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Urban form and watershed management: how zoning influences residential stormwater volumes

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Abstract. This paper reports the results of a study on residential parcel design and development-induced stormwater runoff in the City of Madison, Wisconsin. To assess the influence of municipal zoning and subdivision regulations on residential stormwater production, high-resolution aerial photography and property tax data for over 38 000 single-family residential parcels were used to measure the impervious cover and modeled runoff associated with a typical two-year storm. The results of the analysis suggest that stormwater runoff volumes could be significantly reduced with only modest changes to municipal land-development regulations and with no reduction in the size of the residential structure. Following the presentation of the methodology and findings, the paper concludes with a discussion of targeted revisions to zoning and subdivision regulations that, if implemented, could reduce the runoff volume from new residential parcels in Madison by over 30%.

Introduction

Global cities are presently experiencing a surge in population that is unprecedented in the history of human settlement. As reported by the United Nations Population Division, the global urban population is projected to almost double in size from its 2000 level by the year 2030, a level of annual growth that is almost twice that of the global population growth rate (United Nations, 2001, page 5). A product of high birth rates in some areas of the world, and on-going interregional migration in others, the rapid expansion of urban populations is placing tremendous pressures on the ecological infrastructure of large metropolitan regions. Although the process of urbanization holds significant implications for a wide array of environmental challenges, perhaps the least appreciated of these problems is that of stormwater management. Diverted to extensive subterranean sewer systems and the forgotten channels of urban waterways, the vast quantities of stormwater runoff produced by modern cities have severely degraded once-vital urban watersheds, extinguishing aquatic species, posing a persistent health threat to human populations, and costing hundreds of billions of dollars in annual management. In the United States, such nonpoint source pollution is ranked by the US Environmental Protection Agency as the leading threat to water resources (USEPA, 2000).

Despite the well-documented environmental, economic, and health-related costs of urban runoff (for example, Hoxie et al, 1997; Stepenuck et al, 2002), surprisingly little research has addressed the relationship between the physical structure of cities and stormwater volumes. In large part, the technical literature on stormwater management has approached the problem as an unavoidable byproduct of urbanization—as an effluent to be collected and transported downstream rather than abated through

† This article is dedicated to the memory of Jessica L Bullen, whose creativity, diligence, and unflagging enthusiasm for ecology and planning made this work possible.

more hydrologically responsive design. Although a recent emphasis in the planning literature on site-enhanced infiltration techniques, such as rain gardens, retention ponds, and mandated riparian buffers, signals an interest in stemming the off-site flow of stormwater, these approaches nevertheless fail to address the root cause of the runoff problem: the quantity of land converted from natural land covers to the impervious surfaces of buildings, streets, parking areas, and highly compacted urban soils. To date, there exists in the literature only a small number of studies that have sought directly to evaluate the role of urban form in the generation of stormwater runoff, and fewer still that have addressed the impacts of specific land-development regulations governing the type, scale, and material composition of parcel development on the production of stormwater (for example, Richards et al, 2003; Zheng and Baetz, 1999; Zielinski, 2002).

In light of this gap in the literature, in this research we seek to quantify the influence of specific zoning and subdivision regulations on the production of residential stormwater runoff. Through the development of a parcel-based geographic information system, we quantify the parcel design attributes of over 38 000 single-family residential parcels in the City of Madison, Wisconsin, and statistically associate these attributes with the estimated parcel runoff generated by a typical two-year storm event. The results of our analysis suggest that stormwater runoff volumes could be significantly reduced with only modest changes to municipal land-development regulations and with no reduction in the capacity of the residential structure. Following the presentation of the methodology and findings, the paper concludes with a discussion of targeted revisions to zoning and subdivision regulations that, if implemented, would reduce the runoff volume from the average new residential parcel in Madison by over 30%.

The problem of stormwater runoff

The generalized relationship between urbanization and stormwater runoff has been well established in the literature. The hydrological changes brought about through the conversion of natural land covers to the impervious surfaces of roadways, parking areas, and buildings are known to increase runoff significantly and to promote stream-water degradation. Unable to penetrate the mineral-based materials of urban construction, stormwater is transported across these impermeable surfaces, collected in stormwater sewers, and ultimately diverted into natural stream channels, greatly enhancing the volume, rate of flow, and duration of peak flow in these natural and engineered waterways (Booth and Jackson, 1997). The most direct impact of these hydrological changes is an increase in the frequency and intensity of flooding events. As urbanization has spread, the area of the United States at risk of significant flooding events has greatly expanded, with consequent increases in the cost of emergency flood response and loss of life (FEMA, 1997).

Stormwater runoff has also proven to be an effective vector for the transport of disease agents. It has been estimated that more than half of all waterborne disease outbreaks are now associated with heavy precipitation and runoff events (Curriero et al, 2001), with the largest recorded of these events in the United States, a 1993 outbreak of *Cryptosporidum* in Milwaukee, Wisconsin, resulting in 403 000 illnesses and 54 deaths (Hoxie et al, 1997, page 2032). On an annual basis, the cost of managing waterborne illness in the United States is estimated to be between \$2.1 billion and \$13.8 billion (Gaffield et al, 2003, page 1527).

As concluded by a number of hydrological studies, a threshold effect appears to occur once 10% of the surface area of a watershed has been converted to impervious materials, at which point stream-water quality shows evidence of increasing degradation (Booth and Jackson, 1997; Schueler, 1994; Stepenuck et al, 2002; Wang et al, 2001).

What is less well understood, however, is the role of urban form in this process. For an urban region of fixed population, what pattern of development—concentrated or dispersed—is most conducive to enhanced runoff? More specifically, what specific land-development regulations promote patterns of urban development that are most conducive to surface sealing and reduced rates of infiltration? As noted by Alberti (1999, page 157), "we know... that the urban surface modifies the hydrological cycle and encourages rapid runoff, which may be more than twice as great in urbanized than in rural areas.... However, we do not know how they relate directly to alternative urban configurations." In short, we know what thresholds of impervious cover are associated with watershed degradation, but we do not have a complete understanding of why some patterns of development generate more runoff than others.

