THE LONG-TERM DEVELOPMENT OF A WATERSHED:
SPATIAL PATTERNS, STREAMFLOW AND SUSTAINABILITY

A Dissertation

by

BUREN BROOKS DeFEE II

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2003

Major Subject: Urban and Regional Science

THE LONG-TERM DEVELOPMENT OF A WATERSHED:
SPATIAL PATTERNS, STREAMFLOW AND SUSTAINABILITY

A Dissertation

by

BUREN BROOKS DeFEE II

Submitted to Texas A&M University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Approved as to style and content by:

George Rogers
(Chair of Committee)

Douglas Wunneburger
(Member)

Christopher D. Ellis
(Member)

X. Ben Wu
(Member)

Francisco Olivera
(Member)

Walter Gillis Peacock
(Interim Department Head)

December 2003

Major Subject: Urban and Regional Science

ABSTRACT

The Long-Term Development of a Watershed:
Spatial Patterns, Streamflow and Sustainability.
(December 2003)
Buren Brooks DeFee II, B.S., Texas A&M University;
M.S., Texas A&M University
Chair of Advisory Committee: Dr. George Rogers

This study examines the relationship between the developing landscape and the water flowing through it. The study area was an 86 sq. mi. watershed located in the coastal plains in Harris County, Texas. Daily streamflow data for 52 years was obtained from USGS and coincident precipitation data was obtained from NOAA. Georeferenced parcel-level data was obtained from the Harris County Appraisal District with sufficient detail to determine year of development, parcel area, and impervious cover. Watershed boundaries were obtained from the Harris County Flood Control District. After controlling for daily precipitation, streamflow exhibited significant increases at all levels over time. Increasing streamflow was not associated with climate change.

FRAGSTATS was used to quantify spatial patterns in the developed landscape on an annual basis. Regression analysis was used to determine the relationship between spatial and non-spatial measures of development and streamflow. It was found that models based on the spatial configuration of the developed landscape predict streamflow better than non-spatial measures such as total impervious cover. Several metrics were identified for their potential use as guidelines for urban planning.

DEDICATION

This work is dedicated

to my wife

without whom

I would not

be complete.

ACKNOWLEDGEMENTS

Many thanks to my committee members

who provided support and guidance.

George Rogers

Doug Wunneburger

Ben Wu

Chris Ellis

Francisco Olivera

TABLE OF CONTENTS

Page

CHAPTER

LIST OF FIGURES

FIGURE Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

As humans settle into a landscape, the structure of that landscape is changed. Development often progresses from native landscapes to agricultural uses and later to urban or suburban living. Whether originally a forest or field, the conversion to agriculture, suburban or urban uses alters the way water moves through the landscape. The natural landscape, although always in dynamic change, is a functional living reflection of the structure underneath. Variance in the natural elements such as soil, water, and sunlight create microclimates to which many plant and animal species are adapted. As humans transform the landscape, we become subject to the natural forces that shaped that place into its original pattern.

An important part of sustainability is finding the best way to live within the landscape without exacerbating the effects of natural hazards such as fires, earthquakes, hurricanes, floods, and landslides, just to name a few (eg. Mileti, D., 1999, Disaster by Design). Human changes in the landscape have a particularly strong impact on the way water moves through a watershed. As developed areas increase in size, the amount of streamflow changes and during large precipitation events can reach hazardous proportions. This may threaten property and life for residents of the immediate watershed and those living further downstream. Beyond the immediate impacts of extreme events, changes in development have been associated with degradation of the environment,

---

This dissertation follows the style and format of Landscape Ecology.

particularly within the local streams (CWP, 2003). This has direct implications for sustainability of human populations and infrastructure.

Mitigating hazards is crucial to the sustainability of a community. Development should not occur in hazardous areas, nor should it change the functions of a landscape in such a way as to augment existing hazards or create new hazardous situations. This is the context from which this study is conducted. Understanding the nature of floods is paramount to finding methods to mitigate the hazard while also maintaining the benefits of utilizing the land at without significantly increasing the risk. In order to maintain this balance, land-use planners need better tools to make informed decisions.

Watershed management focuses on clearing excess water as quickly as possible, minimizing storage and maximizing conveyance (Hey, 2001). Hey calls for a reversal of this trend, maximizing storage and minimizing conveyance to prevent the accumulation of water downstream. Because landscape changes occur both in time and space, it is important for hydrologic models to be spatially and temporally explicit, something difficult to achieve in a large study area. With recent advancements in technology, Geographic Information Systems (GIS) are enabling researchers to study landscape changes in greater detail over larger expanses, explicit both in space and time. This study expands on current practices by introducing tools originally developed to study ecological processes into the investigation of land development and flow of water in a watershed. The ecological concepts on which these tools are based have been introduced to the planning community in the form of greenway planning and ecosystem management, but have never been applied specifically to the problem of the outflow from watersheds. The goal of this study is to determine whether landscape metrics, measures of spatial patterns in the landscape, can be used to gain further insight into the relationship between land development and watershed flow.

Landscape Ecology

Landscape ecology is firmly rooted in the mosaic pattern of the land. By dividing the mosaic into three classes; patch, corridor and matrix, it is possible to study the interactions between the landscape elements and the species within them (Forman, 1995). It is important to note that Forman thought of human changes to the landscape as part of the landscape structure to be studied. Because landscapes are subject to change by either human or natural processes, they cannot be considered static entities in either time or space. "Landscapes are dynamic systems that occur in spatio-temporal dimensions (Blaschke and Petch, 1999)."

A greater understanding of how the landscape functions as a whole is gained by studying the structure of the landscape elements. Studying the interaction between landscape elements helps us identify why landscapes change over time. The structure and function of an ecosystem is affected by the size, shape and spatial relationships between different habitat types (Dale, et al., 1999). Changes in any particular element of the landscape can lead to structural changes in other elements, altering the function of the entire landscape.

Land Use Planning and Sustainability

Land use planning balances ecological conservation with the demands for economic stability, usually through the distribution of land uses (van Lier 1998). Sustainable systems seek not to exploit the landscape beyond its capacity to renew, but recognize that humans are part of the system and some use should be permitted. Sustainability has a wide variety of definitions, often influenced by the area of greatest concern to the author. The variety of definitions include concepts of optimal use, satisfaction of needs, maintaining ecological function, freedom from hazards, and preservation of function so the needs of future generations are also met (e.g. Mileti et al. 1999; Burby 1998; Dale et al. 1999).

Because land use planning attempts to find compromise between socio-economic demands and ecological conservation, it is an appropriate forum for moving forward with sustainability issues. Some authors have argued that ecosystem management is a synonym for sustainable development, a process which “attempts to involve all stakeholders in defining sustainable alternatives for the interactions of people and the environments in which they live (Szaro et al., 1998).” In this approach to sustainability proponents of land use planning attempt to recognize and address the interactions between environmental, biological and organizational issues both spatially and at varying scales when managing lands and resources.

Recent research attempts to further sustainability by quantifying issues and using GIS modeling to find optimum land use patterns based on the issues at stake (Seppelt and Voinov, 2002; Joerin and Musy, 2000; Bhaduri et al., 2000). Goals for optimization are predetermined and include objectives such as minimizing transportation networks, minimizing pollution, or achieving specific crop yields. Optimization modeling fits well into the idea of sustainability because reaching specified targets is a good way to measure progress toward the larger objective of a sustainable system. While computer optimizations are becoming more sophisticated, more complex models, such as including concepts of neighborhood effects between pixels are proving computationally difficult as the size of the study area increases (Seppelt and Voinov, 2002). While inherently spatially explicit, the methods do not utilize spatial metrics to quantify resultant landscape qualities. Optimization for specific landscape patterns as goals has not yet been achieved.

Disrupted Function

It is difficult to call a landscape sustainable if a portion of the built environment is subject to serious losses due to natural hazards or if the landscape ceases to function as a synergistic system. “Floods were the most costly natural hazard in the United States in terms of deaths and dollar damage to property and crops over the 1975 to 1994 period (Mileti, 1999).” The landscape functions that lead to periodic flooding are important in understanding the landscape. The impact of increased impervious surface (hardscape) is well documented in the literature (e.g. Landphair and Klatt, 1998; Forman, 1995; Moglen and Beighley, 2002), but none of the research thus far has examined the impact of spatial configuration of the hardscape using spatial metrics.

Study Purpose

The purpose of this study is to investigate the relationship, if any, between the structure and pattern of human-influenced landscapes and streamflow. The goal is to provide land managers with better information about how the landscape is developed. Understanding the relationship between human-influenced patterns and water flow may provide land use managers with tools to understand and control the development of the landscape in a pattern which has a smaller ecological impact. Greater knowledge about the structure and function of the landscape will improve our ability to create sustainable systems.

Significance of the Study

This will be the first study to utilize ecologically derived spatial metrics to describe changes in the broad-scale patterns of human developed portion of the landscape and relate it to changes in streamflow over time. By examining the relationship between land development and the functioning of the watershed in this primary manner, this dissertation provides insight into how land may be developed in a manner that satisfies needs for development without undue environmental degradation. This provides a first step toward a guide for sustainable development, at least with respect to this important dimension of water.

CHAPTER II

LITERATURE REVIEW

The landscape is shaped primarily by three mechanisms: substrate heterogeneity (hills, wet spots, soil types); natural disturbance (fires, floods, tornadoes); and human activity (Forman, 1995). To understand the impacts of development and how they may be mitigated, three fields of study must coincide. Land development is a human activity which can occur in an ad hoc method. Urban planning is a method for controlling development by guiding it to specific parts of the local landscape. The intent of the plan is to provide a balance of uses which meets all of the wants and needs of the local population. But planning may not adequately address the problems associated with a change in hydrological function. Engineers seek to understand and control the influence of development on the hydrology of a watershed primarily to mitigate floods. They create models of the watershed to calculate the influence of development. But while there has been a call for watershed-level analysis, making the link between the structure and function of a watershed has proven difficult.

Landscape ecology has provided methods for observing and quantifying change within a landscape. Understanding how the pattern of development affects streamflow may provide engineers with better tools for modeling watersheds and planners better information for guiding future development.

Land Use Planning

Decisions about land use can induce long-term cumulative changes that may not be observable for decades (Dale et al., 1999). When considered with potential thresholds in systems, the resulting changes in system function can be disastrous. Land use planning and management is gaining a greater understanding of ecological processes and how a lack of or misguided planning can destroy ecological function while effective planning can work with the landscape in a sustainable system (Ahern, 1995; Linehan et al., 1995; Fabos, 1995; Szaro, et. al, 1998). It is unlikely that politics will ever be separated from land use planning. However, greater understanding about the natural services provided by the landscape (and the disasters, both acute and chronic, that can occur when these are disrupted) as well as better tools for incorporating multicriteria analysis and modeling improve the outlook for proper treatment of landscapes as systems while reducing conflicts over use (Joerin and Musy, 2000). “Few applications of metrics in planning have occurred. We maintain that this is due to uncertainty about which metric(s) to apply, and how to interpret the results for planning” (Leitão and Ahern, 2002).

Watershed Modeling

Watershed modeling has recognized that landscapes have a spatial dimension that changes over time. The Rational Model for determining flow addresses this issue by assigning runoff coefficients for different land cover types in the path of flow. By multiplying the intensity of the rainfall (in mm/hr) with the runoff coefficient, peak flow is estimated in cubic meters per second (Strom and Nathan, 1998). As area size increases and patch types become more complicated, the calculations become unwieldy for obvious reasons. One solution is to calculate an average “lumped” runoff coefficient for the entire watershed. The TR-55 method uses “curve numbers” based on cover types, soils types, treatment and hydrologic condition to estimate peak flow (McGarigal et al., 2002). This solution ignores the spatially explicit details but is much easier to calculate.

“Fully-distributed” hydrologic models capitalize on the utility of GIS to create spatially explicit estimates of flow. A good example is seen in the work of Moglen and Beighley (2002). Based on the techniques of the TR-55 method (see Appendix 1 for more information on TR-55), they have created a model that calculates flow at every pixel in their raster map. The calculated flow is based on the land cover of that pixel and flow received from adjacent “upstream” pixels. It provides great detail at any given point in the watershed and has the ability to show how changes in the watershed affect flow over time. Even though it is spatially explicit, it does not utilize spatial metrics such as average distance between developed patches, thus fails to provide information about the broader-scale spatial patterns and how they affect flow.

Landscape Ecology

Ecological processes are linked to landscape patterns (Gustafson, 1998). If the spatial pattern of can be quantified, then the underlying ecological process may be better understood. Spatial measurements of environmental heterogeneity are necessary to make comparisons between landscapes, study changes in a landscape over time, and to relate landscape patterns back to ecological processes.

Landscape metrics can be non-spatial in nature, measuring composition – (e.g., patch count, number of categories (class types), proportions in class, and diversity indices) are just a few. Spatially explicit metrics quantify the geometric structure and spatial properties - the configuration - of the landscape and the patches within (Leitão and Ahern, 2002). For example, metrics like patch shape and nearest neighbor measure the geometry and relative location of landscape elements while more complex metrics like contagion measure the relative interconnectivity of landscape patches of the same class.

Being developed by ecologists, landscape metrics are often thought of as measures of the natural environment. Ecologists recognize that hardscape is a class type that represents human influence on the landscape. It is an interesting exercise to treat hardscape as a "habitat," for in some sense it actually is the preferred place for humans to live. In this context, it is easy to see how landscape metrics can be applied to many spatially distributed phenomena. To avoid confusion between built and natural environments, landscape metrics will be referred to herein as spatial metrics.

Planning, Modeling and Metrics

Land use planning paints the broad strokes that guide the general location of different land uses. Watershed modeling methods are tools used to help engineers make decisions about potential flooding hazards in the landscape. The knowledge and tools "offered by the ecological sciences are rarely used in the decision-making process on private lands" (Dale et al., 1999). This means that two sets of comprehensive tools that could support decision-making in planning are not being utilized to their fullest extent. This study will be an example how these tools can provide information shoring up the long-term sustainability of the landscape.

CHAPTER III

METHODS

Selecting the Study Area

In order to capture long-term trends, the study area must have long-term records in three areas: development, water flow, and precipitation. The United States Geological Survey (USGS) provides land-use /land cover (LULC) for many areas in the U.S. However, these have been determined to lack enough accuracy, level of detail and spatial resolution for modeling applications (Burian et al., 2002). A common method for determining development is the quantification of hardscape through aerial or satellite photography. At appropriate spatial resolutions, these datasets can be quite large and unwieldy, require many labor-hours for classification and often are not available in the historical records, at least consistently enough to be useful.

To capture the greatest length of record, building data will was acquired from the appraisal district for the watershed. As a proxy for more direct measurement methods, appraisal district records should contained all of the necessary data elements, including build date, building size and parcel size. Ancillary hardscape such as driveways and parking lots, if not directly recorded in the dataset, were estimated from other building parameters (i.e., driveways based on garage size and setback requirements; parking lot sizes based on parking requirements).

Long-term water flow records were available for the watershed for a period that encompasses most of the development of the watershed. It is this flow data upon which much of the watershed modeling was based. The source of this data was the United States Geologic Survey, which has been maintaining flow records for the entire U.S.

In a hydrographically isolated watershed, the primary source of water available for stream flow is precipitation. Therefore, a record of precipitation in the watershed must be available for an equally long period of record in order to facilitate modeling. The source for this was the National Oceanic and Atmospheric Administration (NOAA).

Of particular concern in any spatially explicit study is resolution (grain) and extent. Because this study utilized parcel data, the resolution had to be coarse enough to facilitate computation without overlapping parcels and fine enough to capture the smallest parcels within the study area. The extent had to include the entire watershed.

The area selected for this study was the Whiteoak Bayou watershed, a subwatershed of the Buffalo-San Jacinto watershed, USGS Hydrologic Unit Code 12040104. This watershed was located completely within Harris County, Texas. The watershed extended from the just beyond FM1960 at the northwest corner where it flowed generally southeast parallel to highway 290 to just inside the northwest corner of the Hwy 610 Loop. Here it merged with Buffalo Bayou inside the City of Houston (Figure 1).

The Whiteoak Bayou watershed was oriented perpendicular to Houston's outward "growth rings" and parallel to a major transportation corridor, Hwy 290. The linear length of the watershed was approximately 20 miles (32.19km) from headwater to gauging station, draining approximately 86 square miles ($222.7km^2$). The average slope of the watershed was 6.5 ft mi^{-1} (1.2 m km^{-1}). The only sources for water flow in Whiteoak Bayou were precipitation and human activities.

The watershed lies in the Coastal Tallgrass Prairie region of Texas. The high average rainfall in the region (56 inches) typically produces forests (NWRC, 2003), but "drought, fire, and competition from adapted plant species combine to prevent the establishment of woody plants and maintain a grass-dominated ecosystem" (Grafe, 1999). Native plants are adapted to regular exposure to fire, usually started by lightning. Overgrazing, conversion to agriculture, introduction of alien plant species, and land development are all cited as factors that have reshaped the prairie. Typical agricultural uses include cattle grazing, sugar cane and rice production.

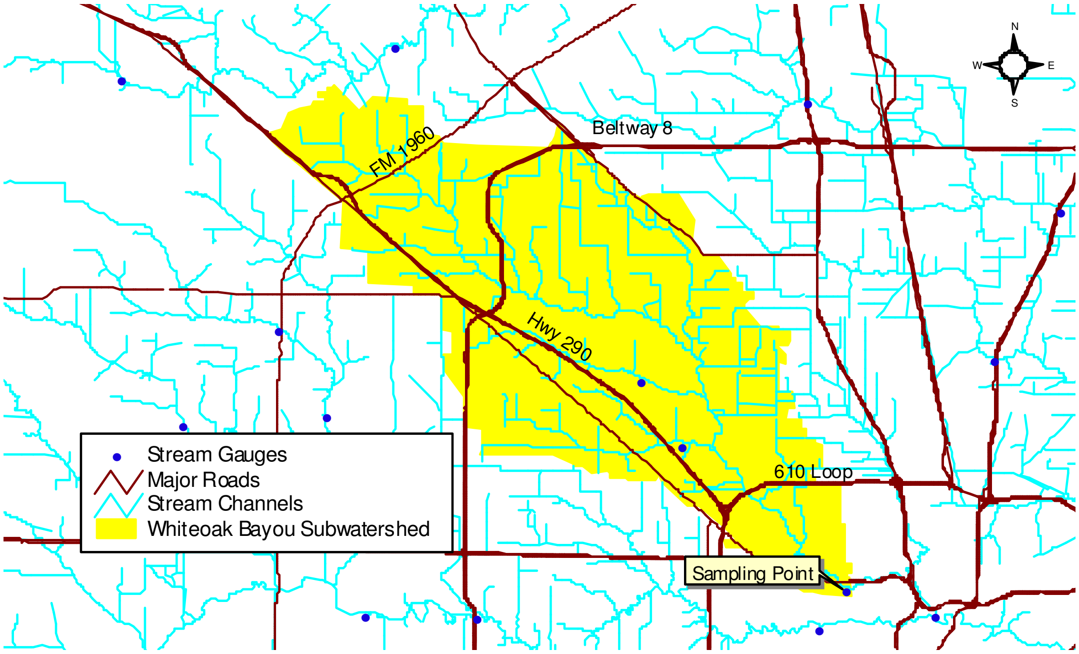


Figure 1. Study area. The boundaries of the study area are highlighted in yellow. They coincide with the watershed boundaries for White Oak Bayou.

The soils within the Whiteoak Bayou watershed are loams characterized by high clay content, low slopes (0 to 1%), moderate to very slow drainage, and high water tables. In the upland coastal prairies (approximately 85% of the watershed area), small depressions form temporary and permanent freshwater ponds, often referred to as "potholes" (Jacob et al., 2002).

The potholes are similar in nature to those found in the prairies of the north central United States, however the geological processes leading to their formation is quite different. Most of the potholes of the north central plains formed as glacial ice retreated and large blocks of buried ice melted, leaving a local depression in the glacial plain (Sloan, 1972). The coastal prairie potholes are thought to be the remnants of rivers which deposited most of the sediments that make up the coastal plain, but are "greatly modified by wind and other agents" (Jacob et al., 2002). The hydrology of both types of potholes is similar. Water enters the pothole from direct precipitation and runoff from the surrounding flats. Water may also move into or out of the pothole via groundwater seepage, a process more fully understood in the northern prairies than in the coastal plains. Other than groundwater seepage, outflow may occur from evapotranspiration or surface overflow.

Applying Ecological Concepts to Development

The landscape can be seen as a mosaic of different habitats (Forman 1995). Any point in the landscape falls within a patch, a corridor, or the background matrix. Forman introduced the patch-corridor-matrix model where every habitat can be classified as a patch in a matrix, a corridor in a matrix, or as the matrix itself. These can be quantified through mathematical means. By treating hardscape as a "habitat," the methods for quantifying patch, corridor and matrix can be applied.

Since the introduction of this model, the number of spatial metrics devised to measure landscape configuration has prompted a study to find commonalities in the metrics and reduce the number through factor analysis (Riiters, et al., 1995). Some are as simple as counting the number of patches in a landscape. Others can be quite complex. These measures provide some basis for comparison between landscapes or the same landscape at different points in time. Comparing different landscapes can be difficult due to differences in spatial extent or scale. However, comparing the same landscape at different points in time is a powerful method for studying change. Studying this watershed over a long time period is one of the primary components of this dissertation.

Theory

When precipitation falls, there are many avenues it may take. That which does not evaporate before reaching the ground may be intercepted by vegetation, immediately absorbed into the ground, or accumulate in quantities great enough to flow. It may collect in pools where it has an opportunity to infiltrate and become part of the groundwater system or move into the atmosphere through evaporation or evapotranspiration. That which does not collect in pools will eventually reach the system of channels which drain the watershed upon which it fell. Every watershed has a natural system which determines the eventual fate of every drop of water. Human activity changes this system.

The introduction of impervious cover into a watershed has been blamed for stream quality issues such as stream temperature change, runoff volume, erosion, pollutant load, and sediment load (Schueler, 1994). The Center for Watershed Protection utilizes impervious cover as its primary independent variable in their Impervious Cover Model (ICM) for determining watershed quality (CWP, 2003). The ICM predicts changes in watershed quality based solely on the quantity of impervious cover within the watershed.

A general diagram of the theory behind this study is seen in Figure 2. Each of these items represents variables which have been correlated to changes in streamflow with the exception of the items listed in blue. These measures have been primarily utilized when looking at the disappearance of natural ecosystems due to human activity. This study will apply these spatial metrics specifically to human activities in order to determine whether the spatial configuration of human influences upon the landscape change the impervious cover model.

