developed sites of equal impervious cover equal in their polluting capacity? The answer of course is no. One study found that "Highway construction increased sediment yield ten times over that expected from cultivated land, 200 times that expected from grassland, and 2,000 times that expected from forest land" (Vice et al. 1969). In addition, 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).

Ross and Dillaha (1993) compared runoff, nutrient, and sediment concentrations from six different pervious surfaces in a simulated rainfall event. The results showed a great difference in the runoff characteristics among different types of pervious surfaces. While 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 impervious calculations.

This difference in the runoff characteristics for various pervious surfaces is critical to land-use planning. 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 given similar soils, soil composition, and topography. This is a result of the construction process: construction activity yields soil compaction and changes in soil profiles, therefore intense development equals more impacted land area that is at best only partially pervious (Booth and Jackson 1997).

Understanding the impact 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 impacts to low flows in streams: precipitation is deflected from infiltration, and advective enhancement of evapotranspiration exacerbates the loss of groundwater, due to the increase in heat from surrounding surfaces (Ferguson and Suckling 1990).

Mature forest stands (and other native covers such as native prairies) are critical as a baseline for planning adequate infiltration in the watershed. Several studies have found that forest stands in a watershed are vital for mediating other land-use impacts on stream habitats (Osborne and Wiley 1988; Steedman 1988; Osborne and Kovacic 1993; Richards et al. 1996). Whereas some water-quality parameters such as woody debris and temperature can be modified by local riparian conditions (Osborne and Kovacic 1993), dominant water-quality trends (nutrients and sedimentation) are more strongly related to catchment-wide land use and geology (Richards et al. 1996). While the critical threshold of forest cover has not been firmly established, at least one study (Taylor 1993) found that at least 15% forested cover should be protected to reduce stream flashiness.

Studies of the effects of forested areas in a watershed have illustrated their potential mitigating effects for other land uses. 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), cited 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% impervious watershed surface, more than 50% forested land area, and more than 80% of the stream with a 200 ft riparian buffer; a low level of impact at 9% impervious surface, 30–50% forest stand, and 50–80% riparian buffer; a moderate level impact with 10–15% impervious surface and 10–29% forest stand, and 20–49% riparian buffer; and a high level of impact with 15% impervious surface, 10% forest stand, and less than 20% riparian buffer. Forest stands directly affect the abiotic factors of stream quality, particularly woody debris and channel enlargement (Hammer 1972), and mitigate channel enlargement due to a higher level of storm-water absorption.

Impacts of Location within Watershed

Although a variety of researchers have acknowledged the importance of impervious surface location within a watershed (Weaver and Garman 1994; Allan et al. 1997; Johnson and Gage 1997; Carignan and Steedman 2000; Wang et al. 2001), few quantitative relationships have been developed between percent impervious surface, placement, and stream quality. Booth and Jackson (1997) identify upland land use as critical in determining overall stream function, degradation, and rehabilitation potential. They found that even with best efforts at mitigation, some downstream aquatic system damage is probably inevitable without limiting the extent of watershed development.

The placement of impervious surface determines a number of changes in hydrologic function including the speed with which surface and subsurface flow enters the stream and potential absorption by pervious surfaces. In general, upstream impacts will create disturbances over more stream miles while downstream disturbances will create more concentrated impacts (Maxted and Shaver 1998). For example, Booth (1990) concluded that increased sediment from streambank erosion occurs particularly when upstream locations in the watershed are paved.

A study in Michigan (Roth et al. 1996) found that 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." 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 (Corbett et al. 1997). Conversely, Yoder and Rankin (1997) found that biological performance was good even with urbanization as high as 15% if the site was developed with estate-type (large, dispersed lots) 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). While nutrient concentrations changed significantly in relation to land use within 150 m of streams in South Carolina, beyond this point land-use change did not significantly effect nutrient concentrations (Tufford et al. 1998). Although total phosphorus and total suspended solids correlated with land use within the stream ecotone in summer, total dissolved solids in summer and ammonium in autumn correlated to land use in the whole catchment (Johnson et al. 1997). In an assessment of Ontario area streams, land uses in an area of 10–100 km^2 above the site of interest were more important to biotic integrity than the land uses within the entire basin (Steedman 1988). These findings correlate well with the buffer findings discussed previously, since imperviousness further from the stream has less impact on the hydrologic system simply by not destroying the buffer.

Although the research on watershed-wide locational impacts is relatively sparse, the findings have been supportive of increased reliance on planning to reduce the hydrologic impacts of development (Booth and Jackson 1997; Lammert and Allan 1999; Wang et al. 2001). Both the type of land use as well as the intensity and location of the use have an impact on watershed hydrology (Roth et al. 1996; Booth and Jackson 1997; Johnson et al. 1997; May et al. 1997; Wang et al. 2001). Although more research is needed to fully understand the underlying relationships, from these studies it is clear that the identification of locations within the watershed that are able to absorb development, and other areas that should be protected, are key aspects of planning for hydrologic health.

Expanding Watershed Protection

This paper reviewed the research and implementation efforts that have characterized watershed planning efforts for the past 30 years. In addition to the many structural, site-level BMPs that have been developed and widely used, more recently the literature has begun to reflect the broadening of efforts to include nonstructural or planning BMPs. Site-level BMPs are not 100% effective in protecting water quality or hydrology, and many research efforts have defined the limits of structural BMPs to achieve predevelopment water quality and watershed hydrology. As such, in an effort to slow or even halt the continued degradation of urbanizing systems, focus has turned to include the patterns of land use and growth management. Based on the preceding analysis of the state of the art in watershed protection, it is clear that the greatest strides can be made in the area of land use and watershed planning to acknowledge pervious as well as impervious thresholds to reduce impacts of development on watershed hydrology.

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