In this work we seek to address this question through the development of a parcel-based indicator of stormwater runoff in residential neighborhoods. An explicit focus on stormwater production at the parcel level is significant in two respects. First, the land parcel is the most disaggregate unit at which land-development regulations are enforced and thus serves as the optimal spatial unit for associating land-use policies with development-induced environmental phenomena. Because spatial units at a higher level of aggregation, such as watersheds or aerially designated land-cover classes (for example, high-density residential zones), typically consist of numerous parcels subject to a diverse array of land-development regulations, any attempt to isolate the direct effect of a specific zoning ordinance, subdivision regulation, or building code on environmental performance is confounded. By estimating runoff at the parcel level, we can most accurately discriminate between the runoff-inducing effects of land-use policies that may change from one parcel to the next.

Second, the adoption of the land parcel as the unit of analysis facilitates comparisons across residential parcels designed to accommodate an equivalent number of residents. Although a number of studies have found higher rates of stormwater runoff in high-density urban districts, a failure to control effectively for the number of housing units or residential capacity in high-density and low-density zones limits the utility of these studies for planning policy. For example, in their analysis of urban land-cover types and stormwater runoff in Munich, Germany, Pauleit and Duhme (2000) found the stormwater production of multifamily housing blocks to be three times as great as that of single-family, detached housing patterns. Yet, in light of the fact that multifamily development models are designed to house a larger number of residents than single-family models, the authors provide an insufficient basis to assess the relative environmental impacts of these dissimilar housing patterns. To reduce the stormwater production of new development most effectively, should Munich planners encourage high-density or low-density models of housing through land-use codes? This central question may be addressed only through the development of what we term a 'capacity-adjusted' indicator of environmental performance.

In this study, we control for the number of housing units and bedrooms per parcel to understand better how dissimilar housing models—and their associated land-development regulations—influence runoff volumes. Recorded through the standard property tax assessment process, the number of housing units and bedrooms per structure is typically maintained in municipal parcel tax databases. Although such measures of residential capacity do not provide direct proxies for parcel occupancy, it should be noted that municipal governments typically are not empowered to regulate single-family housing occupancy. Rather, zoning and design review commissions are empowered to limit the number of units constructed in new developments or infill projects. Thus, it is a capacity-adjusted indicator of stormwater production—a measure of the stormwater generated per housing unit or bedroom—that is most directly relevant to the municipal land-use planning process.

In short, the adoption of the individual land parcel as the unit of analysis for this research facilitates the development of a policy-relevant and capacity-adjusted indicator of stormwater runoff. It is my contention that such an indicator is critically needed to assess accurately the implications of alternative urban development scenarios on regional stormwater production. What follows in this paper is a discussion of the methods employed to derive a parcel-based measure of development-induced runoff in the Madison, Wisconsin, study region; the results of an analysis of parcel design and runoff volumes for a typical two-year storm; and a presentation of design-oriented stormwater management strategies for growing urbanized regions.

Modeling parcel-based stormwater runoff

As noted above, the objective of this study is to estimate the volume of stormwater runoff generated by over 38 000 single-family residential parcels in the City of Madison, Wisconsin, and to associate these runoff volumes with specific land-development regulations governing the dimensions of residential parcels and streets. We focus exclusively on the single-family residential parcel for two reasons. First, as consistent with most large metropolitan regions, the majority of the total developed land area in the Madison area is occupied by single-family housing. Thus, any modifications to this development class would yield significant changes in the landscape. Second, in North American cities, single-family development typically constitutes the leading edge of peripheral expansion, and thus often shapes the direction and form of new development. We believe that modifications in the design and environmental performance of single-family development hold the greatest potential to restructure the nature of urban development at the periphery.

The stormwater runoff estimation process developed for this work consists of two steps. First, we use parcel-based tax records and high-resolution aerial photography to quantify the area of impervious cover of every single-family residential parcel in the Madison study region. Second, we employ a widely used surface hydrology model to estimate the volume of stormwater runoff generated per parcel from a typical two-year storm in the Madison region. What follows in this section is a detailed presentation of the methods adopted to perform these two tasks.

Measuring impervious cover

To quantify the type and area of parcel impervious materials, parcel attribute information was obtained from the City of Madison Engineering Division. The tax attribute database maintained by the City of Madison provides a range of information on parcel characteristics, such as the size of building footprints and the number of bedrooms in the residential structure. In addition, high-resolution aerial photography obtained from the Dane County Land Information Office provides a basis for verifying the accuracy of the tax attribute information and for measuring impervious attributes not directly recorded in tax data. Collected in April 2000 at a ground resolution of six inches, the aerial imagery is of sufficiently high resolution to permit the surface features of high-density residential parcels to be accurately measured. In combination, these datasets were used to quantify four components of residential parcel impervious surface. Presented in figure 1, these are the footprint of parcel structures, the driveway area, the sidewalk area, and a measure of street paving (discussed below) referred to as the 'street allotment'.

