

Pattern and Variation in Development of Small Urban Watersheds

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Abstract

Increased urbanization has been correlated with hydrologic, chemical, geomorphologic, and biologic changes to receiving streams. Therefore, the status quo in watershed management has been to control the amount of impervious surface area. However, because various measures of development and impervious surface area are correlated, it is hard to discern what aspects of development cause adverse ecological impacts: impervious surface area is correlated with stormwater infrastructure, natural vegetation cover, road density, and so on. In practice, the level of variability in any of these parameters can be high at any intensity of development. We can take advantage of that variability to choose landscape configurations that minimize watershed impacts for any given level of urbanization. To do so, we must understand how watershed land cover parameters co-vary with development intensity (percent impervious surface) and which aspects of configuration most directly impact urban streams. To this end, I examined 14 specific aspects of development configuration and stormwater infrastructure for 235 small watersheds in the Piedmont region of North Carolina. For both landscape metrics and infrastructure features, there was a high degree of variability at almost any level of development intensity. In the case of road density for central ranges of development, there was so much variation that the expected positive correlation of roads with development was no longer significant. Our results set the stage for future exploration of the hydrologic and chemical processes that are altered in urban streams. Relation of development pattern to ecological process in this way will support more nuanced methods for management of watershed development so that hydrologic impacts might be minimized for any given level of development intensity.

Introduction

As of 2012, over half the global population lives in cities; that figure is projected to increase over the next 4 decades (UN 2012). In fact, the fourth largest increase in urban population in that time period will likely be in the U.S., following India, China, and Nigeria (UN 2012). Furthermore, in the U.S., conversion of land to urban from other uses outpaces the rate of urban population growth (Alig et al. 2004). As is becoming increasingly well known, the ongoing loss of forest and fields to urbanization alters local climates, energy flows, and native biotic communities (Vitousek et al. 1997, Bernhardt and Palmer 2007). Streams and rivers are especially sensitive to development: as topographically low areas of the landscape, they integrate all the changes that occur over their entire watersheds (Bernhardt and Palmer 2007). Specifically, urban development decreases stormwater infiltration and evapotranspiration, thereby increasing runoff and decreasing groundwater contributions to baseflow. Also, to paraphrase L. Leopold et al. (1964), as “the gutters down which flow the ruins of the continents”, urban streams receive all the pollutants, nutrients, trash, and detritus of their catchments. Studies along urban to rural gradients have documented higher peak flows, channel erosion, including incision and straightening, changes in sediment load, and loss of sensitive macroinvertebrate species in receiving streams (Paul and Meyer 2001, Fitzpatrick et al. 2004, King et al. 2005, Walsh et al. 2005, Roy et al. 2009, Cuffney et al. 2010, Wang et al. 2011).

Because the absolute amount of impervious surface area obviously plays a role in effecting these changes, the status quo in watershed management has been to control the amount of impervious surface area (Stone 2004). However, a large amount of effects are left

unexplained by impervious surface area alone (Roy et al. 2009). The source of these effects is not currently known. Because many common measures of urban development and impervious surface cover are correlated, it is hard to discern what aspects of development cause adverse ecological impacts: impervious surface cover is correlated with human population density, topography, soils, and other aspects of the physical template (Gardner and Urban 2007). In practice, the level of variability in many physical and ecological parameters can be high at any intensity of development (Cuffney et al. 2010, Somers et al. 2013). Furthermore, effects of various predictors on ecological processes can be nonlinear and characterized by small areas of rapid change, especially for macroinvertebrate communities (King et al. 2005, King et al. 2011). The absolute amount of impervious surface cover seems to explain on only a portion of variability in ecological indicators, with patch size, shape and landscape subdivision accounting for a substantial additional proportion (Carle et al. 2005, Kearns et al. 2005).

Therefore, to manage urban watersheds more effectively, we need a better understanding of how to separate effects of development intensity from development pattern. Also, because we are unlikely to be able to reduce impervious surface in the context of ongoing urbanization, we would like to discover the extent to which managing the *configuration* of development and its associated infrastructure might compensate for the absolute *area* of development. This question parallels the development of a great deal of theory in landscape ecology, but with an opposite focus. In landscape ecology, the focus has been on habitat area (e.g., forest) and how the spatial configuration of habitat varies as the amount of habitat declines as forests are progressively converted to other land uses. That issue distills into the question of “area versus configuration”, with a particular focus on habitat connectivity as one

aspect of configuration (Fahrig 2003). The challenge in this conservation application is that, as forests are cleared for other land uses, remnant forest patches become smaller, have higher edge-to-area ratios, and are farther apart and hence, less connected.

