JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 45, No. 3 AMERICAN WATER RESOURCES ASSOCIATION June 2009

IS DENSER GREENER? AN EVALUATION OF HIGHER DENSITY DEVELOPMENT AS AN URBAN STORMWATER-QUALITY BEST MANAGEMENT PRACTICE[1]

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ABSTRACT: A simple spreadsheet model was used to evaluate potential water quality benefits of high-density development. The question was whether the reduced land consumed by higher density development (*vs.* standard suburban developments) would offset the worse water quality generated by a greater amount of impervious surface in the smaller area. Total runoff volume and *per acre* loadings of total phosphorous, total nitrogen, and total suspended solids increased with density as expected, but *per capita* loadings and runoff decreased markedly with density. For a constant or given population, then, higher density can result in dramatically lower total loadings than more diffuse suburban densities. The model showed that a simple doubling of standard suburban densities [to 8 dwelling units per acre (DUA) from about 3 to 5 DUA] in most cases could do more to reduce contaminant loadings associated with urban growth than many traditional stormwater best management practices (BMPs), and that higher densities such as those associated with transit-oriented development could outperform almost all traditional BMPs, in terms of reduced loadings per a constant population. Because higher density is associated with vibrant urban life, building a better city may be the best BMP to mitigate the water quality damage that will accompany the massive urban growth expected for the next several decades.

(KEY TERMS: urban areas; watersheds; urbanization; water policy; modeling; best management practices; stormwater management; watershed management.)

Jacob, John S. and Ricardo Lopez, 2009. Is Denser Greener? An Evaluation of Higher Density Development as an Urban Stormwater-Quality Best Management Practice. *Journal of the American Water Resources Association* (JAWRA) 45(3):687-701. DOI: 10.1111/j.1752-1688.2009.00316.x

A substantial increase in the United States (U.S.) population, mainly in urban areas, is forecast for the next 30 years. Urbanization is already a major contributor of the runoff pollution that degrades many of our waterways. This new urban growth will very likely contribute to further degradation, but because more than half of the urban built environment for 2030 has yet to be built (Nelson, 2006), we have an opportunity to substantially mitigate the effects of the new construction.

Most prescriptions for mitigating contaminated urban runoff involve practices that attempt to restore, to some degree, the predevelopment hydrology, usually through some form of infiltration and/or detention (Brabec *et al.*, 2002; USEPA, 2002; Clar *et al.*, 2004). Relatively low density development,

[1]Paper No. JAWRA-08-0105-P of the *Journal of the American Water Resources Association* (JAWRA). Received June 4, 2008; accepted November 11, 2008. **Discussions are open until six months from print publication**.

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which allows for much more pervious area per unit land area than denser development, is very often a key element of these prescriptions. A counter trend, however, is emerging that suggests that higher rather than lower population density, for a given population, may provide better water quality results at the watershed scale because less total land is paved over (e.g., Richards, 2006a,b). We examine here, through a modeling exercise, the hypothesis that clustering development at densities higher than those typically encountered in American suburbs can be a management tool for reducing the impacts of urbanization on the water quality of receiving water bodies. Our research is one of the first efforts to evaluate total runoff and total pollutant load as a function of urban density in per capita and per land unit terms. The results of this exercise could assist municipalities and other stormwater entities to evaluate the relative merits of high density as a stormwater best management practice (BMP).

THE IMPACT OF URBANIZATION

Urbanization degrades water quality and negatively impacts natural flow regimes (Beard and Chang, 1979; Booth and Jackson, 1997; Brabec *et al.*, 2002; Lee and Heaney, 2003; Hatt *et al.*, 2004; Alberti, 2005; Shaver *et al.*, 2007). Paved, impervious surfaces result in altered stormwater runoff patterns that include both greater volumes and higher rates of runoff, which directly and negatively impact receiving water bodies through channel modification, increased sediment loadings, and destruction of aquatic habitat. In addition, because of its greater speed and lack of opportunity for infiltration, urban runoff entrains significant amounts of contaminated effluvia and detritus, degrading further the aquatic ecology of receiving water bodies.

The Rise of Imperviousness as a Key Indicator

Rather than the degree of urbanization *per se*, imperviousness itself has become the predictor of preference in the literature for assessing the negative impacts of urbanization (Brabec *et al.*, 2002; Shuster *et al.*, 2005). The imperviousness model of the Center for Watershed Protection (CWP) (Schueler, 2003) is widely recognized and has an enormously high didactic value (Arnold and Gibbons, 1996). There is a direct, inverse relationship between the amount of imperviousness in a watershed and a host of chemical and biotic indices for stream health. Of particular note are thresholds at 10 and 25% watershed imperviousness for impacted and degraded watersheds, respectively.

The CWP imperviousness model is based on *watershed* imperviousness, but almost all ordinance and policy measures derived from this model to date focus on *site or project* imperviousness. Most municipalities that incorporate imperviousness into their stormwater ordinances specify a minimum amount of pervious cover to be left on an individual site, with the intent of course to protect the watershed. But by setting the unit of management and policy at the site level rather than a larger area, such as a watershed, managers may overlook denser, more clustered patterns of urbanization that, for a given population, could result in better water quality for the receiving streams and better overall watershed health than more disperse urban patterns that maximize site perviousness (see discussion in Implications, below). In this paper, we use the term "watershed" in its traditional sense of an area of land with a common drainage outlet (Dunne and Leopold, 1978). We contrast here what is often referred to as a "watershed approach" or the "watershed scale," in the sense of a larger, more integrated view of the landscape, regardless of its scale, with a narrower approach that focuses on the site.

BEST MANAGEMENT PRACTICES

The attenuation of polluted urban runoff is accomplished through control measures known as BMPs. The literature on BMPs is extensive (Pennington *et al.*, 2003; Fletcher *et al.*, 2004). Nonstructural BMPs include education and on-site practices such as fertilization control or reduction, good housekeeping, and "zoning restrictions to *limit* population densities" (Tsihrintzis and Hamid, 1997, italics added). Structural BMPs, on the other hand, are physical structures that collect and treat runoff. Treatment usually consists of filtration, detention, retention, and/or infiltration. The most commonly used BMPs are stormwater wetlands and ponds. Other BMPs include grassed swales, pervious pavements, green roofs, infiltration trenches, and sand filters, among others.

How well BMPs work is dependent on a number of features, including the design of the BMP itself, the soil or substrate, the sizing relative to the treatment area, etc. There are a number of ways to measure BMP effectiveness, each method subject to its own set of criticisms (Muthukrishnan *et al.*, 2004). Percent removal of a given contaminant is the most common measure. Table 1 shows removal efficiencies for the

TABLE 1. Median Pollutant Removal (%) of Selected Stormwater Treatment Practices (BMPs), Bracketed by 25th and 75th Percentiles.

