Is Impervious Cover Still Important? Review of Recent Research

Thomas R. Schueler[1]; Lisa Fraley-McNeal[2]; and Karen Cappiella[3]

Abstract: The impervious cover model (ICM) has attracted considerable attention in recent years, with nearly 250 research studies testing its basic hypothesis that the behavior of urban stream indicators can be predicted on the basis of the percent impervious cover in their contributing subwatershed. The writers conducted a meta-analysis of 65 new research studies that bear on the ICM to determine the degree to which they met the assumptions of the ICM and supported or did not support its primary predictions. Results show that the majority of research published since 2003 has confirmed or reinforced the basic premise of the ICM, but has also revealed important caveats and limitations to its application. A reformulated conceptual impervious cover model is presented in this paper that is strengthened to reflect the most recent science and simplify it for watershed managers and policy makers. A future challenge is to test the hypothesis that widespread application of multiple management practices at the catchment level can improve the urban stream degradation gradient that has been repeatedly observed by researchers across the country.

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Introduction

Impervious cover (IC) has unique properties as a watershed metric in that it can be measured, tracked, forecasted, managed, priced, regulated, mitigated, and, in some cases, even traded. In addition, IC is a common currency that is understood and applied by watershed planners, storm-water engineers, water quality regulators, economists, and stream ecologists alike. IC can be accurately measured using either remote sensing or aerial photography (Goetz et al. 2003; Jantz et al. 2005). IC is also strongly correlated with individual land use and zoning categories (Cappiella and Brown 2001; Slonecker and Tilley 2004), which allows planners to reliably forecast how it changes over time in response to future development. Consequently, watershed planners rely on IC (and other metrics) to predict changes in stream health as a consequence of future development (CWP 1998).

Schueler (2004) has utilized IC to classify and manage urban streams, and economists routinely use IC to set rates for storm-water utilities and off-site mitigation (Parikh et al. 2005). Engineers utilize IC as a key input variable to predict future downstream hydrology and design storm-water management practices (MSSC 2005). A number of localities have modified their zoning to establish site-based or watershed-based IC caps to protect streams or drinking water supplies. In recent years, IC has been used as a surrogate measure to ensure compliance with water quality standards in impaired urban waters (Bellucci 2007).

Another noteworthy aspect of IC has been its use as an index of the rapid growth in land development or sprawl at the watershed, regional, and national scale. For example, Jantz et al. (2005) found that IC increased at a rate five times faster than population growth between 1990 and 2000 in the Chesapeake Bay watershed. At a national level, several recent estimates of IC creation underscore the dramatic changes in many of our nation's watersheds as a result of recent or future growth. Elvidge et al. (2004) estimated that about 112,665 km^2 (43,500 mi^2) of IC had been created in the lower 48 states as of 2000. Forecasts by Beach (2002) indicate that IC may nearly double by the year 2025 to about 213,837 km^2 (82,563 mi^2), given current development trends. Although care must be taken when extrapolating from national estimates, it is clear that several hundred thousand stream miles are potentially at risk. For example, a detailed GIS analysis by Exum et al. (2006) indicates that 14% of the total watershed area in eight southeastern states had exceeded 5% IC as of 2000.

Given growth in IC, watershed managers are keenly interested in the relationship between subwatershed IC and various indicators of stream quality. The impervious cover model (ICM) was first proposed by Schueler (1994) as a management tool to diagnose the severity of future stream problems in urban subwatersheds. The ICM projects that hydrological, habitat, water quality, and biotic indicators of stream health decline at around 10% total IC in small (i.e., 5 to 50 km^2) subwatersheds (CWP 2003). The ICM defines four categories of urban streams based on how much IC exists in their contributing subwatershed: *sensitive, impacted, nonsupporting,* and *urban drainage* (Schueler 1994) (Fig. 1). The ICM also outlines specific quantitative or narrative predictions for stream indicators within each stream category to define the severity of current stream impacts and the prospects for their future restoration (Schueler 2004).