Much of our understanding of habitat configuration relative to habitat area has been garnered from studies of so-called neutral landscapes, which are raster lattices of random configuration generated over a range of values of habitat area (" p ", or the proportion occupied by "habitat"). Percolation theory as understood by landscape ecologists is derived from materials science (Stauffer 1985), translated to landscape ecology by Gardner et al. (1987; Gardner and Urban 2007). It provides the expectations of how various aspects of habitat configuration covary with p , with the important insight that most measures of landscape configuration vary with p and generally in distinct, nonlinear ways. Importantly, however, percolation theory emphasizes random maps, while real landscapes are considerably more variable in configuration at any given level of habitat area. This variability is precisely the raw material that allows us to consider using configuration to compensate for loss of habitat area.

In the case of urban watersheds, the focus is the reverse—"habitat" is impervious surface or developed area—but the question is the same: we would like to know how various aspects of development covary with p , the proportion of watershed area that is developed (or impervious). In particular, we would like to separate the effects of hydrologic connectivity of impervious surfaces from the area of those surfaces. In other words, we would like to know to what extent the arrangement of land cover and infrastructure might compensate for the increase in area of impervious surface. We can do this by relating the variability in land cover

parameters at similar levels of p , essentially holding p constant, to ecological outcomes, such as peak flows or nutrient concentrations.

Before we are able to do this however, we must understand how watershed land cover parameters covary and which aspects of configuration most impact draining streams. The objective of the current study, therefore, is to explore how landscape characteristics of small urban watersheds change along the gradient of development. Specifically, we would like to know 1) how do landscape patterns co-vary with development intensity?, 2) how much variation exists in landscape patterns along the gradient of development? and 3) how much variation exists in landscape patterns within the most frequent range of development? Detailed knowledge of these three fundamental issues will provide a foundation for future field investigations, allowing us to distinguish which aspects of watershed urbanization drive ecological impacts. Relation of development pattern to ecological process in this way will support more nuanced methods for management of watershed development.

Study area

The study area includes portions of Durham, Orange and Wake counties within the Piedmont ecoregion of North Carolina (Figure 1). The region as a whole has undergone rapid urbanization over the last 20 years. Populations in the three combined counties have increased 86% between 1990 and 2010 (U.S. Census Bureau 2014a, U.S. Census Bureau 2014b). Land use has concurrently transformed from old fields and successional forest to urban and suburban lands (Giddings et al. 2007). The underlying landscape has irregular plains and rolling hills. Streams have low-moderate gradients with gravel or cobble substrate (Giddings et al. 2007).

Previous work on streams in this area has shown that streams in more intensely developed watersheds experience reductions in macroinvertebrate species richness as compared to streams in undeveloped watersheds (Violin et al. 2011). Furthermore, reach-scale restoration efforts had no effect on returning the altered biological communities to reference conditions, at least over a time scale of 5-7 years (Violin et al. 2011). Based on these findings and those from other regions of the country (Palmer et al. 2010), it appears that only watershed-level management strategies will mitigate the adverse effects of development on urban streams (Bernhardt and Palmer 2011). The ineffectiveness of restoration in improving stream ecosystem function increases the urgency of understanding watershed development patterns as drivers of ecological processes for management purposes.

Methods

The watersheds examined in this investigation were delineated for prior investigations (Somers et al. 2013, Somers et al. *in prep*) from first order streams in the urban portions of the study area using ArcGIS 10.0 (ESRI 2010). Piped stream tributaries were ignored, resulting in watersheds ranging from 0.25 – 4 km² in area (Figure 1). This size watershed corresponds to the National Hydrography Dataset Plus Version 2 (NHDPlusV2) “catchment” (Horizon Systems Corporation 2014). The streams I used for the GIS analysis were obtained along with stormwater infrastructure datasets from individual city governments (City of Raleigh Public Works 2009, Durham Storm Water 2007) and merged in ArgGIS 10.0. I obtained roads data from the NC Department of Transportation (NC DOT 2014). Densities of streams and infrastructure features were calculated for each watershed (Table 1).