Obtained as part of the routine property tax assessment process, the area of all parcel structures is maintained by the City of Madison and was made available for this research. In addition, property tax assessors record information on the presence of sidewalks and garages. For parcels coded as having sidewalks, the sidewalk area was

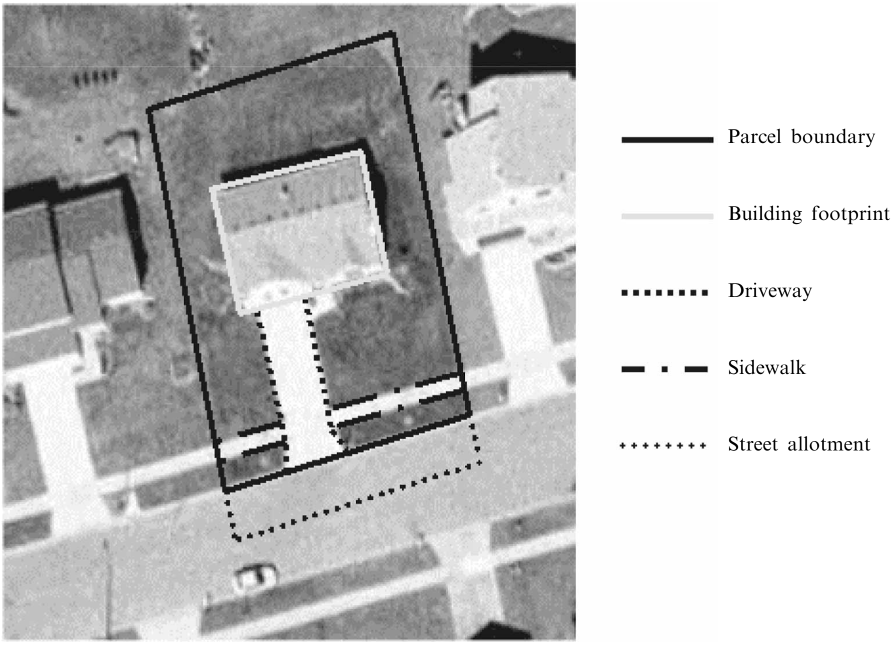

Figure 1. Parcel impervious components (image source: Dane County Land Information Office).

estimated on the basis of the lot frontage (the width of the parcel at the street adjacency) and an average sidewalk width of 1.5 m. The product of these two dimensions yielded an estimate of sidewalk impervious surface area for those parcels containing sidewalks.(1) With the aid of aerial photography, a random sample of over 100 parcel sidewalks was measured and found to comport well with these width and area estimates.(2)

To derive an estimate of driveway paving, an equation based on the front yard setback and number of garage stalls was employed for each residential parcel coded as having a garage. As specified in the Madison Code of Ordinances, all driveways must lead from a street and traverse the length of the front-yard setback (City of Madison Code of Ordinances §28.04, 28.11). In light of this requirement, the setback distance was used as the minimum length dimension for estimating all driveways in the study region. To assess driveway width, a random sample of residential parcels was selected and the driveway widths measured with aerial photography.(3) On average, sample driveways were found to be approximately 3 m in width for each garage stall. Based on these parameters, parcel driveway areas were estimated with the following simple equation:

$$\text{driveway area (m}^2\text{)} = \text{front-yard setback (m)} \times 3\,\text{m} \times \text{number of garage stalls}\,.$$

(1) Because there is an overlap between sidewalk and driveway paving, a uniform area of 4.5 m^2 was subtracted from all parcel sidewalk estimates to avoid a double counting of paved areas. This area is based on an average sidewalk width of 1.5 m and an average driveway width of 3 m.

(2) A random sample of 100 single-family parcels was found to be sufficient to achieve a 95% level of confidence in predicting sidewalk area within 10% of the population mean. The sidewalk area of 100 randomly selected parcels was measured through the use of high-resolution aerial photography and found to vary from the sidewalk area estimates by an average of 2%.

(3) Similar to the sidewalk sample, a random sample of 100 parcel driveways was found to be sufficient to achieve a 95% level of confidence in predicting driveway width and area within 10% of the population mean.

To gauge the accuracy of this estimation routine, a random sample of 100 single-family parcels was selected and the driveway areas measured with the aid of the aerial photography.(4) The results of this sampling process were compared with the driveway area estimates derived with the above equation and found to correspond closely. On average, the difference between the measured and estimated driveway areas was approximately 6%, a level of error deemed acceptable for this type of analysis.(5)

In addition to the impervious surface area of individual land parcels, alternative residential development patterns can degrade regional environmental quality through the area of street paving required to service residential dwellings. In order to capture this extra-parcel imperviousness better within a parcel-based measure, this study quantifies an area of the residential street termed the 'street allotment'. For parcels situated on linear street segments, the street allotment is a polygon bounded by the parcel frontage, the centerline of the street, and an extension of the parcel side lot lines to form a rectangular section of street paving (see figure 1). This street-allotment area is easily calculated by multiplying the length of the parcel frontage by one half of the residential street width.(6) In the Madison study region, 96% of all single-family residential parcels are situated on linear street segments.

For parcels situated on terminal street segments or cul-de-sacs, no street centerline exists and thus a different method was required for estimating the street allotment. For these parcels, the area of the cul-de-sac was manually digitized with the aid of the aerial photography and a geographic information system and then equally allocated to each parcel bordering the cul-de-sac. In essence, each of the over 1400 parcels bordering a cul-de-sac was allocated a wedge-shaped area of street paving defined by the number of neighboring parcels and the radius of the cul-de-sac.

Estimating stormwater runoff volumes

Following the construction of a parcel-level land-cover database, the next step in our methodology was to estimate the volume of 'development-induced' stormwater runoff. By development-induced runoff, we refer to that proportion of the total stormwater production that is directly attributable to the conversion of natural land-cover types to the impervious surfaces of residential land uses. Because all land-cover types, even dense forest canopy, are associated with some level of stormwater production, even the predevelopment parcel generates some volume of natural runoff. To gauge the impact of urban development on the runoff problem, we are interested in isolating the anthropogenic component of stormwater runoff, rather than the combined anthropogenic and natural components. Our rationale in focusing on the development-induced runoff is that large, fully forested parcels located within urbanized regions should not be found to contribute to the human-induced stormwater problem. Likewise, the owners of large parcels who elect to develop only a small proportion of their lot should not be penalized simply for owning a large lot. By subtracting away the quantity of stormwater that is attributable to the natural or predevelopment characteristics of a parcel, we derive a more accurate estimate of a landowner's contribution to the anthropogenic stormwater problem.

(4) A random sample of 100 parcel driveways was found to be sufficient to achieve a 95% level of confidence in predicting driveway width and area within 10% of the population mean.

