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Watershed-scale effects of urbanization on sediment export: Assessment and policy

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[1] Built components of watersheds are associated with impervious surfaces that alter hydrology, disrupt ecosystems, and affect water quality. This study focuses on the impervious factor as a tool for assessment and policy design to address water quality impacts. The empirical model uses a combination of watershed simulation and statistical regression modeling to study sediment loading at various stages of urbanization. The policy design is based on private behavior in a watershed setting to develop appropriate economic approaches. The incentives through taxes, subsidies, and cost sharing are based on water quality impacts. It was observed that nonlinearity in response functions resulted in transition effects that are continuous. This is due to gradual shifts in landscape characteristics as a result of urbanization. On a regional basis, impervious factor had a varying effect on water quality and depend on the state of urbanization and spatial characteristics. Economic policies based on a metric like impervious cover can be used to mitigate the negative effects of urbanization in watersheds through use of appropriate BMPs, urban forestry methods, and spatial targeting. While linear rules in policy are easier to implement, nonlinear rules were more effective in representing the changes in marginal social cost of impervious factor, especially initial and late stages of urbanization. There exists excellent scope in using this targeted policy to address specific problems associated with complex urban systems. *INDEX TERMS*: 1815 Hydrology: Erosion and sedimentation; 1860 Hydrology: Runoff and streamflow; 1871 Hydrology: Surface water quality; 6399 Policy Sciences: General or miscellaneous; 6344 Policy Sciences: System operation and management; *KEYWORDS*: water quality, urbanization, impervious cover, watersheds, economic policies

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1. Introduction

[2] With an annual addition of 78 million persons to the current world population of 6 billion [United Nations (UN), 2000], impacts of urbanization on water resources is expected to increase. Thus the role of urban components in soil and water conservation is critical for developing sound water resources policies. While urban interactions are complex, a simple indicator of urbanization is useful for developing water quality policies that are easier to implement. Impervious factor is one such an indicator of urbanization in landscapes that has cumulative impacts on the hydrologic cycles and also has offsite effects on downstream water resources and ecosystems. (Impervious factor of a watershed is proportion of built components with zero infiltration rates. Terms imperviousness, impervious cover, and impervious factor are used interchangeably.) With recent emphasis on mitigating non point source pollution in the United States through development of total maximum daily load (TMDL) [United States Environmental Protection Agency (U.S. EPA), 1999] and changes in the NPDES (Phase II) permitting rules [U.S. EPA, 2000], the effect of built environments on water quality is an important aspect for watershed assessment and planning. Understanding the

role of impervious factor is important in addressing problems dealing with sediment loading in rivers and water bodies.

[3] Impervious factor and urban nonpoint source (NPS) pollution are two major characteristics of built environments that affect water quality and quantity [Horner *et al.*, 1997] and disrupt natural ecosystems [Lindsey *et al.*, 1997]. Other impacts of urbanization include loss of open space, fragmentation of landscape ecosystems, and reduction in biodiversity, increased storm water runoff, wetland loss, and increased flood damage. Developing alternative technologies, management techniques, and policy options to mitigate these impacts of urban development on water quality requires detailed information on watershed processes and their linkages to downstream effects. Sediment, both suspended and deposited, constitutes a major pollutant in waterways [Schueler, 2000]. Understanding the nature and implications of impervious cover on sediment loading in order to develop appropriate watershed conservation techniques and effective storm water policies is the focus of this study.

[4] While the spread and density of built environments in a watershed alter processes in a multidimensional and complex way, imperviousness factor is a useful tool for rapid assessment of water resources impacts. While complex models are required for complete and detailed assessments, imperviousness is a good initial indicator of

particular hydrologic impacts of land cover changes resulting from urbanization. For example, it could be used to study impacts of land development on infiltration and runoff hydrograph. It also provides an assessment method for rapid and low-cost assessment of the impact of landscape alterations on watershed health. Urban and rural watershed managers and policy makers can use such simpler information that relates imperviousness and water resources to address a variety of watershed issues.

[5] The primary goal of this paper is to study the relationship between the impervious factor and sediment export at a landscape scale in order to identify the nature of impacts at various stages of land development and to develop policy alternatives to mitigate these impacts. Specific objectives are (1) to assess the nature and distribution of impervious cover, (2) to quantify the relationship between imperviousness and sediment export at a watershed scale, and (3) to evaluate policy options to mitigate the negative effects of imperviousness. Alternate hypotheses (H_A) that are tested include the following: (1) percent impervious cover can be used to characterize the nature of watershed urbanization, (2) there exists a curvilinear relationship between impervious factor and sediment loading, and (3) economic policies can be designed to mitigate negative impacts. The first hypothesis tests the role of impervious factor as an indicator of watershed development and water quality. In the second hypothesis, we test a proposition that the relationship between impervious factor and sediment has nonlinearity that can explain both transition effects [Snodgrass *et al.*, 1997; Booth and Reinelt, 1993] and continuity [Maxted and Shaver, 1997; Horner *et al.*, 1997]. The third hypothesis is tested using three policy instruments and their applicability to watershed management. We use a combination of simulation and statistical methods to study the role of increasing watershed impervious cover on sediment loading at a landscape scale and to evaluate the curvilinear effects and policy options.