To calculate land cover pattern metrics, binary maps of developed and non-developed, and forested and non-forested land in Orange, Durham and Wake counties were created from the NLCD 2006 (Fry et al. 2011) using classes 22, 23, and 24 for development and classes 41, 42, 43, and 95 for forest. Class 21 was excluded from the development class as I was most interested in estimated impervious surface cover. Class 21 is defined to represent lawns and other vegetated areas, with impervious surface approximated to be less than 20% (EPA 2007). Although lawns probably do not have nearly the infiltration capacity of undisturbed land, they are likely to store some of the rainfall from smaller storms (Shaver et al. 2007).

Focusing on developed land cover, I next computed indices of landscape patch configuration, connectivity and aggregation and using the eight-neighbor rule in Fragstats 4.1 (MacGarigal et al. 2002) (Table 1). Largest patch index (LPI) represents the size of the largest patch, scaled to the size of the entire watershed. Correlation length is a measure of connectivity that incorporates both patch size and shape. In essence, it estimates the distance from a point in any random patch on the map to the edge of that patch in a random direction (Keitt et al. 1997). Aggregation index is a measure of landscape aggregation in which the number of like adjacencies is expressed as a proportion of the maximum number of possible like adjacencies (MacGarigal et al. 2002). It is most useful for landscapes with a percent occupancy of < 0.5 . The clumpiness metric is also a measure of landscape aggregation, but corrects for the dependency of aggregation index on p by scaling the proportion of like adjacencies to p (MacGarigal et al. 2002). For the clumpiness metric, a value of "0" indicates a random landscape, whereas -1 and 1 are complete disaggregation and complete aggregation respectively.

To assess how landscape patch and stormwater indices covaried with development, I then related each metric to percent development as a scatterplot, focusing on the shape of the relationship and the scatter about the trend. The scatter is particularly important as it illustrates the extent to which variation in that index—at any given level of development—might be used to mitigate watershed impacts at that development intensity. For two key metrics, road density and pipe density, I then created a scatterplot of that metric for the central 50% of the watersheds (as defined by p) as a function of p . Linear regression was used to compare the overall trend on those scatterplots with those that also included the extremes of development. R version 2.15.2 was used to visualize each landscape and stormwater infrastructure metric and for the statistical analysis (R Foundation for Statistical Computing 2012).

Results

As defined by NLCD classes 22, 23, and 24, the study watersheds varied between 0 and 92% developed, with a mean of 35% (Table 2). The percent impervious surface area derived from planimetrics files varied from 5 – 80% with a mean of 33%. The percentage of forest cover across the same landscape was similar, 0 – 91%, with a mean of 16%. Stream density decreased with increasing development, ranging from 296 to 7851 m/km² (Figure 2). Even within small ranges of development intensity, however, there was a large range of values; for example, in two watersheds each developed 21%, stream density ranged from 1,927 to 6,792 m/km², an almost 4-fold difference. Road density increased with increasing development, ranging from 1,257 to 16,612 m/km² across all watersheds (Figure 2). It also had a wide range of variability: two watersheds with 23% development had a range of road density from 3,000 to 10,700

m/km² (Figure 3). When road density for the central half of the dataset was expressed as a function of development using a linear model, the strongly positive correlation of the entire dataset ($R^2 = 0.5447$, p -value $< 2.2e-16$) became not significant ($R^2 = 0.007$, p -value = 0.375) (Figure 4).

Subsurface connectivity

All measures of stormwater infrastructure increased with increasing development, as expected (Figure 2). In general, the variability in pipe and inlet densities was similar to each other and somewhat less than that of roads (Figure 2). Linear models of the pipe density values for the central half of the dataset were similar to those of the whole dataset (Figure 4).

Landscape patch metrics

Consistent with the predicted patterns from random maps, the number of patches of developed land increased until development intensity reached about 30% and then decreased (Figure 5). LPI, mean patch area, correlation length and aggregation index all increased with development intensity. Among those metrics, only LPI showed little variability along the gradient of p (Figure 5). Correlation length, a measure of connectivity and aggregation index showed large variability at all levels of p . Clumpiness showed no obvious pattern in relation to p .

Discussion

Consistent with landscape ecology theory, development patch metrics in small urban watersheds vary in predictable ways with development intensity. Other aspects of landscape pattern, such as roads and stormwater infrastructure features, also vary in predictable, mostly

increasing, ways with development intensity. However, for both patch metrics and built features, there is a high degree of variability in almost all calculated measures of development configuration and subsurface connectivity for any level of development intensity. In the case of watershed road density for central ranges of p , there is so much variation that the expected relationship with roads and development is not significant.