The general predictions of the ICM are as follows: streams with less than 10% subwatershed IC continue to function as *sensitive streams*, and are generally able to retain their hydrologic

[1]Coordinator, Chesapeake Stormwater Network, 117 Ingleside Ave., Baltimore, MD 21228. E-mail: watershedguy@hotmail.com

[2]Research Assistant, Center for Watershed Protection, 8390 Main St., Second Fl., Ellicott City, MD 21043. E-mail: lfm@cwp.org

[3]Director of Research, Center for Watershed Protection, 8390 Main St., Second Fl., Ellicott City, MD 21043. E-mail: kc@cwp.org

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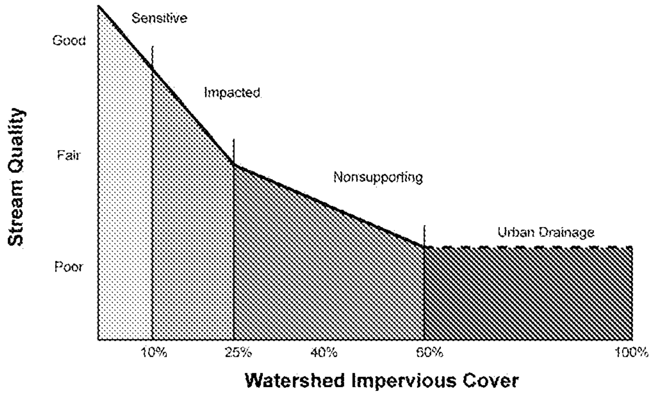

Fig. 1. Impervious cover model [adapted from CWP (1998)]

function and support good to excellent aquatic diversity. Streams with 10 to 25% subwatershed IC behave as *impacted streams* and show clear signs of declining stream health. Most stream health indicators fall in the fair range, although some reaches with extensive riparian cover may score higher. Streams that possess between 25 and 60% subwatershed IC are classified as *nonsupporting*, as they no longer support their designated uses in terms of hydrology, channel stability, habitat, water quality, or biological diversity. Nonsupporting streams become so degraded that it may be difficult or impossible to fully recover predevelopment stream function and diversity. Streams within subwatersheds exceeding 60% IC are often so extensively modified that they merely function as a conduit for flood waters. These streams are classified as *urban drainage* and consistently have poor water quality, highly unstable channels, and very poor habitat and biodiversity scores. In many cases, these urban streams are eliminated altogether by earthworks and/or storm drain enclosure.

The ICM has been extensively tested in ecoregions around the U.S. and elsewhere with more than 250 different reports reinforcing the basic model for single stream indicators or groups of stream indicators (CWP 2003; Schueler 2004). It should be noted, however, that only a third of these reports were published in peer-reviewed journals. For the purposes of this paper, we reviewed new research efforts that have further explored the ICM relationship. The methods used to conduct this review are described in the following section.

Methods

The writers conducted a meta-analysis of 65 new research studies that bear on the ICM and were not included in the papers and reports originally analyzed by CWP (2003). Each paper was reviewed to determine the number of streams, average drainage area, range in urbanization of study subwatersheds, and the receiving water indicator(s) sampled. A database was created to compile this information and four criteria were used to determine whether a paper was suitable for inclusion. First, a minimum of 10 individual subwatersheds must have been sampled. Second, riverine studies that sampled several stations in a progressive downstream direction in the same watershed were omitted. Third, only studies that directly measured impervious cover or an autocorrelated metric, such as % urban land or an urban intensity index (Meador et al. 2005), were included in the database. Fourth, the study must have been published in a peer-reviewed, reliable source, such as a scientific journal article or federal report.