2. Background

[6] Polluted storm water runoff is a leading cause of impairment of nearly 40% of surveyed U.S. water bodies that do not meet water quality standards [U.S. EPA, 1996]. Urban runoff and storm sewer discharges in the U.S. affect 13% of impaired rivers, 21% of impaired lakes and 45% of impaired estuaries. Landscapes with higher proportion of built environments have increased peak flows and reduced time of concentration of runoff water. Contributions of contaminants from nonpoint sources may predominate during the high flows [Pope and Putnam, 1997]. In addition, water contamination and low recharge rates alter stream conditions, affecting fish and macro invertebrate communities. Other impacts include changes to terrestrial wildlife, habitats, recreational value, public health, and quality and quantity of downstream water resources.

[7] In assessing downstream impacts of built environments, impervious cover is widely used as an indicator of water resource degradation. This is because, imperviousness is a feasible, readily identifiable and cost-effective indicator of water pollution useful for decision-making by local communities in order to address the link between land use and water quality. It is also a good indicator of stream

quality and a potential management tool to prevent cumulative impacts at the subwatershed scale [Schueler and Clayton, 1997]. It is preferred over mass measurements in situations that need rapid response, and timely decision-making. Another major reason is that it is impossible to measure every parameter or possible variable because they are not always easily identifiable. Relationships between land use changes and urban density and receiving water characteristics provide one approach for describing and potentially quantifying the stress that watershed development has on surface water ecosystems [Snodgrass *et al.*, 1997].

[8] Effective impervious area (EIA) is the portion of the total impervious area (TIA) that is directly connected to a drainage system. EIA includes street surfaces, paved driveways connected to the street, sidewalks adjacent to curbed streets, rooftops which are hydraulically connected to the curb or storm sewer system and parking lots [Sutherland, 1995]. Estimated impervious area is usually less than TIA. In areas that are highly urbanized, EIA and TIA may become close to equal. Not all precipitation falling on impervious surfaced becomes runoff. Precipitation falling on impervious areas not connected to the drainage system will not always result in direct runoff. Areas that are not hydraulically connected to the drainage network should be subtracted from TIA to get the EIA because it is a more accurate estimation of runoff volumes. Direct measurement of EIA involves field-based measurement and can be more difficult to determine. The effectiveness of the hydraulic connection between each of the impervious area and the major collection systems need to be cataloged and evaluated for effective management decisions.

[9] A common approach used in studying the impact of urbanization on watershed is use of aquatic biological indexes like index of biotic integrity (IBI) [Karr, 1981; Karens and Karr, 1994; Horner *et al.*, 1997]. Biological assessment involves an integrated analysis of functional and structural components of aquatic communities [McCarron *et al.*, 1997]. These approaches provide a better assessment of overall water quality through toxicity and integrated effects on aquatic ecosystems. Evaluation of the resident aquatic communities provides a mechanism for conducting a holistic assessment [Barbour, 1997].

[10] Suspended sediment interferes with respiratory and feeding of stream invertebrates [Lemley, 1982] and fish communities [Gardner, 1981]. Sediment discharge is closely related to change in hydrograph flows resulting from urban development. Impacts on runoff volume are well documented by Sloto [1988] and Braud *et al.* [1999]. Sloto [1988] found that as impervious area increased from 9% to 15%, runoff volume increased from 9 to 18%, with an average increase of 14%. As impervious area increased to 20%, runoff volume increased 19 to 39% with an average increase of 30%. Peak discharge increased 16 to 43% with an average increase of 31%. At 25% impervious area the runoff volume went from 32% to 67% with an average increase of 52%. Peak discharge went from 26 to 80% with an avg. increase of 55% [Sloto, 1988]. Braud *et al.* [1999] used the ANSWERS model and found that rainfall and soil variability, mainly associated with a quasi-impervious area in the middle of the catchment, explained the rapid increases in streamflow. Wigmosta and Burges [1997] used an adap-

tive combination of modeling and measurements to elucidate the various components of flow production and flow paths in undeveloped and suburban areas. There are few studies on the impacts of impervious factor on sediment loading and their policy options. This study fills this gap by using a comprehensive approach to this issue through assessment and policy design to mitigate urban impacts on water resources.