We can take advantage of the high degree of variability in development and infrastructure patterns by directing future research to small ranges of development intensity, wherein p is essentially held constant. This will allow us to distinguish effects that are driven by other aspects of development configuration apart from the absolute value of p . For example, in prior work from our lab, Somers et al. (*in prep*) found that within watersheds ranging from 45-55% development (as defined by NLCD classes 21, 22, 23, and 24), higher traffic volumes and larger mean developed patch sizes drove higher mean stream temperatures. In contrast, heat pulses from storm flow were most explained by higher numbers of pipe-stream intersections and lower proportions of forest in the watershed. The authors concluded that, because stormwater infrastructure variables were the most powerful predictors in every final statistical model, the watersheds were so hyper-connected to the streams that, at 50% developed, the watersheds were above the threshold where connectivity could be separated from proportion of development.

Future research

Based on the results of Somers et al.'s (*in prep*) study, directing future field studies to a small range of development intensity at lower levels, e.g. 10-20%, may allow connectivity to be more easily separated from development intensity. The results of the current study

demonstrate that many possible measurements of development connectivity to streams, such as pipe density and correlation length, have large ranges of variability at even low levels of development. In fact, for the most frequent levels of development when the extremes are excluded, road density had so much variation as to have no obvious correlation with p . By using these highly variable predictors to explain measurements of flow, conductivity, pollutants and other chemical markers of human activities in urban streams, we will be prepared to distinguish which aspects of watershed urbanization drive specific ecological changes.

Conclusion

Proportion of development alone cannot explain many of the hydrologic, chemical and biotic changes that occur in streams draining urban catchments. In this study, we document a large variability in many measures of landscape pattern and surface and subsurface connectivity at all levels of development intensity. Narrowing future field studies to small ranges of development will allow separation of measures of development and stormwater infrastructure configuration from p . Relation of development pattern to ecological process in this way will support more nuanced methods for management of watershed development.

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Table 1. Landscape and stormwater metrics calculated.

Metric	Description	Source
%Developed	Percent of watershed in NLCD classes 22,23, and 24	ArcGIS 10.0
%ISA	Percent watershed impervious surface (from planimetric files)	ArcGIS 10.0
%Forest	Percent of watershed in NLCD classes 41, 42, 43 and 95	ArcGIS 10.0
StreamDens	Density of unpiped streams (m/km ²)	ArcGIS 10.0
PipeDens	Density of pipes (m/km ²)	ArcGIS 10.0
Pipe:stream	Ratio of pipe length to stream length in watershed	ArcGIS 10.0
InletDens	Density of stormwater inlets	ArcGIS 10.0
RoadDens	Density of roads in watershed (km/km ²)	ArcGIS 10.0
NP	Number of developed patches	Fragstats
MeanArea	Mean patch area	Fragstats
LPI	Size of largest patch weighted for watershed area (Gardner et al. 1987)	Fragstats
AI	Aggregation index (proportion of like adjacencies as compared to maximum number possible)	Fragstats
Clumpy	Quantifies like adjacencies, adjusted for area	Fragstats
CL	Correlation length (area-weighted radius of gyration)	Fragstats

Table 2. Variability of landscape and stormwater infrastructure characteristics examined.

	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation
Area square km	0.232	4.129	1.394	0.732	0.525
Developed	0.000	92.052	34.691	19.805	0.571
%ISA	5.3	80.4	32.9	12.2	0.372
%Forest	0.077	90.513	16.844	16.494	0.979
PipeDens	207.790	15267.800	5385.986	2965.692	0.551
InletDens	5.380	515.230	170.789	86.002	0.504
RoadDens	1257.055	16612.186	7937.179	2663.938	0.336
StreamDens	296.037	7850.581	3701.943	1312.332	0.354
Pipe:stream	0.058	28.471	1.976	2.485	1.258
LPI	0.000	92.052	25.212	21.975	0.872
MeanArea	0.000	113.490	9.298	14.955	1.608
Clumpy	0.000	0.920	0.618	0.102	0.165
CL	26.982	852.863	246.433	157.657	0.640
AI	0.000	95.468	75.112	10.916	0.145