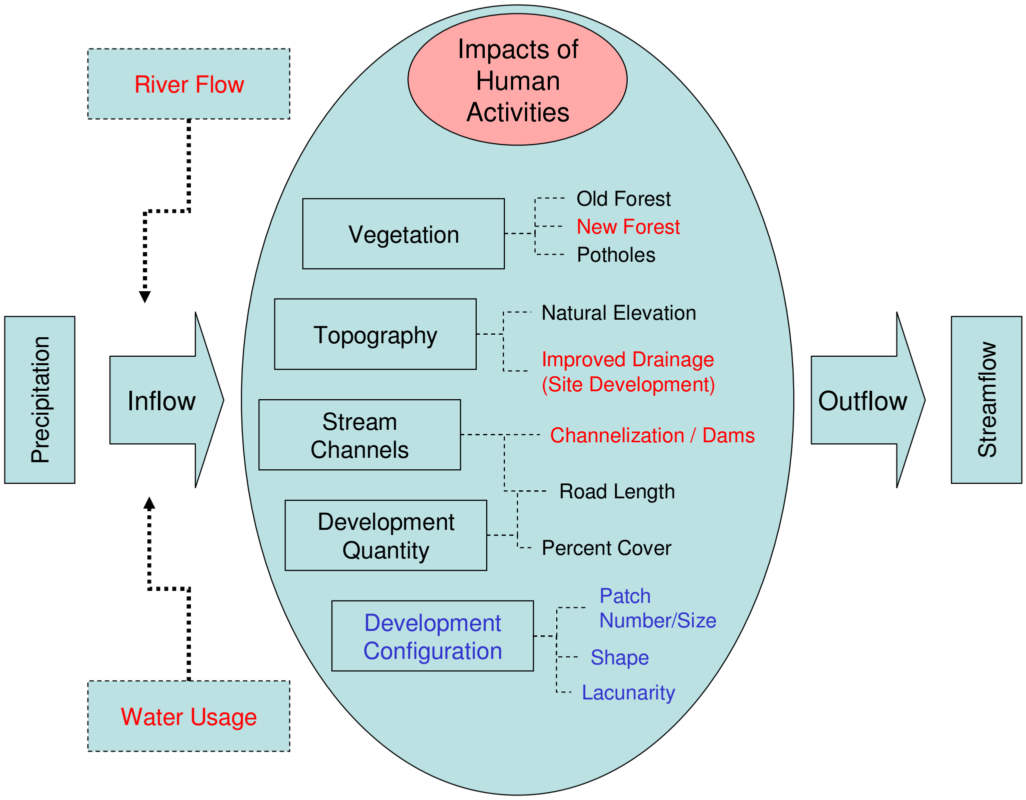


Figure 2. Theory Diagram. Elements in red are either not measurable in this study area or do not apply. Elements in blue are new areas of study.

In a primary watershed, there are two input sources for surface water, precipitation and water for human activities. The latter may come from groundwater or surface water from within or outside of the watershed. A portion of precipitation may fall directly into the drainage system, but the remainder is subject to interception from a variety of factors within the watershed. Listed are five theoretical considerations which may have an effect on streamflow. Each has listed several variables which could be measured. The variables listed in red are recognized for their potential in influencing streamflow, but could not be quantified for this study.

In blue are the new areas of research being applied to the study of streamflow. It is believed that the measures of development configuration will provide additional information which will better explain observed increases in streamflow over time.

Expected Results

As the study area becomes more fully developed, the spatial qualities of the developed hardscape will change. New patches of development will form; others will get larger as undeveloped property within and adjacent to existing patches becomes developed; still others will become connected as undeveloped property which separated them becomes developed and completes the connection. Because water flows more easily over hardscape, the addition of hardscape in the landscape through development should result in greater water flow over time. Although new best management practices focus on keeping water onsite, the effectiveness of these engineering solutions is unclear (CWP, 2003) and as a new solution, their effect on historical development patterns should be negligible. The spatial metrics should give greater insight into the changes in flow.

As new areas are developed in the watershed, the number of patches should increase up to a theoretical maximum. The maximum number of patches is reached when every developed patch is at the minimum patch size of one pixel and none of those pixels share a border. The definition for adjacent pixels will affect the maximum number of patches. This study will use the four-cell rule, so pixels which are adjacent diagonally will not be considered part of the same patch. Hence to be adjacent at least one pixel must share a boundary with another pixel of what would otherwise be a separate patch. It is not expected that the number of patches will reach the theoretical maximum. After an initial increase, patch number should decrease as the patches coalesce, or merge, into fewer, larger patches. These larger, combined patches will drive up the mean patch size over the entire time period.

The shape of the patches can be measured with a shape index. Patch shape is dependent upon the number and size of the patches as well as their deviation from being perfectly circular or square. Because we are using square pixels, the patch shape index will measure deviation from being square. A square patch will have a lower shape index than a patch that is perfectly linear. A single linear patch will have a lower shape index than two perfectly linear patches of the same total area as the single patch. The patch shape index should increase in the beginning as more patches are created and the newly formed patch shapes deviate from circular or square. PSI should decrease as the patches combine to form fewer large and less complex patches.

Edge density is a measure of the number of patch edges within the landscape. A patch edge is the border between one patch type and another patch type. The border between two adjacent pixels of the same patch type is not considered part of the edge for that patch type. Edge density is calculated as the linear measure of the edges divided by the landscape area. Edge density should also follow this same pattern of initial increase and later decrease as predicted for the number of patches.

The nearest neighbor distance (NND) is a bit more difficult to predict. NND depends upon the distance between patches of development as measured from border to border and is the average of those distances. If the selected watershed is primarily served by city services, development will be restricted by the incremental expansion of city infrastructure. This will serve to keep NND low. But if the selected watershed develops via Municipal Utility Districts, the spatial location of additional development will not be restricted by connections to city services. This gives greater potential for longer distances between patches of development. However, NND will eventually decrease as the watershed is filled with development and the distance between coalesced patches gets smaller. As an average of the distance between patches, NND may increase if new development occurs a great distance from previous development, thus skewing the average. Because these situations may occur in the partially developed watershed, it is this portion of the time series that has the greatest uncertainty and variability.

Lacunarity is a spatial metric which is sensitive to patch size, configuration and total cover. It characterizes the amount of distance between patches, in this case, patches of development. As the amount of development increases, lacunarity is expected to decreases, although lacunarity can increase when the total amount of development is low. This happens when new patches are formed far away from the previously developed patches. Sensitivity to configuration and total cover causes lacunarity to decrease as discrete patches aggregate. Lacunarity must decrease over time as development continues in a finite area.

Landscape Division Index is also sensitive to patch size and configuration. It is interpreted as the probability that two randomly selected pixels are not in the same patch of the same patch type (McGarigal et al., 2002). Division is high for a landscape with little development when this is the focal class. As the number and size of developed patches increase, the probability that two pixels will be in the same patch increases, thus division decreases.

Because water flow is less hindered over hardscape, interconnecting hardscape patches should improve the rate of flow through the landscape, which is the central measure of flow on a daily basis (i.e., CFS). All of the metrics described above measure some aspect of the number, size and distribution of development in the landscape. Because the spatial metrics convey information about configuration, it is expected that they will have a stronger relationship to the dependent variable than measures of the quantity of development do alone. A summary of the selected metrics and their categories are listed in Table 1.

Table 1. Study variables.

	Measures
Dependent Variables	Water Flow (Residual Flow Index)
Independent Variables	Patch Number and Density Mean Patch Size Patch Shape Index Edge Density Nearest Neighbor Index Lacunarity Division
Exogenous Variables	Precipitation Channelization Soils

CHAPTER IV

PRECIPITATION & STREAMFLOW

Methods

Historical daily flow data was obtained from the United States Geographical Service (USGS) through their National Water Information System (NWIS) website (USGS, 2001). The gage was selected in conjunction with determination of the study area. The selected gage was USGS surface water gage number 08074500 which has been collecting surface water flow data continuously at the mouth of Whiteoak Bayou since June 1st, 1936. Daily flow was recorded in cubic feet per second and represents the peak flow for the day. There were 23,590 days of record in the data set. There were no missing data points. The data was treated on a calendar year, not broken down by season or water year.

Daily precipitation data was downloaded from the National Climate Data Center website (U.S. Department of Commerce, 1949-2000). Because only two weather stations were located within the watershed and there were missing records from both stations, data from three additional stations near the watershed were included. The chosen stations included COOPID numbers 414321, 414323, 414327, 414317, and 414331. The data for 414317 ended the day before the data for 414331 began and the two stations were located approximately one mile apart, so the data from the two stations was combined to create a single continuous record. These flow gauges and weather stations are presented in Figure 3.

All chosen stations were within nine miles of each other and the station furthest from the watershed boundary was less than 1.5 miles away. There was not enough data prior to 1949 to determine precipitation levels in the watershed, so the time of study was restricted from January 1st, 1949 to December 31st, 2000. Out of 19,207 daily records, 3,339 (17%) were missing a single station and 1,230 (6%) were missing two stations. There were no daily records where more than two stations were missing data. Missing data was estimated using an inverse distance weighted average of the other stations.

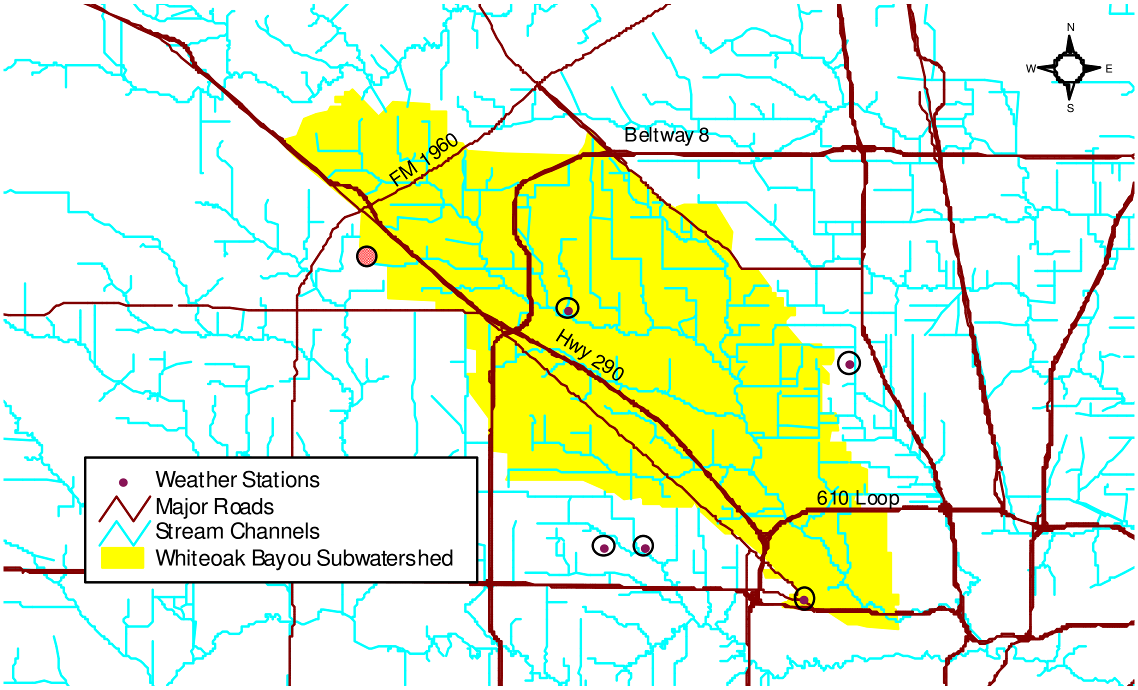


Figure 3. Location of sampling stations within Harris County and the study area. The circled maroon dots are weather stations. The station circled in red was removed from the study.

Recognizing that precipitation is not likely to be evenly distributed over an 86 square mile watershed, it was determined that some method for estimating a single daily precipitation level should be used. A simple average of all the stations' data for a given day was inadequate because of the spatial distribution of the stations.

Thiessen polygons, also known as Voronoi diagrams, are regions around individual points where the borders of the regions are an equal distance from the two nearest points. This region is an estimation of each point's sphere of influence. Thiessen polygons were created using the locations of the weather stations to determine the relative contribution of the precipitation recorded at each station to the precipitation on the whole watershed. The watershed boundaries were intersected with the Thiessen polygons and the percent cover was calculated.

This percent cover was multiplied by the daily precipitation recorded at the corresponding station. The results were summed to determine a final daily precipitation estimate for the entire watershed.

To study changes in precipitation over time, Jennings and Jarnigan (2002) aggregated days of precipitation ≥0mm, ≥ 6mm and ≥ 35mm into 10 and 3 year bins to test for differences in frequency and amount. Changes in precipitation duration were also tested by grouping precipitation values into 10 year bins by 1-day, 2-day, 3-day and > 3-day occurrences which were above 0 and 6mm. Similar methods were used for this study, however, the first and last bins were increased by one year to capture 1949 and 2000. Although these are not technically decades, the temporal range covered, from 1949 to 2000, is more easily subdivided as “decades” and it is should be understood that the first and last “decades” each contain an extra year. For this study, two and three day events were measured as the number of days with at least two prior days of precipitation, regardless of precipitation amount. Differences in frequency were tested using a One Way ANOVA if normally distributed with equal variance, or Kruskal-Wallis One Way ANOVA on Ranks if not. Bivariate tests between decades were either performed using a Tukey Test (if normally distributed) or Dunn’s Method of Pairwise Comparison.

Recent work on climate change indicates that precipitation frequency and precipitation amount has increased in the United States over the past 100 years (Karl and

Knight 1998). The change in frequency was observed over all categories of precipitation amount. They also observed that an increase in the intensity of heavy precipitation events (in the upper 10th percentile) contributes about half of the total increase in precipitation. It is expected that this study area will have similar historical increases in precipitation.

To study changes in watershed flow over time, a similar method was utilized. Days of flow were aggregated into bins representing historical flows greater than 10%, 25%, 50%, 75%, 90%, and 95% of all historical flows by decade. These were tested for differences in frequency by decade using a One Way ANOVA if normally distributed with equal variance, a Kruskal-Wallis One Way ANOVA on Ranks if not, and Dunn's Method of Pairwise Comparison to determine which decades were significantly different.

Jennings and Jarnigan (2002) also created a streamflow response variable for precipitation categories ≥6mm and ≥35mm by dividing the daily mean streamflow value by the precipitation value (Jennings and Jarnagin 2002). They used this measure for observing changes in streamflow response over long periods of time with a temporal resolution of decades. While adequate for observing broad changes, this technique does not account for base flow on days of zero precipitation, may not be ideal for larger watersheds that do not clear stormwater flows in less than one day and cannot provide a good measure for comparison at the annual level.

Selecting the Resolution

Because development data was available at an annual level by calendar year at its finest resolution, a method was needed to consolidate daily streamflow to the annual level while also accounting for precipitation. Minimum and maximum annual values were inappropriate because they use a single value to represent an entire year, and the date of the yearly maximum value for precipitation may not coincide with the same date of the yearly maximum value of streamflow. Average values for precipitation and streamflow utilize all of the daily records, but are influenced by extreme events.

One alternative was to measure the total annual flow. But total annual flow could also be unduly influenced by some extreme precipitation events. Total flow is better suited for analysis between larger time periods.

A second alternative for streamflow was to calculate the yearly base flow. Base flow is defined as that part of stream flow that comes from ground-water discharge instead of overland flow such as seen during precipitation events. Base flow was measured using PART, a program that utilizes long-term stream flow records for discerning base flow (Rutledge, 1998). "The program scans the period of record for days that fit a requirement of antecedent recession, designates ground-water discharge to be equal to streamflow on these days, then linearly interpolates the ground-water discharge on days that do not fit the requirement of antecedent recession." While base flow does account for all daily flows, it interpolates base flow through days of precipitation and averages daily base flow to the annual level. This masks the effects of precipitation, but also masks the response of the watershed to precipitation events.

However, base flow has been shown to be an important indicator of change in impervious cover (Lee and Risley, 2002). Because impervious surfaces cover more pervious soil and increase runoff, the amount of water infiltration is reduced. The change in infiltration results in lower groundwater recharge rates which ultimately affects base flow. Base flow was tested for change between the five decades with a One Way

ANOVA and pair-wise comparisons were made using a Tukey Test. Base flow was expected to decrease over time.

Residual Flow

A residual index was used to account for daily precipitation in the daily streamflow values while creating an annual measure. Before creating an index, the best relationship between daily precipitation and daily streamflow had to be found. In addition to a simple linear relationship, methods that accounted for previous days of precipitation, potential lag times between precipitation and streamflow response, and a non-linear relationship between precipitation and streamflow were considered. To be the "best" relationship between precipitation and streamflow, the selected method had to be logical and have among the highest R^2 scores.

Table 2. Regression results between daily precipitation and daily streamflow.

Model	R^2	B_0	B_1	Beta 1	B_2	Beta 2	Significance
Daily Precipitation, Linear	0.417	34.818	5.481	0.646	-	-	0.000
Two day average Precipitation, Linear	0.348	21.91	6.479	0.590	-	-	0.000
Three day average Precipitation, Linear	0.272	18.231	6.764	0.521	-	-	0.000
Four day average Precipitation, Linear	0.220	16.527	6.896	0.469	-	-	0.000
Five day average Precipitation, Linear	0.186	15.33	6.988	0.431	-	-	0.000
Daily Precipitation, Quadratic	0.433	44.39	4.055	0.478	5.01E-03	0.208	0.000

All of the tests are shown in Table 2. The first relationship tested, a linear regression between precipitation (independent) and streamflow (dependent), became the standard to which all others were compared. To account for the effects of prior days of precipitation on the current day of flow, precipitation was averaged from the day of, to one to four days prior. Each multi-day average precipitation was used to predict streamflow, but as is seen in the chart, the R^2 value for two days average precipitation is lower than seen with daily precipitation predicting streamflow and each additional day averaged into precipitation lowered the R^2 value even more.

McDonnell (2003) stated that “streamflow outputs are not proportional to the inputs across the entire range of outputs.” Because the precipitation-streamflow relationship was not expected to be linear, the curve-fitting function in SPSS 11.0 (SPSS, 2001) was used to find the best fit daily precipitation to daily streamflow relationship. SPSS reported that the best-fit relationship was quadratic. The results are seen in the Table 2. The final relationship tested was daily precipitation vs. one-day lagged streamflow. The best-fit relationship was found to be linear (R^2=0.237, Sig=0.000), however, other tests provided a better fit and the lagged variable was rejected. Multi-day averages of precipitation were not tested against lagged streamflow because the multi-day variables already accounted for one or more prior-days of precipitation.

It was decided the best fit model between daily precipitation and daily streamflow was quadratic, as determined by the amount of variance explained, R^2. The model was calculated and both the predicted values of streamflow and the residuals were recorded.

The residuals above and below the predicted quadratic relationship between daily precipitation and daily streamflow were counted on an annual basis. A Residual Flow index was created by dividing the annual residual counts above the regression line by the counts below the line. This residual flow method has four distinct advantages: 1) The residual flow index captures the full extent of the extreme low-flow days as well as the extreme high-flow days; 2) The index relies upon the entire distribution of available data; 3) Because the regression residuals represent the difference between the expected value of the dependent variable, in this case flow, it is easy to interpret as the variance from the expected flow; and 4) It transforms the daily precipitation data into an annual index that not only accounts for the affects of rainfall, but can be directly analyzed with development on an annual basis. Hence, residual flow amounts to an annual index of precipitation adjusted flow from the watershed.

By controlling the role of precipitation in streamflow through the Residual Flow index, any observed changes in Residual Flow are due to factors other than changes in precipitation due to climate change. Or conversely, for any rainfall x, the residual flow index is the difference between the expected flow for a day with x rainfall and the expected value for a rainfall of size x.

Results

Precipitation

The historical frequency of daily precipitation values greater than 0mm (all precipitation events), greater than 3.2mm (the 50th percentile), greater than 38mm (the 95th percentile) and the coincident average values for each are seen in Table 3. There were no significant differences between periods for frequency in any group. Only in mean precipitation amount for all precipitation events were any significant differences noted. Only two decade pairs were found significantly different, the 1950’s vs. the 1990’s; and the 1960’s vs. the 1990’s.

Tests for changes in precipitation duration showed no significant changes in the frequency of two-day events (F=2.076, df=4, p=0.099). There was a significant difference in the occurrence of greater than three-day events (F=2.743, df=4, p=0.039), however only one time period pair was significantly different, the 1960's vs. the 1980's, and the number of days with at least two prior days of precipitation decreased over time.

Table 3 Changes in precipitation over time. Tested using a Kruskal-Wallis One-Way ANOVA. Results reported as H statistic, degrees of freedom, and significance.

Period	Number of daily precipitation values > 0mm per year	Mean precipitation amount (mm) per value > 0mm ± 95% CI	Number of daily precipitation values ≥ 3.2mm per year	Mean precipitation amount (mm) per value ≥ 3.2mm ± 95% CI	Number of daily precipitation values ≥ 38mm per year	Mean precipitation amount (mm) per value ≥ 38mm ± 95% CI
1950's	133.3	7.83 ± 0.6	68.5	15.6 ± 1.2	5.6	56.6 ± 5.3
1960's	142.3	7.78 ± 0.6	72.8	15.7 ± 1.2	5.6	55.6 ± 5.2
1970's	134.6	9.69 ± 0.8	76.9	17.6 ± 1.3	7.9	57.9 ± 5.1
1980's	123.8	9.79 ± 0.9	72.7	17.2 ± 1.4	6.1	64.5 ± 7.3
1990's	131.5	10.4 ± 0.8	76.6	18.4 ± 1.4	8.5	60.2 ± 6.1
Results	(1.289, 4, 0.288)	(18.521, 4, <0.001)	(8.055, 4, 0.090)	(8.553, 4, 0.073)	(8.097, 4, 0.088)	(4.759, 4, 0.313)

Streamflow

Table 4 is the historical frequency of streamflow values arranged by time periods and by flow volumes. Because the flow values were not normally distributed and were not correctable with data transforms, the results are from the Kruskal-Wallis One-Way Analysis of Variance on Ranks. The tests show that stream flow has increased significantly over time for all flow volumes.

Table 4. Average annual number of days of streamflow by streamflow categories and decade. Comparisons between decades performed with a Kruskal-Wallis ANOVA on ranks. Results reported as H-statistic, degrees of freedom, significance.

	Average Annual Number of Days with Mean Daily Streamflow Value					
Decade	≤ 3.7 cfs	≤ 11 cfs	≤ 34 cfs	≤ 62 cfs	≤ 213 cfs	≤ 438 cfs
1950s	222.3	117	64	45.3	19.2	10.9
1960s	348.5	199.3	88.1	57.2	22.7	11
1970s	365.2	343.9	167.2	108.8	41.4	18.4
1980s	365.3	365.3	278.4	113.5	45.7	22.8
1990s	365.3	365.3	323.1	134.1	55.3	28.8
Results	(34.883, 4, <0.001)	(41.651, 4, <0.001)	(41.832, 4, <0.001)	(29.633, 4, <0.001)	(24.657, 4, <0.001)	(20.244, 4, <0.001)

The trends of the flow categories are easy to see in Figure 4. The overall trend is toward increased flow from the watershed at the outlet studied. The increases at each level are significant, but the smallest flows are most impacted through the study period.

This means the flows with the greatest consequences increase slightly, while those with more moderate consequences are impacted the most.