(5) It should be noted that this estimation routine fails to assign any driveway area to parcels with driveways but no garage. An additional random sample of 100 parcels found that less than 1% of those surveyed have driveways without garages. Nevertheless, this limitation of the study methodology is a source of potential error that should be considered in evaluating the results.

(6) Information on residential street widths was obtained from the City of Madison Engineering Division.

In light of this observation, our methodology for estimating development-induced parcel runoff consists of three steps. First, a runoff estimation equation is employed to quantify the runoff of the present day, single-family residential parcel. This stormwater estimate is referred to as the 'postdevelopment' runoff volume. Second, the 'predevelopment' parcel runoff is estimated by assuming the same residential parcel is occupied by a forested land cover. Finally, the predevelopment runoff volume is subtracted from the postdevelopment runoff volume to produce an estimate of the development-induced runoff for each single-family parcel in the study region.

US Soil Conservation Service runoff estimation equations

To estimate the volume of surface runoff produced by each parcel from a hypothetical two-year, 24-hour storm, we used the US Soil Conservation Service's curve number method (SCS, 1986). This process calculates a uniform runoff depth (Q) over a drainage area by subtracting from the quantity of rainfall (P) infiltration and other losses (I)—such as surface depressions, interception by vegetation, and evaporation—as well as the estimated quantity of water retained in parcel soils, called the potential maximum retention (S). The resulting precipitation excess may be estimated through the following equation:

$$Q = \frac{(P-I)^2}{(P-I)+S},$$

where Q is runoff depth (inches), P is rainfall (inches), I is initial abstraction (inches), and S is the potential maximum retention (inches).

The maximum soil retention (S) is related to the soil and cover conditions through a runoff factor called the curve number (CN). A CN for a site is chosen on the basis of soil type, cover type, hydrological condition, antecedent moisture conditions, and whether impervious areas are connected or disconnected (SCS, 1986). CNs range from 0 to 100, with a higher number indicating a higher runoff potential. For all parcels in the study region, we assumed hydrological soil type 'B' (the most common soil type in Madison), average antecedent moisture conditions, good hydrological conditions, and connected impervious surfaces. An area-weighted composite curve number (CN_c) was calculated for each parcel on the basis of the proportion of the combined parcel and street allotment occupied by impervious and nonimpervious materials. Nonimpervious surfaces were assumed to be equivalent to open space or a mixture of lawn and trees in good hydrological condition.[7]

In substituting a local value of 2.9 in of rainfall for a two-year, 24-hour storm (Dane County, 2002) into the SCS equations, we can derive the following composite equation for estimating the depth of runoff from any parcel in the study region:

$$Q = \left[2.9 - \left(\frac{200}{CN_c} + 2\right)\right]^2 \bigg/ \left(2.9 + \frac{800}{CN_c} - 8\right). \qquad (1)$$

The postdevelopment volume of runoff may then be calculated by multiplying the runoff depth (Q) by the combined area of the parcel and its street allotment. The runoff volume for the predevelopment scenario was calculated in the same manner, assuming the area of the parcel and its street allotment were occupied by a forested land cover in good hydrological condition.[8] As a final step, the predevelopment

(7) The CN is related to S by the following equation: $S = (1000/CN) - 10$. The SCS has found the relationship between I and S to be $I = 0.2S$. By substituting these equations for I and S, above, we can derive equation (1). A CN of 61 was used for the pervious areas and a CN of 98 was used for impervious surfaces (SCS, 1986).

(8) A CN of 55 was used to represent a predevelopment, forested land cover (SCS, 1986).

runoff volume is subtracted from the postdevelopment runoff volume to derive the estimated volume of development-induced runoff for each single-family parcel.

Residential design attributes

Following the derivation of a parcel runoff estimate, the next step in the methodology was to quantify a series of regulated parcel design attributes that may be associated with stormwater runoff volumes throughout the study region. Four parcel attributes were quantified to associate impervious cover with planning regulations: lot size, lot frontage, front-yard setback, and number of stories in the residential structure. In addition, the width of the adjacent residential street was derived to assess the role of extraparcel imperviousness in runoff production. Finally, as noted above, the number of bedrooms was used as a control variable for residential capacity.

Directly regulated by municipal zoning and/or subdivision regulations, each of these variables is hypothesized to influence the volume of stormwater runoff through its influence on the surface area of impervious materials. The definition and hypothesized significance of each variable are presented in table 1.

Table 1. Parcel design attributes.

Variable	Definition	Hypothesized association with runoff
Lot size	The area of the parcel measured in m^2	Positive: increments in lot size increase runoff by expanding the buildable area of the parcel.
Lot frontage	The width of the parcel in m at the point of its adjacency to the street	Positive: increments in lot frontage increase runoff by expanding the size of the street allotment.
Front-yard setback	The linear distance in m between the street curb and the residential structure	Positive: increments in the front-yard setback increase runoff by extending the length of the residential driveway.
Number of stories	The number of above ground floors in the residential structure	Negative: increments in the number of stories decrease runoff by reducing the area of the building footprint.
Street width	The width of the primary residential street in m	Positive: increments in street width increase runoff by expanding the size of the street allotment.
Number of bedrooms	The number of bedrooms in the residential structure	Control variable: the number of bedrooms serves as a control for the capacity of the residential structure.

How parcel design influences stormwater runoff

Once constructed, the parcel design and stormwater runoff database was analyzed to assess the relationship between regulated parcel design attributes and runoff volumes resulting from a typical two-year storm in the Madison study region. In the first component of the analysis, descriptive statistics are presented to illustrate the distribution of development-induced runoff volumes across variable lot sizes. In the second component, a sensitivity analysis is performed to assess the magnitude of benefits that may be achieved through modifications to current zoning and subdivision regulations.