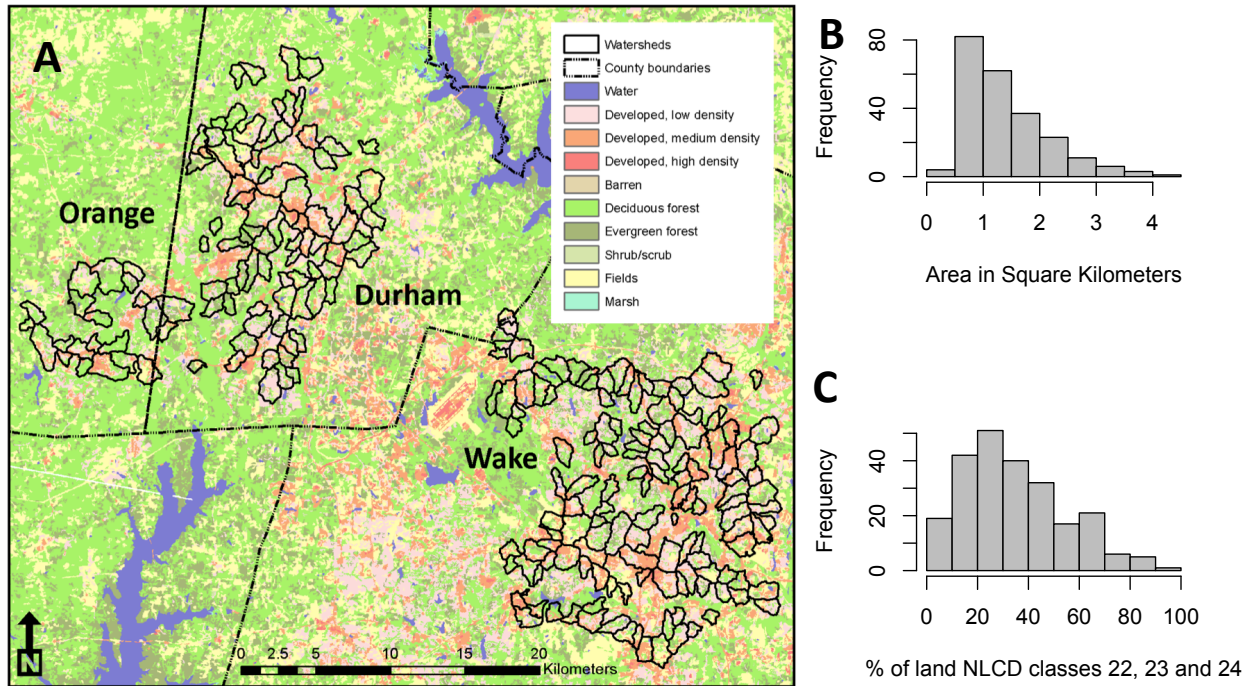


Figure 1. A. The study area encompasses the urbanized centers of Durham, Orange and Wake counties in the Piedmont ecoregion of North Carolina. B. Histogram of area of study watersheds. C. Histogram of percent development in study watersheds.