Based on these criteria, 30 studies were excluded from the analysis, which yielded a total of 35 papers: 25 from peer-reviewed journals, four from the U.S. Geological Survey, five from peer-reviewed conference proceedings, and one from a state research institute. When researchers sampled multiple indicators, these were considered as separate entries only if they measured more than one major indicator group (e.g., water quality, biological diversity, geomorphology, hydrology, habitat). Multiple measures within the same indicator group were considered a single entry (i.e., sediment, nitrogen, and chloride within the water quality group). As a result, the final ICM database contained 61 individual entries. The complete database is maintained by CWP and is available upon request.

Each paper was then evaluated to determine the degree to which it met the assumptions of the ICM and supported or did not support its primary predictions, resulting in entries being sorted into four categories:

1. *Confirming papers* met the following criteria:
   a. Primarily sampled small subwatersheds (5 to 50 km^2);
   b. Directly estimated impervious cover;
   c. Tested subwatersheds over a broad range of IC;
   d. Reported a strong linear negative relationship for the indicator with increasing IC; and
   e. Showed an initial detectable shift in indicator quality in the 5 to 15% IC range.
2. *Reinforcing papers* either did not meet criteria 1a and 1c described above OR relied on percent urban land or an urban index in lieu of IC. These studies demonstrated a strong linear negative relationship between the indicator and the metric used to describe urbanization.
3. *Inconclusive papers* were defined as studies that met most of criteria 1a though 1c described for confirming papers but reported a mixed, weak, or inconsistent relationship between indicator quality and the metric used to describe urbanization.
4. *Contradicting* papers met most of criteria 1a through 1c described for confirming papers but did not show a negative or detectable relationship between urbanization and the indicator category analyzed.

General Findings from the Database

The geographic scope and intensity of recent research related to the ICM model has been impressive. Sampling has been conducted in more than 2,500 subwatersheds located in 25 states for more than 35 different indicators of environmental quality. Most studies focused on various indicators of freshwater stream quality (75%), but an increasing number explored the ICM relationship in tidal waters (25%). The majority of research has been conducted on the East Coast, with a strong emphasis on the piedmont and coastal plain regions. Much less attention has been focused along the Northern Tier, Rocky Mountains, and arid Southwest, although the Pacific Northwest was well represented.

Three additional factors complicated the comparison of individual studies. First, researchers relied on many different metrics to characterize urbanization including IC, % urban land, % developed land, and an urban intensity index, among others. Although most of these metrics are autocorrelated, some are less accurate or more variable than others (e.g., % urban land or developed land). Second, researchers applied a wide range of different statistical methods and transformations to analyze their watershed data. While it is outside the scope of this paper to critically evaluate

Table 1. Overall Summary of Recent ICM Research Included in ICM Database[a]

Confirming	Reinforcing	Inconclusive	Contradicting	Total
19	23	9	10	61

[a]For definitions, see "Methods" section.

these methods, we acknowledge that this may have caused researchers to draw different statistical inferences from the same data. Third, the geographic scale at which subwatersheds were sampled varied greatly. While most studies conformed to headwater ICM assumptions (e.g., subwatershed area ranging from 5 to 50 km^2), several regional studies had a mean subwatershed area as large as 75 to 150 km^2, which lies beyond the predictive power of the ICM (CWP 2003). An overall summary of the ICM research is provided in Table 1, and more specific results for individual indicators in freshwater and tidal ecosystems are provided in Tables 2 and 3.

The following general findings were drawn from the ICM research review, with the caveat that they may not fully apply to every ecoregion or watershed condition. Nearly 69% (this number was not tested for statistical significance due to the limited number of studies in the database) of studies confirm or reinforce the ICM, which suggests it is a robust indicator of stream quality when applied properly. On the other hand, IC does not appear to be the best metric to predict stream quality indicators below 10% subwatershed IC. Other metrics, such as subwatershed forest cover, riparian forest cover, road density, or crop cover may be more useful in explaining the variability within sensitive subwatersheds.