Descriptive analysis

A series of descriptive statistics for each of the independent variables and impervious surface measures is presented in table 2. Within the Madison study region, the average single-family residential parcel is approximately 900 m^2 in size; is characterized by three bedrooms, a 23 m frontage, a 13 m front-yard setback; and is two stories in height. The average volume of development-induced stormwater runoff resulting from a two-year storm is 16.4 m^3, a quantity roughly equivalent to the weekly water consumption of a family of four (Mayer et al, 1999). As suggested by the standard deviation for lot size, there is a wide variability in housing densities throughout the study region, providing an ideal range of housing patterns to associate with stormwater production.

Table 2. Descriptive statistics.

Variable	Minimum	Maximum	Mean	Standard deviation
Lot size (m^2)	74.0	8 146	895.0	476.0
Frontage (m)	0.6	131	23.0	8.8
Setback (m)	1.5	137	13.0	3.9
Number of stories	1.0	4	2.0	0.6
Street width (m)	3.1	26	9.7	2.3
Number of bedrooms	1.0	10	3.1	0.8
Total impervious cover (m^2)	68.0	1 473	330.0	104.0
Development-induced runoff (m^3)	3.3	76	16.4	5.3

To gauge the general association between lot size and impervious cover, figure 2 illustrates the variation in the individual impervious components for parcels ranging from less than 500 m^2 to more than 4000 m^2 in area. The figure indicates that, on average, parcel impervious cover is closely associated with lot size. As the parcel area increases from less than 500 m^2 to over 4000 m^2, the total impervious surface area, including the street allotment, increases by approximately 176%. The average percentage coverage of each impervious component is listed in parentheses.

Although strongly positive in the aggregate, there is evidence of significant variation in the quantity and type of impervious cover over increasing lot sizes.

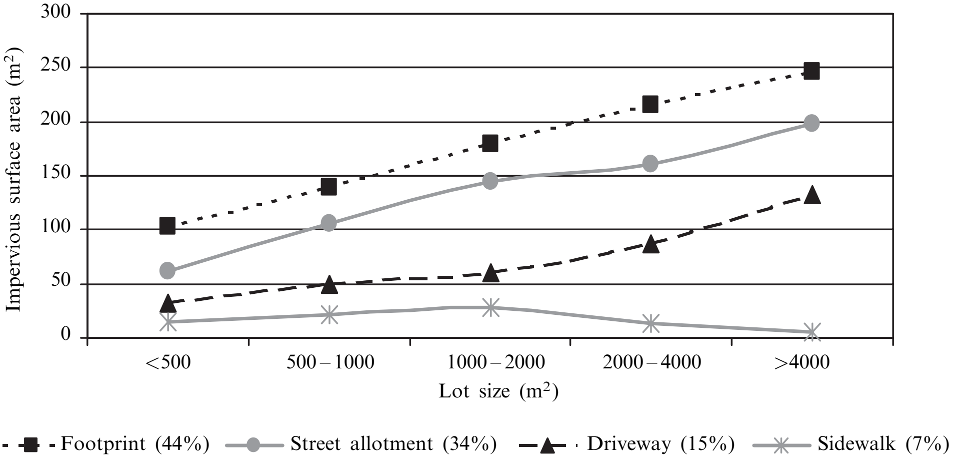

Figure 2. Impervious cover and runoff volume by lot size. Percentage coverage for the average parcel is listed in parentheses.

For example, although the combined footprints of residential structures (houses, detached garages, and miscellaneous buildings) account for over 49% of the total impervious cover for parcels less than or equal to 500 m^2 in area, this component accounts for only 42% of the impervious cover of parcels over 4000 m^2 in area. Likewise, as a proportion of the total parcel impervious cover, the sidewalk falls from approximately 7% to less than 1% between the highest and lowest density categories. In contrast to these trends, on average, the residential driveway accounts for an increasing proportion of the total parcel impervious cover with increasing lot size (rising from 15% to 23% from the smallest to the largest lot size category).

As illustrated in figure 3, the volume of development-induced stormwater runoff increases consistently with increments in lot size. Overall, an increase from less than 500 m^2 to over 4000 m^2 in parcel area is associated with an approximate 400% increase in stormwater production from the modeled two-year storm. It is important to note, however, that this relationship is likely to be attributable in part to the tendency for larger parcel areas to be associated with greater housing capacities (that is, houses with more than three bedrooms). Of greater import for the purpose of planning for new developments of fixed population is the question of how development-induced runoff volumes vary when controlling for residential capacity. In short, do lower density patterns of development generate more or less runoff on a per bedroom basis?

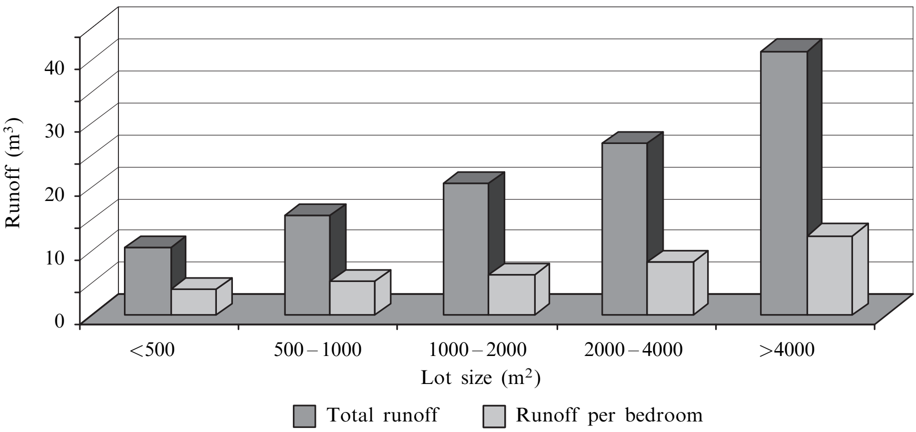

Figure 3. Development-induced runoff (m^3) by lot size.