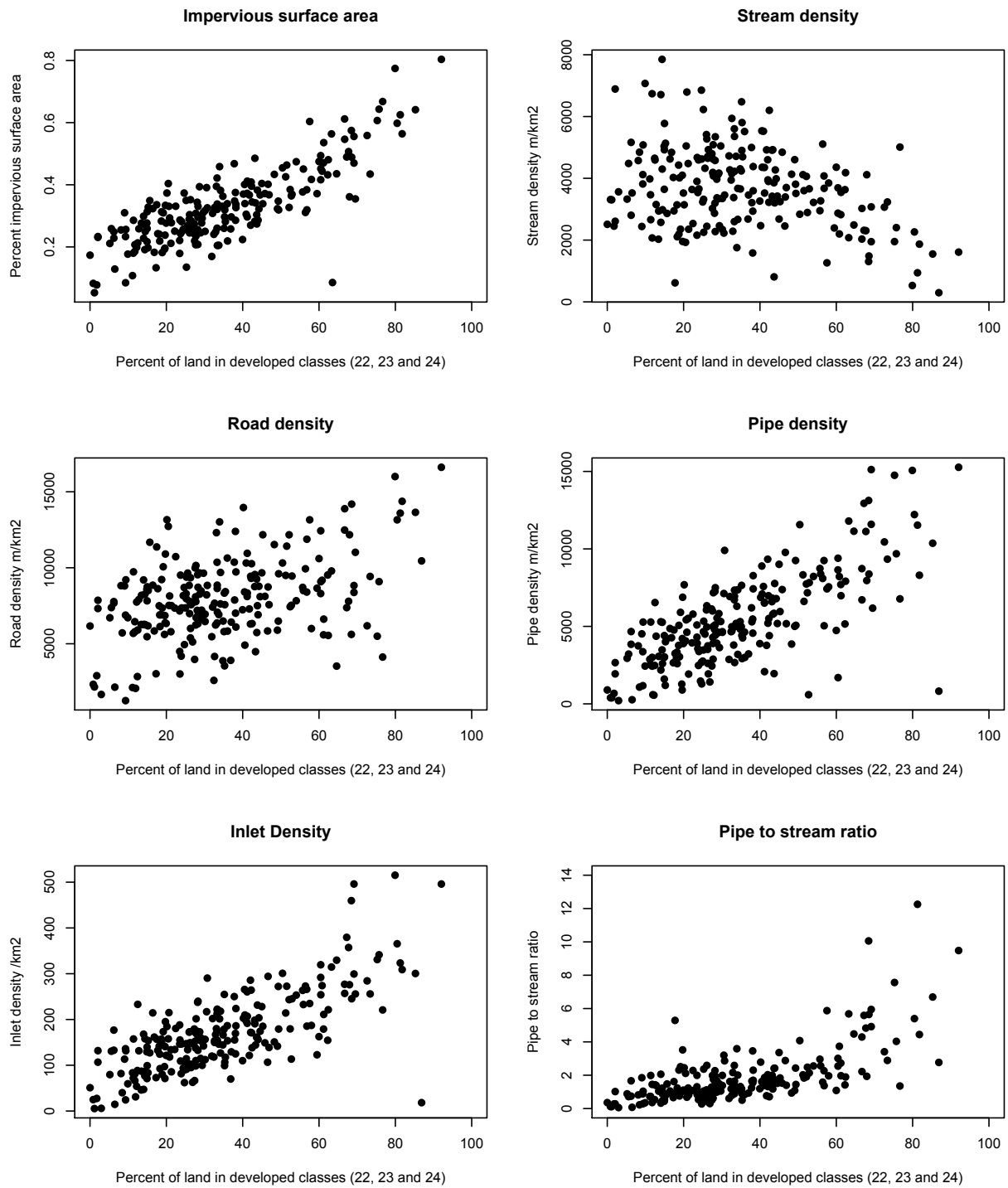


Figure 2. Stream and infrastructure variables in relation to p . Although similar, impervious surface area was not synonymous with development. Stream density decreased with development, but had large variability at low levels thereof. Road, inlet and pipe densities all increase with increasing development. Pipe-to-stream ratio had highest variability at high levels of development.