The average IC at which stream degradation was first detected was about 7% (range of 2–15%), depending on the indicator and ecoregion. There appears to be some evidence that lower IC thresholds are associated with extensive predevelopment forest or natural vegetative cover present in the subwatershed (Ourso and Frenzel 2003). By contrast, higher initial thresholds appear to be associated with extensive prior cultivation or range management in a subwatershed or region (Cuffney et al. 2005). Researchers who evaluated a second threshold concluded that many stream indicators consistently shifted to a poor condition at about 20 to 25% subwatershed IC. Each study was reviewed to identify the maximum subwatershed IC that was sampled. However, many of the studies focused on suburban or urbanizing subwatersheds, and did not sample the full range of possible IC within the study area.

Table 2. Distribution of Database Entries with regard to Freshwater Streams

Indicator	Total	Confirming	Reinforcing	Inconclusive	Contradicting
Hydrology[a]	4	0	0	1 (Poff et al. 2006)	3 (Coles et al. 2004; Fitzpatrick et al. 2005; Sprague et al. 2006)
Geomorphology	3	2 (Cianfrani et al. 2006; Coleman et al. 2005)	0	1 (Short et al. 2005)	0
Habitat	6	2 (Ourso et al. 2003; Schiff and Benoit 2007)	1 (Snyder et al. 2003)	0	3 (Coles et al. 2004; Fitzpatrick et al. 2005; Sprague et al. 2006)
Water quality[b]	6	3 (Ourso et al. 2003; Schiff and Benoit 2007; Schoonover and Lockaby 2006)	0	2 (Coles et al. 2004; Sprague et al. 2007)	1 (Sprague et al. 2006)
Benthic macros	10	4 (Alberti et al. 2006; Ourso et al. 2003; Schiff and Benoit 2007; Walsh 2004)	5 (Coles et al. 2004; Cuffney et al.2005; Kratzer et al. 2006; Walsh et al.2001; Moore and Palmer 2005)	0	1 (Sprague et al. 2006)
Fish	9	0	7 (Fitzpatrick et al. 2005; Meador et al.2005; Miltner et al. 2004; Moore and Plamer 2005; Roy et al.2006a,b; Snyder et al. 2003)	1 (Coles et al. 2004)	1 (Sprague et al. 2006)
Composite[c]	1	1 (Goetz et al. 2003)	0	0	0
Other[d]	5	1 (Ourso and Frenzel 2003)	1 (Riley et al. 2005)	2 (Coles et al. 2004; Potapova et al. 2005)	1 (Sprague et al. 2006)

Note: $n=44$.

[a]Primarily baseflow.

[b]Primarily water quality parameters sampled during dry weather; no studies evaluated storm-flow quality.

[c]Combined index measuring habitat, benthic macroinvertebrates, and fish.

[d]Other includes sediment quality, algae, and amphibian abundance.

Table 3. Distribution of Database Entries with regard to Small Estuaries

Indicator	Total	Confirming	Reinforcing	Inconclusive	Contradicting
Water quality[a]	4	1 (Holland et al. 2004)	2 (Deacon et al. 2005; Xian et al. 2007)	1 (King et al. 2005)	0
Sediment quality	3	1 (Holland et al. 2004)	1 (Paul et al. 2002)	1 (Comeleo et al. 1996)	0
Benthic macros	5	1 (Holland et al. 2004)	4 (Bilkovic et al. 2006; Deacon et al. 2005; Hale et al. 2004; King et al. 2005)	0	0
Fish	3	1 (Holland et al. 2004)	2 (Hale et al. 2004; King et al. 2004)	0	0
Other[b]	2	2 (Holland et al. 2004)[c]	0	0	0

Note: $n=17$.

[a]Ambient water quality usually measured in dry weather.

[b]Other includes hydrology and shrimp.

[c]Both confirming entries were for the reference Holland et al. (2004); one was for hydrology and the other for shrimp.

Further testing is required to identify the IC% at which natural stream channels disappear from the urban landscape and are replaced by pipes, channels, and other forms of storm-water infrastructure.