3. Methodology

[11] The conceptual model is developed based on the water quality (sediment) function, represented in (1).

$$S = f(I(P)/E) \quad (1)$$

where S is the sediment loading in the watershed, $I(P)$ is the impervious factor in the watershed which is dependant upon policy P , and E represents all other factors influencing water quality. A policy instrument P is designed to minimize external cost of impervious factor through water quality impacts. Policy instruments that are considered are impervious tax, subsidies for effective impervious BMPs, and cost sharing incentives. These are designed using the following concepts.

3.1. Policy Design

[12] The land manager is assumed to maximize equation (2) in making land development decisions.

$$\text{Max}(B(I) - C^P(I) - C^S(I)) \quad (2)$$

Here $B(I)$ represents the benefits derived from impervious cover, $C^P(I)$ is the private abatement cost for impervious externalities, and $C^S(I)$ is the social cost of imperviousness. The manager selects optimal impervious abatement level by equating marginal benefits, $\partial B/\partial I$, with marginal private costs, $\partial C^P/\partial I$. If the manager incorporates the external damages, the optimal condition becomes $\partial B/\partial I = \partial C^P/\partial I + \partial C^S/\partial I$. The policy design question on how to achieve this internalization of social costs $\partial C^S/\partial I$. A tax policy needs to equate P to $\partial C^S/\partial I$. The subsidy design for BMPs should equate to $-P$ to compensate for internalizing $\partial C^S/\partial I$. The cost sharing design is to cost share part of the cost, α , such that $\alpha \partial C^S/\partial I + \beta \partial C^S/\partial I$, where $\beta = 1 - \alpha$.

[13] These basic sets of equations are used in development of the conceptual model presented in Figure 1. The analysis consists of three steps to evaluate urbanization impacts on water quality. The first step is to evaluate the extent of built components of the landscape using impervious cover as an indicator. Next, the hydrologic and sedimentation processes are evaluated using a continuous-time simulation model. The impacts of built components are evaluated using both linear and nonlinear statistical models. Finally, these response functions are used in development of economic policies to mitigate these impacts.

3.2. Impervious Cover Estimation (I)

[14] Impervious cover in land use/land cover was assessed using a stratified sampling approach. The sampling is stratified based on the distance to urban core and is designed to estimate site-specific impervious coefficients in each land use category in the study area. Using GIS (ESRI's

Figure 1. Conceptual model of impervious factor assessment and policy.

ArcView software), five random polygons in each land use category were sampled using a stratified random sample. Aerial photographs (digital orthophotos with 0.5 m resolution) and infrared imagery (color infrared photos, leaf-off) were used to map the impervious area in a representative subwatershed. The impervious areas were mapped by on-screen digitizing in GIS of all recognizable impervious surfaces including rooftops, streets and highways, sidewalks, parking lots and driveways. Impervious coefficient of each land use category was determined as a percent of total area in each land cover.

3.3. Simulation Model (S)

[15] The Soil and Water Assessment Tool (SWAT) explained by *Arnold and Allen* [1992] was used to simulate contaminant transport and water quality in the study watershed. SWAT is a continuous time step model capable of long-term simulations of basins of several thousand square miles. The model operates in a semi-distributive manner to account for spatial differences in land use, soil, crops, topography, channel morphology, and weather conditions. The SWAT model can be used to predict the effect of management practices and land use changes on water, sediment, nutrient and pesticide yields with reasonable accuracy on large, ungaged river basins [*Arnold et al.*, 1998]. Simulations include hydrology, pesticide, and nutrient cycling, erosion and sediment transport. One of this model's strengths is that it allows subdivision of a basin into several subbasins. Within the subbasins, further subdivisions can be made to account for differences in soils, land use, crops, topography, and weather. The model components consist of weather, surface runoff, return flow, percolation, ET, transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loading, and water transfer. The SWAT model was used to assess sediment loading and the variables in each subbasin in the Blackstone Watershed. A total of 80 subwatersheds were used in the simulation. The model was calibrated and validated using information on flows and sediment loading from selected EPA's STORET Data sets and local monitoring information.

3.4. Statistical Models (M)

[16] To determine the relationship between impervious cover and soil loss at a landscape scale, statistical models were used. The observations used in the statistical model constitute simulations in individual subwatersheds of the Blackstone River Watershed. Three types of functional forms were used: Linear, Logarithmic, and Polynomial functions. All the models assume continuity over various impervious percentages and transition changes were represented by higher nonlinearity in the response function.

