The Importance of Imperviousness

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The emerging field of urban watershed protection has often lacked a unifying theme to guide the efforts of its many participants--planners, engineers, landscape architects, scientists, and local officials. The lack of a common theme has often made it difficult to achieve a consistent result at either the individual development site, or cumulatively, at the watershed scale.

In this paper, a unifying theme is proposed based on a physically defined unit--imperviousness. Imperviousness here is defined as the sum of roads, parking lots, sidewalks, rooftops, and other impermeable surfaces of the urban landscape. This variable can be easily measured at all scales of development, as the percentage of area that is not "green".

Imperviousness is a very useful indicator with which to measure the impacts of land development on aquatic systems. This paper reviews the scientific evidence that relates imperviousness to specific changes in the hydrology, habitat structure, water quality and biodiversity of aquatic systems. This research, conducted in many geographic areas, concentrating on many different variables, and employing widely different methods, has yielded a surprisingly similar conclusion--stream degradation occurs at relatively low levels of imperviousness (10-20%). Most importantly, imperviousness is one of the few variables that can be explicitly quantified, managed and controlled at each stage of land development.

THE COMPONENTS OF IMPERVIOUSNESS

Imperviousness represents the imprint of land development on the landscape. It is composed of two primary components--the rooftops under which we live, work and shop, and the transport system (roads, driveways, and parking lots) that we use to get from one roof to another. As it happens, the transport component now often exceeds the rooftop component, in terms of total impervious area created. For example, transport-related imperviousness comprised 63% to 70% of total impervious cover at the site in 11 residential, multifamily and commercial areas where it had actually been measured (City of Olympia, 1994b). This phenomenon is observed most often in suburban areas, and reflects the recent ascendancy of the automobile in both our culture and landscape. The sharp increase in per capita vehicle ownership, trips taken, and miles travelled have forced local planners to increase the relative size of the transport component over the last two decades.

Traditional zoning has strongly emphasized and regulated the first component (rooftops) and largely neglected the transport component. While the rooftop component is largely fixed in density zoning, the transport component is not. As an example, nearly all zoning codes set forth the maximum density for an area, based on dwelling units (=rooftops). Thus, in a given area, no more than one single family home can be located on each acre of land, and so forth.

Thus, a wide range in impervious cover is often seen for the same zoning category. For example, impervious area associated with medium density single family homes can range from 25% to nearly 60%, depending on the layout of streets and parking. This suggests that significant opportunities exist to reduce the share of imperviousness from the transport component.

IMPERVIOUSNESS AND RUNOFF

The relationship between imperviousness and runoff may be widely understood, but it is not always fully appreciated. Figure 1 illustrates the increase in the site runoff coefficient as a result of site imperviousness, developed from over 40 runoff monitoring sites across the nation. The runoff coefficient ranges from zero to one, and expresses the fraction of rainfall volume that is actually converted into storm runoff volume. As can be seen, the runoff coefficient closely tracks percent impervious cover, except at low levels where soils and slope factors also become important. In practical terms, this means that the total runoff volume for a one acre parking lot (Rv=0.95) is about 16 times that produced by an undeveloped meadow (Rv=0.06).

To put this in more understandable terms, consider the runoff from a one-inch rainstorm. The total runoff from a one acre meadow would fill a standard size office to a depth of about two feet (218 cubic feet). By way of comparison, if that same acre was completely paved, a one-inch rainstorm would completely fill your office, as well as the two next to it. The peak discharge, velocity and time of concentration of stormwater runoff also exhibit a striking increase after a meadow is replaced by a parking lot.

It is thought that groundwater recharge decreases as impervious cover increases, due to lower infiltration during storms. This, in turn, should translate into lower dry weather stream flows. Actual data, however, that demonstrates this effect is rare. Indeed, Evett (1994) could not find any statistical difference in low stream flow between urban and rural watersheds, after analyzing 16 North Carolina watersheds. Simmons and Reynolds (1982) did note that dry weather flows dropped 20 to 85% after development in several urban watersheds in Long Island, New York.

It should be noted that transport-related imperviousness often exerts a greater hydrological impact than the rooftop-related imperviousness. In residential areas, runoff from rooftops can be spread out over pervious areas, such as backyards, and are not always directly connected to the storm drain system. This may allow for additional infiltration of runoff. Roads and parking lots on the other hand, are usually directly connected to the storm drain system.