Three papers accounted for the majority of contradicting entries (Sprague et al. 2006; Fitzpatrick et al. 2005; Coles et al. 2004). It should be noted that each study had a mean subwatershed drainage area ranging from 75 to 100 km^2. In each case, the authors also cited a "legacy effect," including historical stream corridor disturbance and current water regulation in the front range watersheds; dams, impoundments, and wetland complexes in the New Hampshire seacoast region; and watershed and soil effects of glaciation on midwest watersheds.

Few studies examined hydrological indicators, and the results were generally contradicting or ambiguous (Table 2). In particular, the inverse relationship between subwatershed IC and stream baseflow was not found to be universal, as nontarget irrigation and leakage from existing water infrastructure appeared to increase baseflow in many urban watersheds, regardless of IC. None of the studies reviewed directly measured the relationship between IC and increased storm-water runoff, although a recent review by Shuster et al. (2005) provides numerous case studies where this relationship was very strong. Researchers that have relied on existing USGS hydrologic gages are often hindered by the generally large subwatershed areas they serve [mean 90 km^2—Poff et al. (2006)].

In general, researchers found the ICM to be an initial but not final predictor of individual stream geomorphology variables, when drainage area and stream slope were properly controlled for [Table 2 and Cianfrani et al. (2006)]. IC was frequently found to be related to aggregate measures of stream habitat, although in-stream and riparian habitat components may behave differently within the same stream reach. Most habitat metrics were initially sensitive to IC in the 5 to 20% range but exhibited a nonlinear habitat response thereafter (which suggests that habitat metrics may not be well calibrated for highly urban streams).

Researchers also reported inconsistent relationships between IC and dry weather water quality. While differences between urban and nonurban sites were frequently noted, there was seldom a linear trend with increasing subwatershed IC. The relationship between IC and storm-water quality would be expected to be strong, but no researchers in this review had simultaneously sampled a large population of storms and subwatersheds. A national review of nearly 8,000 urban storm events compiled by Pitt et al. (2004) indicates event mean concentrations of 20 storm-water pollutants statistically were more closely related to urban land use and regional and first flush effects than impervious cover per se. One study of various pollutants in the Tampa Bay watershed found that the load of storm-water pollutants delivered, however, is still strongly dominated by subwatershed IC (Xian et al. 2007).

Benthic macroinvertebrates appeared to conform to the ICM more than any other stream indicator (Table 2). More than 90% of the studies directly supported or generally reinforced the ICM. Researchers generally found a strong negative relationship between fish IBI scores and subwatershed IC, but there were also confounding effects due to differences in stream slope, type, or subwatershed size (Walters et al. 2003; Wang et al. 2003) or the degree of prior headwater stream alteration (Morgan and Cushman 2005).

Several researchers have recently examined whether the ICM applies to tidal coves and small estuaries (see Table 3). Holland et al. (2004) indicate that adverse changes in physical, sediment, and water quality variables can be detected at 10 to 20% subwatershed IC, with stronger biological responses observed between 20 and 30% IC. The primary physical changes involve greater salinity fluctuations, sedimentation, and sediment contamination. The biological response includes declines in benthic macroinvertebrates, shrimp, and finfish diversity. Although none of the studies in the database examined algal blooms as an indicator in tidal coves and small estuaries, a study by Mallin et al. (2004) found that algal blooms and anoxia resulting from nutrient enrichment by storm-water runoff also are routinely noted at about 10 to 20% subwatershed IC.

Approximately 25% of the papers reviewed explored the effect of riparian conditions on the ICM. The studies that evaluated this relationship showed a consistent riparian effect, generally manifested as (1) a decline in the quality and extent of cover in the riparian network as subwatershed IC increases; (2) little or no statistical difference in the proportion of forest cover found in the riparian zone and the subwatershed as a whole; and (3) generally higher habitat and biological scores for streams with extensive riparian cover or palustrine wetland complexes. Riparian forest cover appears to be an important factor in maintaining stream geomorphology and various indexes of biotic integrity. As a group, the studies suggest that stream indicator values increase when riparian forest cover is retained over at least 50 to 75% of the length of the upstream network (Moore and Palmer 2005; Goetz et al. 2003; Wang et al. 2003).