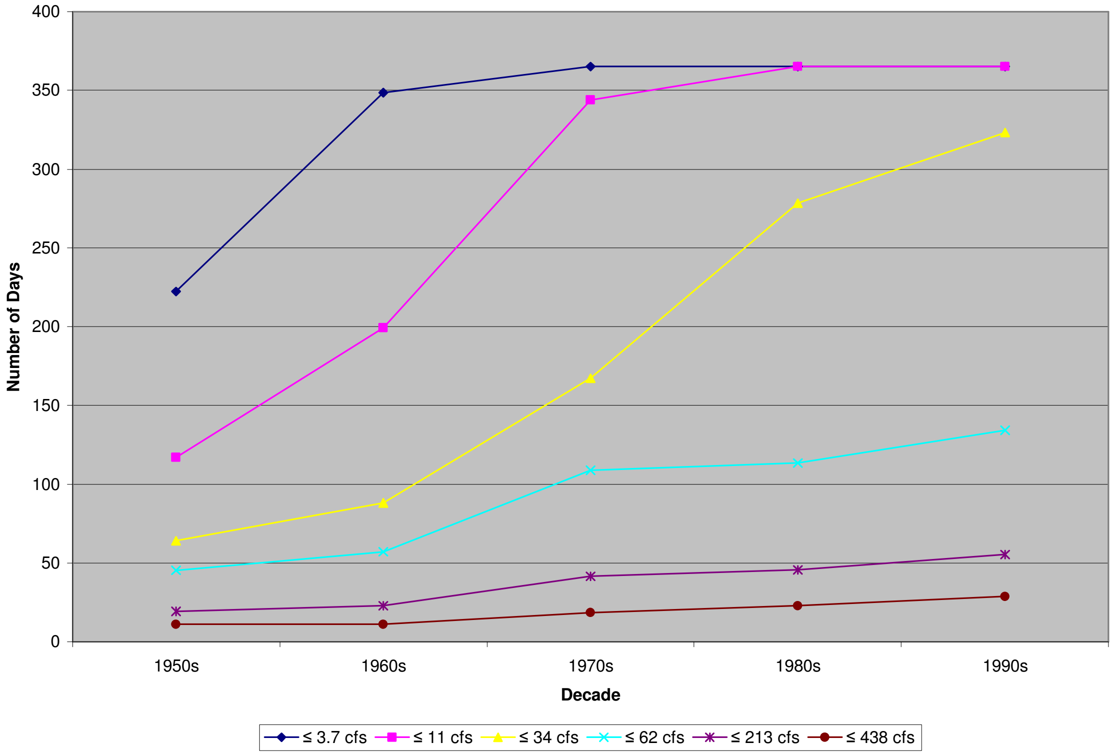


Figure 4. Average annual number of days of streamflow by streamflow category and by decade.

Base flow was found to have changed significantly between decades (F=50.452, DF=4, P=<0.001). Only the final two decades, the 80's and 90's, were not significantly different. The most surprising change seen in base flow was the direction of the change. The literature suggests that base flow should decrease over time in a humid environment but may increase over time in an arid environment (CWP, 2003). Despite being located in a humid environment (greater than 50 inches of precipitation per year), base flow in this study area actually increased from 1.448 inches per year to 7.159 inches per year. Base flow for the final period was nearly 5 times greater than the first period. One possible explanation is the use of local water treatment plants instead of a single central water treatment facility. This needs further research for confirmation.

Residual Flow

Annual residual frequencies above and below the quadratic regression line between daily precipitation and mean daily flow are seen in Figure 5. The regression line was described as $y = 44.39 + 4.055x + 5.01E\text{-}03x^2$, where x is maximum daily precipitation in hundredths of an inch and y is outflow from stream in CFS. The ratio of annual residual counts above the regression line to the annual residual counts below the regression line, Residual Flow, is shown in Figure 6. Because Residual Flow was not normally distributed, changes by time period were tested using a Kruskal-Wallis One Way ANOVA on ranks. Residual Flow was found to have changed significantly (H=34.220, df=4, p=<0.001) over time.

Conclusions

These conclusions are limited to the descriptive patterns in the data and are summarized according to the area of analysis under the headings precipitation, streamflow and residual flow index below.

Precipitation

Analysis of varying intensities and durations of precipitation revealed evidence for climate change in only two situations: the mean amount of precipitation for all events;

Figure 5. Annual residual counts from quadratic regression between daily precipitation and daily streamflow by year.

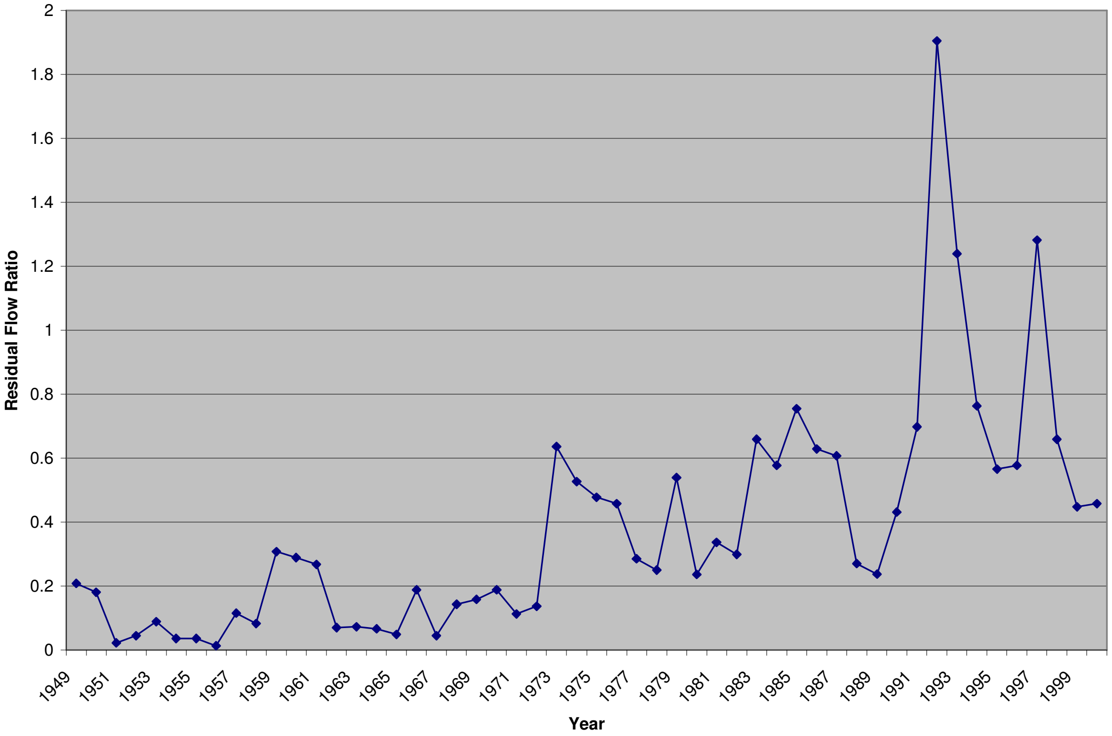


Figure 6. Residual flow. Ratio of annual residual counts above to below quadratic regression by year.

and the number of days with two prior days of precipitation. In addition, the 1960s had a significantly greater number of days involved in precipitation events lasting at least three days. The evidence suggests that precipitation events may be shorter and more intense in the latter part of the study, a condition which would increase the mean daily precipitation amount. However, the overall characterization of precipitation did not change.

Streamflow

Streamflow during the study period was shown to have changed significantly at every level of flow, from the 10th percentile to the 90th percentile. When observed pairwise by time period, only adjacent periods were not found to be significantly different. Every pair separated by at least one decade was found to be significantly different. Considering the lack of evidence for change in precipitation, the observed changes in streamflow suggest that other factors must be affecting streamflow in this watershed.

Residual Flow Index

The residual flow index provides a clear method for accounting for the variability in streamflow for a given precipitation event. Even after precipitation is statistically controlled, residual flow still exhibits a significant increase over time. This solidifies the argument that factors other than precipitation are responsible for the observed changes in streamflow, and subsequently, residual flow.

CHAPTER V

DEVELOPMENT

Introduction

This chapter focuses on the investigation and interpretation of the changes in the landscape that capture elements of quantity, not configuration. The methods used to prepare the data for the GIS are the same as those for non-spatial data. In addition to increase of impervious cover, other consequences of development such as the loss of natural areas are observed as well.

While many of the reasons for looking at development as a primary cause for change in streamflow, an important consideration is the method for observing changes in development. Restricting the measurement of development only to observed changes in quantity of impervious cover ignores the changes made to a landscape as it developed and how those changes might affect how water moves on and infiltrates into the newly developed landscape.

Consider the typical suburban residential subdivision. Homes are built to prevent the buildup of water on the roof and around the foundation. Ponding water in the yard surrounding the home is undesirable because of the negative effects it has on grass and the potential for harboring pest insects such as mosquitoes. The yard is sloped to move water away from the home and into a drainage system. The roads in the subdivision may act as the conduit to carry water away from the homes, but structures such as storm sewers or ditches associated with the roads may also serve this role. With the exception of open areas designed specifically to hold water or act as temporary storage facilities for water, the typical suburban neighborhood, both pervious and impervious surfaces, is designed to shed water.

Despite these concerns, rooftops are considered disconnected impervious surfaces (Schueler, 1994). A disconnected impervious surface is one that drains into a pervious area. Impervious surfaces are considered connected when there are no areas of impervious cover between the source of the water and the final drainage system. Two studies have shown runoff volumes from disconnected impervious cover to be up to 75% less than runoff from connected impervious cover of the same area (Pitt, 1987; Schueler, 1994).

However, treating impervious cover as the only cause for urban runoff may not accurately reflect the changes in the landscape due to development. In this study, changes in the landscape were measured on both the impervious cover and the total landscape area developed.

Methods

This section contains detailed instructions for every observed and recorded change within the watershed during the study period. It is broken into several sections including soils, the loss of natural areas, and several measures directly concerning the parcels including total parcel area, impervious cover, and roads. How errors in parcel area were controlled is also discussed.

Data Sources & Compilation in GIS

The variables discussed up to this point have been applied equally to the entire watershed. But changes in impervious cover occur both in time and space. A Geographic Information System (GIS), computer software which maps spatial features and stores information about those features in a database, can combine spatially-explicit information with temporally explicit information. This makes studying the spatial and temporal variability within the watershed possible.

Two GIS were used for this study. Much of the preparatory work was accomplished in Intergraph's Geomedia Pro. This included reprojecting the data, trimming the data to the boundaries of the watershed, and performing basic queries. The rest of the work was completed in ArcView 3.3 because of the availability of software extensions which expanded ArcView's capabilities to include spatial analysis.

Simple spatial measures can be performed within the GIS without extensions. For example, the amount of development per year can be tabulated as the total area of developed parcels and converted to a percent cover variable for the watershed. Other spatial measures are more complicated and require the additional software to calculate. These are explained below.

Soils

Soils data was obtained from the National Resources Conservation Service, a division of the United States Department of Agriculture. The soil data was provided as part of the Soils Survey Geographic (SSURGO) Data Base, downloadable from their website (USDA, 2002).

The data is provided in a Geographic projection using the North American Datum of 1983. It was reprojected into Universal Transverse Mercator, zone 15 in order to match the projection of other data. The SSURGO layer was then intersected with the watershed boundary to create a new layer containing only soils data for the watershed.

The soils in the watershed are dominated by Addicks Loam, Gessner Loam, Clodine Loam and Aris-Gessner Complex. The percent of the watershed is 38%, 24%, 19%, and 12%, respectively for a total of 93% of the watershed. The soils are characterized by low slopes (0 to 1%), moderate to very slow drainage with soil depths up to 105 inches. In these descriptions, it is not clear whether drainage is a measure of runoff, percolation, or a combination of both. An additional 5% of the watershed is listed as urban area within the soils descriptions. The remaining 2% is divided among a large number of soils which are all moderate to poorly drained, with moderate to low permeability, low slopes and are characterized as deep. The water table can be found from four to thirty inches below the surface and these soils are known to form ponds three to six months of the year.

NRCS classifies soils into different hydrologic groups based on their minimum infiltration rate. The four dominant soil types in the watershed all fell into the most impervious group, hydrologic soil group D.

The soils data was accumulated and utilized primarily in the generation of the Area Weighted Curve Number, an independent variable discussed in Appendix 1. Because of the homogenous nature of the soils and their relative stability over the time period under investigation, the soils data by itself could not be treated as a separate independent variable.

Natural Areas

A generalized vegetation data layer was obtained from Texas Parks and Wildlife (TPW). The vegetation data layer was created from Landsat imagery and ground survey (McMahan et al., 1984). It was provided in a Lambert projection using the North American Datum, 1983.

According to TPW, the entire watershed is located in the Upland Prairies and Woods region of coastal Texas. This region is described as a "mixture of woodlands developing along alluvial valleys, and prairies on coarse sandy soils" (McMahan et al., 2002). However, the region extends from the coast to over a hundred miles inland, so the general soils description is not accurate for this watershed. The vegetation description within the soils data characterizes the watershed as a series of native prairies with agricultural use and some encroachment of oak and pine woodlands. The prairies are classified as Coastal Tallgrass Prairies as mentioned above. Native prairies are known for ponding in "prairie potholes," but the impact of these landscape features on watershed flow remains unclear.

Aerial photography and satellite imagery were used for visual inspection and for digitizing features at one or both of two time points, 1944 and 1994. False-color infra-red digital ortho-quads were obtained for 1994 from the Texas Natural Resources Information System (TNRIS, 2002). Black and white aerial photography for 1944 was also obtained from TNRIS, but was in hard-copy form which was scanned and georeferenced to the digital ortho quads. All forested areas without development were digitized at 1:25,000 scale. In addition to forested areas, each discernable prairie pothole was digitized from the 1944 aerial photos at 1:12,500 scale. The full area drained by each pothole was not visible and was not quantified. See Figure 7 for examples. Non-forested, undeveloped areas were not digitized separately. Instead, all areas not developed, covered by forest, or covered by potholes were treated as open land as of 1944.

The total forested area was calculated as a percentage of the total watershed area. To determine the amount of forested area lost to development annually, the digitized forested area from 1944 was intersected with the parcels data layer (discussed below). The forested area coinciding with the intersecting parcel boundary was marked as cleared on the year the intersecting parcel was developed. This method gives you the quantity, but not the pattern, of lost forest.

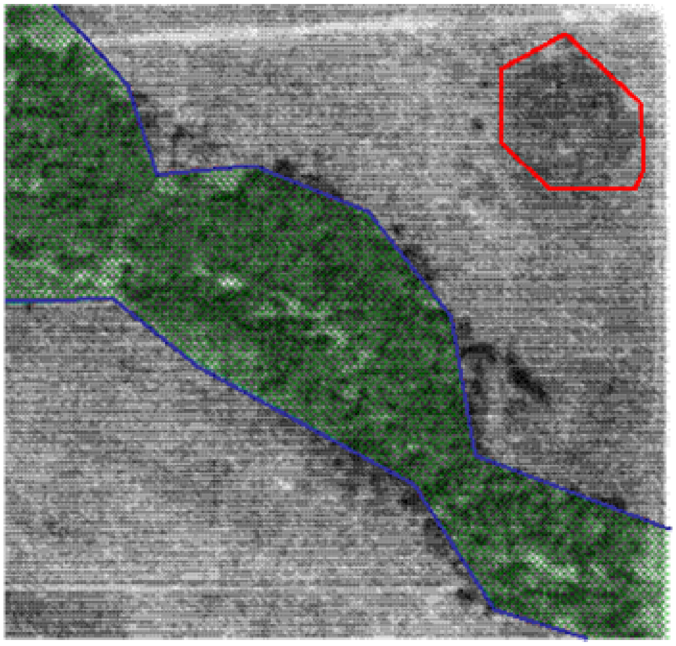


Figure 7. Examples of natural areas from 1944 aerial photos. Dark, roughly circular or oval shapes were digitized as prairie potholes at 1:12,500 scale and were outlined in red for identification. Forested areas were digitized at 1:25,000 scale and were covered by a green hatch.

Urban forests have been shown to reduce runoff by an average of 10% (Sanders, 1986). The amount of reduction is a function of percent impervious cover and percent tree canopy cover. Because of limited information on the overall development of urban forests, no attempt was made to quantify developed areas which contained trees.

It was found that some of the forested areas present in the 1994 data did not coincide with historically forested areas in 1944. However, with data from only two time periods, it was impossible to determine what year the land was left to later become forest or intentionally reforested. Therefore, the effects of reforestation are not examined in this study.

The total area of the prairie potholes was calculated as a percentage of the total watershed as well. The disappearance of prairie potholes was also documented by intersecting the digitized pothole areas from 1944 with the parcels data layer. Potholes were considered developed once the first intersecting parcel was developed. No consideration was made for the partial loss of a pothole because it was assumed that once development encroached upon a pothole, the drainage pattern was changed and the pothole was not collecting runoff any longer. If this were not the case, then any development encroaching on a pothole could be subject to flooding as the pothole collects water from the surrounding landscape. In some instances, a pothole was marked as “developed” before 1944. In these cases, the parcel was rural in nature and had a very small developed area which did not encroach upon the pothole. These were marked as undeveloped as of 2000.

Observations of the aerial photography suggest that the forests and prairie potholes cover only a small portion of the watershed. This, combined with a lack of information on the growth of new forested areas, suggests that the influence of these areas on streamflow will be limited.

Developed Parcel Area

Utilizing aerial or satellite photography to estimate land use restricts the number of samples to only those years where photography was obtained. For the watershed in this study, aerial imagery was collected approximately once per decade until the 1970s when satellite data became available and the frequency of collection for both types of imagery increased. However, the historical record is incomplete for some decades as aerial imagery only covered a portion of the watershed. In order to get the most complete record on an annual basis, it was necessary to devise an alternative method for estimating land cover and development.

Parcel-level data collected by the Harris County Appraisal District (HCAD) was used to estimate development both temporally and spatially. The HCAD development data provided annual snapshots of the state of development in the watershed. The data was acquired in two parts, an ArcView shapefile of all parcel boundaries with identification numbers; and a comma-delimited text file of the parcel parameters and improvements. While there were a large number of parcel data fields, the fields chosen for this study included parcel area, building type, year of construction, building square footage, and number of floors. The building type was only segregated into residential or commercial. All non-residential uses were considered commercial.

Because the data are provided at the parcel level, there is no distinction between parcels that have 100% impervious cover and parcels that have 1% impervious cover. Total impervious cover was estimated using the parcel parameters and improvements data. While impervious cover for residential properties should include the building footprint, the driveway, the sidewalks, and any associated patios, all of this data is not available. The same is true for commercial properties.

Determining Parcel Impervious Cover

Building footprints for residential properties were estimated by dividing the total square footage of the building by the number of floors. The footprint was verified by comparing it to the parcel area. If the footprint was larger than the parcel, the building and parcel parameters were verified manually and corrected. Estimates for driveway, sidewalk and patio sizes were not possible because the data was not available in the database and development within the Whiteoak Bayou watershed was not controlled by a single entity; therefore there were no consistent standards for building setbacks, driveway widths, or requirements for sidewalks. It is understood that this method will underestimate the true footprint of the building and all associated impervious cover.

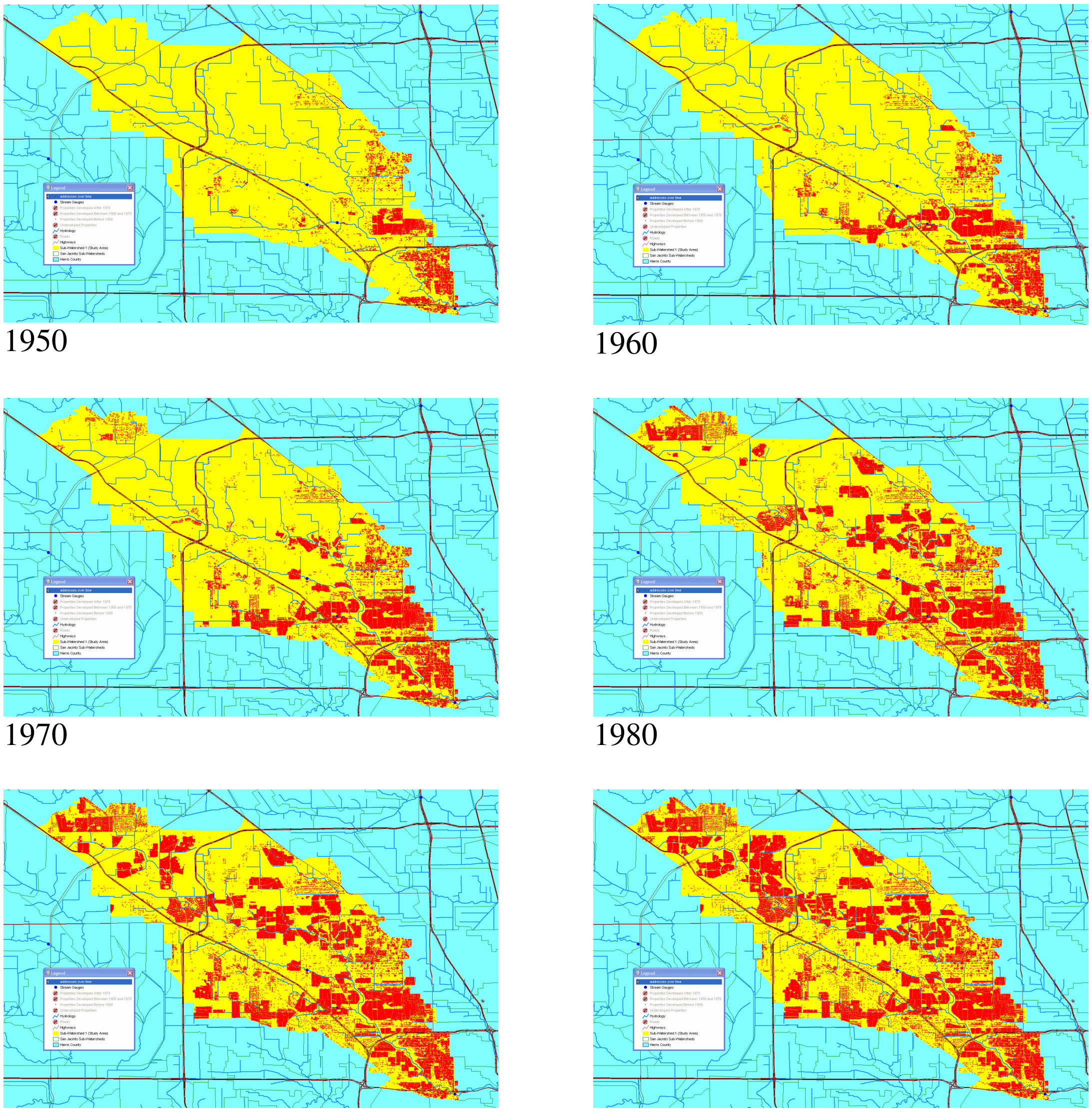
Commercial building footprints were estimated in the same manner. Because the database only included general land use classifications, parking requirements were estimated using the building square footage. The City of Houston Codes and Ordinances (City of Houston, 2002) was used as a reference for determining parking requirements. The number of parking spaces per 1,000sqft of building space ranged from 2.5 to 10 with restaurants and bars in the highest categories – 8 and 10, respectively. Most other occupancy types required four to five spaces per 1,000sqft of building space. Five parking spaces per 1,000sqft of building space were used to estimate non-residential parking requirements in this study.

Parking space size and the aisles needed to service the spaces also varies by parking lot type. A stall size of 10ft by 20ft (200sqft) with an aisle width of 20ft was used to create a general estimate of 400sqft of parking lot area per parking space required. Estimated parking lot area was added to the building footprint for non-residential properties. Once total footprints were calculated for both residential and commercial properties, the estimated percent impervious cover was calculated as the percent of total parcel area for each parcel.

Parcels Overlapping Study Boundary

Because parcel boundaries do not conform to the watershed boundaries, a rule was applied to determine whether or not a parcel should be included within the study area. If more than 50% of the parcel area was within the watershed boundary, the parcel was included. This means that parcels that have only a small portion in the watershed will be eliminated without regard for the amount of acreage within the watershed. The area for all of the parcels that have some overlap into the watershed was approximately 77 square miles. After applying the rules, the total area for the parcels included in the study was approximately 72 square miles, a decrease of 8%, but when the roads areas were added in, this was very close to the true watershed area of 86 square miles.