	TN	TP	TSS
Stormwater dry ponds	5-24-31	15-20-25	18-49-71
Stormwater wet ponds	16-31-41	39-52-76	60-80-88
Stormwater wetlands	0-24-55	16-48-76	46-72-86
Filtering practices	30-32-47	41-59-66	80-86-92
Infiltration practices	2-42-65	50-65-96	62-89-96
Water quality swales	40-56-76	−15-24-46	69-81-87
Bioretention	40-56-76	−76-5-30	15-59-74

Notes: BMPs, best management practices; TN, total nitrogen; TP, total phosphorous; TSS, total suspended sediment.
Adapted from Center for Watershed Protection (2007).

most common BMPs. There is considerable variability in the reported removal efficiencies for any one BMP for any given pollutant.

Density as a Best Management Practice

Denser development, principally under the guises of Smart Growth and New Urbanism, has been touted as "greener" than conventional development (Berke *et al.*, 2003). Berke *et al.* (2003), for example, suggest that New Urbanist developments consume less land than traditional developments, making them greener than conventional developments. They document how "new urban developments are more likely to incorporate impervious surface reduction techniques and restore degraded stream environments than conventional developments." They appear to be suggesting that developments that are more compact enable greater options, on an overall project basis, for incorporating stormwater BMPs than do conventional developments, because less land is used per dwelling unit, and the unused land could therefore be used for BMPs. Girling and Kellett (2002) examined stormwater impacts of conventional, New Urban, and "open space" developments with relatively denser urban patterns, finding less pollutant loadings for the open space development, attributing the decreased pollution to preservation of open space. Density itself, however, is not considered as a BMP in either of these studies.

The question we explore here is whether by clustering populations, and thus ignoring to large degree individual site runoff characteristics, a better result is obtained for a larger area, for the same number of people. It is a question of total pollutant loading for a receiving water body. For a given population, what development pattern is going to result in the smallest *total* load, regardless of the amount of open space preserved? Low density suburban patterns, or denser patterns that use less land, even though runoff at the site level may be much worse? The hypothesis here is that *per capita* loading will be less with denser development *vs.* development that is more spread out. We already know, based on an extensive literature (e.g., Brabec *et al.*, 2002; Brett *et al.*, 2005; Shuster *et al.*, 2005), that the denser the development, the greater the pollutant load *per unit land area.* We wish to explore how per capita loadings play out in progressively denser development patterns *vs.* standard suburban densities. If per capita loadings decrease, then *for a given population*, the total load will also decrease, in which case higher density should be considered as a BMP in its own right, albeit with its own set of cautions and qualifications just like any other BMP.

How Dense is Dense?

Urban density is measured as gross or net density. Gross density is measured as number of people per unit land area and includes any and all open space, such as streets, parks, parking lots, etc., and the full spectrum of *net* density found in the area of concern (Churchman, 1999). Net density, on the other hand, is the density of residences only, which excludes streets and other open areas, and gives a somewhat more intuitive feel for what a given population density might look like on the ground. Net density is measured as dwelling units per unit land area, or dwelling units per acre (DUA) in the U.S.

An urbanized area is officially defined in the U.S. as at least 1,000 people/square mile population density (U.S. Census Bureau, 2000), calculating out to less than 1.6 people/acre, or about 0.6 households/acre, using the U.S. average household size of 2.61 people/household (U.S. Census Bureau, 2008). About 0.5 DUA is thus the minimum net density required to be considered urban under this definition. At low population densities (≤1,000 people/square mile), the correspondence between net and gross densities is often relatively straightforward, but things get more complicated at higher densities, where density can be much more uneven over the square miles that gross density is measured on, and one cannot simply multiply out the net density figures. There is no simple formula for converting gross to net density.

A full range of densities can be found in American urbanized areas and cities (Campoli and MacLean, 2007), from the minimum of 0.5 to 330 DUA (corresponding to a gross density upwards of 70,000 people/square mile) in the densest census block in America in Manhattan (Belmont, 2002). A comparison of water quality associated with denser development should examine the full range of urban densities that are being built in the U.S., but most such studies to date ignore the higher density ranges. Burns *et al.* (2005), for example, in examining the effects of suburban development on runoff generation in New York State, qualified 1.1 DUA as "high density" development (compared with a "medium density" of 0.6 DUA), finding altered runoff patterns at the higher densities. Brander *et al.* (2004) modeled runoff from "new urban" development with 7,300 square-foot lots, or about 5-6 DUA, also finding altered runoff from the new urban developments, but less overall impact than that associated with standard suburban densities.

In almost every water quality study looking at the impact of urbanization, urbanization itself is the nuisance that must be ameliorated (e.g., Hatt *et al.*, 2004; Alberti, 2005; Brett *et al.*, 2005). To many stormwater practitioners, higher density urbanization as a solution for the environmental impacts of urbanization must seem somewhat like treating lead poisoning with more lead, perhaps explaining why few of them have ventured into studying the environmental benefits of higher density.

MODELING URBAN RUNOFF

Most studies of urban runoff water quality are limited to broad categories of residential, commercial, and industrial zones, with occasional reference to low-density and high-density residential zones (Brabec *et al.*, 2002; Brander *et al.*, 2004). There are very few, if any, studies of urban runoff water quality that characterize land use in terms of both density and land use in any detail. We can find no study that characterizes urban runoff in terms of the residential and mixed-use densities that might be found in many emerging transit-oriented developments (e.g., 40-100 DUA). We use a modeling approach here to examine the water quality impacts of the full range of residential densities found in U.S. cities.

There are a variety of runoff models available, from the very simple to the very complex. For comparative purposes, particularly in terms of policy, the simpler the model the better, because simpler models tend to focus on fewer but highly predictive factors. There are any number of very complex models available to model urban runoff (e.g., Chen and Adams, 2006) but the precision that a complex model might provide is not always warranted given the error associated with the data available to populate the models (see below). Simple models are best for comparing broad land use differences, such as we are interested in here, and one of the best and most commonly used simple urban runoff models is simply known as the "Simple Method" (Shaver *et al.*, 2007). We do not mean to imply, by using a simple model, that urban runoff is a simple process; it most certainly is not. But given that state of our current knowledge, the Simple Method model provides enough precision for the level of management decisions that we are addressing here, without getting lost in extraneous details.

The Simple Method

The Simple Method utilizes simplified runoff parameters that strip the runoff process down to its barest essentials. The review here is taken directly from Schueler (1987) and the Center for Watershed Protection (2004). The Simple Method equation is

$$L = 0.226 \times R \times C \times A, \tag{1}$$

where L is the annual load (lbs); R is the annual runoff (inches); C is the pollutant concentration (mg/l), which is a function of land use; A is the area (acres); and 0.226 is a unit conversion factor (to convert to English units). Runoff R (inches) is derived from

$$R = P \times P_{\mathrm{j}} \times Rv, \tag{2}$$

where P is the annual rainfall (inches), P_{j} is the fraction of annual rainfall events that produce runoff (usually 0.9), and Rv is the runoff coefficient, which is derived from

$$Rv = 0.05 + 0.9\ \mathrm{Ia}, \tag{3}$$

where Ia is the impervious fraction.

The Simple Method model ignores contributions from soils, such as are accounted for in the Curve Number method (USDA, 1985). In this exercise, we are holding all factors constant except those associated with land use; we thus need not be concerned with soil factors in this comparison. The two components of this equation that can be varied to model land use in a given area are the pollutant concentration factor, C, or event mean concentration (EMC) as it is more commonly referred to in the literature, and the impervious fraction, Ia.