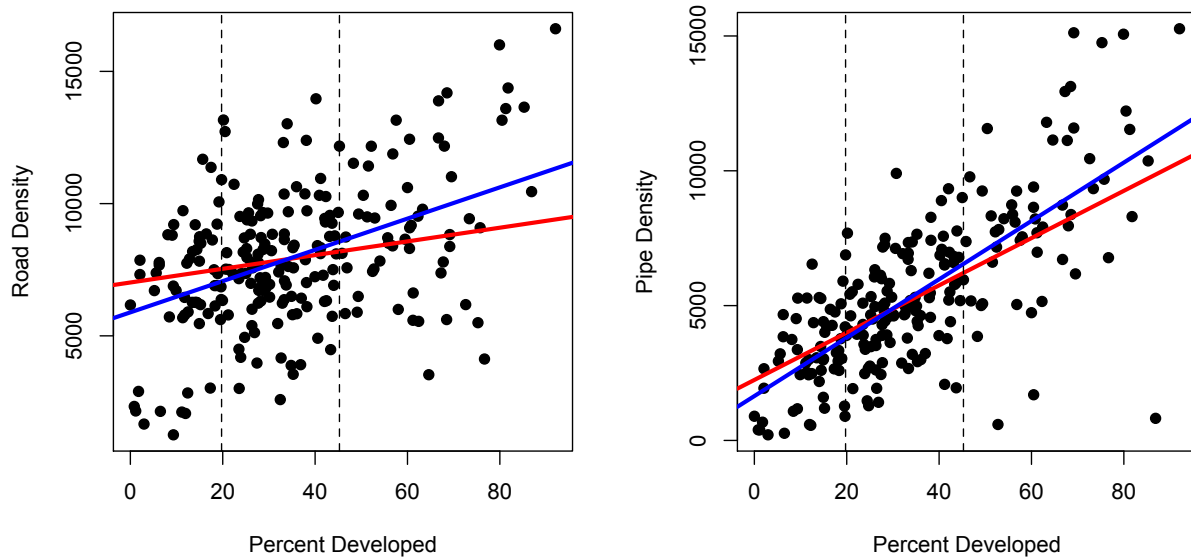


Figure 3. A. The correlation between road density and percent development becomes much less strong when only the most frequent range of percent development in the watershed is considered. The blue line represents a linear model of the entire dataset ($R^2 = 0.1942$, p -value = $2.68e-12$), while the red line excludes the high and low extremes of development ($R^2 = 0.007$, p -value = 0.375). For road density, this renders the correlation not significant. B. The relationship between pipe density and development does not change as much as road density when excluding the extremes of development (all watersheds: $R^2 = 0.53$, p -value = $2.2e-16$; middle half: $R^2 = 0.1202$, p -value = 0.000157).

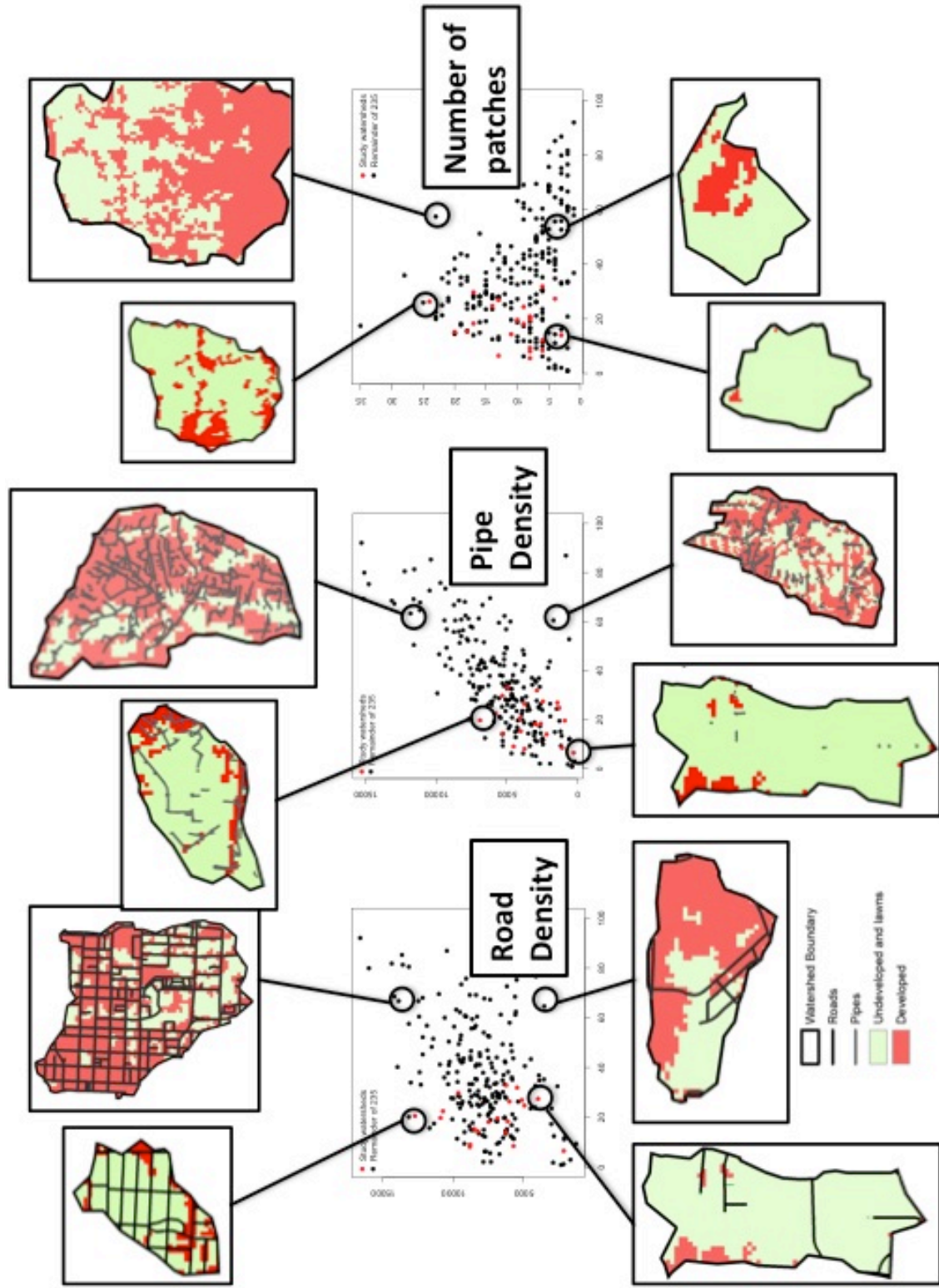


Figure 4. Wide variability in landscape metrics exists at almost all levels of development intensity. The top figures are maps of watersheds with high road and pipe densities and high patch numbers from each of high and low development ranges. The bottom maps show watersheds from the low end of values for the same metrics, for each of the high and low development ranges.