Linear model

$$S = \beta_0 + \beta_1 I \quad (3)$$

Logarithmic model

$$S = \phi_0 \cdot \ln(I + \phi_1) + \phi_2 \quad (4)$$

Nth degree polynomial model

$$S = \sum_{i=0}^n \pi_i I^i \quad (5)$$

[17] The linear model (3) assumes a constant effect (β_1) of imperviousness on sediment loading. This is a common assumption used in previous studies [Schueler and Claytor, 1997] to assess stream impacts. A logarithmic model (4) assumes a higher marginal effect during initial stages of increasing imperviousness and decreases logarithmically on further increases in impervious factor. A polynomial model (5) captures the nonlinear relationship over a wider range of imperviousness by incorporating higher-order moments of the distribution. This form is useful to study nonlinear transition effects resulting from various stages of watershed development.

3.5. Study Area

[18] The Blackstone River Watershed (Figure 2) covers parts of both Massachusetts and Rhode Island states. This watershed is facing increasing urbanization that could have severe urban impacts on water resources. These impacts include sedimentation of water bodies. The watershed encompasses 24 communities and covers more than 350,000 acres. The terrain is characterized by gently rolling hills with higher altitudes toward the western parts of the watershed. Elevations range from almost 427 m above sea level near the city of Worcester to about 46 m at interstate border. The watershed includes urban areas like the city of Worcester and parts of Providence, old industrial villages, town centers, and suburban development.

[19] The river itself is approximately 48 miles long, stretching from the headwaters in Worcester, Massachusetts, to Narragansett Bay in Rhode Island. The Watershed encompasses approximately 1300 acres of lakes, ponds, and reservoirs. The Blackstone River continues to discharge pollutants (sediment, nutrients, metals, and organics) to the Narragansett Bay. The Blackstone River is a major tributary to the Narragansett Bay, and the most significant in terms of pollution loading to the Bay, which is Rhode Island's premier resource for saltwater fishing, shell fishing, tourism and recreation.

[20] The Blackstone River Watershed has a variable, temperate climate with an average annual temperature of 49 degrees Fahrenheit. The mean annual precipitation in the watershed is around 41 inches. Mean annual flow from the Blackstone River into the Narragansett Bay is estimated to range from 1.7 to 2.1 csm. Sediment in runoff is a serious problem affecting aquatic ecosystems and water bodies. A reconnaissance investigation conducted by the U.S. Army Corps of Engineers identified the continued sediment loading as a significant problem affecting the watershed. The study evaluated several reaches of the river and found water quality problems resulting from high levels of sediments, nutrients, metals, bacterial, and Low Dissolved Oxygen.

Overland sources of these contaminants included urban runoff, storm sewers, combined sewer overflows, and overland erosion. The streamflow at the sampling point had a mean value of 16.79 m³/s, and a variability of 12.83 (Standard deviation). Low flow was 1.13 m³/s and peak flow was 53.24 m³/s. The suspended sediment concentration had a mean of 10.42 mg/L, with a variability of 10.4 mg/L (standard deviation). The concentration values ranged from a low of 1 mg/L to a high of 40 mg/L.

3.6. Data

[21] The watershed data was compiled by aggregating state-level data from GIS data-repositories in three states: Massachusetts (MASSGIS), Rhode Island (RIGIS), and Connecticut (MAGIC). Because of different land use classifications followed in each state, data were recompiled to Massachusetts's classification because of two reasons: (1) Massachusetts had much detailed classification scheme and (2) the state covered majority of the watershed area. Other sources included EPA's BASINS model for a regional coverage.

4. Results and Discussion

[22] This section is presented in four stages. The results of the impervious assessment are discussed here followed by the results of the simulation. The third section presents the results of the statistical analysis, followed by the last section that deals with policy approaches based on using these results as a design criterion.

4.1. Impervious Assessment

[23] The distribution of percent impervious cover in the Blackstone River Watershed is presented in Figure 3. The mean impervious factor at a subwatershed scale is 7.1%. A total of 80 subwatersheds were used in the assessment. The impervious estimates in individual subwatersheds ranged from a low of 1% to a maximum value of 38% in the watershed. The maximum value corresponds to the Worcester Metropolitan area of Massachusetts, which is located in the headwaters of the Blackstone River. Urban areas of towns bordering the Worcester City had impervious cover ranging between 21–24%. Subbasins located in the middle section of the watershed are relatively less developed with low levels of impervious factor. Higher values were also observed in subwatersheds located on the eastern part of the watershed that is developed along the beltway (I-495) of the city of Boston. The large subbasin in the southeast contains parts of the city of Providence and suburbs. This subbasin has a direct effect on the water quality of Narragansett Bay. Majority of the sub watersheds (greater than 80%) had less than 10% impervious factor. This is important to watershed management because water quality degradation starts at relatively low level of imperviousness. Booth and Reinelt [1993] suggested that a transition for urban stream stability exists at about 10% imperviousness in a watershed- watershed development beyond this transition consistently resulted in unstable and eroding channels. Similar transition at lower imperviousness was observed by Klein [1979], Horner et al. [1997], and May et al. [1997].