We used this equation to construct a simple spreadsheet model to gauge the effects of urban density on runoff water quality. We chose total nitrogen (TN), total phosphorous (TP), and total suspended sediment (TSS) as pollutants to model, as these are among the most common urban pollutants in the country (USEPA, 1983; Center for Watershed Protection, 2007). We examined urban densities ranging from 4 to 256 DUA (Figure 1), encompassing most of the range of developments in the U.S. (Campoli and MacLean, 2007). There are other measures of urban density that more accurately address nonresidential areas, such as occupancy in terms of person-days for commercial zones. For simplicity, we restrict ourselves to residential density. We used 4 DUA as our basis for comparison with higher densities. Using 2000 census tract data, our measurements of gross suburban densities in Houston, Texas average between 3,000 and 4,000 people/square mile. Measured net density of residential subdivisions in these areas is about 4 DUA. Both values are consistent with ranges reported for suburban environments in the U.S.

We used 32 inches annual rainfall value, the value at Austin, Texas (National Weather Service, 2004), and Ia and EMC values as discussed below.

Impervious Fraction

We chose 30% imperviousness for our 4 DUA scenario, which is the default model value that the CWP uses for "medium density residential" land use of 2-4 DUA (Center for Watershed Protection, 2004). For the 16 DUA scenario, we chose the model default value of 60% imperviousness for commercial zones. For 256 DUA, we assumed 100% imperviousness. Intermediate values were chosen somewhat arbitrarily by selecting values that gave a smooth runoff volume curve (Figure 2) using the simple model to obtain R as described above. The numbers chosen bias the results somewhat against higher density development in this comparison. Much of the literature, for example, uses values closer to 40% imperviousness for standard suburban densities (e.g., Brabec *et al.*, 2002). Sixteen DUA, approximately equivalent to 2,500 square-foot lots, is likely less impervious than the typical commercial district.

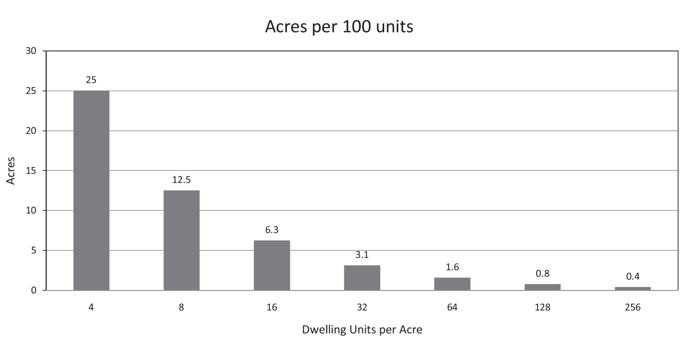

FIGURE 1. Density Range Examined in This Paper With the Number of Acres Occupied by 100 Units at the Given Densities.

Event Mean Concentrations

The EMC is an average or "flow-weighted" pollutant concentration that is "representative" for runoff from a particular land use (Shaver *et al.*, 2007). The EMC can be thought of as the total pollutant load divided by the total volume of a particular storm. As might be expected, EMC values vary greatly between land uses (Table 2), but also within land uses when measured from region to region, and to a lesser degree, even within land uses at a given location (USEPA, 1983; Fletcher *et al.*, 2004; Pitt *et al.*, 2004).

Given the relatively high variability of EMC values for urban runoff, is it reasonable to expect that we can confidently model runoff as a function of density? We can because in terms of policy we are interested in trends, not absolute values. Given a particular set of data, we want to know how denser development compares with lower density and with other BMPs acting on lower density development in reducing stormwater runoff and loadings. And because we are using a simple spreadsheet model, the datasets can easily be varied for an analysis of the sensitivity of the model to varying EMC and imperviousness values.

One of the most detailed studies of urban runoff was accomplished by Barrett *et al.* (1998) for creeks in the Austin, Texas area. This study characterized urban runoff in terms of percent impervious surface and in terms of land use. They found percent impervious surface to be a better overall predictor of water quality than land use. We chose to use the equations developed in the Bartlett study as the input for our modeling effort (Table 3). Note from Table 3 that predictive equations could not be obtained for all pollutants, as the R^2 values were too low. We used the average values developed by Barrett *et al.* (1998) for nitrate and TSS as model input values for these pollutants that were too variable for a predictive equation. Nitrate was added to total Kjeldahl nitrogen (TKN) to obtain TN (Barrett *et al.* provided no values for NO_2, which we assumed to be negligible for this modeling exercise).

We used the impervious fraction values for given residential densities as described above as input into the predictive equations derived in the Austin study to obtain EMC values for our modeling. These values constitute the basis of our "model scenario." Both TN and TP EMCs increased with increasing density using the formulas derived from the Austin study (Table 3). The Austin study did not characterize land

TABLE 2. Median Event Mean Concentrations by Land Use Category (USEPA, 1983).

	Residential		Mixed		Commercial		Open/Non-Urban	
Pollutant	**Median**	**CV**	**Median**	**CV**	**Median**	**CV**	**Median**	**CV**
TSS	101	0.96	67	1.14	69	0.85	70	2.92
TKN	1.90	0.73	1.29	0.50	1.18	0.43	0.97	1.00
$NO_3 + NO_2$ N	0.74	0.83	0.56	0.67	0.57	0.48	0.54	0.91
TP	0.34	0.69	0.26	0.75	0.20	0.67	0.12	1.66

Notes: TKN, total Kjeldahl nitrogen; TP, total phosphorous; TSS, total suspended sediment.
All event mean concentration values are in mg/l.

TABLE 3. Event Mean Concentration Values, Austin Scenario (mg/l) Derived From Barrett *et al.* (1998).

Ia	TP $y = 0.3177x + 0.1944$ $R^2 = 0.1546$	TKN $y = 1.4104x + 0.6852$ $R^2 = 0.4419$	NO_3	TN	TSS
0.30	0.29	1.09	0.82	1.91	190
0.45	0.34	1.16	0.82	1.98	190
0.60	0.39	1.23	0.82	2.05	190
0.75	0.43	1.30	0.82	2.12	190
0.85	0.46	1.34	0.82	2.16	190
0.95	0.50	1.39	0.82	2.21	190
1.00	0.51	1.41	0.82	2.23	190

Notes: TKN, total Kjeldahl nitrogen; TN, total nitrogen; TP, total phosphorous; TSS, total suspended sediment.
$TN = TKN + NO_3 + NO_2$.

use in detail, however, and it is unlikely that both TP and TN would increase with increasing density in residential land uses, as lawns may contribute as much as 50% of the total P load from suburban residential areas (Pitt *et al.*, 2004), a loading that would logically decrease as density increases and lawn size decreases. The values used here are thus somewhat conservative in terms of the effect that density will have on water quality (i.e., the model will likely predict worse water quality values for higher density than may be the case if better data were available for both land use and density).