IMPERVIOUSNESS AND THE SHAPE OF STREAMS

Confronted by more severe and more frequent floods, stream channels must respond. They typically do so by increasing their cross-sectional area to accommodate the higher flows. This is done either through widening of the stream banks, downcutting of the stream bed, or frequently, both. This phase of channel instability, in turn, triggers a cycle of streambank erosion and habitat degradation.

The critical question is at what level of development does this cycle begin?. Recent research models developed in the Pacific Northwest (Booth, 1991, and Booth and Reinelt, 1993) suggest that a threshold for urban stream stability exists at about 10% imperviousness. Watershed development beyond this threshold consistently resulted in unstable and eroding channels. The rate and severity of channel instability appears to a function of subbankfull floods (Hollis, 1975, Schueler, 1987, MacRae and Marsalek, 1992), whose frequency can increase by a factor of 10 even at relatively low levels of imperviousness.

A major expression of channel instability is the loss of instream habitat structures, such as the loss of pool and riffle sequences and overhead cover, a reduction in the wetted perimeter of the stream and the like. A number of methods have been developed to measure the structure and quality of instream habitat in recent years (Plafkin et al, 1989, Gibson et al, 1993, and Galli, 1993). Where these tools have been applied to urban streams, they have consistently demonstrated that a sharp threshold in habitat quality exists at approximately 10 to 15% imperviousness (Shaver et al, 1994, Booth, 1993, Galli, personnel communication). Beyond this threshold, urban stream habitat quality is consistently classified as poor.

IMPERVIOUSNESS AND WATER QUALITY

Impervious surfaces collect and accumulate pollutants deposited from the atmosphere, leaked from vehicles or derived from other sources. During storms, accumulated pollutants are quickly washed off, and are rapidly delivered to aquatic systems.

Monitoring and modeling studies have consistently indicated that urban pollutant loads are directly related to watershed imperviousness. Indeed, imperviousness is the key predictive variable in most simulation and empirical models used to estimate pollutant loads. For example, the Simple Method assumes that annual pollutant loads are a direct function of watershed imperviousness (Schueler, 1987), as imperviousness is the key independent variable in the equation.

Threshold Limits for Maintaining Background Pollutant Loads

Suppose that a watershed drains to a lake that is phosphorus- limited. Further assume that the present background load of phosphorus from a rural land use amounts to 0.5 lbs/ac/yr. The Simple Method predicts that the postdevelopment phosphorus load will exceed background loads once watershed imperviousness exceeds 20 to 25% I, thereby increasing the risk of nutrient overenrichment in the lake.

Urban phosphorus loads can be reduced when urban best management practices (BMPs) are installed, such as stormwater ponds, wetlands, filters or infiltration practices. Performance monitoring data indicates that BMPs can reduce phosphorus loads by as much as 40 to 60%, depending on the practice selected. The impact of this pollutant reduction on the postdevelopment phosphorus loading rate from the site is shown in Figure 3. The net effect is to raise the phosphorus threshold to about 35% to 60% imperviousness, depending on the performance of the BMP we install. Therefore, even when effective practices are widely applied, we eventually cross a threshold of imperviousness, beyond which we cannot maintain predevelopment water quality.

IMPERVIOUSNESS AND STREAM WARMING

Impervious surfaces both absorb and reflect heat. During the summer months, impervious areas can have local air and ground temperatures that are 10 to 12 degrees warmer than the fields and forests that they replace. The trees that could have provided shade to offset the effects of solar radiation are absent, as well.

Water temperature in headwater streams is strongly influenced by local air temperatures. Stream temperatures throughout the summer are increased in urban watersheds, and the degree of warming appears to be directly related to the imperviousness of the contributing watershed (Galli, 1991). He monitored five headwater streams in the Maryland Piedmont over a six month period that had differing levels of impervious cover. Each of the urban streams had mean temperatures that were consistently warmer than a forested reference stream, and the size of the increase (referred to as the delta-T) appeared to be a direct function of watershed imperviousness. Other factors, such as lack of riparian cover and ponds, were also demonstrated to amplify stream warming, but the primary contributing factor appeared to be watershed impervious cover (Galli, 1991).