The beneficial impact of riparian forest cover appears to diminish as subwatershed IC increases (Roy et al. 2005, 2006a; Walsh et al. 2007; Goetz et al. 2003). At a certain point [15% urban land as identified by Roy et al. (2006a) or 10% IC as identified by Goetz et al. (2003)], the degradation caused by upland storm-water runoff shortcutting the buffer overwhelms the more localized benefits of riparian canopy cover. A study by McBride and Booth (2005) was not included in the database, but found that downstream improvements in some stream quality indicators may still be observed when an unforested stream segment flows into a long segment of extensive riparian forest or wetland cover.

The issue as to whether watershed treatment (i.e., storm-water treatment practices, buffers, land conservation) can prevent the stream impacts forecasted by the ICM is largely unresolved. The recent literature is largely silent on this topic, with the exception of the riparian buffer research noted earlier. It is worth noting that most regions where the ICM has been tested have had some degree of storm water, buffer, or land development regulations in place for several decades (e.g., MD, VA, NC, WA, GA), although the extent or effectiveness of watershed treatment has seldom been measured and is often incomplete.

Discussion: Reformulated ICM

While this review has found that 69% of peer-reviewed papers generally support or reinforce the original ICM, it has also revealed ways the ICM can be strengthened to reflect the most recent science and simplify it for watershed managers and policy makers. A reformulated version of the ICM is presented in Fig. 2. Fig. 2 is a conceptual model that illustrates the relationship between watershed impervious cover and the stream hydrologic, physical, chemical, and biological responses to this disturbance. The model is intended to predict the average behavior of this group of indicator responses over a range of IC, rather than predicting the precise score of an individual indicator. Based on the response, streams fall into the sensitive, impacted, nonsupporting, or urban drainage management categories, whose boundaries represent a compilation of different approaches to interpret stream condition (e.g., research studies that evaluate the same stream quality indicator may have similar quantitative outcomes that represent different qualitative conditions depending on the approach used).

The reformulated ICM includes three important changes to the original conceptual model proposed by Schueler (1994). First, the IC/stream quality relationship is no longer expressed as a straight line, but rather as a "cone" that is widest at lower levels of IC and progressively narrows at higher IC. The cone represents the observed variability in the response of stream indicators to urban disturbance and also the typical range in expected improvement that could be attributed to subwatershed treatment. In addition, the use of a cone rather than a line is consistent with the findings that exact, sharply defined IC thresholds are rare, and that most

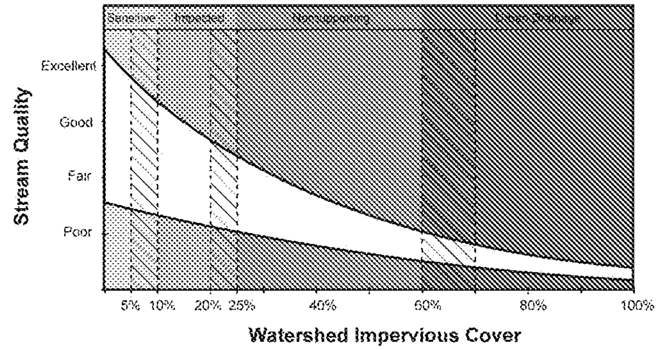

Fig. 2. Reformulated impervious cover model

regions show a generally continuous but variable gradient of stream degradation as IC increases.

Second, the cone width is greatest for IC values less than 10%, which reflects the wide variability in stream indicator scores observed for this range of streams. This modification prevents the misperception that streams with low subwatershed IC will automatically possess good or excellent quality. As noted earlier, the expected quality of streams in this range of IC is generally influenced more by other watershed metrics such as forest cover, road density, riparian continuity, and cropping practices. This modification suggests that IC should not be the sole metric used to predict stream quality when subwatershed IC is very low.