RESULTS OF THE MODELING

We are interested in comparing *per acre* and *per capita* stormwater loadings from different density scenarios. For comparative purposes we chose 100 units as our basis of comparison. The numbers of acres occupied by 100 units for varying densities are shown in Figure 1. The fundamental question is whether the reduced acreage from which the contaminated runoff is originating offsets the presumably progressively worse runoff water quality from the denser urbanizations.

Table 4 contains the results of modeling urban runoff on a log-2 DUA-density scale using the Simple Method with the “model scenario” input values. Results for annual loadings for the three selected pollutants and runoff volume are detailed on both per acre and per 100-units bases. The results are graphically displayed in Figures 2-10.

TABLE 4. Annual Loadings and Runoff Volumes Associated With Higher Density Development, Austin EMC Values.

		Annual Pollutant Loadings (lbs/year)									Annual Runoff Volume (cf/year)/10,000		
		TN			TP			TSS			*R*, cf		
DUA	Ia Fraction	Per Developed Acre	Per 100 ‘Units	% Reduction *vs.* 4 DUA	Per Developed Acre	Per 100 Units	% Reduction *vs.* 4 DUA	Per Developed Acre	Per 100 Units	% Reduction *vs.* 4 DUA	Per Developed Acre	Per 100 Units	% Reduction *vs.* 4 DUA
4	0.30	4.0	100	0	0.60	15	0	396	9,893	0	3.3	84	0
8	0.45	6.3	79	26	1.00	12	17	563	7,034	29	4.8	59	29
16	0.60	9.0	56	51	1.48	9	39	730	4,560	54	6.2	39	54
32	0.70	11.0	34	69	1.92	6	58	841	2,802	72	7.1	22	73
64	0.80	13.2	21	82	2.33	4	74	952	1,575	84	8.0	13	85
128	0.95	16.8	13	90	2.92	2	85	1,119	874	91	9.5	7	91
256	1.00	18.0	7	95	3.17	1	92	1,175	459	95	9.9	4	95

Notes: DUA, dwelling units per acre; EMC, event mean concentration; TN, total nitrogen; TP, total phosphorous; TSS, total suspended sediment.

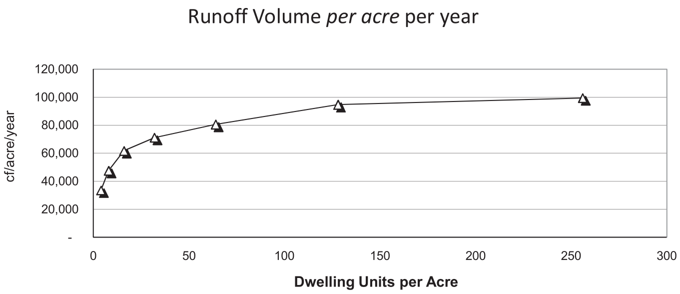

FIGURE 2. Runoff Volume, Per Acre Per Year, as a Function of Dwelling Units Per Acre, From Values in Table 4.

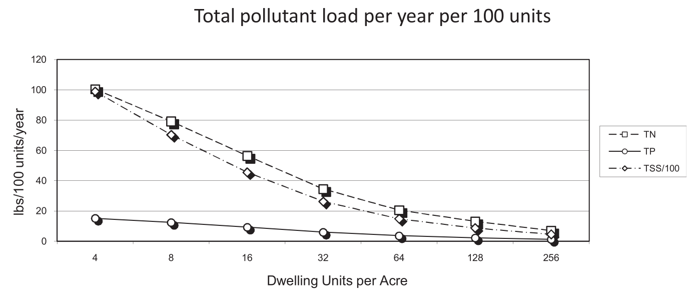

FIGURE 6. Total Pollutant Load Per Year Per 100 Units.

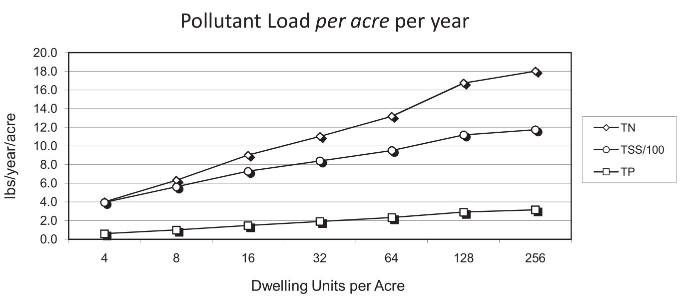

FIGURE 3. Pollutant Load, Per Acre Per Year, for Selected Pollutants as a Function of Dwelling Units Per Acre.

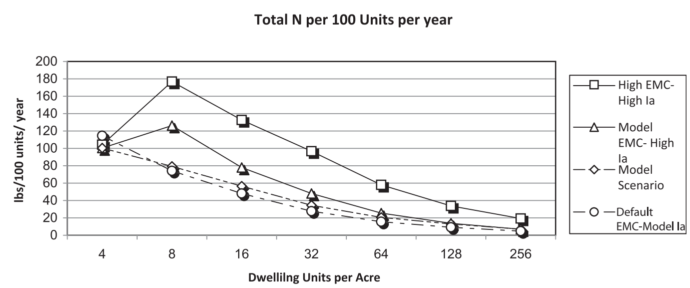

FIGURE 7. Total N, Per 100 Units, as a Function of DUA and EMC and Ia Variability.

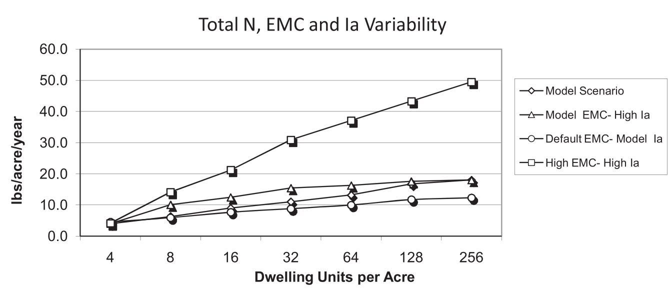

FIGURE 4. Total N, Per Acre Per Year, as a Function of DUA and EMC and Ia Variability.

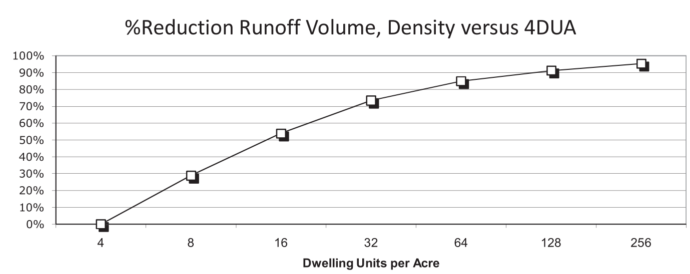

FIGURE 8. Reduction in Runoff Volume Per 100 Dwelling Units for Higher Densities *vs.* 4 DUA.