IMPERVIOUSNESS AND STREAM BIODIVERSITY

The health of the aquatic ecosystem is a strong environmental indicator of watershed quality. A number of research studies have recently examined the links between imperviousness and the biological diversity in streams. Some of the key findings from this body of research are summarized in Table 2.

Aquatic Insects

The diversity, richness and composition of the benthic or streambed community has frequently been used to evaluate the quality of urban streams. Not only are aquatic insects a useful environmental indicator, but they also form the base of the stream food chain in most regions of the country.

Klein (1979) was one of the first investigators to note that macroinvertebrate diversity drops sharply in urban streams in Maryland. He found that diversity consistently became poor when watershed imperviousness exceeded 10% to 15%. The same basic threshold has been reported by all other research studies that have looked at macroinvertebrate diversity in urban streams.

In each study, sensitive aquatic insects species were replaced by ones that were more tolerant of pollution and hydrologic stress. Species such as stoneflies, mayflies and caddisflies largely disappear and were replaced by chironomids, tubificid worms, amphipods, and snails. Species that employ specialized feeding strategies--shredding leaf litter, grazing rock surfaces, filtering organic matter that flows by, and preying on other insects-- were lost.

A typical example of the relationship between imperviousness and macroinvertebrate diversity is shown in Figure 5. The graph summarizes the trend in diversity for 23 sampling stations in headwater streams of the Anacostia watershed (Schueler and Galli, 1992). While good to fair diversity was noted in all headwater streams with less than 10% imperviousness, nearly all stations with 12% or more impervious cover recorded poor diversity. The same sharp drop in macroinvertebrate diversity at around 12 to 15% imperviousness was also observed in streams in the coastal plain and piedmont of Delaware (Shaver et al,1994).

Other studies have utilized other indicators to measure the impacts of urbanization on stream insect communities. For example, Jones and Clark (1987) monitored 22 stations in Northern Virginia and concluded that benthic insect diversity composition changed markedly after watershed population density exceeded 4 or more individuals per acre. The population density roughly translates to half-acre or one acre lot residential land use, or perhaps 10 to 20% imperviousness.

Steedman (1988) evaluated 208 Ontario stream sites, and concluded that benthic diversity shifted from fair to poor at about 35% urban land use. Since "urban land" includes both pervious and impervious areas, the actual threshold in the Ontario study may well be closer to 7 to 10% imperviousness (Booth, 1994). Steedman also reported that urban streams with intact riparian forests had higher diversity than those that did not, for the same level of urbanization.

While the exact point at which stream insect diversity shift from fair to poor is not known with absolute precision, it is clear that few, if any, urban streams can support diverse benthic communities at moderate to high levels of imperviousness (25% or more). For example, Benke (1981), Garie and McIntosh (1986), Yoder (1991) and Black and Veatch (1994) all failed to find stream insect communities with good or excellent diversity in any highly urban stream.

Fish Surveys

The abundance and diversity of the fish community can also serve as an excellent environmental indicator. Surprisingly, relatively few studies have examined the influence of imperviousness on fish communities in headwater streams. The results of one study is illustrated in Figure 6. Four similar subwatersheds in the Maryland Piedmont were sampled for the number of fish species present. As the level of watershed imperviousness increased, the number of fish species collected dropped. Two sensitive species were lost as imperviousness increased from 10 to 12% (trout and sculpin), and four more were lost when impervious cover increased to 25%. Significantly, only two species remained in the fish community at 55% imperviousness. Sensitive species, defined as those with a strong dependence on the substrate for feeding and/or spawning, showed a more precipitous decline. Klien (1979) found a similar relationship between fish diversity and watershed imperviousness in several dozen headwater streams in the Maryland Piedmont.

Salmonoid fish species (trout and salmon) and anadromous fish species appear to be most negatively impacted by imperviousness. Trout have stringent temperature and habitat requirements, and seldom are present in mid-Atlantic watersheds where imperviousness exceeds 15% (Galli, personal communication). Declines in trout spawning success are evident above 10% I (Galli, 1994). In the Pacific Northwest, research by Luchetti and Feurstenburg (1993) indicate that sensitive coho salmon were seldom found in watersheds beyond 10 or 15% imperviousness. Booth (1994) noted that most urban stream reaches had poor quality fish habitat when I exceeded 8 to 12%.