To visualize the changes in development over time, the centroid of each developed parcel was marked and mapped in Figure 8.



1950

1960

1970

1980

1990

2000

Figure 8. Development mapped as address points over time. The study area is marked in yellow. Centroid for each developed parcel is marked in red.

Once completed, the new GIS parcel data layer was ready for the study. In addition to the boundaries, each parcel record included the total area of the parcel, the area of the building footprint, the area of other impervious cover on the parcel, the year the parcel was developed, and the total percent impervious cover for the parcel.

Roads

GIS data for roads was widely available from several sources including U.S. Census TIGER files, the Texas Department of Transportation and the Houston-Galveston Area Council of Governments. All of the datasets suffered from several problems which made them inadequate for this study.

When compared to the parcel data obtained from the Harris County Appraisal District, all of the road datasets suffered from alignment problems. Roads often passed through parcel boundaries. None of the road databases contained any information on the original date of construction for the road segments. Finally, all of the roads datasets were vector-based lines, inappropriate for a study which depends on areas for measurement.

To solve this problem, it was determined that the road data needed to be created from the parcels data. Using the parcel shapes as a template, a new data layer was created then clipped to form a negative image of the parcels – the roads. While the road name was not deemed important for this study, the area of the road and the date of construction were of considerable interest.

The date of construction for the road was determined by a simple rule: the road must have been in place to service the oldest building adjacent to that road. Three steps were used to assign construction dates to the roads. First, a 180m grid was created which covered the entire watershed. This size was chosen as a multiple of 30m so it would align properly with Digital Ortho Quadrangle aerial photography and so each cell would be large enough to cover multiple parcels.

Second, for each grid cell, the overlapping parcels were queried and the year of construction for the oldest building was assigned to the cell. In the event that there were no developed parcels within the cell, the date from the oldest adjacent cell was assigned to the empty cell. The third step was to intersect the grid with the roads layer to create segmented roads with an estimated date of construction for each segment.

The biggest problem with this method is the presence of isolated road segments early in the study. It is reasonable to assume that a road connected the isolated segment to other road segments; however, it would be difficult to determine the exact route of connection. It was understood that this method would result in an underestimation of road length for a given year except late in the study when the method accounts for all road segments. The underestimation error was consistent throughout the study.

This method for estimating road areas also does not differentiate between different road types. Where road length was measurable, the boundaries for the road width were based on administrative boundaries, not physical widths of roads. A sample of road widths created from the administrative boundaries revealed an average road width of 55ft for residential areas and 300ft for highways. This revealed that the distance from parcel to parcel across a road was a measure of the road easement, not the road surface. To estimate the width of the road surface, a standard cover of 70% was applied. The resulting road widths are more in line with common construction practices, but it is understood that some areas would be overestimated and others are underestimated.

It is important to note the terminology used at this point. “Parcels” is used to refer to boundaries that define where buildings may be built. “Road segments” is used to refer to the roads as they were split into grid cells, not as lengths of roads that would represent a street block. Finally, “units” is used when the reference is to both parcels and roads as a combined area.

Watershed Impervious Cover

With the parcel and road databases in place, it was possible to measure changes in development over time without consideration to spatial distribution. There is a notable difference between methods for measuring developed area. The first method accounts for the entire area of every parcel, disregarding the actual amount of impervious cover within the parcel boundaries. When summed for all developed properties annually, it is defined as the total developed area (TDA). While this method does display the development of parcels over time, it does not accurately portray the amount of impervious cover in the watershed.

Because each road segment and each parcel contained a variable estimating percent impervious cover for the unit, both average impervious cover by unit and total impervious cover for the watershed could be calculated. To estimate total impervious cover for the watershed, the amount of impervious cover within each unit was summed for a given year and all previous years. This resulted in a measure called Watershed Impervious Cover (WIC). This measure allowed for more precise determinations of impervious cover within the watershed than the total unit area.

Incremental changes in development could also be calculated by measuring TDA or WIC on an annual basis without regard to previous years. All of the above variables were lumped into the decades defined before and comparisons were made over time using a One Way ANOVA if normally distributed with equal variance, or Kruskal-Wallis One Way ANOVA on Ranks if not. Bivariate tests between decades were either performed using a Tukey Test (if normally distributed) or Dunn's Method of Pairwise Comparison.

Results

The results are limited to the observed changes over time for the non-spatially explicit variables in this chapter. The results are broken into the loss of natural areas and all other changes due to development.

Natural Areas

In 1944, approximately 3,294 hectares (8,141 acres) of forested land was measured in the watershed. This comprised just over 15% of the total watershed area. These forested areas were concentrated in the riparian areas around stream channels. By the beginning of the study period, 1949, development in the forested areas had reduced the total forested area to only 14% of the watershed area. An average of 1.1% of the forested area was removed each year until the end of the study where the forested areas only covered 5% of the watershed area. This change was found to be significant by decade with a Kruskal-Wallis One Way ANOVA (H=48.964, df=4, p=<0.001). Dunn's Pairwise Comparison showed all decades separated by one or more decades to be significantly different.

The newly forested areas measured in 1994 covered 10% of the total watershed area not covered by forest in 1944. This resulted in a shift in location for forested lands away from the riparian zones. Because the timing of this shift was not discernable from the current data, no attempts were made to capture this reforestation and shift in location.

The prairie potholes covered less than 224 hectares (554 acres) in 1944. This was just over 1% of the total watershed area. Although the area of the potholes themselves was measurable, the drainage area for each pothole was not. Development removed an average of 1.6% of the total prairie pothole area per year, resulting in a total pothole area of 26 hectares (65 acres) in 2000, 0.12% of the watershed area. A One Way ANOVA between decades revealed the loss of pothole area changed significantly (F=300.617, df=4, p=<0.001) and a Tukey test showed all decades to be significantly different from each other.

Despite the unknown total drainage area, the loss of prairie potholes was recorded as a variable, pothole loss, for use in the final analysis. This variable exhibited a strong inverse correlation to residual flow. In addition, both the loss of forested area and loss of pothole area were combined into a single variable with the total natural area impacted by development as a percent of the watershed. This was termed loss of natural areas (LNA).

Development

The changes in TDA and WIC during the study period are seen in Figure 9. It clearly demonstrates the differences between measuring developed area and measuring impervious cover. When analyzed by decade, TDA showed significant changes (F=306.102, df=4, p=<0.001) and the changes were also significant at the 0.05 level between every decade. WIC also changed significantly (F=285.727, df=4, p=<0.001) and the changes were significant between all decades at the 0.05 level.

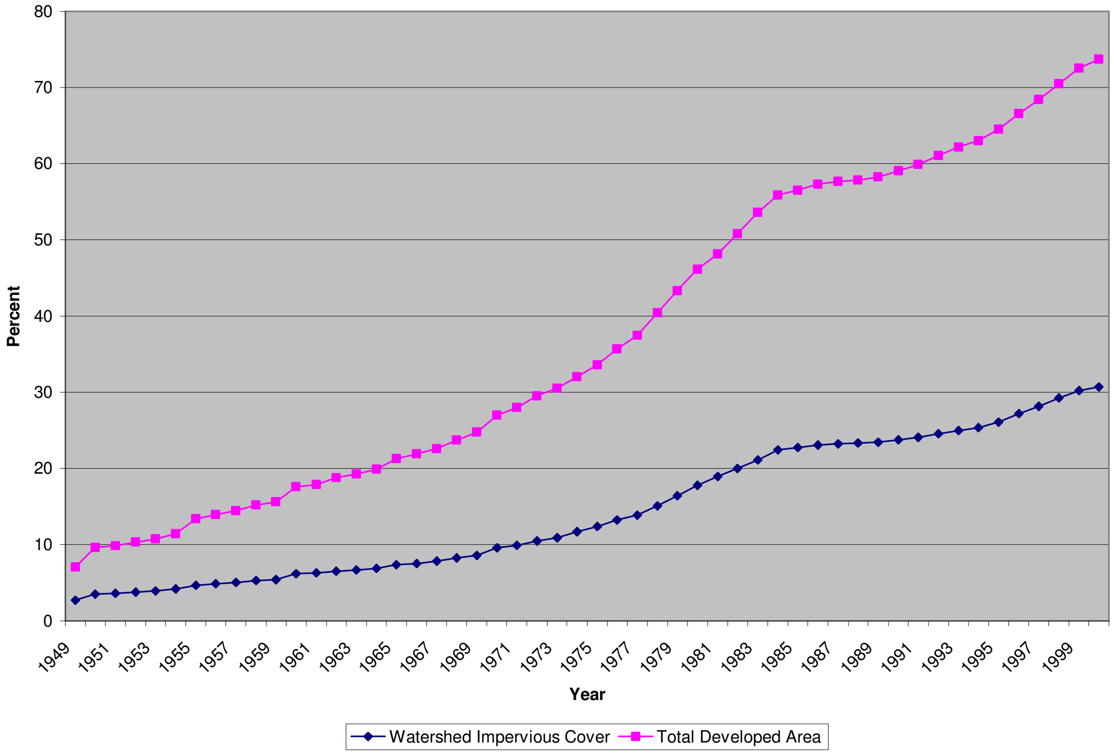


Figure 9. Watershed impervious cover and total developed area as a percentage of total watershed area by year.

To determine the components of the observed discrepancy between TDA and WIC, development was broken into commercial and residential units and observed for changes in parcel size as well as footprint. Because roads were treated as having a standard percent cover, TDA and WIC for roads was perfectly correlated and only TDA for roads was observed for changes over time.

As seen in Figure 10, average residential lot size ranged from a maximum of 13,702sq.ft. in 1963 to a minimum of 6,702sq.ft. in 1984. The overall trend was a significant decrease in residential lot size over time (F=31.922, df=4, p=<0.001), however this was primarily driven by the lot sizes in the 1960s, which were significantly larger than all other decades, including the 1950s. On average, residential lot size during the study period was 9,263sq.ft.

Average parcel size does not convey the complete story. Also of interest is the average amount of impervious cover per parcel (Figure 11) and the percent impervious cover per parcel (Figure 12). For residential parcels, the average amount of impervious cover was found to be significantly higher (F=25.019, df=4, p=<0.001) in the 1960s and 1990s. This does not represent a trend in residential impervious cover over time. However, decreasing parcel size combined with impervious cover remaining relatively constant results in the average residential impervious percent cover increasing significantly over time (F=44.224, df+4, p=<0.001). The only decades not found significantly different were the 1970s versus the 1980s and the 1950s versus the 1960s.

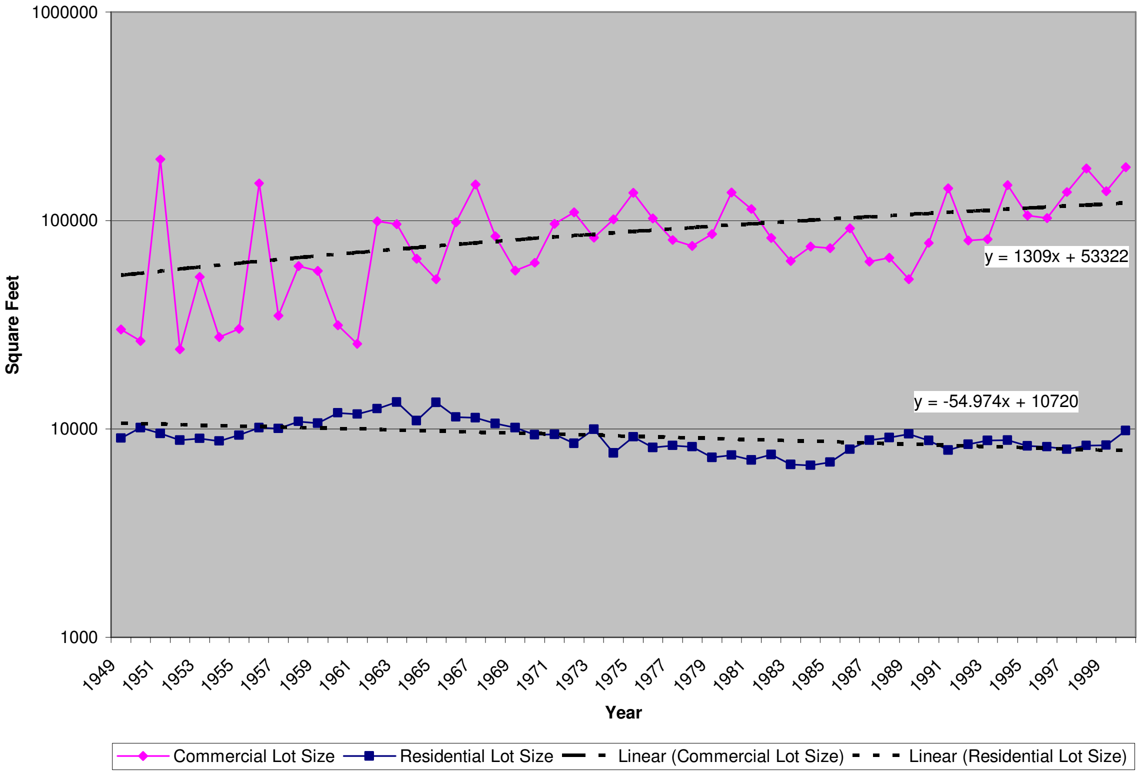


Figure 10. Residential and commercial average lot size by year.

Changes in commercial parcel size were seen as well. Commercial parcel size increased significantly (F=4.091, df=4, p=0.006) during the study period, ranging from a minimum of 24,148sq.ft. to a maximum of 196,673sq.ft. Although the general trend is increasing over time, lot size was more variable early in the study period and large averages were typically driven by a few large commercial projects. The 1950s were the most variable period, with a standard deviation of 57,252 sq. ft., which was over twice the standard deviation of 20,547 sq. ft. in the 1970s. The variability in lot size in the 1950s and 1960s prevented them from being statistically different from any decade except the 1990s. In contrast to residential lot size, average commercial lot size was 9.5 times larger at 88,009sq.ft.

Commercial impervious cover per parcel yielded similar results. Tested using Kruskal-Wallis One-Way ANOVA because of non-normal distribution and unequal variance, significant changes were seen (H=14.731, df=4, p=0.005). However, using Dunn's method, impervious cover was only found to be significantly different at the 0.05 level between the 1950s versus the 1970s and 1990s. In contrast to residential parcels, commercial average percent impervious cover was not found to have changed significantly.

To reiterate these points, residential impervious cover remained stable, but the percent cover per parcel has increased significantly because of decreasing parcel sizes. Commercial impervious cover has increased significantly, however the percent cover per parcel has not changed significantly because parcels sizes have increased over time.

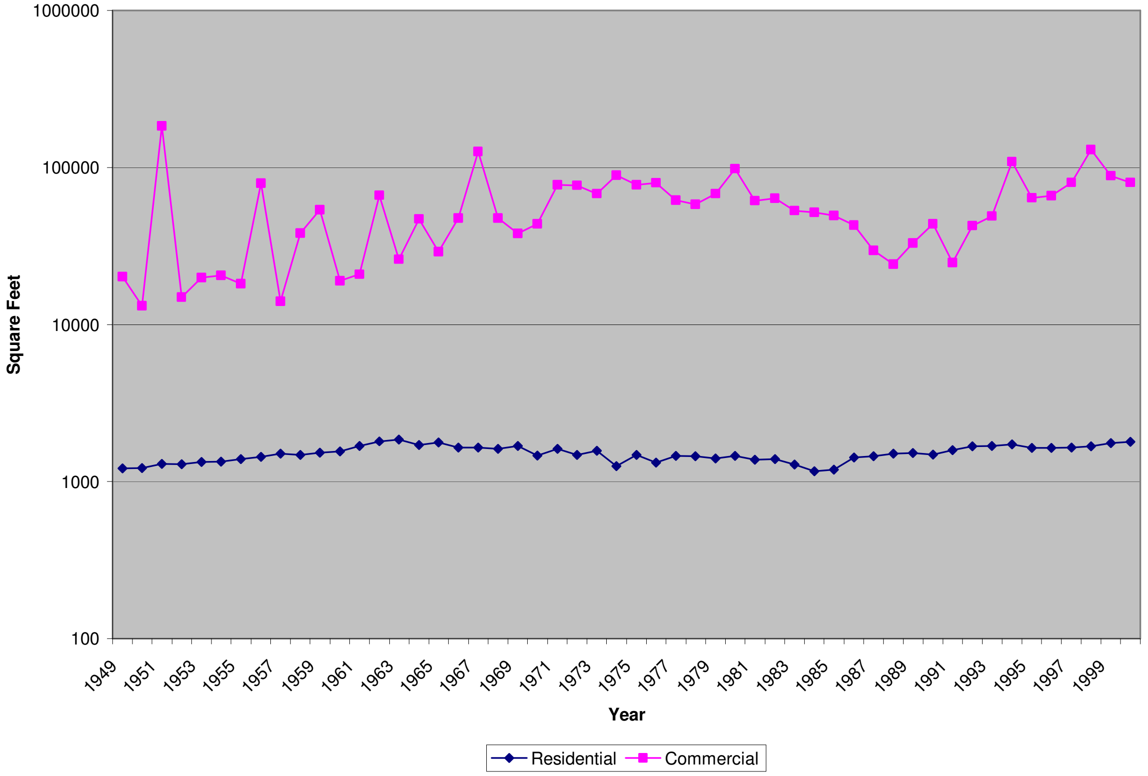


Figure 11. Average amount of impervious cover per parcel by year.

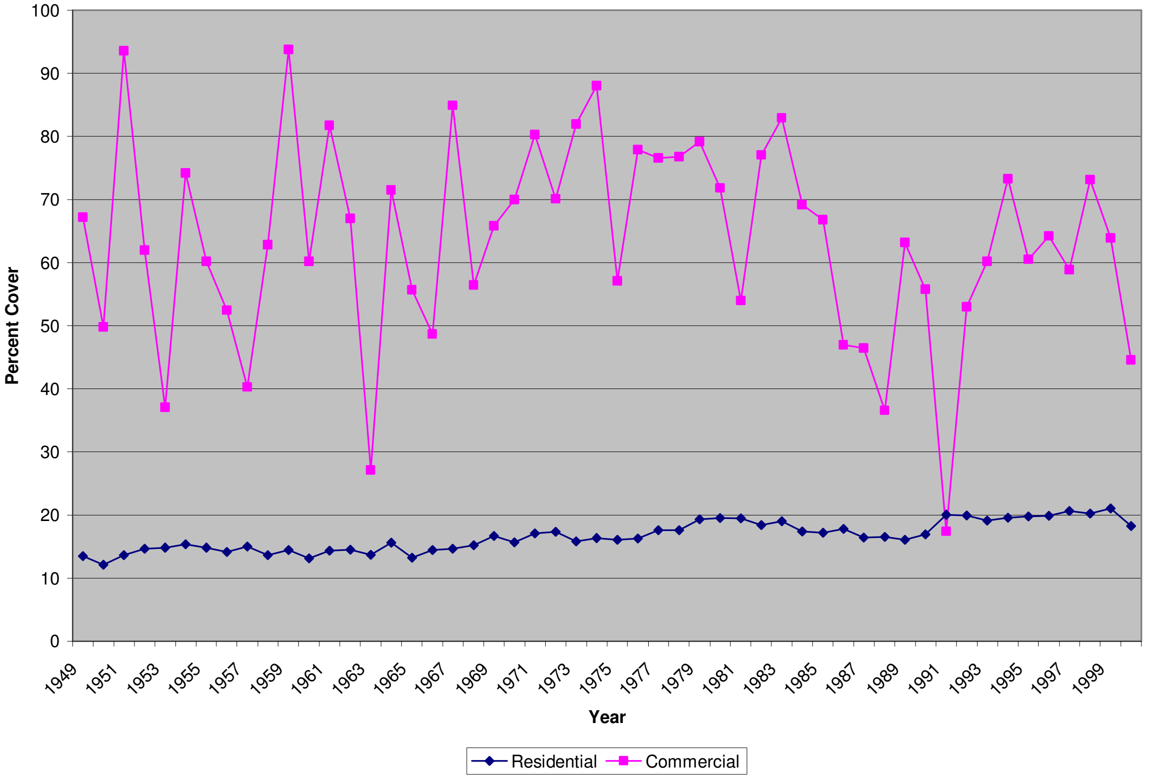


Figure 12. Average parcel percent impervious cover by year.

During the study period, residential total developed area (TDA) was found to be as much as 28 times higher than commercial TDA, and averaged 3.9 times higher on an annual basis. Cumulatively, residential TDA was always higher than commercial TDA, ranging from 8.5 times higher in 1949 to 1.5 times higher in 2000 (Figure 13). However, in Figure 14, it is easy to see that impervious cover due to residential development was higher than impervious cover due to commercial development only until 1967. After 1967, impervious cover due to commercial development averaged 3.7 times residential impervious cover annually.

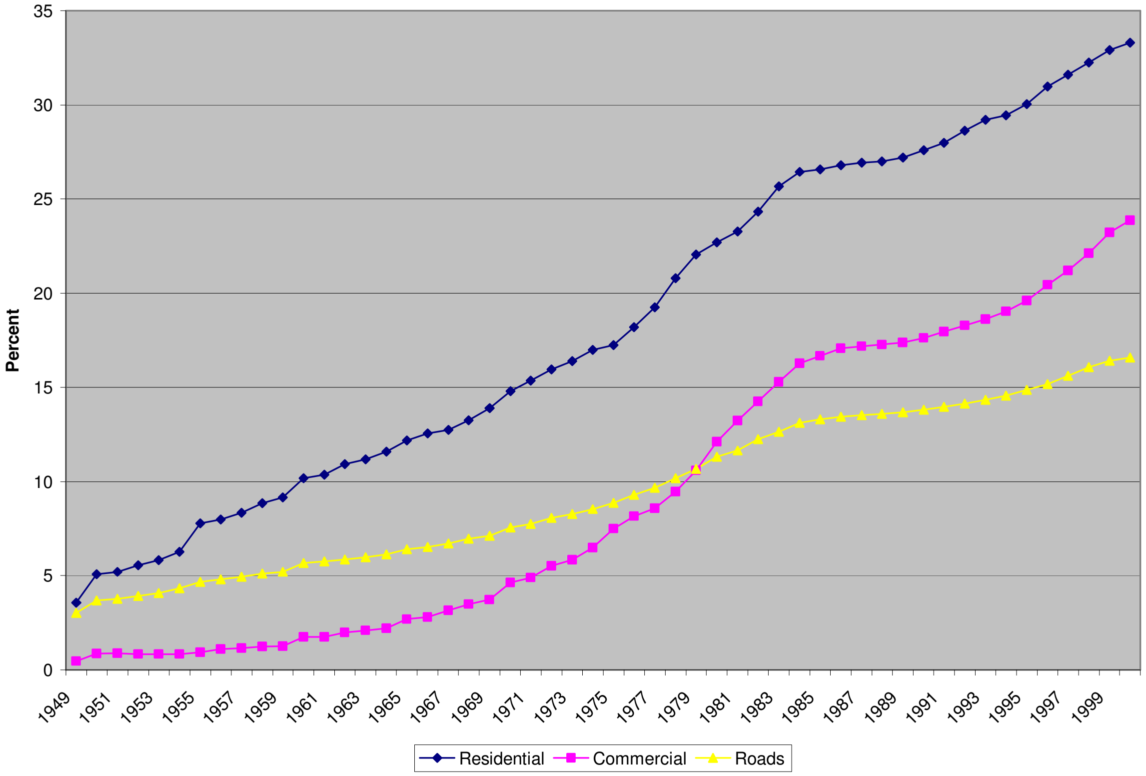


Figure 13. Total developed area as a percentage of the watershed by year.