To evaluate this basic question, figure 3 also reports the quantity of development-induced runoff per bedroom across increasing parcel areas. As indicated in the figure, the average volume of runoff per bedroom also increases consistently across increasing parcel sizes, with an overall increase of about 300% between the smallest and largest lot size categories. This finding suggests that, in the Madison area, lower density patterns of development tend to generate more runoff per unit of capacity, an outcome attributable to a disproportionate increase in impervious materials and/or lawn area per bedroom with increasing parcel size.

Sensitivity analysis

Having established an association between lot size and average development-induced runoff values, there is a need to assess how specific land-development regulations influence runoff volumes. Although increasing lot sizes are associated with an increase in the total area of impervious cover, this correlation is not a sufficient basis to conclude that lot size zoning regulations are the principal causal factor in runoff volumes.

Rather, an increase in lot dimensions independent of lot size, such as the front-yard setback or lot frontage, for example, can contribute to increasing stormwater volumes by expanding the area of driveway paving or the street allotment. In fact, were an increase in lot size to be associated with no increase in impervious cover or uncanopied lawn area (for example, the additional area was characterized by a fully forested land cover), no additional development-induced runoff would be expected to occur. Thus, there is a need to quantify the relative contribution of specific parcel design attributes.

To do so, we employed the runoff equations presented above to model the development-induced runoff produced by parcels of varying size in response to changing land-development regulations. For example, what reduction in development-induced runoff could be achieved through a 25% reduction in the front-yard setback? Thanks to the association between the front-yard setback and the area of driveway paving, such a modification to local zoning regulations would be expected to reduce runoff volumes, assuming other elements of parcel design remain unchanged. In order to assess how changes in lot design would influence development-induced runoff, we modeled the following specific changes to each parcel in the study region: (1) 25% reduction in lot size; (2) 25% reduction in the lot frontage; (3) 25% reduction in the front-yard setback; (4) reduction in the street width to 7.9 m,(9) and (5) increase in the number of stories from one to two for all single-story houses.(10) By modeling the sensitivity of runoff volumes to these changes in lot design, we were able to quantify the benefits of potential land-development changes on both parcel runoff volumes and the quantity of runoff per bedroom. Figure 4 reports the results of this modeling exercise and serves as the basis for the following discussion of specific planning strategies that may be employed to reduce stormwater volumes in new and existing development.

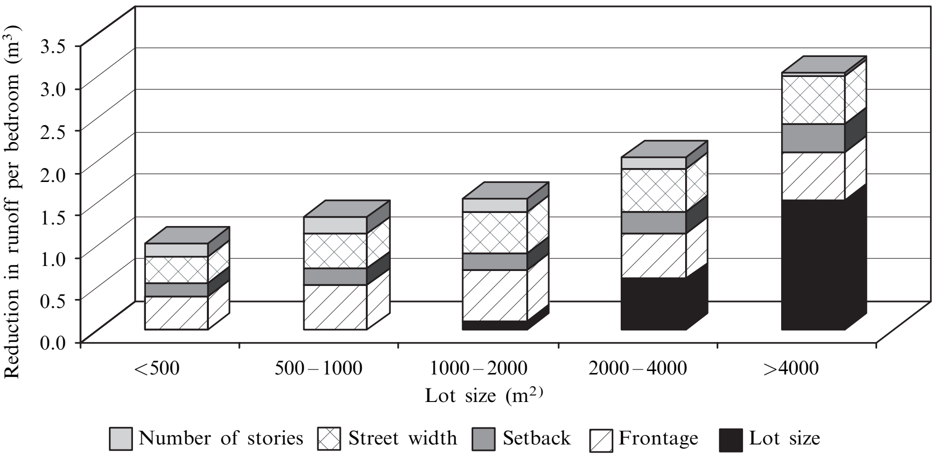

Figure 4. Reduction in development-induced runoff per bedroom resulting from a uniform change in parcel attributes by lot size. Chart illustrates decrements in runoff resulting from a 25% reduction in the average lot size, frontage, and front-yard setback; a reduction in the average street width to 7.9 m; and an increase in all one-story houses to two stories.

(9) A street width of 7.9 m is sufficient to allow two lanes of traffic and one lane of on-street parking.

(10) An increase in the number of stories from one to two while holding the total area of the house constant results in a halving of the building footprint.

Design-oriented approaches to the stormwater problem

As illustrated in figure 4, modifications to each of the five regulated parcel dimensions were found to yield measurable and significant reductions to stormwater volumes per bedroom, albeit with differing magnitudes across increasing lot sizes. What follows in the concluding sections of the paper is a discussion of three specific planning strategies that, if adopted in municipal land-use regulations, would be likely to be effective in reducing stormwater volumes from new and existing development in the Madison study region.

Reconfiguring the lot: how the parcel frontage and setback influence runoff

The results of this analysis indicate that the single most effective design-based strategy for reducing development-induced runoff across a range of density levels entails a narrowing of the lot frontage. The benefits of a reduced parcel width are twofold. First and most importantly, a narrowing of the lot frontage reduces the quantity of street paving required to service the parcel (that is, the street allotment), which was found to account for roughly one third of the total impervious cover for an average residential parcel. For example, a reduction of the average lot frontage of 25%—a narrowing from 22.5 m to 16.9 m—is associated with a reduction in the street allotment of one quarter as well.(11) For a new residential development of 100 lots, such a reduction could eliminate almost 5500 m^2 of impervious cover—a quantity equivalent to the footprint area occupied by over 50 homes of average size in the Madison region.

Second, a narrowing of the lot frontage appears to increase the likelihood of multistory construction. When controlling for the capacity of the residential structure, the lot frontage was found to have a weak but significant negative correlation with the number of stories in the house ($r = -0.07$; $p < 0.001$), suggesting that builders may respond to narrow lot dimensions with multistory construction designed to maintain a minimum floor area in new homes. However, while measurable, the stormwater benefits associated with multistory construction are marginal. for a parcel between 500 and 1000 m^2, an increase in the number of floors from one to two stories reduces development-induced runoff per bedroom by only 3%, on average.