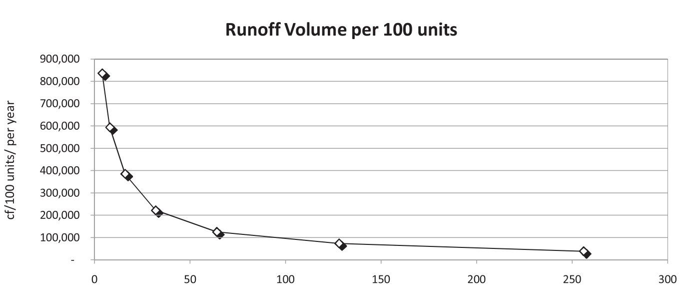

FIGURE 5. Runoff Volume, Per 100 Units Per Year, as a Function of Dwelling Units Per Acre, Model Scenario.

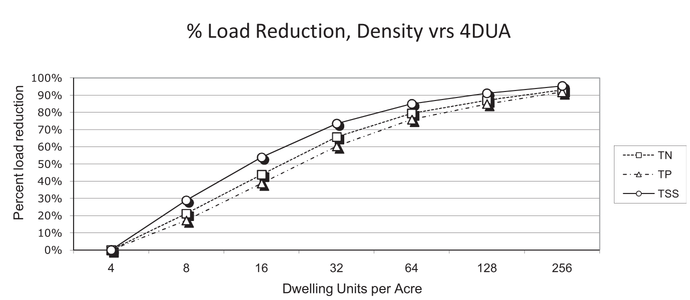

FIGURE 9. Reduction in Total Pollutant Load Per Year Per 100 Dwelling Units for Higher Densities *vs.* 4 DUA.

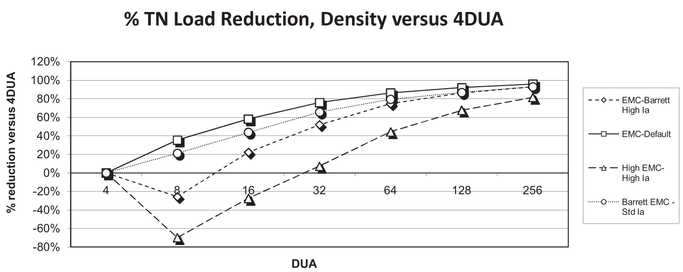

FIGURE 10. Reduction in Total Nitrogen Load Per Year Per 100 Dwelling Units for Higher Densities *vs.* 4 DUA, EMC and Ia Scenarios.

As expected, per acre runoff volume and pollutant loadings increased dramatically as density, as measured by DUA, increased from 4 to 256 DUA (Figures 2 and 3). Runoff volume on a per acre basis increased threefold, and TN, TP, and TSS loadings increased four, five, and threefold, respectively. These per acre results are well documented and do not represent a novel finding (e.g., Wang *et al.*, 2001). These figures of course are for a discrete set of data, which, as discussed above, are highly variable from place to place.

As a test of the sensitivity of the model, we chose higher and lower values for EMC and Ia and modeled the effects on TN (Figure 4). The Model Scenario used the same EMC and Ia values in Tables 3 and 4, and is the same TN curve as in Figure 3. The Model EMC – High Ia scenario used the same EMC values as the Austin or model scenario but increased Ia to 0.75 and 0.85 for 8 and 16 DUA respectively, and 1.00 for higher DUAs. The High EMC – High Ia scenario used the same Ia as the Model EMC – High Ia run, but increased the EMC for 4 DUA to 2.00 mg/l and increased the EMC for each successive density increment by 1.00 mg/l, ending with a very high and likely unreasonable value of 8.00 mg/l for 256 DUA. The EMC default scenario used the Ia values associated with the Austin or "model" scenario above but the EMC "default values" used by the CWP for the Simple Model (Center for Watershed Protection, 2004), which is 2.2 mg/l for 4 DUA and the commercial zone value of 2.0 mg/l for all higher densities.

The lines in Figure 4 might be thought of as a kind of envelope for a range of values that might be expected in an urban setting, given the variability for both Ia and EMC values. The High EMC – High Ia scenario, however, is likely outside the range that would be encountered for TN in most urban settings, as discussed above.

Inverse results are obtained when the data are looked at on a per capita, or in this case, a per-100-dwelling unit basis (Figures 5 and 6). Runoff volume (Figure 5), graphed on a standard rather than log-2 scale, decreases precipitously between 4 and 32 DUA, with an asymptotic decline beyond 64 DUA. The total pollutant load per 100 units, plotted on a log-2 scale (Figure 6), mirrors the runoff volume pattern.

For the values used in this "model" scenario, 100 units with any density at least twice that of suburban densities results in *less* of a *total* runoff and pollutant load for the same 100 units developed at a lower density. In spite of the fact that *per acre* loads are higher for higher density, the reduction in area from which polluted runoff occurs more than offsets the higher concentration of pollutants emanating from the reduced area, at least with the model values used here. This is a reduction achieved strictly with higher density (and thus a lower impact area) with no additional treatment of the runoff, and irrespective of any land savings that might be achieved. This simple result is the most salient and important result of this study. Results would vary from location to location, of course, using input values other than those we have used here. As discussed above, the higher density EMC values used in this model scenario, particularly for TN and TP, may be significantly higher than is likely to be the case in most dense residential conditions. Smaller EMCs for the higher densities would result in even greater reductions in runoff volume and loadings per 100 units, *vs.* suburban densities, than we show in the model scenario.

Interestingly, the most significant reductions in per capita loadings *vs.* 4 DUA occur between 8 and 64 DUA, well within the range of compact development patterns occurring in many cities and towns across the country (Campoli and MacLean, 2007), suggesting that high-rise density is not required to achieve significant load reductions. The reduction shown in Figures 5 and 6 is of course for one particular set of data, our "model" scenario. What happens under higher EMC and higher Ia scenarios? Figure 7 reveals, using the same scenarios as Figure 4, that higher EMCs and/or Ia fractions could indeed result in higher per capita loadings as density increases, particularly for the High EMC – High Ia scenario. But even under this worst-scenario, higher densities (above 32 DUA in this case) do eventually result in a per capita load reduction *vs.* 4 DUA, with per capita loadings in fact asymptotically approaching zero at very high densities.

It would appear, then, that in very many cases higher density will eventually result in much lower pollutant loads, for a constant population, than those associated with the standard suburban 4 DUA-density pattern. At what point higher density actually results in a load reduction will depend on the specific EMC values and imperviousness fractions used. The data modeled here suggest that for residential land uses with average runoff pollutant characteristics, a simple doubling in density will result in a significant total load reduction, for a given population, with higher densities resulting in progressively greater per capita load reduction. If that is the case, then higher density should be considered a stormwater BMP in its own right, given that the purpose of BMPs is to reduce pollutant loads.

One way to evaluate density as a stormwater BMP is to compare per capita load reductions obtained with higher density against the reductions that might be obtained with "normal" (be they standard or low impact development) BMPs acting on standard suburban density developments. Because normal stormwater BMPs are evaluated in terms of percent reduction of a given pollutant, we constructed a set of curves (Figures 8-10) showing the percent reduction in runoff volume and pollutant loads for higher densities *vs.* 4 DUA. These curves of course inversely mirror the total per capita runoff volume and pollutant load curves of Figures 5-7. Figure 10 is again the "envelope" of possible percent load reductions for TN using the same scenarios as that described for Figures 4 and 7.