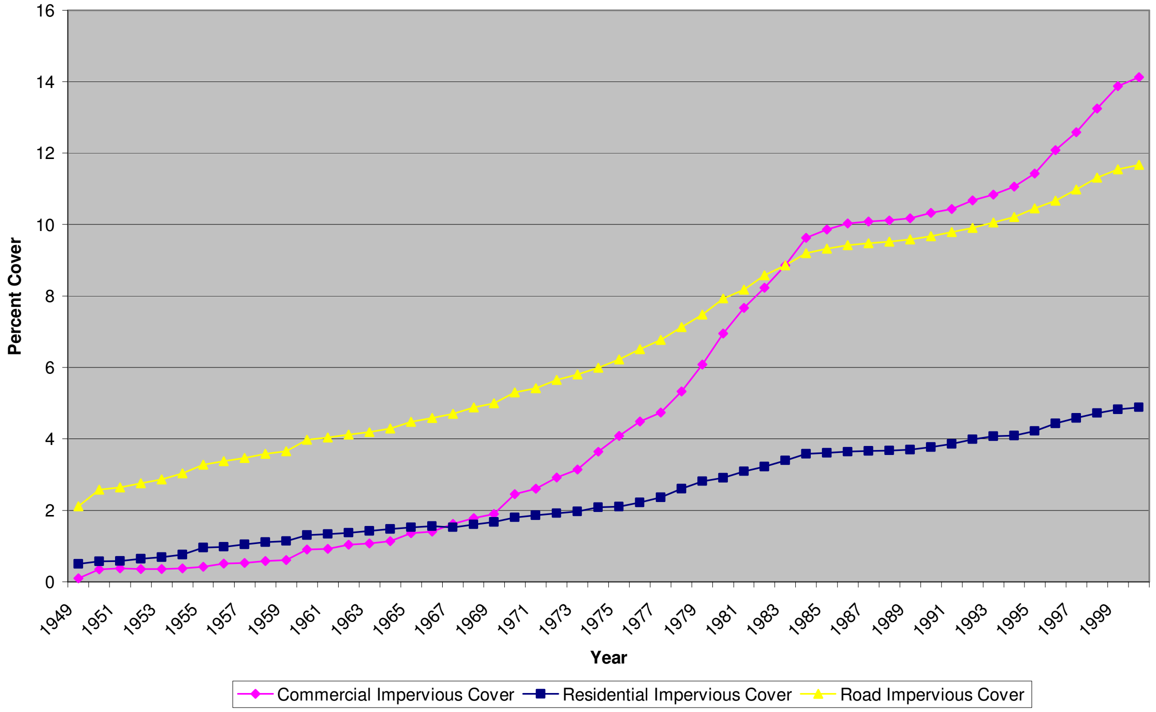


Figure 14. Cumulative impervious cover as a percentage of the watershed by year.

At the end of the study, commercial impervious cover accounted for 14% of the watershed area while residential impervious cover accounted for less than 5% of the watershed area. The ratios commercial TDA to residential TDA and commercial IC to residential IC will be tested as independent variables to predict residual flow.

The assumption of 70% impervious cover when measuring roads is close to the study average of 63% impervious cover per parcel observed in commercial development. The large amount of impervious cover per unit for roads, combined with the large amount of land dedicated to roads early in the study Figure 13, total impervious cover due to roads dominates the watershed until 1983 when it is surpassed by commercial development Figure 14. Residential impervious cover never exceeds road impervious cover, despite residential TDA always being higher than road TDA. No significant trends were found in the annual additional road TDA, likely because of the high variability as seen in Figure 15.

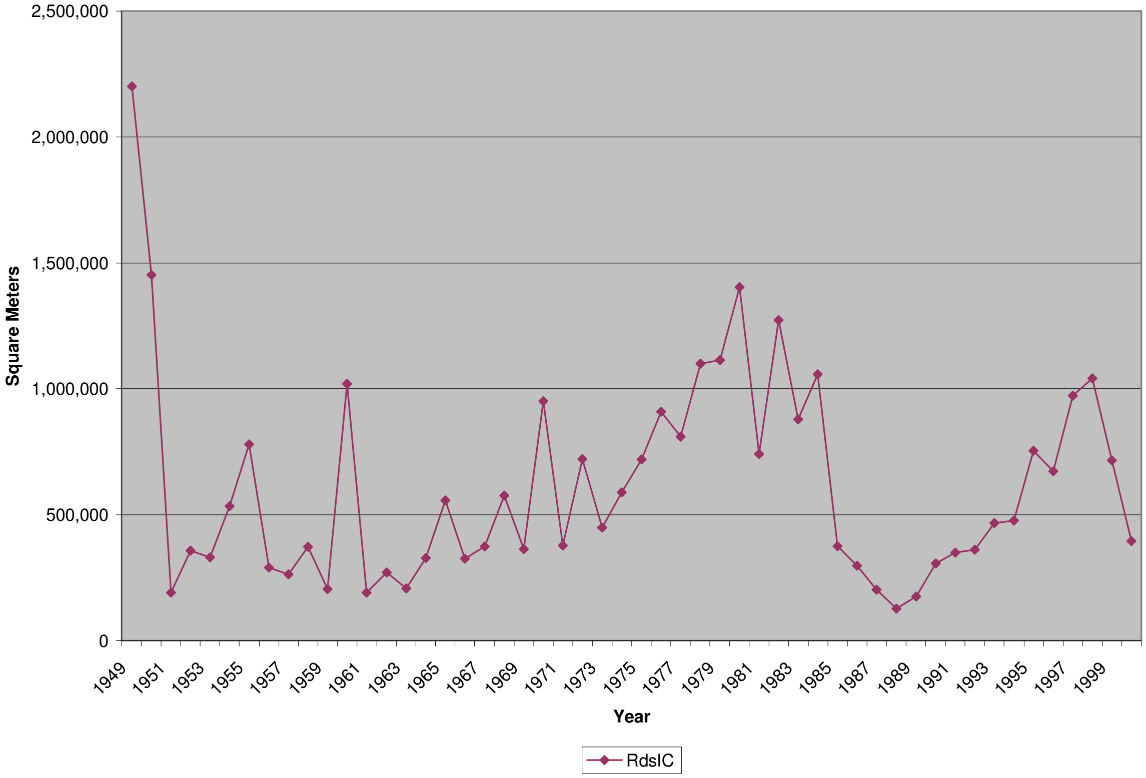


Figure 15. Annual additional roads impervious cover by year.

Conclusions on Development

From the observed changes in development over time, several trends are clear. First, development, whether measured as the total area developed or just as impervious cover, has increased over time. The components of that development exhibit unexpected results. When development is defined as total developed area, the leading component of development is residential. When development is defined as the increase in impervious cover, roads are the primary source until 1983 when commercial development takes over.

Although residential homes have been getting larger, the footprint of those homes has remained relatively unchanged. This does not mean that residential development has not changed – decreasing lot sizes have increased the total percent impervious cover per residential parcel. Combined with the total amount of land developed for residential uses, it is clear that residential development may have a major impact on streamflow.

Commercial development has paralleled residential development in total developed area, but increasing lot sizes resulted in greater amounts of impervious cover per parcel. Commercial development surpassed residential development in total impervious cover in 1967 and eventually surpassed roads in 1983. As a major contributor to impervious surface in the latter two-thirds of the study period, commercial development is also expected to have a major impact on streamflow.

The last component of development is the roads. Until 1979, the total developed area dedicated to roads exceeded the area dedicated to commercial development, but road TDA never exceeded residential TDA. Despite the relative areas, roads contributed from two to four times as much impervious cover to the watershed as did residential development. Roads remained the major contributor of impervious cover until the rapid increases of commercial development seen in the 1970s and early 1980s caused commercial development to take on that role in 1983. The impervious cover contributed by roads is expected to be the primary cause of increased runoff during the first two-thirds of the study period.

Because of the observed differences in the three different components of development in both TDA and WIC, each will be treated as a separate independent variable in addition to the all-inclusive measurement of development. This is to determine if any particular component of development has a greater effect on streamflow. Understanding which component is most important may help decision-makers improve the quality of development and reduce the impacts on streamflow.

CHAPTER VI

SPATIAL METRICS

Introduction

The relative placement of impervious cover on a parcel is understood to have an impact on the flow of water from that parcel. Consider a hypothetical parcel of land adjacent to a stream which is sloped to drain into the stream (Figure 16). The parcel is to be covered by a single parking lot which occupies only 50% of the total area. If the parking lot is placed so that all of the water from a storm drains through the undeveloped portion of the parcel, the water will be slowed by the vegetation and have an opportunity to infiltrate and evaporate instead of becoming a part of the storm-water flow in the stream. If the positions were reversed, all of the storm-water flow generated from the parking lot would flow immediately into the stream.

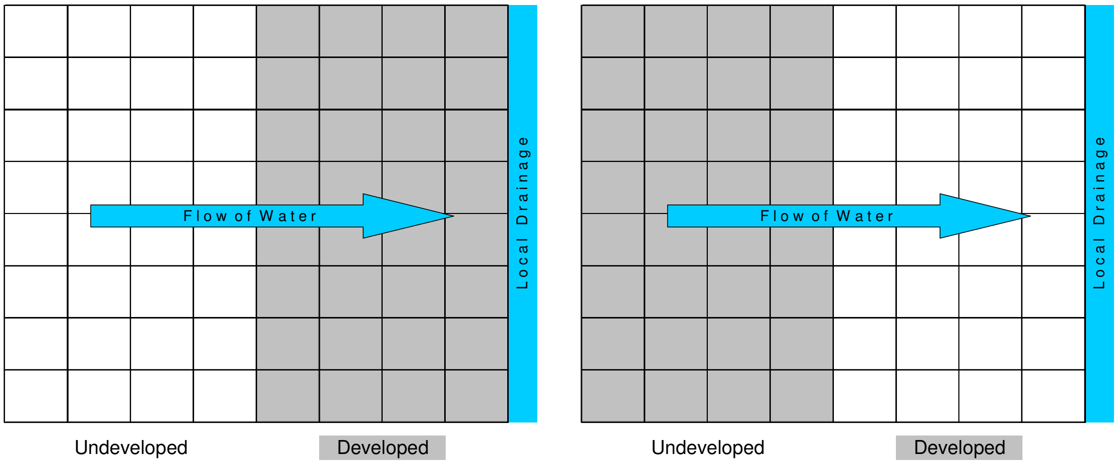


Figure 16. Simplified examples of development configuration.

While this is a simplistic example which ignores many issues which could be solved by design, the implications are clear. Configuration of impervious cover on the landscape is expected to have an impact on how that landscape transports or holds water. Issues that could be solved by design at the parcel or neighborhood level may not be addressed at broader scales.

This part of the study addresses landscape configuration at the watershed scale as a set of independent factors affecting streamflow. "Very few pattern indices produce values that are useful by themselves" (Gustafson 1998). Because of this, the best use of spatial metrics is the comparison of the same landscape between two or more time periods or landscapes with similar spatial data resolution and extent. The long period of study within the unchanging boundaries of a single watershed allows for analysis of the same landscape as it changes over time.

The first attempt to select the appropriate set of spatial metrics was to measure all of the possible factors, test for correlation to the dependent factor, residual flow, and use a drill-down process to determine the best model while eliminating the least appropriate metrics. This method did not work as anticipated because of colinearity problems between the independent variables. Instead, it was decided that the selected metrics should cover basic landscape concepts such as composition, quantity and configuration.

Although the total developed area and the watershed impervious cover were measured in the previous chapter, the measurements were totals for all development in the watershed. Important questions about the configuration of the development were not answered. Did the development occurred as a single contiguous patch of development or was it divided into a large number of smaller patches? If divided into smaller patches, were the patches perfect squares or long strips of development? How far apart were the patches of development? How were the patches interconnected?

These questions revealed that the selected spatial metrics should represent basic configuration issues such as the size and shape of the developed patches, the perimeter of the patches, the proximity of the patches to each other, and the connectivity of the landscape as a whole. But it was also recognized that roads play an important role within the landscape that should be addressed separately.

While roads do contribute impervious cover which increases runoff, roads also play a major role in the connectivity of the landscape in two important ways. First, roads connect non-contiguous patches of developed parcels. Second, roads, or infrastructure associated with roads, act as the primary drainage system for both residential and commercial development and deliver the concentrated flow to the local stream system.

Because of this, accounting for the spatial metrics for roads, including patch size and area, shape, and connectivity was deemed important. It was also thought that the perimeter of the road patches may be important as the perimeter of the roads represents the connectivity of the roads to developed parcels. Finally, the length of the road network was measured. If the relationship between road length and streamflow is strong, this would provide an easy measurement for gauging the state of a watershed.

In this chapter, the selection, measurement, and findings of the spatial metrics are discussed. The final step, relating all of the development data, both spatial and non-spatial, is in the final chapter of this paper.

Methods

The GIS prepared for the previous chapter was utilized to observe the variables which focused on configuration. The methods are presented in two parts: the selection of the appropriate spatial metrics; the software and the data requirements for measurement.

Selected Spatial Metrics

Inter-correlation between spatial metrics is a recognized problem (Leitão and Ahern, 2002; Riiters, et al., 1995; Li and Reynolds, 1995; Gustafson, 1998; McGarigal et al., 2002; Hargis et al, 1998; Tinker et al., 1998). Each author dealt with the inter-correlation problem either through correlation matrices, principle component analysis, or theoretical consideration. After considerable review, Leitão and Ahern (2002) proposed the following as a core set of landscape metrics: Patch Richness and class area proportion; Patch number and density; Mean patch size; Patch shape (perimeter to area ratio); Edge contrast (TECI); Patch compaction (RGYR); Nearest neighbor distance; Mean Proximity Index; and Contagion.

This was used as a guideline when selecting spatial metrics for this study. Some metrics, such as patch richness and contagion, were not selected. Historical data limitations on land use and land cover, plus the focus on growth in the hardscape, the overall richness of patch type is not at issue. Contagion, a measure of connectedness between varying patch types, requires at least three to be meaningful. With only two patch types defined in this study, contagion was an inappropriate metric.

The number of patch types also affects TECI. Without varying contrast between different patch types, edge contrast is expected to remain constant and can be replaced by edge density. However, TECI may be used to differentiate between adjacent patch types. By setting TECI to measure contrast between developed roads and developed parcels while ignoring edges of both road and parcels adjacent to undeveloped land, we can gain a better understanding of the interaction between roads and developed parcels.

Aggregation index (AI), a measure of the connectivity within a single class, was substituted for patch compaction. Patch compaction is measured as the radius from the centroid of the patch to the furthest cell and may be influenced by line of single cells moving away from the bulk of the patch. Patch compaction is also measured on a per-patch basis and averaged for all patches in the landscape. Aggregation index is measured using the number of like adjacencies between cells of the same class versus the number of like adjacencies if the class was maximally aggregated. AI reaches its maximum when the class is a single square patch. As the patch becomes more linear or is broken into smaller patches, AI decreases.

Patch number (PN) and patch density (PD) may indicate the increase in number and eventual consolidation of hardscape patches over time. Because the area is static, PN and PD produce the same information, thus only PN will be reported. Mean patch size (MPS) is a complement to PN and PD, with all three indicating the relative amount of hardscape within the landscape. “Most roads and parking lots are directly linked to the storm drain system and are termed *directly connected impervious areas*. Nearly all the rain that falls on these surfaces is converted into stormwater runoff” (Schueler, 1994) Because of the role of roads as a transport system for water, spatial metrics which describe the shape and connectivity of roads to other developed parcels should be extremely important.

Patch shape (PS), especially in the case of roads, may provide insight into the ability for hardscape to act as a conduit for water transport. Edge density (ED) is measured as the total length of all patch perimeters divided by the landscape area and converted to hectares ED may indicate how roads interact with the surrounding landscape and act as a transport system for water. Although rarely applied in the literature (Herzog and Lausch, 1999), the spatial configuration metric nearest neighbor (NN) represents the relative interconnectivity of hardscape.

In addition to the metrics suggested by Leitão and Ahern, the following metrics were tested: Weighted Mean Patch Size (WMPS), Lacunarity (LAC), Mean Proximity Index (MPI), and Landscape Division (DIVIS).

WMPS is a spatial metric introduced by Li and Archer (1997) to prevent extremely large or extremely small patches from skewing the measurement of mean patch size. Both MPS and WMPS will be used. Lacunarity provides an indication of “gappiness” within the landscape and also indicates the heterogeneity of the landscape and the domain of scale (Plotnick et al. 1993). High lacunarity values are an indication of large gaps between patches. Mean proximity index is another method for gauging the relative distribution of the patches relative to one-another. Landscape division is defined as “the probability that two randomly chosen places in the landscape are not situated in the same undissected patch” (McGarigal, et al., 2002). Lacunarity and division will be discussed at length below. Once the spatial metrics were chosen, the testing process could begin.

Quantifying Spatial Metrics

FRAGSTATS is a GIS software package developed to calculate spatial metrics by McGarigal, et al. (2002) and has been widely used in previous studies (e.g. Apan, et al., 2002; Griffith, et al., 2000; Marsden, et al., 2002; Pearson, et al., 2002; Raines, 2002). FRAGSTATS computes spatial indices for each class type in the landscape and for the landscape as a whole (McGarigal, et al. 2002).

It was necessary to convert all of the development data from vector to grid format for each year in the study for compatibility with the software used to measure the metrics. Optimum grid cell size is roughly one-half the smallest dimension of the smallest unit of measure. The smallest unit in the study area was parcels and the smallest width for parcels was roughly 20 meters. A cell size of 10 meters square was selected for the vector to grid conversion. ArcView 3.3 with the Spatial Analyst extension was used to make the conversions. All grids were stored in ArcGrid format.

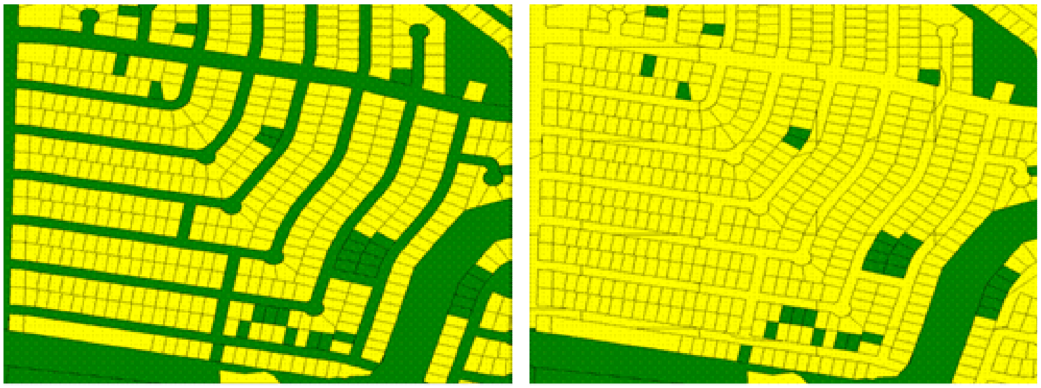
Once a building or road was constructed, the unit was classified as “developed.” For any point in time, the watershed could be defined as a binary system of developed and undeveloped units. For each year of the study, units of the same development status (developed or undeveloped) which shared a boundary became part of a contiguous patch. The entire area of each unit was considered for the spatial metrics because it was impossible to determine the exact location of any impervious cover within each unit. Once converted to cells, diagonal cells of the same development status were not considered part of the same patch.

It was necessary to create datasets where roads could be treated separately. Roads act as both a barrier and a conduit. In its role as a barrier, a road interrupts and redirects flowing water. Roads, or elements often associated with roads, act as a conduit to carry water into a drainage system, whether natural or man-made. The final role of roads is as impervious cover. In this role, roads contribute to runoff by preventing infiltration and as such, belong in the measure of impervious cover with parcels.

Three sets of maps were created for each year in the study. The first only mapped developed roads with all other cells being treated as undeveloped. The second set of maps contained only developed parcels without roads. The third set of maps combined the elements of the previous two and contained both developed roads and parcels in a matrix of undeveloped land. Creating three datasets per year allowed the configuration of the road to be treated separately and allowed the observation of parcels separately when necessary. The inclusive dataset was used to investigate the spatial distribution of all impervious cover in the watershed. The three methods for determining developed areas are referred to as Roads, Parcels, and Parcels With Roads (PWR).

If only parcels are considered, two parcels on opposite sides of a street would be treated as separate patches when both are developed. When only roads are considered, all parcels are treated as undeveloped, changing the size and shape of the developed patches. Finally, when both parcels and roads are considered, developed parcels on opposite sides of a street are connected by the road and treated as part of the same patch.

The method for determining patch composition changes the character of the measurements. In a single large development, if all parcels are developed and only parcels are measured, multiple patches are prevalent and the shape of the patches is closer to round. When only the roads are counted, the same development produces a single patch of road which is much more linear in configuration. When both roads and parcels are counted, a completed development is treated as a single large patch (Figure 17).



Parcels Only

Parcels With Roads

Figure 17. Example of the difference between rules for determining developed patches. Yellow areas mark developed areas. Green denotes undeveloped areas.

Once the grids were complete, FRAGSTATS was used to calculate the selected spatial metrics. The results were imported into Microsoft Excel for tabulation and exported to SPSS 11.0 for statistical analysis. As with all previous measurements of change in the watershed, the spatial metrics were tested for significant changes by decade, with the first and last decades each containing an extra year. The tests included One-Way Analysis of Variance and Tukey pair-wise comparisons if the data was normally distributed and equally variant, or Kruskal-Wallis One Way ANOVA on Ranks and Dunn's Method of Pairwise Comparison if not.

Results

From the maps seen in Figure 18 it is clear how the method for determining the location and construction date for road segments affects the measurement of development within the watershed. Isolated patches of development should not be possible – all roads should be connected and all developed parcels should be connected to a road. However, this is a known limitation of this study, the error is consistent, and the error results in a conservative estimate for development and impervious cover.

Also clear from Figure 18 is how much of the landscape is covered by development during the study period. Although impervious cover is lower than the total parcel area, it is unlikely that the amount of impervious cover will increase significantly once a parcel has been developed.

Table 5 shows the results of the statistical analyses between decades for all of the spatial metrics. All of the tests show a significant change between decades, however the table does not indicate which decades were found significantly different. Also not indicated in the table is which decades were different and if any trends were present. Decadal differences and trends are discussed below.

The number of patches for Roads and PWR is seen in Figure 19. The number of road patches remains remarkably constant until 1978 when the patches start coalescing. There are no statistical differences in the number of patches between any of the first three decades. The first significant difference occurs between the 1970s and the 1980s when the median number of patches drops from 319 to 256. The 1980s was not found

Table 5. Test statistics for spatial metrics compared between decades. All tests had four degrees of freedom and were found significant at the 0.001 level.