4.2. Sediment Loading

[24] The spatial distribution of the rates in sediment loading is presented in Figure 4. The mean sediment loading

Figure 2. Blackstone River watershed.

in the watershed was estimated at 2.18 tons/ha. There existed a large variation in sediment loading rates, ranging from 0.17 to 21.78 tons/ha among various hydrologic units. Sediment loading into overland runoff is through various

rural and urban nonpoint sources through their effect on the rate of soil erosion and sedimentation. Rural land use activities in the watershed include cropland, pasture, and forest land, that impact sediment loading through tillage and

Figure 3. Distribution of imperviousness in Blackstone River watershed.

management operations. Urban sources include residential and industrial uses, commercial and industrial operations, and transportation infrastructure. Urban impacts to sediment loading are through imperviousness and landscaping activities. Imperviousness increases storm flow by two to 16 times than its predevelopment rate [Schueler, 1994]. These higher flow events are capable of performing more “effective work” in moving sediment than they had done before [Wolman, 1954]. The sediment loadings were high in

suburbanized subbasins in the headwaters of Blackstone river watershed, especially subbasin in the eastern section of Grafton and subbasin on the western section of the city of Worcester.

[25] The Sediments in the watershed are especially high in the subbasins covering the towns of Sutton, Douglas, in spite of low impervious factor that range from 3 to 6%. This emphasizes the results in previous literature that sediment loading occurs at very low impervious levels. The subbasin

Figure 4. Distribution of sediment loading in the Blackstone watershed.

containing parts of the city of Worcester had elevated sediment concentrations. This might be due to higher runoff rates resulting from shifts (magnitude and intensity) in hydrograph of urban areas.

[26] There existed a clear clustering of high sediment loading in headwater subwatersheds and in those closer to the outlet. While some of these are associated with higher impervious percent, subwatersheds with less than 10%

imperviousness accounted for 76% of the total sediment loading in the Blackstone River Watershed.

4.3. Impervious-Sediment Relationship

[27] The distribution of sediment loading responses at various levels of impervious factor (scatterplot) is presented in Figure 5. Majority of the observations were clustered within the 15% levels of impervious cover. A general

Figure 5. Sediment loading frontiers at varying impervious levels.

observation was that as impervious cover increased, higher variance in sediment loading between observations at each impervious level was observed (divergence). This is evident from the expansion in the variability range in Figure 5. For areas with less than 10% impervious factor, the variance in loading rates was less among observations. Within this range, more observations were rural subbasins with clustering in sedimentation rates. In a range of 11 to 25 impervious percent levels, the variance in sediment loading rates was restricted to a band of constant width and is even in spread, with less clustering. At impervious levels that ranged above 25%, the variance in sediment loading was higher within a particular level of impervious factor. Observations in this range are associated with subbasins in larger cities or urban centers.

[28] The disparity is further studied using upper and lower envelopes of the distribution (Figure 5). The upper envelope that encompassed all the observations is considered a suboptimal frontier because of relatively higher loading rates compared to similar subbasins at the same level of impervious factor. Out of the 80 subbasins in the watersheds, approximately 10 subbasins were suboptimal in handling sediment loading. The lower envelop of the observations, where lower sediment rates were assessed for same level of impervious cover, can be categorized as on an efficiency frontier. Observations on this frontier represent best approaches to handling sediment loading at those impervious levels. This advantage in sediment efficiency might also be due to the locational advantage of the subbasin within the watershed. Another factor that plays a role in sediment efficiency is the role of best management practices and natural systems within the subbasin. Observations between these frontiers are at various states of sediment reduction technologies and locational characteristics.

[29] Sediment loading in a watershed has a temporal dimension that is based on the type of land use activity and stage of imperviousness. The initial sediment loading (predevelopment stage) is through agricultural and forestry

operations. As a watershed gets urbanized, erosion from construction sites is the first pulse in sediment load [Schueler, 2000]. Rates of erosion can vary depending on factors that include topographical characteristics, land cover, conservation measures, and storm event. The influence of imperviousness starts at this stage through enhanced flow hydrographs and resulting loading of sediments in runoff and water bodies. A second, and possibly greater sediment pulse, occurs as stream banks begin to erode in response to the greater volume and frequency of storm water flows generated by impervious cover [Schueler, 2000]. As urban development continues in the watershed, influence of higher impervious cover continues to influence the magnitude and frequency of storm water hydrograph that impact sediment concentration of streams. Urban runoff contains moderate to high concentration of sediment and other contaminants [Schueler, 1987]. There is a potential for reduction in concentration in high impervious areas with concrete-lined channels, sediment management, and structural designs.