Fish species that migrate from the ocean to spawn in freshwater creeks are also very susceptible to the impacts of urbanization, due to fish barriers, pollution, flow changes and other factors.. For example, Limburg and Schmidt (1990) discovered that the density of anadromous fish eggs and larvae declined sharply after a 10% imperviousness threshold was surpassed in 16 subwatersheds draining to the Hudson River.

THE INFLUENCE OF IMPERVIOUSNESS ON OTHER URBAN WATER RESOURCES

Several other studies point to the strong influence of imperviousness on other important aquatic systems such as shellfish beds and wetlands.

Even relatively low levels of urban development yield high levels of bacteria, derived from urban runoff or failing septic systems. These consistently high bacterial often result in the closure of shellfish beds in coastal waters, and it is not surprising, that most closed shellfish beds are in close proximity to urban areas. Indeed, Duda (1982) maintains that it is difficult to prevent shellfish closure when more than one septic drain field is present per seven acres--a very low urban density. Although it is widely believed that urban runoff accounts for many shellfish bed closures (now that most point sources have been controlled), no systematic attempt has yet been made to relate watershed imperviousness to the extent of shellfish bed closures.

Taylor (1993) examined the effect of watershed development on 19 freshwater wetlands in King County, Washington, and concluded that the additional stormwater contributed to greater annual water level fluctuations (WLF). When the annual WLF exceeded about 8 inches, the richness of the both the wetland plant and amphibian community dropped sharply. This increase in WLF began to occur consistently when upstream watersheds exceeded 10 to 15% imperviousness.

IMPLICATIONS AT THE WATERSHED LEVEL

The many independent lines of research reviewed here converge toward a common conclusion-- that it is extremely difficult to maintain predevelopment stream quality when watershed development exceeds 10 to 15% impervious cover. What implications might this apparent threshold have for watershed planning?

Should Low Density and High Density Development be Encouraged?

At first glance, it would seem appropriate to limit watershed development to no more than 10% total impervious cover. While this approach may be wise for an individual "sensitive" watershed, it is probably not practical as a uniform standard. Only low density development would be feasible under a ten percent zoning scenario, perhaps one acre lot residential zoning, with a few widely scattered commercial clusters. At the regional scale, development would be spread over a much wider geographic area than it would otherwise have been. At the same time, additional impervious area (in the form of roads) would be needed to link the community together.

Paradoxically, the best way to minimize the creation of additional impervious area at the regional scale is to concentrate it in high density clusters or centers. The corresponding impervious cover in these clusters is expected to be very high (25% to 100%), making it virtually impossible to maintain predevelopment stream quality. A watershed manager must then confront the fact that to save one stream's quality it may be necessary to degrade another.

A second troubling implication of the impervious/stream quality relationships involves the large expanses of urban areas that have already been densely developed. Will it be possible to fully restore stream quality in watersheds with high impervious cover? Some early watershed restoration work does suggests that biological diversity in urban streams can be partially restored, but only after extensive stormwater retrofit and habitat structures are installed. For example, fish and macroinvertebrate diversity has been partially restored in one tributary of Sligo Creek, Maryland, (Galli, pers comm). In other urban watersheds, however, comprehensive watershed restoration may not be feasible, due to a lack of space, feasible sites, or funding.

A Proposed Scheme for Classifying Urban Stream Quality Potential

The thresholds provide a reasonable foundation to classify the potential stream quality in a watershed, based on the ultimate amount of impervious cover. One such scheme is outlined in Table 3. It divides urban streams into three management categories based on the general relationships between impervious cover and stream quality:

1. Stressed Streams: (1 to 10% Impervious cover)
2. Impacted Streams:(11 to 25% Impervious cover)
3. Degraded Streams:(26 to 100% Impervious cover)

The resource objective and management strategies in each stream category differ to reflect the potential stream quality that can be achieved. The most protective category are "Stressed Streams" in which strict zoning, site impervious restrictions, stream buffers and best management practices are applied to maintain predevelopment stream quality. "Impacted Streams" are above the threshold, and can be expected to experience some degradation after development (i.e., less stable channels and some loss of diversity). The key resource objective for these streams is to mitigate these impacts to the greatest extent possible, using effective best management practices.