Spatial Metric	Normality Test	Equal Variance	Model	Test Statistic	Degrees Freedom	P-value
PWR NumP	Passed (p = 0.372)	Failed (p = 0.001)	Kruskal-Wallis	H = 46.889	4	< 0.001
PWR MPS	Failed (p = <0.001)	N/A	Kruskal-Wallis	H = 48.967	4	< 0.001
PWR WMPS	Failed (p = <0.001)	N/A	Kruskal-Wallis	H = 48.771	4	< 0.001
PWR ED	Passed (p = 0.076)	Passed (p = 0.056)	One-Way ANOVA	F = 241.105	4	< 0.001
PWR AWMSI	Passed (p = 0.286)	Passed (p = 0.220)	One-Way ANOVA	F = 218.787	4	< 0.001
PWR MNN	Passed (p = 0.156)	Passed (p = 0.404)	One-Way ANOVA	F = 290.457	4	< 0.001
PWR MPI	Failed (p = <0.001)	N/A	Kruskal-Wallis	H = 48.964	4	< 0.001
PWR AI	Passed (p = 0.114)	Failed (p = <0.001)	Kruskal-Wallis	H = 48.981	4	< 0.001
PWR Std. Lac.	Passed (p = 0.523)	Passed (p = 0.399)	One-Way ANOVA	F = 296.889	4	< 0.001
PWR Division	Passed (p = 0.638)	Failed (p = <0.001)	Kruskal-Wallis	H = 43.789	4	< 0.001
Rd NumP	Failed (p = <0.001)	N/A	Kruskal-Wallis	H = 40.453	4	< 0.001
Rd MPS	Failed (p = <0.001)	N/A	Kruskal-Wallis	H = 48.874	4	< 0.001
Rd WMPS	Failed (p = <0.001)	N/A	Kruskal-Wallis	H = 48.878	4	< 0.001
Rd ED	Passed (p = 0.371)	Passed (p = 0.344)	One-Way ANOVA	F = 322.084	4	< 0.001
Rd AWMSI	Failed (p = <0.001)	N/A	Kruskal-Wallis	H = 48.701	4	< 0.001
Rd MNN	Passed (p = 0.500)	Failed (p = <0.001)	Kruskal-Wallis	H = 47.048	4	< 0.001
Rd MPI	Failed (p = <0.001)	N/A	Kruskal-Wallis	H = 48.528	4	< 0.001
Rd AI	Failed (p = 0.020)	N/A	Kruskal-Wallis	H = 49.036	4	< 0.001
Rd Std. Lac.	Passed (p = 0.334)	Passed (p = 0.448)	One-Way ANOVA	F = 250.667	4	< 0.001
Rd Division	Passed (p = 0.214)	Passed (p = 0.211)	One-Way ANOVA	F = 318.289	4	< 0.001

significantly different than the 1990s, but surprisingly, the same is true between the 1980s and the 1950s. This is likely caused by the small number of patches in 1949.

The number of patches for PWR follows a similar pattern with a few differences. Instead of remaining steady through 1978, the number of patches increases from 1960 to its peak in 1972, but the increase is not enough to create a significant difference between any of the first three decades. The patches start coalescing in 1973 and the first significant difference in the number of patches is seen between the 1980s and both the 1960s and 1970s. The 1980s are not significantly different from the 1950s and the 1990s. The median value of 230 patches in the 1990s is significantly different than all other decades except the 1980s. Because the road network acts to bind parcels together in PWR, it is expected that the number of patches for each metrics merges at the end of the study as the watershed is covered with developed parcels.

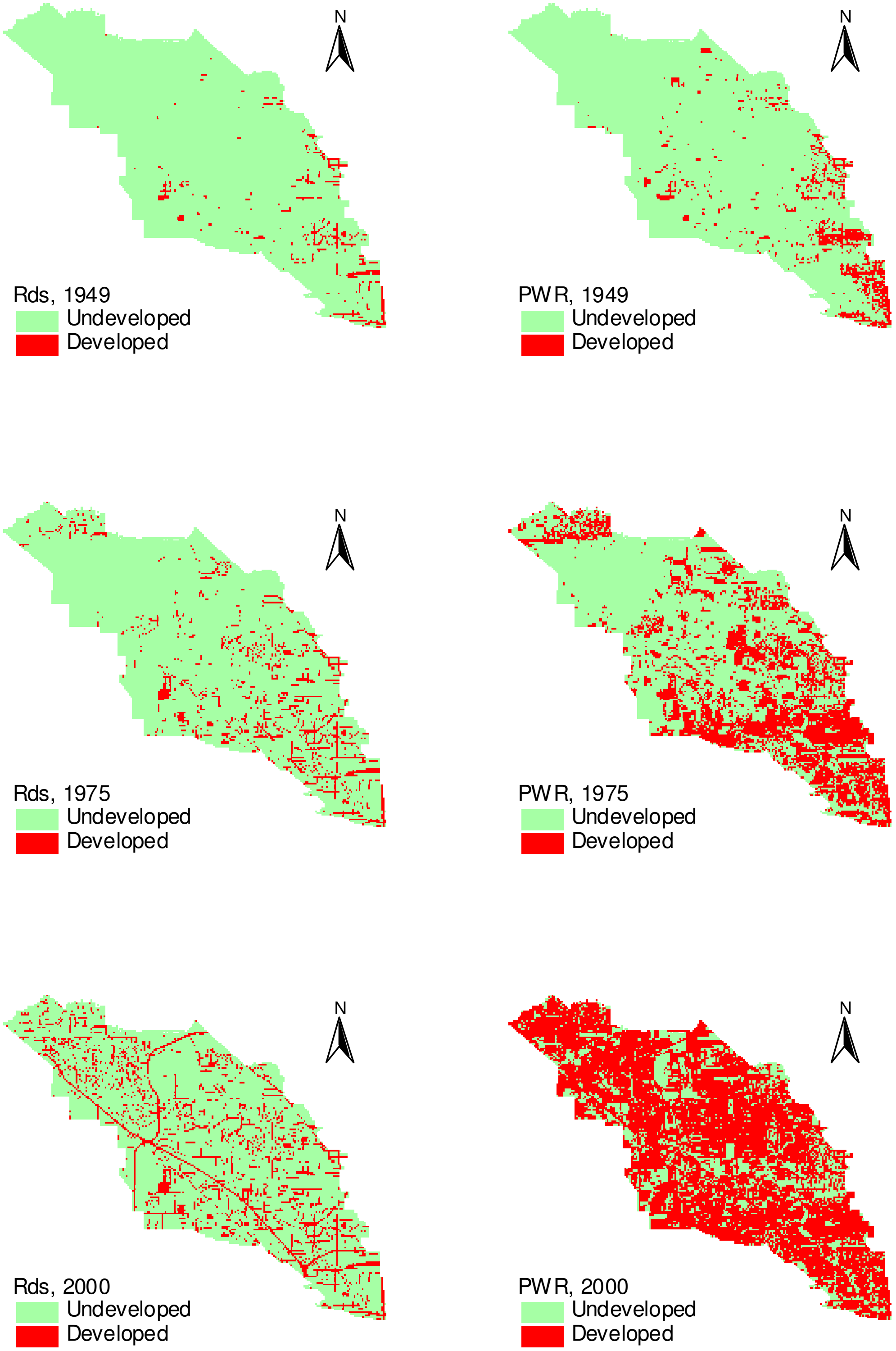


Figure 18. Maps of the study area showing development patch configuration for roads (Rds) alone and parcels with roads (PWR) for selected years.

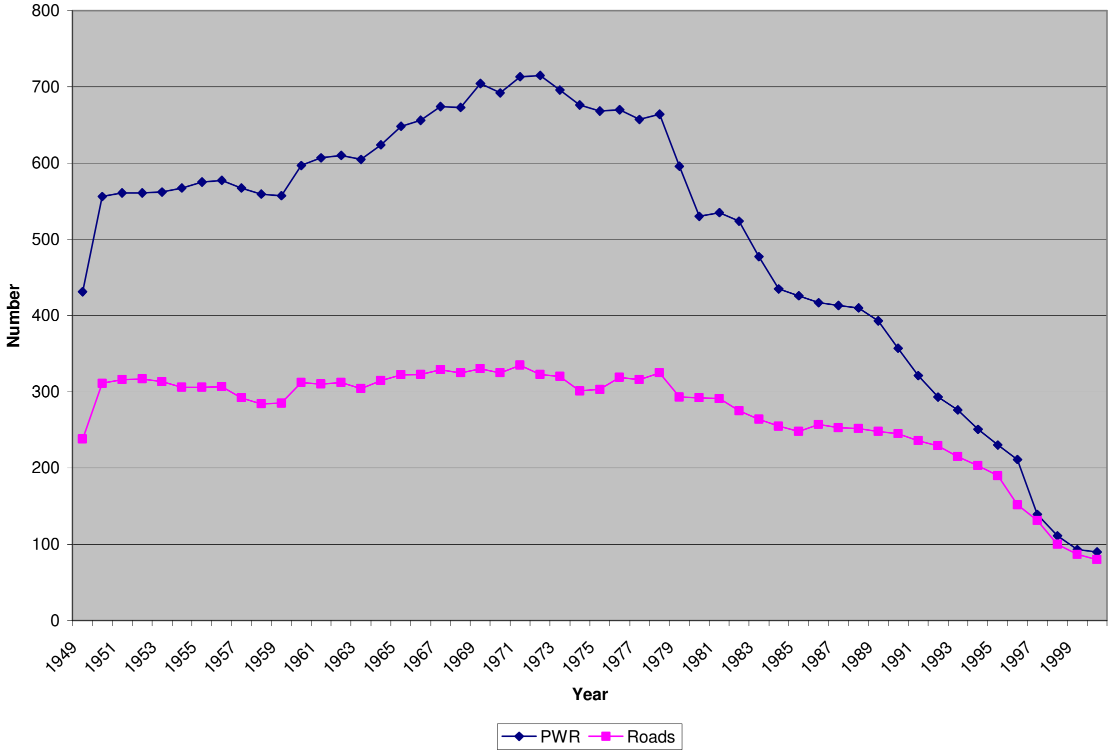


Figure 19. Number of patches for roads and parcels with roads by year.

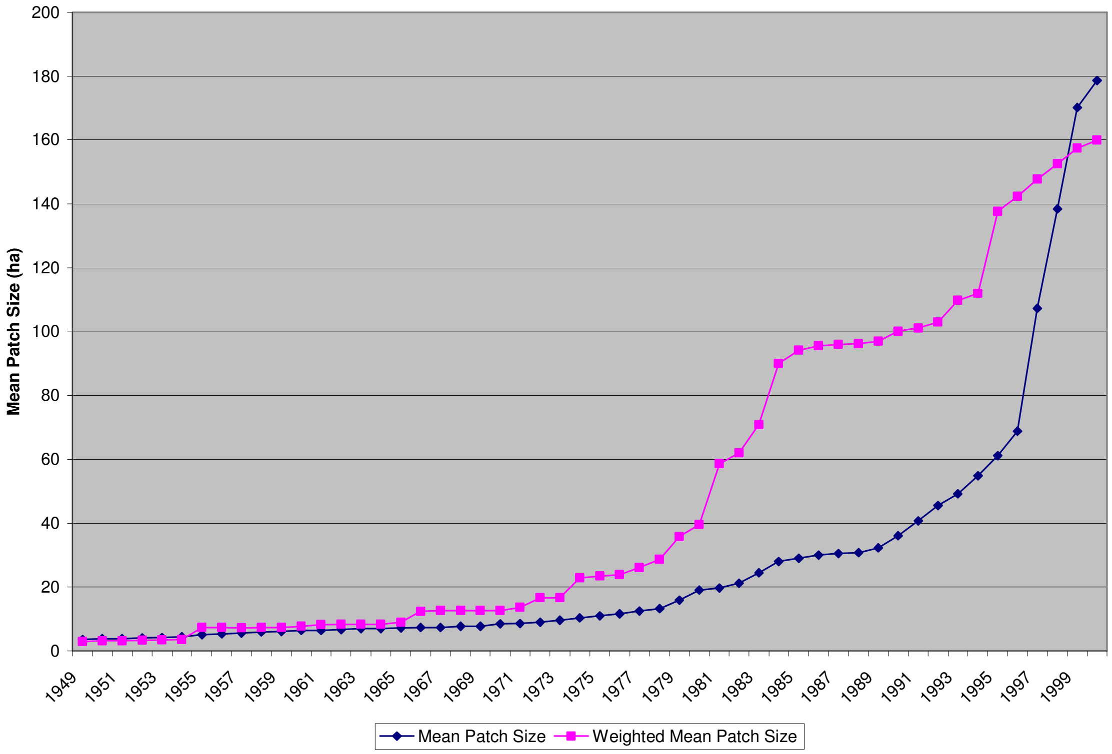


Figure 20. Mean patch size and weighted mean patch size for parcels with roads by year.

Patch size and weighted mean patch size for PWR are seen in Figure 20. The two measures of patch size begin to diverge in 1966, indicating a change in the distribution of patch size with larger patches becoming more common in the landscape. Where WMPS is sensitive to this change, MPS is not. Within the variables over time, both WMPS and MPS follow the same pattern. There are no significant differences between any adjacent decades for either measure of patch size, however, all non-adjacent decade pairs were found significantly different.

The median values per decade are nearly identical between MPS and WMPS for the 1950s and 1960s. In the 1970s, the median value for WMPS, at 23 ha, is double the median for MPS. The difference is greatest in the 1980s when the median value for WMPS is 92 ha and MPS is 28 ha.

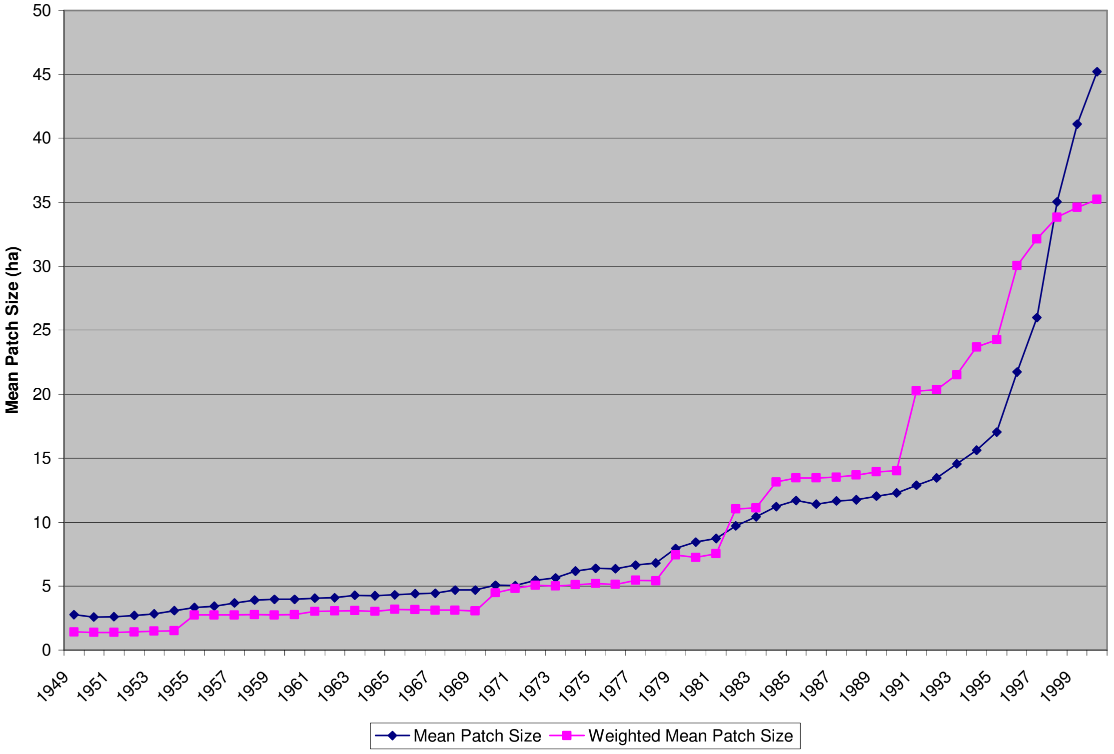


Figure 21. Mean patch size and weighted mean patch size for roads by year.

The differences between MPS and WMPS for roads seen in Figure 21 were not nearly as great as those seen in PWR. Both measures of patch size show steady increases until the 1990s when the individual patches started coalescing into larger patches.

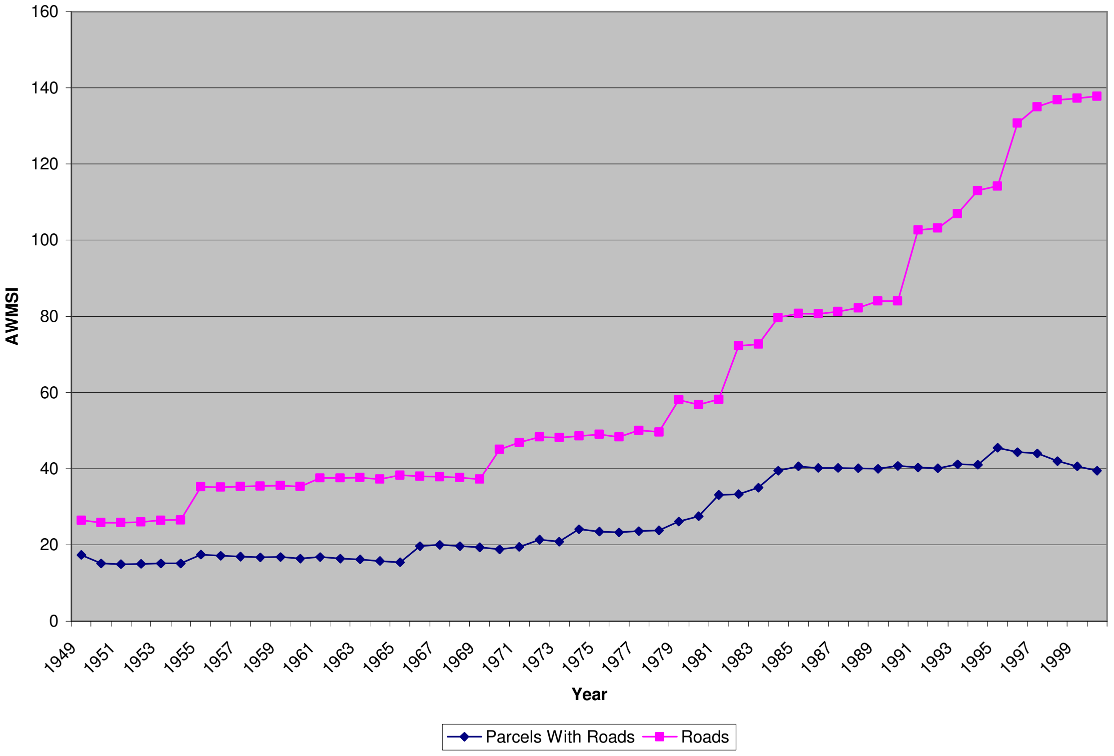


Figure 22. Area weighted mean shape index for roads and parcels with roads by year.

The change in the shape of the patches for both Roads and PWR is shown in Figure 22. As expected, the shape of the road patches becomes more linear over time as the patches coalesced. The increases seen in the linearity of the roads are not significant between adjacent decades, but are significant in all other pairwise comparisons. The same is true for between-decade comparisons for PWR. The differences between AWMSI for Roads and PWR are because of the shape of the smallest whole units. Parcels in this watershed are typically square or rectangular, thus the larger patches should be expected to have a similar shape. Despite the linearity of roads, when the two are combined the overall patch shape remained closer to the maximally compact patch.

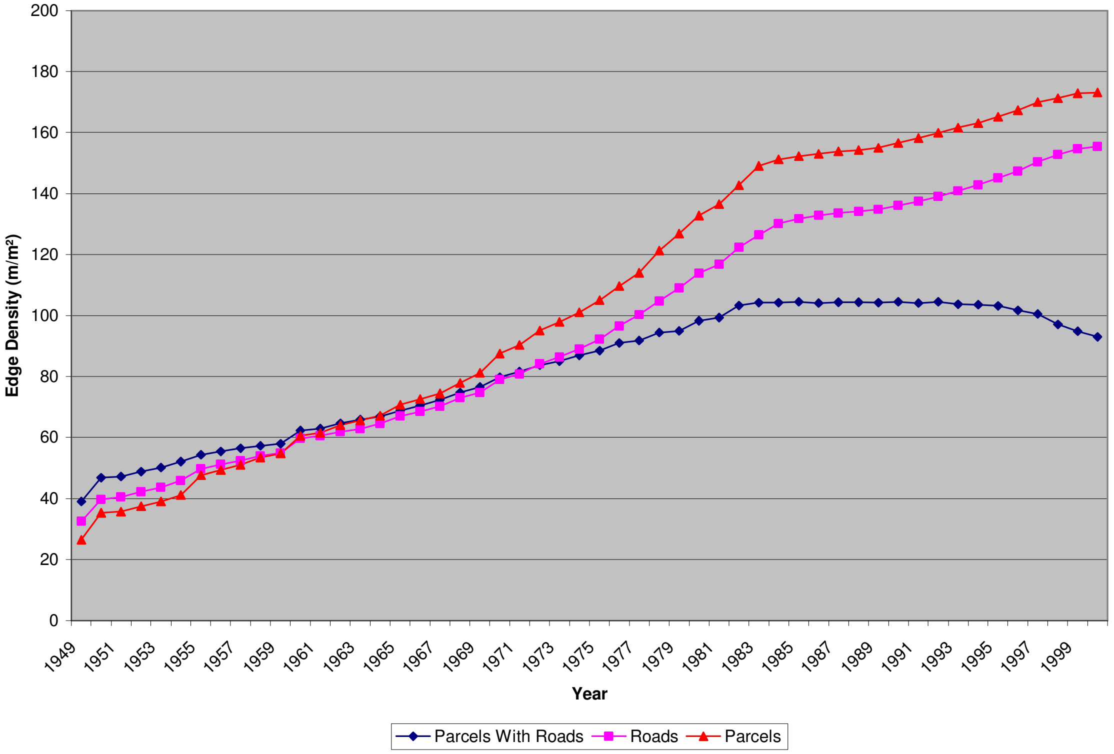


Figure 23. Edge density for roads, parcels with roads, and parcels without roads by year.

As expected, the ED for roads continually increased throughout the study period (see Figure 23). The increase was significant for every decade pair, including all adjacent decades. ED for PWR also increased continually until 1982 where it leveled off until it took a downward turn in 1996. When tested by decade, all decade pairs were found significantly different except for the final pair, the 1980s versus the 1990s. ED for parcels is discussed below.