For TP, for example, pollutant removal efficiencies for standard stormwater BMPs range from 5% to 65%, depending on the specific practice, with considerable variation for each BMP as well (Table 1). If we make our basis of comparison 100 dwelling units at 4 DUA, then we can compare the percent reduction in TP that higher density provides (Table 4 and Figure 9), using the Ia and EMC values in the Austin or model scenario. Densities above 64 DUA (which gave a 74% reduction in Total P *vs.* 4 DUA) outperform the median reduction values of even the best performing BMPs (65%, Table 1). This is a broad comparison of course – there is considerably more slack and overlap than is implied by the comparison of a few data points (e.g., Figure 10). Nonetheless, we can at least confidently state that, with this data, in general DUAs of 64 and above are at least comparable to and likely provide greater reductions in terms of TP than most of the "normal" treatment BMPs acting on runoff from standard suburban densities of 4 DUA.

It is important to remember in this comparison that BMP efficiency is limited by the area of treatment. In the comparison so far, we have assumed that 100% of the 100 dwelling units at 4 DUA would be treated by the BMPs, a result not always obtainable in practice. Further, if we used somewhat more realistic values consistent with the reported reduction in P loadings as density increases (Pitt *et al.*, 2004), then density would rate considerably better. For example, using the EMC model default values of the Center for Watershed Protection (2004) of 0.4 mg/l P for residential areas for 4 DUA and the default commercial value of 0.2 mg/l for 8 DUA and above, then 8 DUA results in a 60% P load reduction *vs.* 4 DUA development, a value that exceeds the median value of almost all the BMPs.

Curves for comparing load reduction efficiencies for high-density development *vs.* standard 3-5 DUA development could easily be constructed for any locality. The more local the data, the more precise the comparison will be, particularly if local data is available for BMPs as well. How well BMPs work is very much dependent on local soil, geology, and climatic conditions (e.g., USEPA, 2002).

At least two caveats are associated with this modeling. One is that we only deal with pollutant load and total runoff volume. We have not directly addressed the hydrologic flashiness that is associated with impervious areas (e.g., Dunne and Leopold, 1978; Lee and Heaney, 2003). The issue of stormwater detention and floodwater control is a separate, although not unrelated issue from the water quality that is the focus of our paper. Nothing we present here suggests that higher density alone would absolve cities of the responsibility they have always had to address the downstream impacts of greater amounts and rates of runoff. The data developed here do suggest, however, that per capita and thus total volumes of runoff for a given population would be reduced, reducing therefore the overall energy of the flashiness.

A second caveat is that an underlying assumption of our use of the Simple Method is that all imperviousness is "equally impervious," and more importantly, perhaps, that all imperviousness is connected (see Alley and Veenhuis, 1983). We recognize that this may not always be the case. But while lawns and similar open areas in suburban zones are more pervious than concrete, because of construction processes and associated compaction, they are certainly not nearly as pervious as undisturbed prairies (Booth and Jackson, 1997). Thus for our purposes, the assumption of connected imperviousness may not be too far from the mark.

IMPLICATIONS

The data from this modeling exercise suggest that for given populations substantial stormwater pollutant load reductions can be obtained by increasing urban densities relative to standard suburban densities.

The key phrase here is "for given populations." For a single watershed, or any specific area for that matter, higher density over the *entire area* will invariably result in a greater total pollutant load than development at lower density over the same area. The challenge here is to determine at what scale a per capita approach to loading would be more appropriate than a per unit land area approach. For example, the Houston metro area expects another three to four million people or so within the next 20-30 years (http://www.h-gac.com/rds/forecasts/default.aspx). At current suburban densities of 4,000 people/square mile, those four million people will occupy an additional 1,000 square miles of farmland, forests, and prairies. A simple doubling of average residential density to 8,000 people/square mile (roughly equivalent to 8 DUA) would save 500 square miles of open and natural areas, and, according to the modeling in this study, result in a significantly less total pollutant load on area bays and bayous. At this larger, more regional scale, a per capita approach is clearly advantageous in terms of managing total loads.

At the local scale, however, there will always be special areas that should not be developed at all or at most be subjected to very diffuse development. The advocacy or use of higher density as a stormwater BMP does not absolve stormwater or watershed managers of the necessity to conduct rigorous site analyses as to where development should go in any particular watershed, or what areas should be preserved, should their jurisdiction have the power to control the location of development. This exercise merely reveals that consolidated development in denser zones for a given population has a demonstrable water quality benefit. Choices must still be made about where development should and should not go.

Enabling denser development to some degree would remove development pressure from some areas, but some mechanisms would still be required to preserve open space, particularly sensitive areas, at least in the short run. Open space, particularly relatively undisturbed natural areas, has ecological benefits and values that go well beyond water quality (Howarth and Farber, 2002; Benedict and McMahon, 2006). It may be somewhat presumptuous to think that simple stormwater treatment BMPs in suburban settings can restore anything beyond the simplest watershed functions of natural areas. There is some evidence (cited in Brabec *et al.*, 2002, p. 508), in fact, that BMPs may not be able to mitigate the adverse impacts of urbanization on some aquatic parameters above about 20% watershed imperviousness. This is not to say that steps should not be taken to restore some natural functions of urban streams, as Derek Booth (2005) suggests we should do in spite of the fact that it is unlikely we could have any hope of fully restoring all natural functions of these streams in urban settings. Analogously, we should attempt to mitigate urban runoff where we can, since any pollutant reduction is beneficial. The point here is that natural areas have some intrinsic values that normal stormwater BMPs cannot hope to replicate, and that we should not delude ourselves that we are protecting these functions, in any significant manner, by installing some relatively simple stormwater BMPs to improve stormwater runoff. There is much more that we do not know about natural ecosystems than we do know, and perhaps more than we can know or even imagine (Gardner, 1991). From watershed policy perspective, then, BMPs which both reduce pollutant loads and enable the preservation of larger and thus more ecologically significant areas (Collinge, 1996) should rank higher than those that do not.

Implementing density as a BMP in terms of land consolidation would be problematical but worth considering for achieving a higher level of watershed health. Sensitive areas are often managed by imposing a maximum impervious surface requirement on development, something much easier and fairer to implement at the site level even though the intent is protection at the watershed level. The City of Austin, Texas, for example, has a maximum impervious surface limitation of 15% for the sensitive Barton Springs recharge zone, and it is administered on a site basis (City of Austin, Texas, n.d.). Consolidating the imperviousness into one area, say by allowing much greater density in that area, could certainly have greater benefits at the watershed scale (e.g., in terms of less habitat fragmentation), but would be much more difficult to administer, likely involving sticky property rights issues. While more difficult, consolidating open space or developed areas could perhaps be made more feasible by mechanisms such as transfer of development rights (Johnston and Madison, 1997).