Third, the reformulated ICM now expresses the transition between stream quality classifications as a band rather than a fixed line (e.g., 5 to 10% IC for the transition from sensitive to impacted, 20 to 25% IC for the transition from impacted to nonsupporting, and 60 to 70% IC for the transition from nonsupporting to urban drainage). The band reflects the variability in the relationship between stream hydrologic, physical, chemical, and biological responses and the qualitative endpoints that determine stream quality classifications. It also suggests a watershed manager's choice for a specific threshold value to discriminate among stream categories should be based on actual monitoring data for their ecoregion, the stream indicators of greatest concern and the predominant predevelopment regional land cover (e.g., crops or forest).

The ICM is similar to other models that describe ecological response to stressors from urbanization in that the stream quality classifications are value judgments relative to some endpoint defined by society (e.g., water quality criteria). The ICM differs from most other models in that it provides a broader focus on a group of stream responses, yet focuses on only one stressor, impervious cover. The focus on IC allows watershed managers to use the ICM both to predict stream response and to manage future impacts by measuring and managing IC.

This review also has identified several important caveats to keep in mind to properly apply and interpret the ICM in a watershed context. The first caveat is that watershed scale matters, and that use of the ICM should generally be restricted to first to third order alluvial streams. The second caveat is that the ICM may not work well in subwatersheds with major point sources of pollutant discharge, or extensive impoundments or dams located within the stream network. The third caveat is that the ICM is best applied to subwatersheds located within the same physiographic region. In particular, stream slope, as measured from the top to the bottom of the subwatershed, should be in the same general range for all subwatersheds (Morgan and Cushman 2005; Snyder et al. 2003; Fitzpatrick et al. 2005). The last caveat is that the ICM is unreliable when subwatershed management practices are poor, particularly when IC levels are low (e.g., deforestation, acid mine drainage, intensive row crops, denudation of riparian cover). When these caveats are applied, the available science generally reinforces the validity of the ICM as a watershed planning tool to forecast the general response of freshwater and tidal streams as a result of future land development.

Conclusions

The reformulated ICM organizes and simplifies a great deal of complex stream science into a model that can be readily understood by watershed planners, storm-water engineers, water quality regulators, economists, and policy makers. More information is needed to extend the ICM as a method to classify and manage small urban watersheds and organize the optimum combination of best management practices to protect or restore streams within each subwatershed classification.

The challenge for scientists and watershed managers is no longer proving the hypothesis that increasing levels of land development will degrade stream quality along a reasonably predictable gradient—the majority of studies now support the ICM. Rather, researchers may shift to testing a hypothesis that widespread application of multiple management practices at the catchment level can improve the urban stream degradation gradient that has been repeatedly observed. The urgency for testing the catchment effect of implementing best management practices is underscored by the rapid and inexorable growth in IC across the country.

Appendix

The following references, Alberti et al. (2006), Bilkovic et al. (2006), Cianfrani et al. (2006), Coleman et al. (2005), Coles et al. (2004), Comelo et al. (1996), Cuffney et al. (2005), Deacon et al. (2005), Fitzpatrick et al. (2005), Goetz et al. (2003), Hale et al. (2004), Holland et al. (2004), King et al. (2004, 2005), Kratzer et al. (2006), Meador et al. (2005), Miltner et al. (2004), Moore and Palmer (2005), Morgan and Cushman (2005), Ourso and Frenzel (2003), Paul et al. (2002), Poff et al. (2006), Potapova et al. (2005), Riley et al. (2005), Roy et al. (2006a,b), Schiff and Benoit (2007), Schoonover et al. (2006), Short et al. (2005), Snyder et al. (2003), Sprague et al. (2006, 2007), Walsh (2004), Walsh et al. (2001), and Xian et al. (2007), denote research papers that were included in the ICM database. A list of additional papers that were reviewed, but did not meet the criteria for inclusion in the ICM database, is available upon request from the Center for Watershed Protection.

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