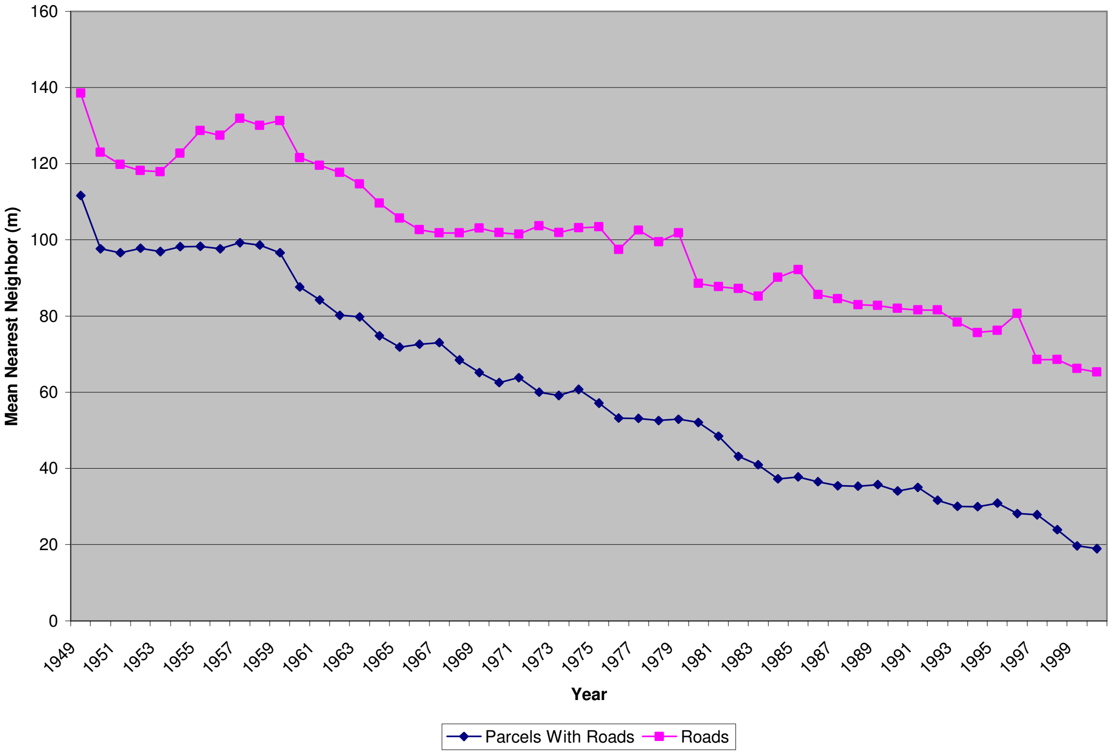


Figure 24. Mean nearest neighbor for roads and parcels with roads by year.

Figure 24 shows MNN for roads and PWR. The graph indicates that overall, nearest neighbor distance is decreasing for both roads and PWR over time. During a few brief periods, MNN was increasing for PWR, however, when aggregated into decades, these trends disappeared and all decade pairs were found significantly different. For the roads, these upward trends were strong enough to cause all adjacent decade pairs to not be significantly different. MNN for the roads in the 1990s were found significantly smaller than the 1950s, 1960s, 1970s, and 1980s. The only other pair found significant was the 1950s versus the 1980s.

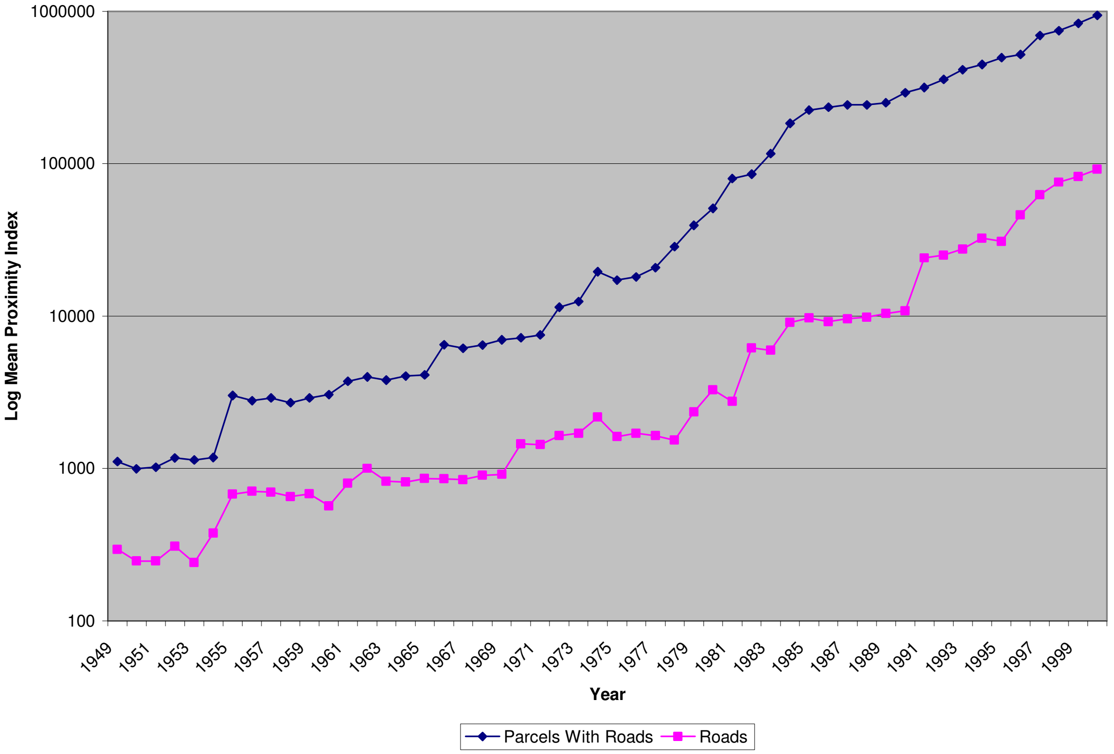


Figure 25. Mean proximity index for roads and parcels with roads by year.

MPI increases when patches get larger, get closer together, or when more patches are found within the search radius. In this test, the search radius was set large enough to capture all of the parcels within the landscape. MPI increased by several orders of magnitude for both Roads and PWR as seen in Figure 25. The increases between adjacent decades were not great enough to make any adjacent decade pairs significantly different for either Roads or PWR. In both groups, all other decade pairs were found to have changed significantly.

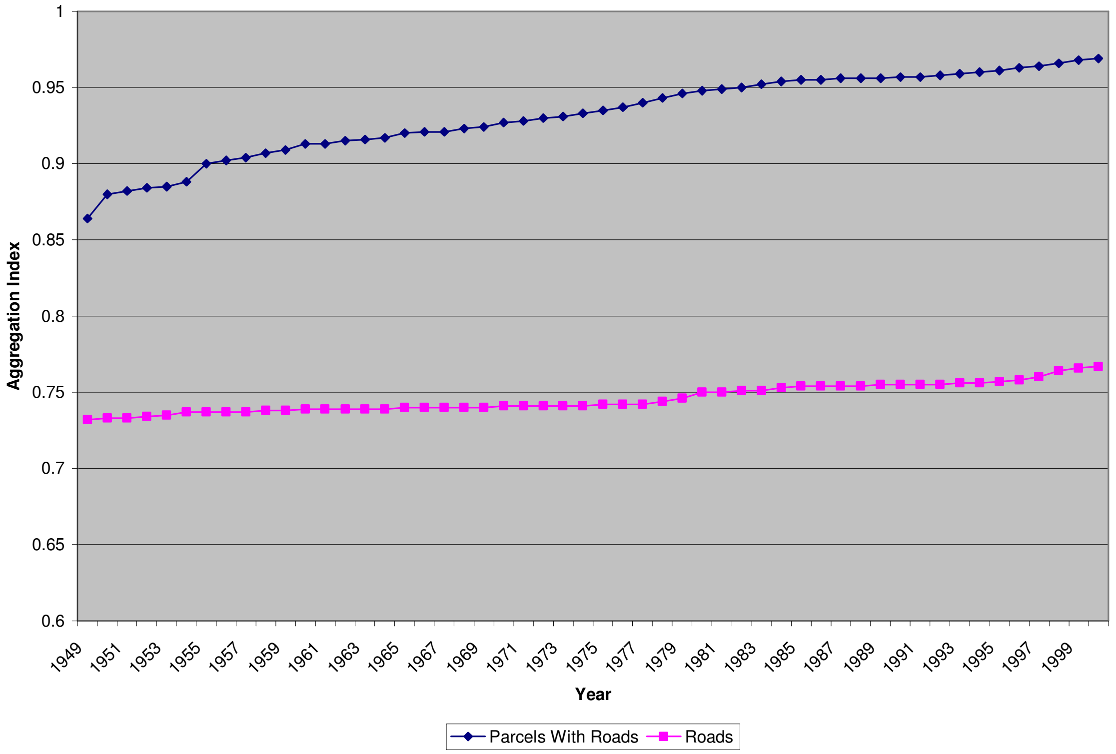


Figure 26. Aggregation index for roads and parcels with roads. Index ranges from zero to one with one being maximal aggregation by year.

The changes in AI for Roads and PWR are seen in Figure 26. For both Roads and PWR, the increases in AI over time were not great enough for any adjacent decade pairs to be significantly different. Despite the gradual increase, all non-adjacent decade pairs were found to be significantly different. The greater amount of connectivity in PWR is due to the roads connecting adjacent patches of parcels. The mechanism driving the higher rate of increase seen in PWR is most likely the roads connecting more distant patches.

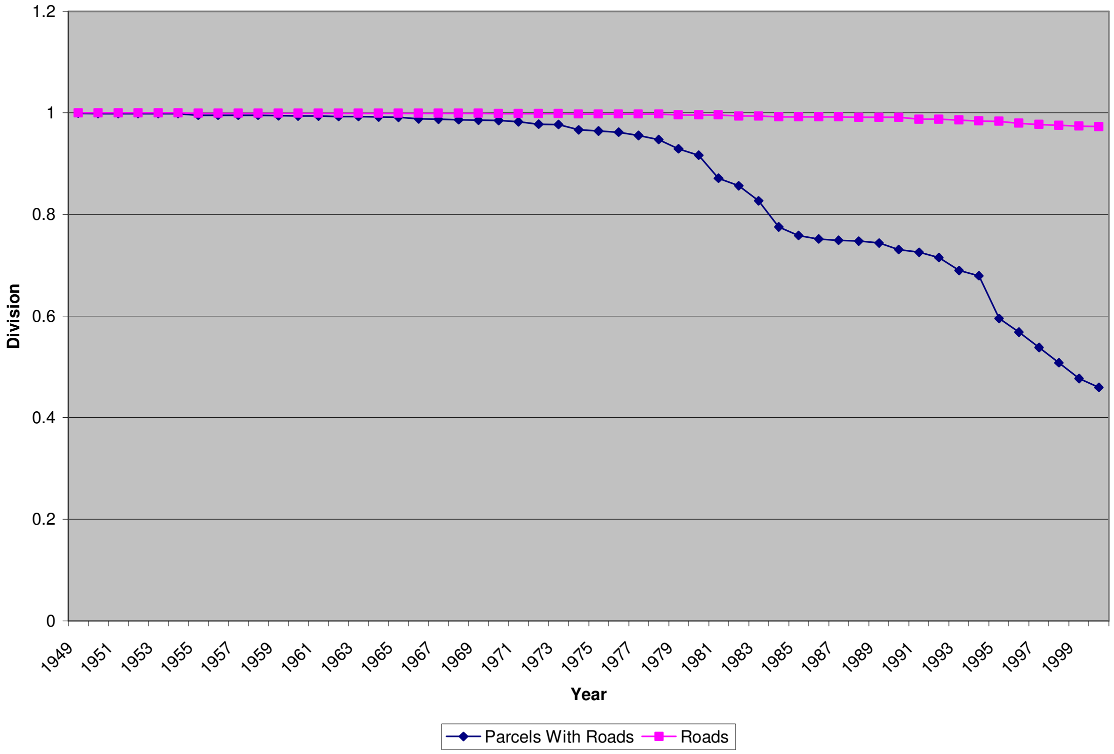


Figure 27. Landscape division for roads and parcels with roads by year.

Division approaches one as the size and number of the developed patches becomes smaller. Early in the study period, the probability of two random points being in the same patch of development was very small, thus division, the probability of two random points NOT being in the same patch, is near one. Although the change in division for roads seen in Figure 27 was also very small, the change over time was found to be significant, although not for adjacent decade pairs. Much more obvious is the change in division for PWR. Although greater than that seen in roads, the changes are gradual enough to keep adjacent decades from being significantly difference different as well. In both roads and PWR, all non-adjacent decade pairs were found to be significantly different. The decrease in division over time indicates that the probability of two random points being in the same patch of development was becoming greater.

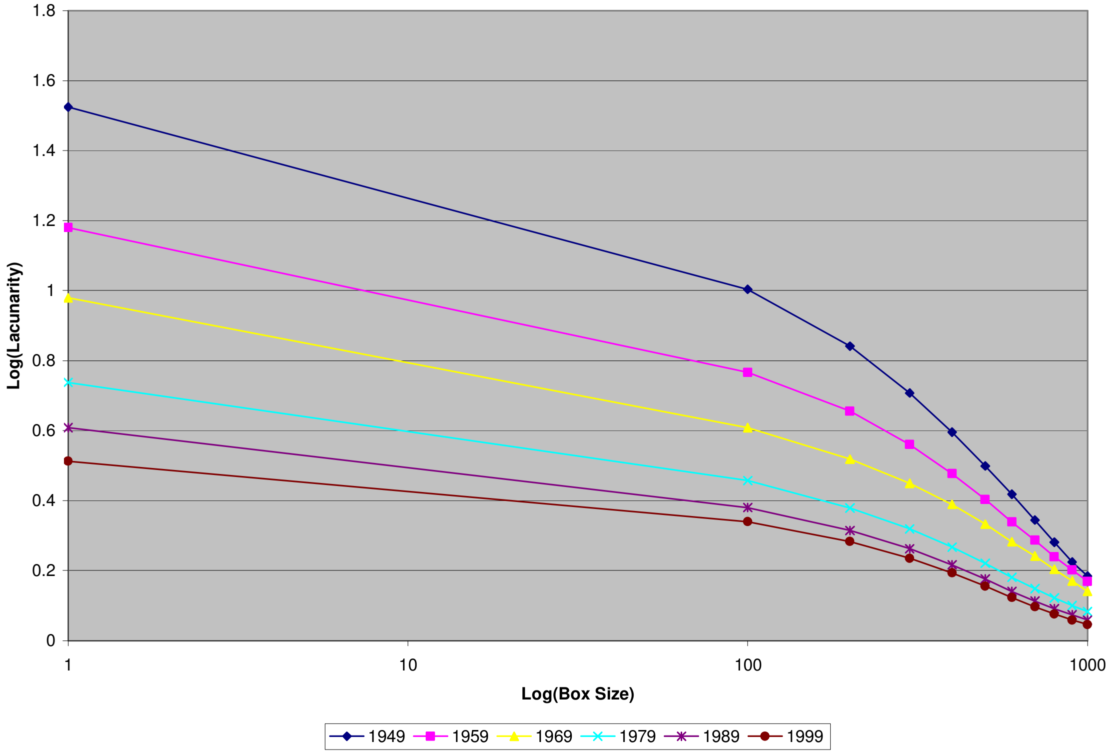


Figure 28. Lacunarity curves for parcels with roads for five time points.

Lacunarity is measured using a gliding box. As the box is moved through the landscape, the number of cells which match the focal patch type (i.e. developed parcels) are counted. These counts are converted into a frequency distribution and lacunarity is the variance to mean ratio of this distribution. The size of the box is then changed and the process is repeated. The box size can range from the size of a single cell to the size of the entire map. Lacunarity ranges from one for the box size that encompasses the map to infinity. Lacunarity of box size 1 is the proportion of the map occupied by the focal patch type.

Lacunarity is normally plotted as the log of the box size versus the log of lacunarity (Figure 28). The purpose of this graphing technique is to detect shifts in the slope of the curve, which are indicators of a shift in scale within the landscape. These shifts correspond to processes which shape the landscape. For more on this technique, see Plotnick, et al. (1993).

Lacunarity curves can be normalized by dividing the lacunarity for a given box size by the lacunarity of box size one. Normalizing is useful for comparing the lacunarity for different datasets. In this study, normalizing would have removed the effects of cover. This was deemed undesirable because we wished to test the changes in lacunarity both in cover and geometry.

The lacunarity curves for PWR in Figure 28 are all close to linear after box size 200 which is 400 hectares (approx. 1.5 sq mi.). Because of the similarity in pattern for lacunarity of box size over time, the box size with the least variability over box size 200 was selected for analysis. This was box size 1000. A plot of PWR lacunarity over time for all box sizes (Figure 29) shows the similarity in pattern over time for all box sizes with only changes in the slope between curves. Lacunarity of box size 1000 over time for roads and PWR are also similar in pattern (Figure 30), thus lacunarity of box size 1000 was used for roads as well.

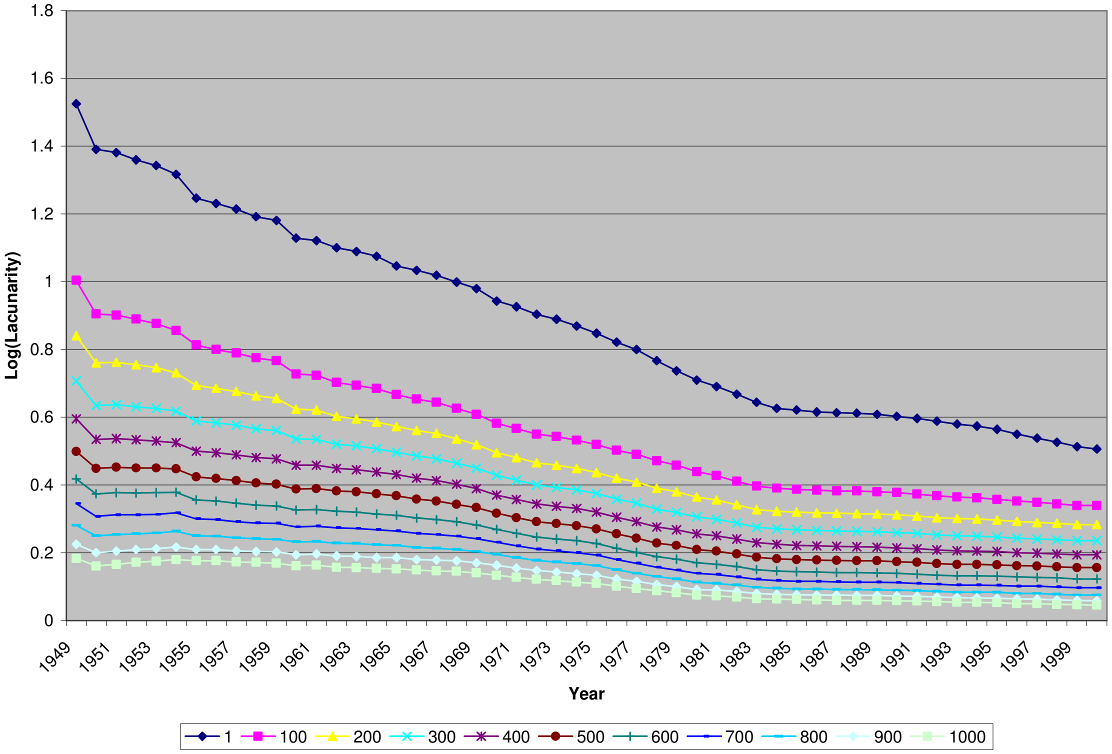


Figure 29. PWR lacunarity over time for each box size by year.

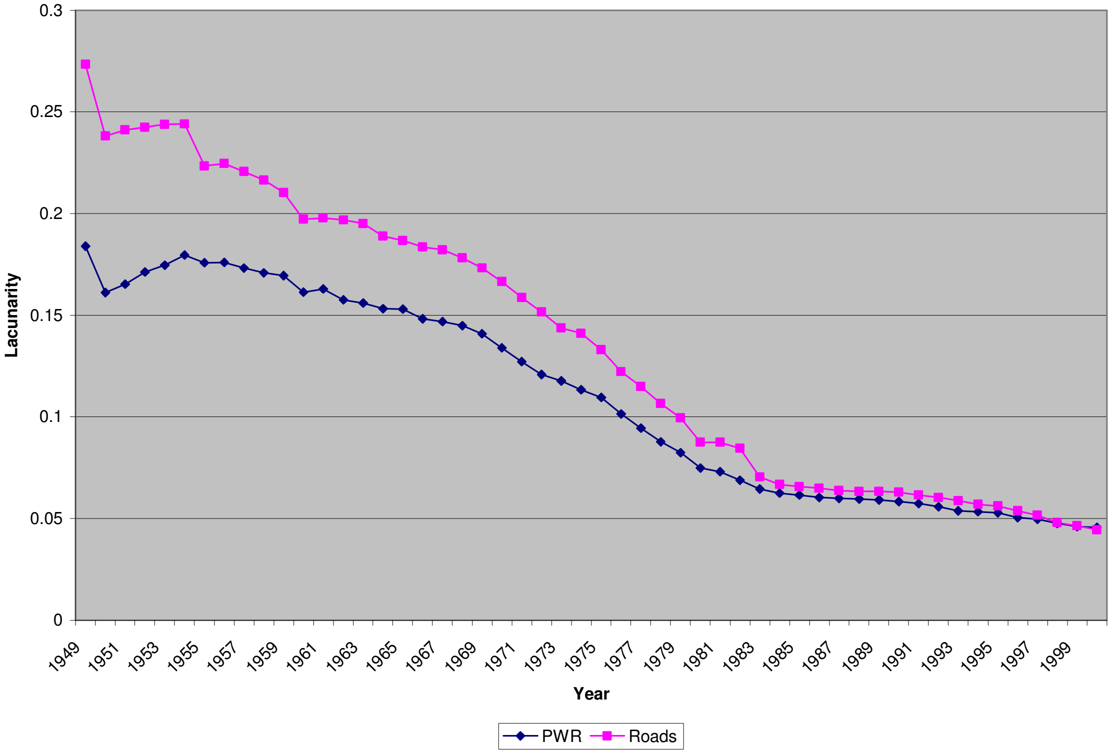


Figure 30. Lacunarity of box size 1000 for roads and parcels with roads by year.

Conclusions on Spatial Metrics

The conclusions here are for the observed changes in the spatial metrics. They are group into changes observed on the patch level and the landscape level.

Patch Statistics

The number of patches and the distribution of the patch sizes are indicators of changes in the way the landscape was developed. Until 1972, the number of PWR patches generally increased over time. This trend was not reflected in the number of road patches which remained relatively constant. During this period, MPS and WMPS for PWR remain close, indicating an even distribution of patch sizes. In 1966, WMPS for PWR shows an increase over MPS, indicating an upward shift in the distribution of patch sizes, but the two measures remain relatively close until 1972. This also the year of the highest number of PWR patches. All of this suggests that development before 1972 occurred as both additions to existing patches and as new small patches.

Although the number of PWR patches begins a decline in 1972, the process accelerates after 1978. The number of road patches also begins a long steady decline after 1978 which is only interrupted in 1986. WMPS for PWR, although increasing since 1972, also accelerates in rate from 1978 through 1984. From these observations it is clear that development changed during this period. Either development was occurring more often adjacent to existing development, or roads were connecting previously isolated patches.

The AWMSI for both roads and PWR provided some insight into the change in development. AWMSI for roads and PWR increased during this period, an indication that both were becoming more linear. However, AWMSI for PWR increases at a lower rate.

The roads were making the connection between isolated patches of parcels which increased the linearity of PWR. However, after 1985 AWMSI for PWR exhibits little change while roads continue to become more linear. This may indicate a threshold in development where additional development serves only to increase the size of the patches and does little to change the shape.

Edge Density (ED) for roads increases steadily with no remarkable inflections in the curve until 1984. ED for PWR similarly increases until 1982, where it levels off and eventually decreases. When graphed together, the two lines cross between 1971 and 1972, the latter being the first year ED for roads exceeds ED for PWR. In the case of PWR, the edges represent the interaction between developed areas (both road and parcel) and the undeveloped landscape. In contrast, ED for roads represents the interaction of the roads with both the developed parcels and the undeveloped landscape. To discern whether the changes in ED for Roads and PWR are due to changes in total area or changes in shape, it is useful to look at two additional spatial metrics: ED for parcels (without roads); and Total Edge Contrast Index (TECI) for parcels (without roads) and roads.