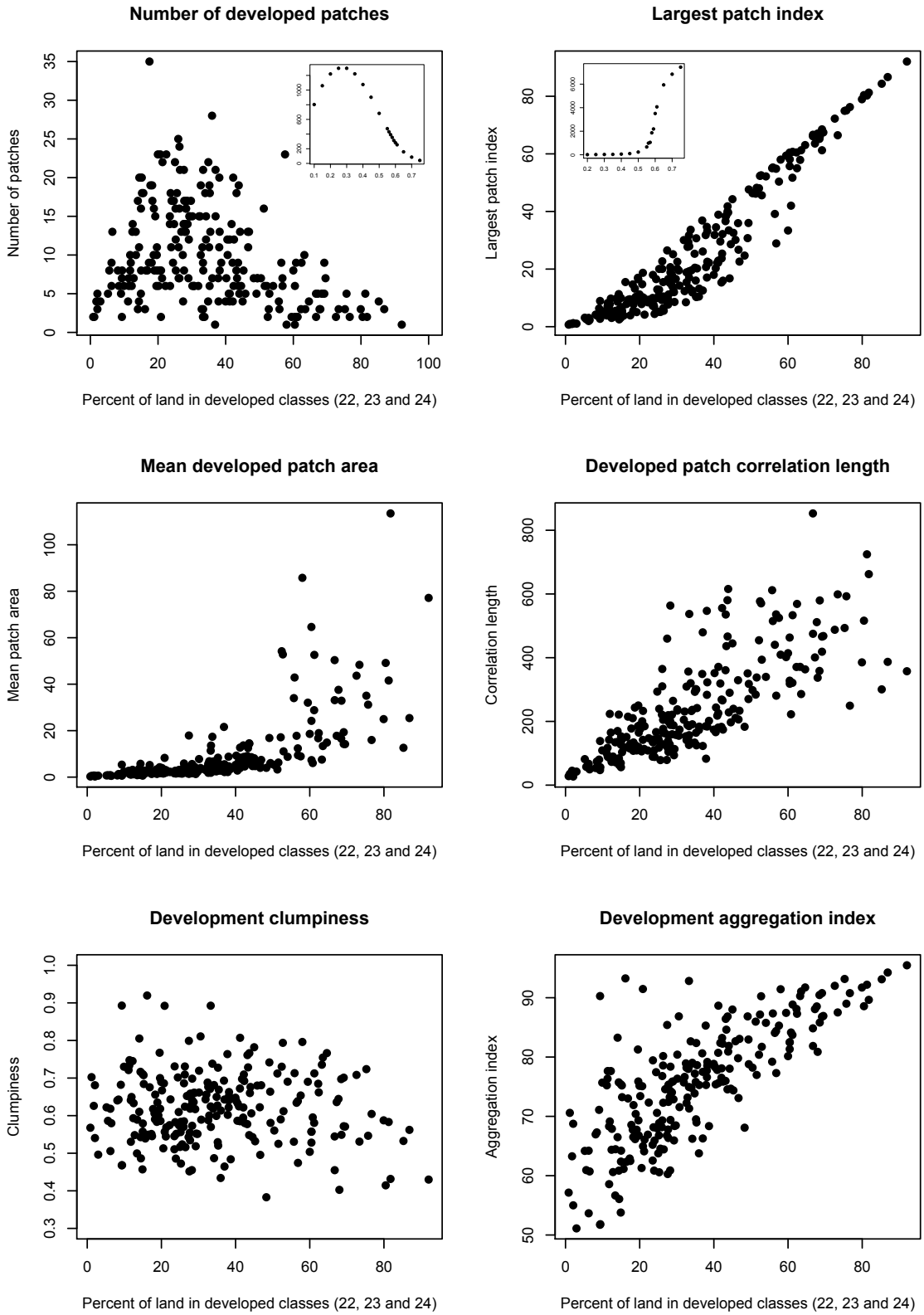


Figure 5. Patch metrics in relation to p . Inset graphs show patch metrics for random maps.