Overall, a 25% reduction in the lot frontage, holding all other variables constant, is associated with an approximate 10% reduction in development-induced runoff per bedroom for a parcel of average size in Madison. For a new subdivision of 100 homes of average size and configuration, such a reduction would reduce stormwater runoff from a two-year storm by approximately 165 m^3.

In addition to narrowing the lot frontage, a reduction in the length of the front-yard setback was also found to be significantly related to runoff volumes. Without any reduction in the size or capacity of the residential lot, a shortening of the average front-yard setback from 12.5 m to 9.4 m—a 25% reduction—would reduce the minimum mandated driveway area for a parcel of average size by about 15 m^2. For a new subdivision of 100 homes of average size and capacity, such a change in policy would reduce cumulative runoff volumes by approximately 60 m^3. The combined effects of a 25% reduction in the average lot frontage and front-yard setback would be a reduction in stormwater runoff of about 14%, or a volume equivalent to that retained by a rain garden of average dimensions.(12)

(11) This computation assumes a street width of 9.7 m.

(12) The University of Wisconsin—Extension rain garden manual notes that an average sized residential rain garden is between 9.3 m^2 and 27.9 m^2 in area and 15.2 cm deep. This observation assumes a rain garden area of 18.6 m^2 and a depth of 15.2 cm (Bannerman and Considine, 2003, pages 6–7).

Decreasing lot size: how density influences runoff

Higher density zones—areas characterized by smaller lot sizes—were found to be associated with lower runoff volumes per parcel than lower density zones. Although smaller lot sizes are correlated with narrower frontages and shorter front-yard setbacks, the effects of parcel area on runoff were found to be independent of its positive association with the width of the lot or positioning of the residential structure. Rather, larger lot sizes most directly influence runoff through the size of the building footprint and the area of lawn and landscaping. Controlling for the lot frontage, setback, number of bedrooms, and number of stories in the residential structure, lot size was found to have a significant positive correlation with both the combined building footprints ($r = 0.32$ $p < 0.001$) and the area of lawn and landscaping ($r = 0.99$; $p < 0.001$), indicating that lower density parcels are typically characterized by more impervious area and lawn area per bedroom than higher density parcels. It is this increased area of both impervious and pervious materials per unit of capacity that explains the positive association between lot size and development-induced runoff volumes.

In light of this finding, a straightforward approach to reducing runoff volumes simply would be to decrease the average lot size of new development. However, as illustrated in figure 4, reductions in the lot size of high-density parcels yields little measurable reduction in development-induced runoff volumes. This finding is reflective of the fact that, for small lot sizes, the proportion of the lot occupied by impervious materials is relatively large, and thus a reduction in the lawn area has only marginal impact on runoff volumes. As parcels increase in size, the percentage of the parcel occupied by impervious materials decreases and more of the runoff equation is dominated by lawn areas. As a result, a reduction in the size of the lot for large parcels, while holding the size of the impervious footprint constant, yields increasingly significant reductions in runoff. For parcels greater than 4000 m^2, a 25% reduction in the lot size is associated with a 12% reduction in average development-induced runoff volumes per bedroom, an improvement that is attributable largely to a reduction in the area of lawn and landscaping.

Although the stormwater benefits of higher density development can be statistically distinguished from the impacts of variable lot configurations, in actuality, smaller lot sizes are typically associated with narrower frontages and shorter front-yard setbacks. In combination with a 25% reduction in the lot frontage and front-yard setback, a 25% reduction in the average lot size is associated with a 16% reduction in stormwater runoff volumes per bedroom, on average, across all density classes. Also typically associated with higher density development is a narrower street width and multistory construction. If we reduce the average street width in Madison from an average of 9.7 m to 7.9 m—a dimension sufficient to support two lanes of traffic and one lane of on-street parking—and increase all one-story houses to two, in combination with these other strategies, the modeled reduction in stormwater volumes per bedroom increases to over 25%.

As illustrated in figure 4, the potential stormwater benefits associated with these design-based strategies in new development are greater for larger lot sizes. For lot sizes of 4000 m^2 or more, a 25% reduction in the lot size, frontage, and front-yard setback, in combination with a reduction in the residential street width to 7.9 m and an increase in the number of stories from one to two (for single-story houses), produces a reduction in stormwater runoff per bedroom that is approximately three times greater than that achievable through the same set of modifications to a parcel of 500 m^2 or less. Figure 4 also indicates that changes in these design attributes would yield variable benefits in different zones of the city. As discussed above, the stormwater benefits derived from reductions in the lot size, front-yard setback, and street width are greatest in low-density zones, whereas the benefit of a reduction in the frontage remains largely constant at any density level.

Managing stormwater in existing development

Although the potential to reduce the impacts of new growth is impressive, it is important to note that changes to a city's land-development regulations will have little, if any, impact on existing development. As the vast majority of the Madison region's 2020 built area is already in place, changes in future peripheral development will have only limited effects on total regional impervious land cover. In light of this observation, the most effective strategies for reducing regional impervious cover must address both new and existing development. One strategy for doing so would entail the modification of existing residential driveways and sidewalks. Found to account for a third of the average parcel impervious area,(13) driveways and sidewalks constitute a significant source of regional impervious cover, yet this component of parcel imperviousness could be reduced in area or modified to facilitate the infiltration of stormwater during the process of periodic resurfacing. Two approaches to reducing the stormwater impacts of established residential parcels include the replacement of traditional driveways with driveway 'runners' and the use of permeable paving materials in the resurfacing of driveways and sidewalks.

Driveway runners consist of two parallel strips of paving running the length of the driveway and separated by a two or three foot swath of gravel or grass. Through the removal of the middle component of driveway paving, roughly 8% of the impervious cover of a typical parcel can be eliminated with no loss of useful parking area. In light of the need to resurface residential driveways every ten to twenty-five years, runners can be constructed at little or no additional cost to homeowners beyond the expense of routine maintenance. Were runners to be used in place of driveways throughout the Madison study area, over 29 000 m^3 of stormwater runoff could be eliminated—offsetting the development-induced runoff resulting from approximately 1800 single-family parcels.