Clustering of development into higher density areas raises another issue not addressed here. We used the Simple Method to measure the effect of changes in net density on discrete pieces of land only. But as development gets more spread out, there is an additional increment of public impervious cover that we have not accounted for. The larger the frontage and the lower the density, the greater the portion of public right of way that each driver or pedestrian would have to traverse to get to the next parcel, which could amount to a significant fraction of the overall impervious cover, especially considering the wider roads favored in recent years (L. Nisenson, October 7, 2007, personal communication). Accounting for this additional imperviousness would only improve the high-density comparison *vs.* low suburban densities.

Higher urban densities also have significant benefits not related to water quality or habitat conservation. While not addressed directly in this paper, they should not go unmentioned because planners can rarely limit themselves to a single aspect of any one issue related to urban form. Environmental practices that benefit several sectors or issues provide a much better overall return on investment. The reduction in per capita stormwater loadings with increasing urban density correlates well with emerging research suggesting infrastructure costs of cities grow by fractional power law functions of population (Bettencourt *et al.*, 2007; Lehrer, 2008). Consistent with this, a well-developed body of literature is emerging that documents a growing list of benefits associated with compact growth patterns: reduced emissions of greenhouse gases (Norman *et al.*, 2006), greater health benefits associated with more walking (Frank *et al.*, 2005), potentially more resilience to coastal hazards (Jacob and Showalter, 2007), and in general more "livable" cities (Macdonald, 2005). The amenities we associate with urban life – walkability, proximity of shopping and restaurants, transit, etc., are progressively more available at higher densities and virtually unavailable at suburban densities (Farr, 2007).

This intersection of environmental and quality of life benefits associated with higher urban densities is particularly promising given the projected potential greater demand for housing in compact urban environments in the coming decades (Nelson, 2006). It is unfortunate that a site or project focus on stormwater impacts often militates against this convergence, as it does when minimum perviousness requirements reduce the amount of density that can be developed on a particular site, when in fact a greater environmental benefit might be obtained by higher density in many if not most cases, as documented above.

To our knowledge, higher density development (e.g., ≥16 DUA) is rarely incorporated into stormwater policy at either the federal or the state level. The Environmental Protection Agency's 2004 Stormwater BMP Design Guide (Clar *et al.*, 2004), for example, makes no mention of compact growth of any kind. But more recent publications from the USEPA (Nisenson, 2005; Richards, 2006b; USEPA, 2008) do promote density as a stormwater BMP, such that policy links may not be far behind.

Many states and municipalities do recognize the benefits of "conservation development." Conservation development (Arendt, 1996) is a form a higher density development that is based on concentrating development on a given tract, putting open areas resulting from the concentration into undevelopable conservation easements accessible by the development residents. Home sites in such projects often fetch a premium price because of the open space associated with the development. But densities in these kinds of developments rarely exceed 6-12 DUA on the developed portion of a site, and are extremely unlikely to be found on urban infill sites.

The Minnesota Stormwater Manual (Minnesota Stormwater Steering Committee, 2006) both recognizes the value of conservation development and provides a method for giving credits for preserved areas in conservation developments. But those credits only reflect the areas preserved, irrespective of the density of the developed portion of a project tract. A high-density development, greenfield or infill, would receive no credits unless land were preserved on site or perhaps elsewhere. Conservation development is a central focus of "better site design" in the Minnesota manual, which the manual describes in this language: "Few watershed management practices simultaneously reduce pollutant loads, conserve natural areas, save money, and increase property values. Indeed, if such 'wonder practices' were ever developed, they would spread quickly across the nation." High-density development, with no explicit land preservation, meets all of these requirements. The Better Site Design chapter in the Minnesota stormwater manual, as in most other stormwater manuals, makes no mention of higher density, except in relation to conservation development as described above.

There is much to extol, of course, in the better site design principles articulated in recent stormwater manuals, and in terms of conservation development and issues such as smaller lots and narrower streets, many of the principles are consistent with higher development densities. Some manuals, however, encourage design elements that promote automobile dependency and thus lower density development or sprawl. For example, the 2004 Connecticut Stormwater-Quality Manual (Connecticut Department of Environmental Protection, 2004) recommends a lollipop and cul-de-sac street design instead of a grid pattern because the former pattern results in less linear feet of street per unit land area. No mention is made that a grid pattern with higher connectivity is more conducive to denser, more walkable neighborhoods (Leslie *et al.*, 2007). If higher density were recognized as an effective stormwater BMP, then the grid pattern would be recommended instead of the cul-de-sacs.

A municipality or other stormwater entity is unlikely to decrease stormwater-quality requirements for higher density developments, much less incentivize them, without some kind of a standard procedure for making valid comparisons between BMPs, including density. Use of the Simple Method, as developed in this paper, with locally derived EMC and imperviousness values, could provide a very simple and direct method for evaluating the relative merit of denser developments, in spite of the variability associated with the available data.

Based on the model run here with the Austin EMC values, developments with an average DUA of at least eight could conceivably be given some kind of stormwater credit or reduction in treatment BMP requirements, and developments with DUAs higher than about 16–32 should likely be incentivized, the greater the density, the greater the incentive. Such incentives would of course have to be based on locally derived data.

Grand Rapids, Michigan, appears to be one of the first communities in the country to grant stormwater management waivers for higher density developments (Lemoine, 2007). If a high-density development can demonstrate at least an 80% reduction in the "equivalent impervious area" of the same development at low density (5 DUA in their case), then a waiver is granted for stormwater management features, in terms of detention, not necessarily water quality. Grand Rapids has determined that on average a DUA of 38 will result in an 80% reduction in impervious area (not too dissimilar, interestingly, from the 71% reduction in runoff volume *vs.* 4 DUA obtained from 32 DUA in this study) (see Table 4 and Figure 8). At present, the waiver is only granted for infill and not for greenfield development.

An emerging approach to stormwater management is to develop overall "runoff limits" for particular zones or watersheds (Wenger *et al.*, 2008). The idea is to establish the total volume of new runoff allowable in sensitive areas, regardless of what kind of development takes place. The case reported by Wenger *et al.* (a habitat conservation plan area near Atlanta, Georgia) allows for "development nodes" that could have higher density than other zones in the plan area. While this study focuses on on-site infiltration techniques to limit runoff volumes, there is no reason the high-density paradigm developed here could not be incorporated into such a scheme. Once a limit was established, it would be up to the community to decide what pattern of development to take: more people and higher density in a smaller area, or fewer people at lower densities over a larger area. The national Total Maximum Daily load system is of course based on similar allocations.

Up to this point, high density has been played off against low density and treatment BMPs as somewhat of an either/or state of affairs. In reality, this is rarely the case. Stormwater managers most often view individual BMPs as part of a treatment train, and rarely rely on a single BMP to solve all stormwater problems. High urban density can be viewed as one tool (albeit one of the best tools) within the BMP toolbox, and other BMPs can of course be used to reduce further the runoff from higher density developments. The data presented here, however, suggest that higher density development should not bear the same burden for runoff mitigation as lower density development, inasmuch as the total runoff load is potentially much less.

In terms of using density as a BMP, it comes down to context. Where does higher density work as a stormwater BMP, and what BMPs work in high-density environments? Some stormwater BMPs clearly do not fit in higher density environments and may even act to curtail density.