The last category of "Degraded Streams" recognizes that predevelopment channel stability and biodiversity cannot be fully maintained, even when best management practices or retrofits are fully applied. The primary resource objective in degraded streams shifts to protect downstream water quality by removing urban pollutants. Efforts to protect or restore biologically diversity in degraded streams are not abandoned; in some priority subwatersheds intensive stream restoration techniques are employed to attempt to partially restore some aspects of stream quality. In other subwatersheds, however, new development (and impervious cover) is encouraged to take place (so as to protect stressed and impacted streams).

Watershed-based Zoning

Watershed-based zoning is based on the premise that impervious cover is a superior measure to gauge the impacts of growth, compared to population density, dwelling units or other factors. The key steps in watershed-based zoning are as follows. *First*, a community undertakes a comprehensive physical, chemical and biological monitoring program to asses the current quality of its entire inventory of streams. The data is used to identify the most sensitive stream systems, and to refine impervious/stream quality relationships. *Next*, existing imperviousness is measured and mapped at the subwatershed level. Projections of future impervious cover due to forecasted growth are also made at this time.

The *third* step involves designating the future stream quality for each subwatershed based on some adaptation of the urban stream classification scheme presented earlier. The existing land use master plan for is then modified to ensure that future growth (and impervious cover) is consistent with the designated stream classification for each subwatershed.

The *final* step in the watershed-based zoning process involves the adoption of specific resource objectives for each stream and subwatershed. Specific polices and practices on impervious cover limits, best management practices, and buffers are then instituted to meet the stream resource objective, that are to be directly applied to future development projects.

Watershed-based zoning should provide managers with greater confidence that resource protection objectives can be met in the face of future development. It also forces local governments to make hard choices about which streams will be fully protected, and those that will become at least partially degraded. Some environmentalists and regulators will be justifiably concerned about the streams whose quality is explicitly sacrificed under this scheme. The explicit stream quality decisions which are at the heart of watershed-based zoning, however, are preferable to the uninformed and random "non-decisions" that are made every day under the present zoning system.

A Cautionary Note

While the research on the links between impervious cover and stream quality are compelling, it is doubtful whether it can serve as the sole foundation for legally defensible zoning and regulatory actions at the current time. One key reason is that the research has not been standardized. Different investigators, for example, have used different methods to define and measure imperviousness. Second, researchers have employed a wide number of techniques to measure stream quality characteristics that are not always comparable to each other. Third, most of the studies have been confined to few ecoregions in the country. Little research has been conducted in the Northeast, Southeast, and Midwest and semi-arid regions of the West. Lastly, none of the studies has yet examined the effect of widespread application of best management practices on impervious cover/stream quality relationships. Until a controlled study is undertaken to determine how much BMPs can "cheat" the impervious cover/stream quality relationship, it can be argued that structural practices alone can compensate for the effects of imperviousness.

On the positive side, it may be possible for a community to define the impervious cover/stream quality relationship in a short time frame at relatively low cost. A suggested protocol for conducting a watershed monitoring study is presented in Table 4. The protocol emphasizes comparative sampling of a large population of urban subwatersheds of different increments of imperviousness (perhaps 20 to 50).

A rapid sampling program collects consistent data on hydrologic, morphologic, water quality, habitat and biodiversity variables within each subwatershed. For comparison purposes, series of undeveloped and undisturbed reference streams is also monitored. The sampling data is then statistically and graphically analyzed to determine the presence of imperviousness/stream quality relationships.

The protocol can be readily adapted to examine the impacts of best management practices in shifting the stream quality/impervious relationship. This is done by adjusting the sampling protocol to select two groups of study subwatersheds--those that are effectively served by best management practices and those that are not.

Minimizing Impervious Cover at the Site

Reducing impervious cover can be an effective element of the overall BMP system for a development site. As noted earlier, imperviousness need not be a fixed quantity. A site designer can utilize a wide range of techniques to minimize impervious cover at development site that collectively can reduce imperviousness by 10 to 50% (See Technical Notes 38 and 39 in this issue).

CONCLUSION

Research has revealed that imperviousness is a powerful and important indicator of future stream quality, and that significant degradation occurs ar relatively low levels of development. The strong relationship between imperviousness and stream quality presents a serious challenge for urban watershed managers. It underscores the difficulty in maintaining urban stream quality in the face of development.

At the same time, imperviousness represents a common currency that can be measured and managed by planners, engineers and landscape architects alike. It links the activities the individual development site with its cumulative impact at the watershed scale. With further research, impervious cover can serve as an important foundation for more effective land use planning decisions.

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