A second promising strategy for mitigating the stormwater impacts of established development entails the use of porous paving for the resurfacing of driveways and sidewalks. As the name suggests, porous cement and asphalt products are engineered to permit the infiltration of rainwater through small pores in the paving aggregate. Through proper installation over suitable soil types and continued maintenance, porous paving can achieve infiltration rates up to 80% (USEPA, 2002). For a typical parcel in the study region, the resurfacing of driveway and sidewalk areas with porous paving would reduce total parcel runoff volumes by approximately 16%. If used in the resurfacing of residential sidewalks and driveways throughout Madison over the next two decades, this strategy would offset the equivalent volume of about 6000 new single-family parcels. Although the potential benefits of porous paving are promising, an important disadvantage is the cost of installation, which can exceed that of traditional paving aggregates by a factor of two to three (USEPA, 2002).

One means of encouraging the use of alternatives to traditional driveway paving is through the creation or modification of a regional stormwater utility. Stormwater utilities are regional governing bodies created to assess a stormwater impact fee for all residential, commercial, and industrial development within a stormwater management district. Generally based on the square footage of impervious land-cover materials per parcel, stormwater utility fees create a monetary incentive for developers and

(13) This statistic does not include the street allotment in the computation of parcel impervious cover.

property owners to reduce the surface area of impervious materials. In the Madison region, for example, general impervious surface estimates based on the parcel area, square footage of the residential structure, and number of garage stalls are used to assess a stormwater fee twice annually for residential landowners. Such a fee structure could be modified in two ways to create a greater incentive for retrofitting driveway areas with paving alternatives.

First, the taxable impervious area could be expanded to capture the street allotment, creating a greater incentive to reduce impervious areas and assessing a greater impact fee on neighborhoods characterized by wide streets. Second, driveway areas could be taxed at a higher rate than building or street surfaces, and porous driveway areas not taxed at all, to create a targeted incentive to redesign driveway areas. The imposition of such a two-tier tax structure would hold the potential to modify existing development over time and would raise additional revenue to fund regional stormwater management.

Conclusions

The aim of this research has been to assess the role of municipal land-development regulations in the production of stormwater runoff in residential areas. Although the design of cities has long been responsive to the imperative of collecting and diverting stormwater away from urban centers, it is only with the emergence of large, sprawling metropolitan regions that the need to consider the impact of cities on regional water quality and availability has also become apparent. If municipal governments are to play a role in safeguarding regional water resources, the influence of municipal development policies on the problem of runoff must be better understood. To this end, this research has sought to quantify the influence of specific residential land development regulations on the production of stormwater runoff.

The results of this study provide compelling evidence that the regulated dimensions of residential parcels have a strong influence on the quantity of development-induced stormwater runoff produced from a typical two-year storm in the Madison, Wisconsin, study region. Specifically, the analysis suggests that reductions in the dimensions of the average residential lot size, frontage, front-yard setback, and street width contribute to a reduction in the volume of stormwater produced at the parcel level. In addition, an increase in the number of stories in the residential structure was also found to contribute to a reduction in parcel stormwater volumes. Significantly, these relationships were found to exist when controlling for the residential capacity of the parcel, suggesting that, for parcels designed to accommodate the same number of residents, lower density patterns of residential development in the Madison study area are associated with more stormwater production than higher density patterns. Overall, our findings suggest that physical changes to the dimensions of new residential parcels combined with the use of porous paving materials could reduce development-induced stormwater volumes by over 30% for the average parcel.

We believe the results of this research advance the field of urban environmental management in two important respects. First, the methodology developed to model stormwater runoff at the parcel level highlights the need to account for both the use and the intensity of urban development in measuring environmental performance. Because different zones of the city are governed by different land-use policies, any study seeking to gauge the environmental impact of a specific policy must isolate the zone of enforcement. As the most spatially disaggregate unit of regulatory control, the land parcel provides an optimal analysis unit for gauging the impacts of planning policies enforced at the parcel level. Related to this objective is the need to account for the distribution of population in assessing the environmental implications of alternative development patterns. In this study we control for the residential capacity of the single-family parcel to facilitate statistically valid comparisons between high-density and low-density models of development.

Second, this study demonstrates the runoff-inducing potential of specific land-use policies governing the size, configuration, and material composition of residential zones in a typical Midwestern city of the United States. Through the association of stormwater runoff with the parcel attributes of lot size, lot frontage, front-yard setback, number of stories, and street width, the contribution of specific zoning and subdivision regulations to parcel-based runoff can be reliably assessed. The benefits of these findings are twofold. First, municipal governments can better forecast the stormwater impacts of future growth in response to the established set of development codes; and, second, the relative effectiveness of various design-based and conventional stormwater remediation strategies can be better evaluated and compared, equipping municipal governments with an expanded array of stormwater management tools.

In closing, it should be noted that the design-oriented stormwater management strategies outlined herein will not prove sufficient to address the runoff problem in large urban regions fully. Although modifications to municipal development codes can significantly reduce the volume of runoff in new development at the urban periphery, remediation techniques, such as the use of detention basins, rain gardens, and vegetative roofing techniques, are essential strategies for mitigating runoff in the established urban core. Furthermore, although design-oriented strategies can significantly reduce runoff volumes, it is the deposition of chemical and pathogenic contaminants on urban surfaces that most directly contributes to the degradation of regional water bodies. These issues also require a more comprehensive approach to stormwater management. Nevertheless, municipal land-development regulations provide a critical tool to address the stormwater problem and one that has only rarely been employed aggressively for this purpose. It is our hope that this work can contribute to a better understanding of the role of local land-use planning policies in regional water quality management.

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