THE TRANSECT MODEL

The Urban Transect (Duany, 2002; Duany and Brain, 2005) is a recently developed conceptual model of the urban continuum, based on the biological transects method used to study biotic gradients. The Urban Transect artificially divides the urban gradient into six segments for the purpose of conceptualizing and developing appropriate urban standards for each segment. There is no specific DUA tied to these zones, but density obviously increases markedly from left to right (Figure 11). The T6 Urban Core zone would likely have DUAs in excess of at least 40-50, and could of course have much more. The urban transect model is a convenient schema for conceptualizing appropriate contexts for stormwater BMPs.

We argue above that urban density is as effective a BMP as many if not most standard stormwater treatment BMPs, depending on land use characteristics that shape EMC and Ia. If indeed density is a highly effective BMP, then any additional BMP that reduces density would have the possible effect of worsening rather than improving stormwater runoff on a per capita basis from dense urban areas. In effect, any BMP that disrupts the urban fabric could be counterproductive from a water quality point of view, and would most certainly be counterproductive from the point of view of urban vibrancy discussed above. The urban context of particular stormwater BMPs thus becomes very important.

In Figure 11, we attempt to place some of the more common stormwater BMPs in an urban context. This attempt is presented here only as a first approximation and to generate discussion and research about where particular BMPs might be most effective in the urban transect. It is not based at this point on a rigorous quantitative analysis. For example, it seems obvious that good housekeeping practices such as proper storage of fertilizer and prevention of fuel spillage would apply across all zones, as should environmentally friendly or "watersmart" landscaping. Landscaping would play an important role in all zones, but would seem less significant in the T6 zone simply because there would be less landscaping overall in that zone. Porous pavement could conceivably play a role in denser urban environments, in parking lots, for example,

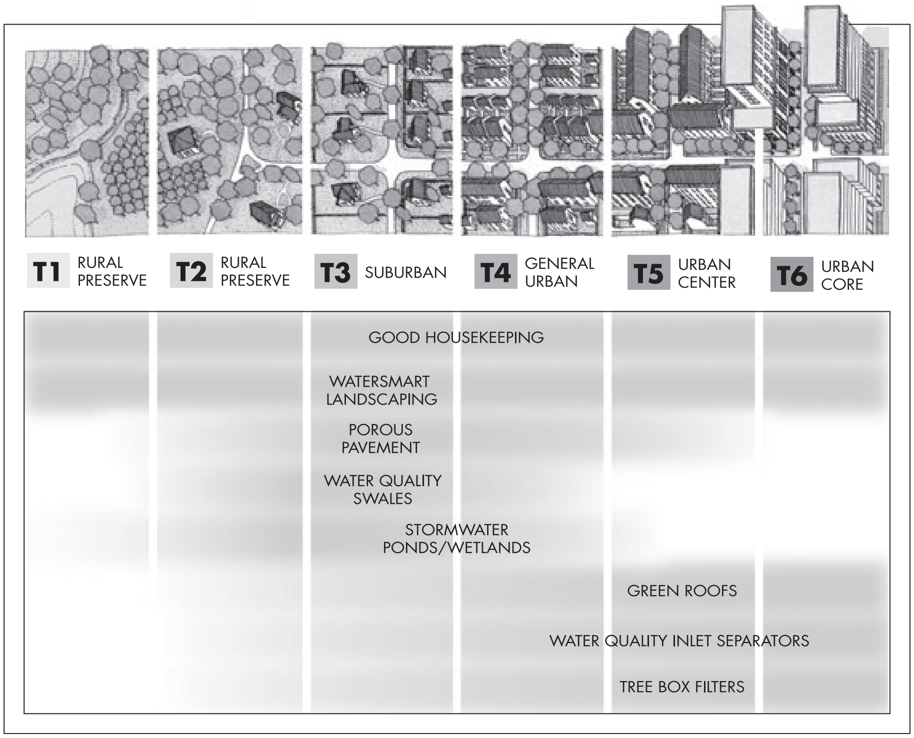

FIGURE 11. The Urban Transect (upper frame – adapted from Duany, 2002) and Proposed Alignment of Best Management Stormwater Practices.

but would not likely stand up to the intense use that would be required in the most trafficked areas of these zones (e.g., T5-T6). Water quality swales and stormwater wetlands would appear to be out of place within the T5 and T6 zones proper. This does not mean that stormwater wetlands could not be located in close proximity to a T5 or a T6 zone, only that it would make no sense to disrupt the urban fabric in order to incorporate a wetland. An argument could be made, in fact, that larger wetlands just outside dense urban zones treating runoff from these zones might be more productive from both a water quality and an ecological perspective than small on-site infiltration systems treating the same runoff.

There are many stormwater practices that are completely consistent with dense urban zones, such as green roofs, tree box filters, and water quality inlet separators. These are fairly effective practices that do little to disrupt the urban fabric and therefore are not likely to result in a decrease in density.

CONCLUSION

The Simple Method for modeling runoff water quality enables a fairly robust method for comparing stormwater runoff water quality amongst developments of varying densities. This modeling exercise demonstrated that high-density development in a great many cases could result in less of a stormwater pollutant runoff load than that associated with standard suburban densities with the same number of dwelling units in the same environment. In most cases, at least double standard suburban densities (e.g., ≥8 DUA) would be required to have a significant reduction in per capita pollutant loads *vs.* suburban densities. In almost all cases it is very likely that densities above 16-32 DUA would have substantial per capita reductions in both runoff volume and pollutant load.

The reduction in per capita pollutant load is not strictly a function of land savings as a result of clustering development. Modeling across a range of input data revealed that the reduction is more a function of the reduced area from which the runoff is generated. The reduction in impacted area appears to more than offset the higher per acre pollutant loads that are generated from the denser development. This phenomenon is more pronounced the greater the density.

The land savings associated with higher density development is an ancillary but very important benefit of a more compact urban pattern. Higher density development would not automatically preserve natural areas of local or regional importance, although it would certainly reduce development pressure if it occurred in high enough proportions. In the short run, at least, communities would need to take action independent of promoting higher density to preserve these areas.

Higher density development could fit into the existing regulatory stormwater framework under the rubric of "alternate site design." Some agencies already give stormwater credits to developments (e.g., conservation subdivisions) that preserve open space or natural areas in particular projects. Given the benefits demonstrated here of higher density development independent of any land savings, it would seem reasonable for stormwater regulators to give stormwater credits for developments above certain densities, not associated with any land banking or set asides, with the thresholds to be determined based on local site characteristics.

Because well designed, higher density is emerging as a key parameter in defining walkable, more livable cities (Farr, 2007), it would seem that building a denser city is not only not contrary to improving runoff water quality from urban areas, it may be the single most important practice any city can undertake to improve the surrounding environment.

ACKNOWLEDGMENTS

This paper benefited from substantive reviews by Lisa Nisenson, Randel Lemoine, and Chet Arnold. Three anonymous reviewers for an American Planning Association special session at their national meeting in 2008 and three reviewers for this journal also contributed greatly to the improvement of this paper. We are grateful to all.

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