[30] The statistical relationship between impervious cover and sediment rates was estimated using linear and nonlinear models. The estimated functional relationships are presented in Figure 6. At ranges less than 5%, nonlinear models performed well in explaining increasing rate of sediment loading. Linear model was poor in explaining this increasing rate of loading in rural subbasins with less than 5 to 8% impervious factor. The linear and logarithmic models coincided between 7% and 23% impervious coverage. The polynomial fit was different from estimates of linear and logarithmic models within this range. At ranges above 23% impervious cover, the fitted equations from all models varied. This variation indicates the higher influence of nonlinearity and variability (divergence as observed from Figure 5).

[31] The role of various ranges in impervious factor is discussed through the existence of transition zones and the role of continuity. The transition effect between percent impervious cover and aquatic system response is widely studied. Snodgrass *et al.* [1997] observed that there existed

Figure 6. Impact of imperviousness on sediment in runoff water.

a continuous relationship with distinct zones of change in these relationships, which is useful for communicating the impervious cover-water resource relationship. *MacRae* [1997] found the demarcation between stable and unstable channels after an increase in imperviousness of 10% indicates that a transition may exist. *Booth and Reinelt* [1993] suggest that a transition for urban stream stability exists at about 10% imperviousness in a watershed; watershed development beyond this transition zone consistently resulted in unstable and eroding channels [*Snodgrass et al.*, 1997]. Various authors also study the role of continuity in responses. *Masted and Shaver* [1996] found that there is no apparent transition zone because the imperviousness relationship is continuous. *Horner et al.* [1997] studied several lowland streams and wetlands of Puget Sound to evaluate the effects of urbanization on freshwater ecosystems. They assessed the ecological condition and functioning of freshwater ecosystems using benthic index of biological integrity (BIBI) and total impervious area (TIA) to characterize the extent of urbanization in the watershed. Results show higher impacts on freshwater ecosystems during smaller impervious levels and impacts were continuous with curvilinear transition zones. Similar curvilinear results were obtained by *Schueler* [1994], *May et al.* [1997], and *Horner et al.* [1997]. The current study agrees with both arguments and establishes incidence of both transition zones and continuity through nonlinearity and smooth transition effects on a continuous response curve. A transition zone is defined in this study as changes in curvature properties (both first and second order) of the response curve, i.e., the transition zone effects arise because of nonlinear influences.

[32] In the study area, three transition zones (<5%, 5–10%, and >10% imperviousness in Figure 6) were identified

based on the polynomial model. These are discussed below as A, B, and C transition zones, respectively. These were based on shifts in first order (marginal effect) and second order (convexity) curvature properties. Two data-points corresponding to greater than 30% impervious level were not used in estimating models because of limitation in sample size at that stage of imperviousness. At transition zone A, there is a transition from early effects of imperviousness that has higher loading rates to constancy in marginal loading. At this zone, the slope of the curve is 1 ton/(hectare-% imperviousness). The polynomial model exhibited higher convexity at this range. This corresponds to smaller levels of imperviousness where sediment loading is due to land use activities. At transition zone B, the slope of the curve was 0.2 tons/(hectare-% imperviousness) with potential increase in channel erosion due to increasing flows. The estimated model was less convex in this range. At transition zone C, the slope of the curve was 1.2 tons/(hectare-%imperviousness) with higher convexity in the curve. At this zone, imperviousness is slowly increasing resulting in higher storm flows and corresponding changes in sediment loads and from stream bank erosion. These transition effects of impervious factor can be used in development of appropriate policy measures.

[33] The estimated linear equation (6) indicates that for each increase in the impervious factor of a subbasin, the sediment loading increased by 0.25 tons per hectare.

$$S = 0.34 + 0.25 * I \quad (6)$$

The constancy of response assumed in this model is a limitation in assessing variable impacts. This model fails to

Table 1. Summary Statistics of the Statistical Models^a

Model	R ²	F Value	Significance
Linear	0.48	23.29	*
Logarithmic	0.46	21.24	*
Polynomial (third degree)	0.53	28.62	*

^aAsterisk indicates significant at the 99th percentile of the F distribution. R² is calculated with appropriate transformation for nonlinear models.

capture the nonlinearity evident in smaller and larger levels of imperviousness.

[34] The estimated logarithmic model is presented in equation (7).

$$S = 7.91 \times \ln(I + 23.21) - 24.71 \quad (7)$$

In this model, each percent increase in the impervious factor contributed to a marginal increase of 7.91/(I + 23.21) tons/hectare. While logarithmic model captured nonlinearity at smaller levels of imperviousness, marginal responses during intermediate and late states are almost constant. The linear and logarithmic models had similar explanatory power and marginal estimates at larger levels of imperviousness.

[35] The estimated values of the polynomial model are presented in equation (8). It is evident from this form that quadratic and cubic components (nonlinearity) of the function are significant in influencing sediment loading. Coefficients of polynomial order higher than 3 are less significant in their marginal contribution.

$$S = 0.03 + 0.52*I - 0.04*I^2 + 0.001*I^3 \quad (8)$$

The polynomial model has captured most of the nonlinearity in the relationship and is considered as the best fit among all three specifications.

[36] The R² values of estimated models are presented in Table 1. The polynomial model was able to explain 53% of the variation in sediment loading rates. The Linear model had explanatory power of 48% of the variation, while the Logarithmic model explained 46% of the variation. All F-values were significant at 1% level.

4.4. Policy Implications

[37] The impervious taxing policy is easier to design with a linear model by linking tax rates to the impervious percent. Establishing the baseline rate is difficult, as it need to reflect the marginal social cost. One way to assess the social cost is to use watershed-scale abatement or treatment cost of sediment contamination. If the social cost of a ton of sediment is ω , as estimated using restoration or treatment costs, then the impervious tax can be assessed using the linear model as $P = \omega * (0.34 + 0.25 * I)$. For example, if the external damage cost per ton of sediment is estimated at \$20, in addition to an initial tax of \$6.80, the incremental tax per unit of impervious cover is \$5.04. This is evident as a linear function in Figure 6.

[38] In the case of variable policies using nonlinear models, marginal effects vary over the range of impervious levels. The impervious tax using the logarithmic estimates (equation 7) can be calculated as $P = \omega * [7.91 \times \ln(I + 23.21) - 24.71]$. For a damage cost of \$20, the taxing function is $P = 158.12 \times \ln(I + 23.207) - 494.26$. In this

type of taxing, different tax rates are used at different impervious levels. For logarithmic increments, rate of increase in penalty is higher in smaller levels of imperviousness. The polynomial model is approximated as $S = 0.03 + 0.52 * I - 0.04 * I^2 + 0.002 * I^3$, by considering up to third order coefficients (based on significance of marginal values). Here the impervious tax can be calculated as $P = \omega * [0.03 + 0.52 * I - 0.04 * I^2 + 0.002 * I^3]$. Here the tax rates are varied at all levels of imperviousness based on the marginal response changes. For the damage cost of \$20, the taxing function can be written as $P = [0.68 + 10.44 * I - 0.86 * I^2 + 0.03 * I^3]$. The changes in tax levels over the range of imperviousness are presented in Figure 7. While linear taxing model indicate a constant rate, taxes based on polynomial and logarithmic model change over the range of impervious levels. Logarithmic tax curve was close to linear taxing, while polynomial model based tax have varying rates based on the imperviousness transition zones.

[39] While taxing policy (P) is designed to penalize for no mitigation efforts through BMPs, an abatement subsidy policy ($-P$) rewards for adoption of BMPs. The estimates derived in taxing design can also be used in the design of subsidies. After identifying the levels of subsidy ($-P$) using linear and nonlinear models, subsidies to install BMPs can be constant for each increment in impervious cover or changed according to the derived equations. To make the subsidy more effective and targeted, it is desirable to design subsidies as in-kind BMP installation rather than direct financial transfers. A cost-sharing policy can be used to share the cost of BMP, thereby providing partial rewards, while encouraging investment by the landowner. In the case of designing cost-sharing policy, the estimated value of P (as derived in the taxing calculation) can be appropriated using the proportion (α) to be shared by the society. For an equal share, 50% of the P estimate need to come from the manager and 50% from the society. In cases of higher impervious zones, the cost sharing could be designed higher than those that for lower transition zones.

4.5. Practical Implications

[40] Impervious taxes have been implemented in the form of storm water utilities or rain tax in several urban watersheds (for example, Greensboro, NC; McKinney City, TX; city of Wauwatosa, WI; Monstesano, WA; city of Broken Arrow, OK) of the U.S.. These impervious taxes ranged from \$1 to \$3 per Equivalent residential Unit (ERU) and are assessed are based on square footage of imperviousness. The tax assessment is often based on historic costs involved in storm water management. The procedure proposed in this study can provide more comprehensive assessment of the external cost associated with imperviousness. To implement the proposed concept in other watersheds, response function need to be adjusted to account for a range of conditions that include watershed topography (slope conditions, land use/cover, rainfall erosivity, and soil erodibility), existing BMPs (riparian protection, urban forestry, and runoff practices), spatial distribution of imperviousness within a watershed (impervious proportion in headwaters, riparian zones, and main stem). While the linear approach is more practical, the estimates need to be updated based on changes in the landscape and potential BMPs applied to the impervious area.

Figure 7. Tax on impervious factor based on linear and nonlinear impacts.

[41] There are several BMPs that could be considered in mitigating the effect of imperviousness. Landuse practices can be parts of a system design are buffer zones, setbacks, and easements. These are effective at reducing stream bank erosion and providing sediment removal functions. Buffer zones downstream to impervious areas can slow runoff water and trap pollutants. Setbacks restrict imperviousness development in certain zones in a watershed, while easements are restriction of development rights in sensitive areas of the watershed.

[42] Dry detention basins can be added to impervious areas to temporarily detain storm water runoff and released slowly to reduce flooding and enhance pollutant removal. These basins are effective in removal of sediments while less effective in removing nutrients. Porous pavement is intended to reduce imperviousness and consequently minimize surface runoff. The design includes a reservoir of coarse aggregate stone beneath the pavement for storm water storage prior to exfiltration into surrounding soils [Schueler *et al.*, 1992]. A common problem with this BMP is high failure rate because of clogging [Schueler *et al.*, 1992].

[43] Sand filters are used to treat storm water from drainage areas as much as five acres in size. Larger size of these filters benefit from economics of scale than small filters. Pollutant removal can vary from site and climate and performs well for removal of sediment and trace metals than more soluble pollutants. Infiltration devices (like infiltration basins, infiltration trenches and dry wells) can be used to mitigate runoff from impervious areas, to remove pollutants, and to recharge groundwater. Pollutant removal is high for both sediment and nutrients.

[44] Rain Gardens [Hunt and White, 2001] is a BMP based on landscape design that can be used to mitigate imperviousness effects. These are low elevation areas with vegetation for temporary retention of runoff. Constructed wetlands are created wetlands designed and developed specifically for water treatment [Fields, 1993]. These are effective as part of a BMP system and can reduce runoff volumes. Sediment and nutrient removal is comparatively higher than other BMPs, depending on design and maintenance. Wet Retention Ponds can be used to temporarily detain runoff water and release gradually. This BMP can be used to reduce sediment load and nutrients. Selection of a particular BMP is dependant on installation and maintenance costs, pollutant removal rates, and mitigation of other effects of imperviousness. An impervious tax can provide incentive for landowners to mitigate effects of imperviousness through appropriate choice of BMPs. More detailed information on BMPs is presented by Schueler [1987], U.S. EPA [1990], and Schueler *et al.* [1992].

5. Conclusions

[45] Understanding the role of urbanization on water quality is important for watershed management and policy. The impervious factor in watersheds can be used as an indicator of the level of urban effects on hydrological and sedimentation processes. This information is also critical in development of appropriate watershed conservation techniques and effective policies to address Nonpoint source pollution and runoff volume. In this paper, a combination of simulation and statistical models was used to study the role of increasing watershed impervious cover on sediment

loading at a watershed scale and to evaluate the nonlinear effects and policy options. It was observed that in addition to urbanized subwatersheds, subbasins with less than 10% impervious factor dominated the study area. This result corroborates other studies that used IBI and biological indicators [Horner *et al.*, 1997]. This is important in developing conservation policies as higher rates of sediment loading were observed during smaller levels of imperviousness. The sediment loading was also high in subwatersheds with higher impervious factor. There existed two distinct regions of high sediment loading rates -low impervious level and high impervious level. On a spatial scale, impervious factor in headwaters contributed to higher loading rates.

[46] Transition zones (changes in curvature property) were observed on a continuous range of impervious coverage. The transition effects arise because of nonlinear influences at varying stages of urbanization. As impervious factor increased, higher variance in sediment loading was observed among various observations (divergence).

[47] There existed lower sediment loading in some subwatersheds compared to those at the same level of impervious factor. These subwatersheds formed the lower envelop of the distribution and represent best approaches to handle sediment loading. This advantage in sediment efficiency is due to locational advantage, Best Management Practices, and proportion of open space. The role of nonlinearity in influence varied based on various levels of impervious cover. In general the role of nonlinearity played a major role in explaining sediment-impervious relationship.

[48] Three types of policy instruments were evaluated. Impervious taxes could be a viable option to reduce impervious factor. If properly designed it could provide incentives of reducing external impacts through BMPs. While a linear model is easier to translate to tax rates, nonlinear models involved changing tax rates based on variable impacts at varying impervious levels. These elements need to be constantly updated to include changes in landscapes and practices and for transferability to other watersheds. Subsidies to reduce impervious cover or to incorporate BMPs can also be used to address water quality problems in urbanizing areas. Another incentive policy is cost sharing to encourage adoption of new BMPs or to voluntarily reduce impervious percentage.

[49] The study results are useful in approaching the water quality problems relates to urbanization by using targeted policy measures. While this is a wide area of study, future extensions of the work could incorporate other pollutants and quantity issues. Other policy approaches could be studied through implicit modeling of economic behavior of a land manager. Given that storm water runoff, sediment dredging, suburbanization, and nonpoint source pollution are becoming major problems facing communities, policy and assessment approach like this study provides an alternative approach to mitigate urban influence on water quality.

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