The results for ED of Roads and ED of parcels are seen in Figure 23. Although ED of PWR and ED of roads cross in 1972, ED of parcels crosses both ED of roads in 1960 and ED of PWR in 1965. Until 1960, the roads have a greater amount of edge than parcels. But neither roads nor parcels exceed ED of PWR, indicating that most of the patch edges are not shared and both roads and parcel patches are primarily bounded by the undeveloped matrix. It was expected that PWR patch sizes would increase as boundaries between roads and parcels became shared. In 1965, parcel ED surpassed PWR

ED, a sign that parcel patches were being bound together by road patches. This is also seen in WMPS, which increased the year after. Road ED surpassed PWR ED in 1972, an event also seen in PWR WMPS. Edge density continued to increase for roads and parcels when measured individually, but became level for PWR in 1983 and eventually declined in the 1990s. This indicates that additional development after 1983 occurred adjacent to existing patches.

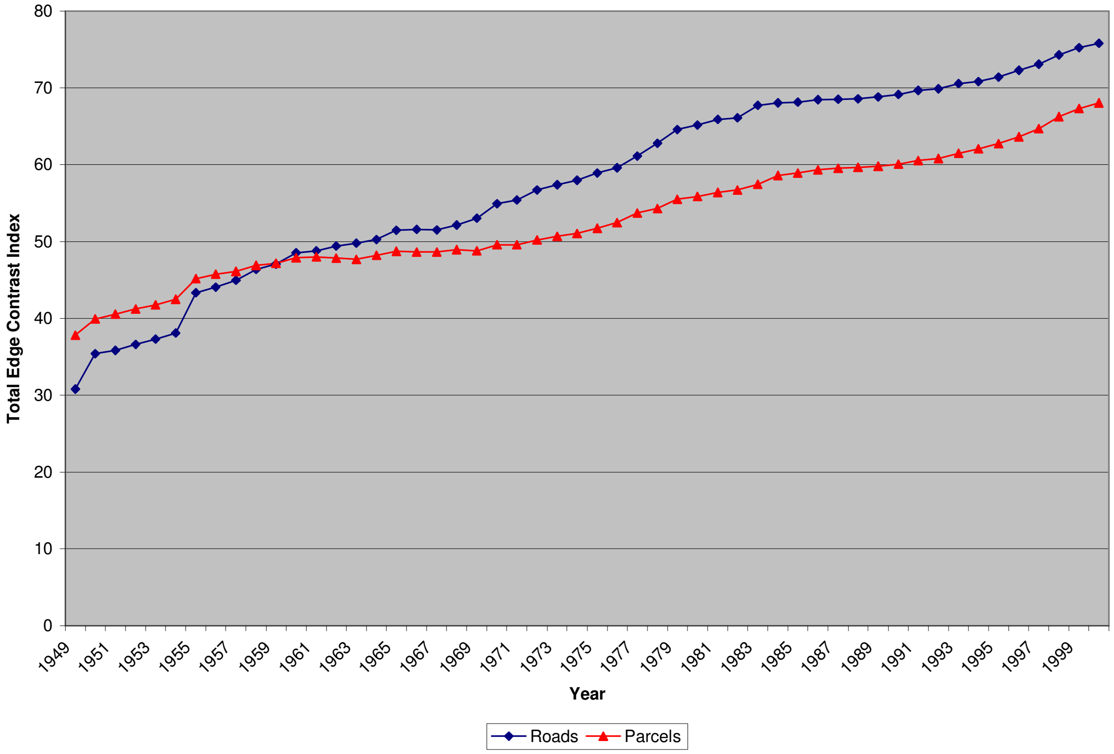


Figure 31. Total Edge Contrast Index for parcels and roads by year.

TECI confirms the relative contribution of roads and parcels to PWR patch measurements. TECI, seen in Figure 31, measures patch perimeter (edge), but weights the measure based on the adjacent landscape type. To distinguish between road edges adjacent to parcels and road edges adjacent to undeveloped patches (the matrix), the former was given a weight of one while the latter was weighted as zero. The same weights were applied to parcel edges adjacent to roads and parcel edges adjacent to undeveloped land, respectively. The weights serve to count edges adjacent to other developed patches while ignoring edges adjacent to undeveloped patches. The weighted edge counts are divided by the total amount of edge for that patch type and multiplied by 100 to create a percentage. With the weights used in this study, TECI is interpreted as the percent of edge of the focal patch type (i.e. roads) adjacent to patches of other developed patch types (i.e. parcels).

Before 1960, parcel TECI was higher than road TECI. A greater proportion of the total parcel edge was adjacent to developed roads than the proportion of road edge that was adjacent to developed parcels. After 1960, the opposite was true. This is evidence that roads were sharing their edges with parcels and making the connections between groups of parcels. A greater proportion of parcel edge was being shared with the undeveloped matrix. Two other points of interest in TECI are 1965 and 1972, the years that road TECI and parcel TECI surpassed the 50th percentile, respectively.

Except for the first decade, the overall trend for PWR MNN was decreasing over time. Brief periods of increases in MNN were observed, but the exact cause for the increases could not be determined. MNN of roads followed a similar pattern to MNN of PWR, although the exceptions to the general pattern occurred in slightly difference time points. Some of the increases correspond with increases WMPS, suggesting one potential mechanism. As patches of development grew larger, the distance between them decreased, reducing MNN. As patches merged, MNN was measured from the new, larger patch, thus changing the distribution of individual patches in the study area.

MPI and MNN are similar in nature, though different in measure. Although MPI increases over time, it too exhibits brief periods where it switches direction. The anomalies are in similar locations as observed in MNN, thus the mechanisms are probably the same. Because of the similarity between MNN and MPI in this study, either could be used as a substitute for the other.

Landscape Statistics

Although the Aggregation Index is similar in concept to the shape index, AI is calculated at the class level, using all of the patches in a single measure. AI is maximal when the entire landscape is a single square patch, but decreases as the focal patch type becomes disaggregated and more linear. In this study, AI was expected to be lower for roads since they occupy less total area. AI was also expected to increase over time for both roads and PWR. The results showed that AI acted as expected, with significant increases over time for both roads and PWR. While other measures exhibited drastic changes in slope and even changes in direction, AI did not exhibit either of these qualities. AI suggests there is a high degree of connectivity within the developed landscape, especially in PWR.

Landscape division was dramatically different for roads and PWR. As the probability that two random points in the watershed are in the same patch, road division is affected by the relatively small area occupied by roads and how those roads are distributed. Where patches in PWR may have several different opportunities to connect, the linear nature of roads restricts connections to one end or the other.

Landscape division for PWR decreases as the size of the PWR patches increase and the number decrease. The changes observed at specific points in time in other measures are also seen in Division. The year of the greatest number of PWR patches, 1972, is also the inflection point for the change in the Division curve. Division decreases over time after 1972, but is also subject to the other changes in the landscape noted in 1978, 1984 and 1994.

Lacunarity for box size 1000 for roads and PWR over time is seen in Figure 29. The pattern between roads and PWR over time is remarkably similar. Lacunarity exhibits considerable variability within the first decade. The initial decrease is followed by several years of increase. This was caused by the addition of new patches of development at greater distances from the initial cluster of development near the mouth of the watershed. The decline in lacunarity is steady for both roads and PWR until 1980, where roads increases slightly before following the decreasing trend again. The slope changes in 1984 for both roads and PWR. This inflection is common between most of the spatial metrics. Lacunarity for roads and PWR was found to have changed significantly over time with every decade pair being significantly different.

All of the spatial metrics demonstrated significant changes over time and the changes were in the directions predicted. However, there was some unexpected variability in the short-term. It is interesting that the same inflection points were observed within many of the spatial metrics. The years 1972 and 1984 were common points where changes in slope occurred in many of the metrics. Changes in 1972 include the number of PWR patches is maximal, ED of roads crosses ED of PWR, PWR WMPS changes slope, PWR Division slopes down, and parcel TECI passes 50%. Changes in 1984 include:

PWR WMPS levels off; PWR roads levels off after a rise that started in 1978; ED for roads changes slope; MPI for roads and PWR levels off; and AWMSI for roads and PWR levels off. These could be indications of a change in function of the landscape and the processes which shaped it.

CHAPTER VII

PREDICTING RESIDUAL FLOW

Introduction

The evidence thus far shows that streamflow in the study area changed significantly, the amount of development in the watershed changed significantly, and the spatial configuration of the development in the watershed changed significantly. The next step was to establish a direct relationship between the three. If a direct relationship could be found through regression modeling, the case for the link between structure and function could be stronger.

Methods

From Figure 6, it is obvious that residual flow is not linear. The curve estimation function in SPSS 11.0 was used to determine that residual flow over time is best described with a compound, growth or exponential curve (see Table 6). Residual Flow was transformed into a more linear form using the natural log (i.e. ln(residual flow). This transformed variable residual flow was used as the dependent variable for the last set of tests.

As mentioned in the previous chapter, instead of selecting variables for regression analysis based on theoretical considerations, it was thought the variables would self-select based on their relationship to the dependent variable. The first attempt to make the connection between structure and function was a two-step process. First, all of

Table 6. SPSS results for best fit curve analysis for the dependent variable residual flow.

Method	R^2	d.f.	F	Sig. F	b_0	b_1	b_2	b_3
LIN	0.472	50	44.68	0	-0.0537	0.0164		
LOG	0.313	50	22.74	0	-0.3005	0.2262		
INV	0.074	50	4.02	0.05	0.4351	-0.6339		
QUA	0.484	49	22.97	0	0.0387	0.0061	0.0002	
CUB	0.513	48	16.84	0	0.2191	-0.0329	0.002	-2.00E-05
COM	0.608	50	77.67	0	0.0525	1.0583		
POW	0.452	50	41.16	0	0.0195	0.8291		
S	0.093	50	5.12	0.028	-1.258	-2.1601		
GRO	0.608	50	77.67	0	-2.9472	0.0566		
EXP	0.608	50	77.67	0	0.0525	0.0566		

the available independent variables, both spatially explicit and non-spatial, were compared to the dependent variable, residual flow, using a Pearson's Correlation in SPSS. Second, the 25 variables with the highest correlations to residual flow were used in a procedure where all were entered as independent variables in a multiple linear regression with residual flow. After each completed run, the variable with the worst relationship (least significant) with residual flow was removed from the model. Variables removed by SPSS because of exceeding tolerance limits were not forced back into the regression. This process continued until all of the remaining variables were found to contribute significantly to the model. The model components were observed carefully for errors caused by inter-correlation between the independent variables.

It was found that inter-correlation within the independent variables confounded the models and yielded results that were at best difficult to interpret and at worst erroneous. The most obvious problems changed the sign in the model for an independent variable. For example, streamflow was expected to increase as impervious cover increased, and it did so when tested in a bivariate model. However, the sign for the impervious cover variable would reverse in the multi-variate model, suggesting that streamflow should increase as impervious cover decreased. After repeated attempts to make this work, it was finally abandoned. For a complete example of the process, see Appendix 2.

After discovering that inter-correlation problems between the independent variables prevented self-selection, it was decided that a different approach was necessary. By focusing on what each spatial metric represents and how each might influence the collection or conveyance of water in a theoretical sense, a group of metrics was selected for analysis. The variables selected are discussed below.

Instead of working from the top down as in the process described above, it was decided to work from the bottom up and test each variable in three steps. First, Pearson’s Correlation was used to test for bivariate correlation to the dependent variable and each of the other independent variables. Because the intent of the study is to determine the role of spatial configuration, it was determined that the metrics which should be carried forward in the process must have a zero-order correlation with residual flow at least equal to the non-spatial metric, WIC. The second step was to identify potential inter-correlation problems between the selected variables using the zero-order Pearson’s correlation between the selected variables. The primary selection criterion was to minimize the correlation to WIC, while maximizing the relationship with the natural log of residual flow.

Once the zero-order correlations were understood, the final step was to combine the variables in more complex linear models to find the best model. Because WIC and the loss of natural areas are thought to be primary factors in streamflow, it was determined that a variable representing these concepts should be included as a base for the model. The remaining spatial metrics were used individually with the impervious cover variable in trivariate linear regressions to predict the natural log of residual flow. The models were compared using the R value to determine the "best" model.

Selected Metrics

The independent variables selected for this portion of the study included both spatial and non-spatial metrics. The variables represented both the quantity and configuration of the development that occurred during the study period. Representing quantity were total developed area (TDA) and impervious cover (IC), both broken down into roads and parcels with roads (PWR). Although TDA and IC encompassed total development, the non-spatial distribution of that development was important as well. A group of metrics were chosen as a subset of TDA and IC. Because weighted mean patch size (WMPS) showed a sensitivity to patch size not observed in mean patch size, WMPS was selected to represent average patch size. TDA and IC were also subdivided into residential and commercial development (both without roads) because TDA and IC do not convey the distribution of development between commercial and residential causes. However, these are presented as the ratio of commercial to residential development. This ratio could be an important planning tool. The loss of natural areas, both prairie potholes and forest, was also included. These were presented together as the annual decrease in the natural area as a percent of the watershed. The final non-spatial metric was the cumulative road length. This metric may provide a simple method for estimating the effects of development.

The spatial metrics tested were edge density (ED), total edge contrast index (TECI), mean proximity index (MPI), area-weighted mean shape index (AWMSI), aggregation index (AI), area-weighted mean fractal dimension (AWMFD), division, and lacunarity. Each was tested for both roads and PWR to distinguish between effects due to total impervious cover and effects due to road configuration.

Results

The results of the bivariate and trivariate analyses between the independent variables and residual flow are presented below, grouped by analysis type.

Bivariate Analyses

Table 7 shows the results of the Pearson's bivariate correlation between each independent variable and residual flow. The independent variables are arranged in descending order based on the absolute value of the correlation. The correlation between WIC and residual flow was 0.767. Fourteen variables were found to be more closely related to residual flow than WIC. Including WIC, a total of fifteen variables were carried forward to the next step of analysis. Some of these variables were derivations or subsets of WIC, including: residential impervious cover (ResIC), roads impervious cover (RIC), and the ratio of commercial impervious cover to residential impervious cover (COMIC/ResIC). Other metrics were based on total developed area, including PWR total developed area (PWRTDA), roads total developed area (RdsTDA), the ratio of parcel total developed area to roads total developed area (ParcTDA/RdsTDA), and the ratio of commercial total developed area to residential total developed area (ComTDA/ResTDA).

Four spatial metrics were in this group. Two were related to road edges, roads total edge contrast index (RdsTECI) and roads edge density (RdsED), while the other two were measures of lacunarity, parcels with roads lacunarity (PWRLAC) and roads

Table 7 Pearson's zero-order correlation to the natural log of residual flow.

Variable	Acronym	LNQAB	ABS(LnQAB)
Parcels With Roads Lacunarity 1000	PWRLAC	-0.7967	0.7967
Roads Lacunarity 1000	RLAC	-0.7876	0.7876
Ratio of Commercial to Residential Total Developed Area	TDA COM/RES	0.7872	0.7872
Road Edge Density	RED	0.7845	0.7845
Ratio of Commercial to Residential Impervious Cover	PCUA COM/RES	0.7843	0.7843
Ratio of Developed Parcels to Road Total Developed Area	TDA Parc/Rds	0.7803	0.7803
Loss of Natural Areas	LNA	-0.7764	0.7764
Road Total Developed Area	RTDA	0.7753	0.7753
Road Length	RL	0.7753	0.7753
Parcels With Roads Total Developed Area	PWRTDA	0.7752	0.7752
Parcels With Roads Edge Density	PWRED	0.7750	0.7750
Roads Impervious Cover	RIC	0.7749	0.7749
Roads Total Edge Contrast Index	RdsTECI	0.7716	0.7716
Residential Impervious Cover	ResIC	0.7709	0.7709
Watershed Impervious Cover	WIC	0.7668	0.7668
Parcels With Roads Area Weighted Mean Shape Index	PWRAWMSI	0.7602	0.7602
Commercial Impervious Cover	ComIC	0.7569	0.7569
Parcels With Roads Aggregation Index	PWRAI	0.7534	0.7534
Roads Area Weighted Mean Fractal Dimension	RAWMFD	0.7524	0.7524
Parcels Total Edge Contrast Index	ParcTECI	0.7487	0.7487
Parcels With Roads Area Weighted Mean Patch Fractal Dimension	PWRAWMFD	0.7404	0.7404
Roads Aggregation Index	RdsAI	0.7162	0.7162
Roads Area Weighted Mean Shape Index	RAWMSI	0.7052	0.7052
Parcels With Roads Weighted Mean Patch Size	PWRWMPS	0.6934	0.6934
Parcels With Roads Division	PWRDiv	-0.6505	0.6505
Roads Weighted Mean Patch Size	RdsWMPS	0.6471	0.6471
Roads Division	RdsDiv	-0.6176	0.6176
Parcels With Roads Mean Proximity Index	PWRMPI	0.5645	0.5645
Roads Mean Proximity Index	RdsMPI	0.4687	0.4687

lacunarity (RdsLAC). The remaining two metrics were loss of natural areas (LNA) and roads length (RdsL).

The zero-order Pearson's correlation between each of the fifteen variables is seen in Table 8. All of the correlations were found statistically significant at the 0.001 level. The lowest correlation was between WIC and PWRED at 0.902. The highest correlation was 1.00. Twelve variable pairs were selected from all of the variable pairs by using a maximum correlation value of 0.95. The correlation value for each selected pair is underlined in Table 8. Eight of the twelve variable pairs consisted of a non-spatial measure of development and a measure of spatial configuration. Three of the variable pairs consisted of a non-spatial measure of development and the loss of natural areas. The final variable pair consisted of two different spatial metrics.

Multiple Linear Analyses

These variable pairs were used as independent variables in a multi-variate linear regression with the log of residual flow as the dependent variable. The results of the regressions are seen in Table 9. Every model was found significant; however, a closer inspection of the component variables reveals at least one and sometimes both independent variables were not significantly different than zero. These are marked in bold and underlined.

Because the multiple linear models were not possible due to colinearity, it was decided that each of the fifteen variables should be tested in a bivariate linear regression

Table 8. Results from Pearson's bivariate correlation between independent variable pairs. Underlined correlation values highlight values below 0.95.

Variables	PWRTDA	WIC	PWRED	LNA	RdsED	RdsTDA	RdsIC	RdsL	ResIC	ComIC/ ResIC	ComTDA/ ResTDA	ParcTDA/ RdsTDA	RdsTECI	PWRLAC	RdsLAC
PWRTDA	1.000														
WIC	0.999	1.000													
PWRED	**0.922**	**0.902**	1.000												
LNA	**-0.945**	**-0.927**	-0.987	1.000											
RdsED	0.997	0.993	**0.944**	-0.964	1.000										
RdsTDA	1.000	0.997	**0.929**	-0.953	0.999	1.000									
RdsIC	1.000	0.997	**0.928**	-0.952	0.999	1.000	1.000								
RdsL	1.000	0.997	**0.929**	-0.953	0.999	1.000	1.000	1.000							
ResIC	0.998	0.997	**0.909**	**-0.939**	0.995	0.998	0.998	0.998	1.000						
ComIC/ResIC	0.975	0.967	0.967	-0.966	0.982	0.977	0.976	0.977	0.962	1.000					
ComTDA/ResTDA	0.987	0.983	**0.947**	-0.952	0.988	0.987	0.986	0.987	0.976	0.996	1.000				
ParcTDA/RdsTDA	0.962	**0.946**	0.984	-0.997	0.977	0.968	0.967	0.968	0.957	0.975	0.965	1.000			
RdsTECI	0.968	0.955	0.965	-0.989	0.980	0.974	0.974	0.974	0.968	0.963	0.957	0.995	1.000		
PWRLAC	-0.979	-0.971	-0.965	0.968	-0.985	-0.980	-0.980	-0.980	-0.968	-0.997	-0.995	-0.979	-0.967	1.000	
RdsLAC	-0.970	-0.957	-0.982	0.991	-0.983	-0.976	-0.975	-0.976	-0.964	-0.984	-0.975	-0.997	-0.993	0.987	1.000

Table 9. Trivariate linear regression models to the natural log of residual flow. All models significant at the 0.001 level. Underlined significance values mark model components not found to be significant.

							Unstandardized Coefficients		Standardized Coefficients		
Model	Model Number	R Square	Adjusted R Square	df	Sig.	Model Components	B	Std. Error	Beta	t	Sig.
						(Constant)	-4.048	0.588		-6.890	0.000
PWRED	1	0.625	0.610	2	3.62E-11	PWRED	0.024	0.011	0.447	2.204	0.032
WIC						WIC	2.06E-08	1.15E-08	0.364	1.793	**0.079**
						(Constant)	-0.558	1.153		-0.484	0.631
WIC	2	0.619	0.603	2	5.52E-11	WIC	1.90E-08	1.33E-08	0.335	1.428	**0.160**
LNA						LNA	-0.168	0.085	-0.466	-1.985	**0.053**
						(Constant)	-4.371	0.832		-5.254	0.000
WIC	3	0.617	0.601	2	6.25E-11	WIC	1.54E-08	1.54E-08	0.272	0.999	**0.323**
ParcTDA / RdsTDA						ParcTDA / RdsTDA	0.913	0.477	0.523	1.916	**0.061**
						(Constant)	-3.993	0.611		-6.538	0.000
PWRTDA	4	0.625	0.610	2	3.62E-11	PWRTDA	9.75E-05	5.44E-05	0.405	1.793	**0.079**
PWRED						PWRED	0.021	0.012	0.402	1.778	**0.082**
						(Constant)	-0.899	1.374		-0.654	0.516
PWRTDA	5	0.619	0.603	2	5.42E-11	PWRTDA	9.35E-05	6.49E-05	0.388	1.441	**0.156**
LNA						LNA	-0.148	0.097	-0.410	-1.520	**0.135**
						(Constant)	-4.153	0.539		-7.705	0.000
PWRED	6	0.626	0.611	2	3.36E-11	PWRED	0.017	0.014	0.316	1.193	**0.239**
RdsED						RdsED	13.903	7.569	0.486	1.837	**0.072**
						(Constant)	-3.770	0.680		-5.546	0.000
ComTDA / ResTDA	7	0.628	0.613	2	2.96E-11	ComTDA / ResTDA	2.645	1.385	0.516	1.910	**0.062**
PWRED						PWRED	0.015	0.014	0.287	1.063	**0.293**
						(Constant)	-4.081	0.568		-7.186	0.000
PWRED	8	0.626	0.611	2	3.42E-11	PWRED	0.023	0.011	0.427	2.040	0.047
ResIC						ResIC	0.314	0.172	0.383	1.827	**0.074**
						(Constant)	-4.153	0.539		-7.705	0.000
PWRED	9	0.626	0.611	2	3.36E-11	PWRED	0.017	0.014	0.316	1.193	**0.239**
RdsL						RdsL	13.903	7.569	0.486	1.837	**0.072**
						(Constant)	-4.208	0.538		-7.817	0.000
PWRED	10	0.623	0.607	2	4.22E-11	PWRED	0.021	0.013	0.402	1.704	**0.095**
RdsIC						RdsIC	6.92E-08	4.07E-08	0.401	1.700	**0.095**
						(Constant)	-4.204	0.540		-7.784	0.000
PWRED	11	0.623	0.607	2	4.23E-11	PWRED	0.021	0.013	0.400	1.681	**0.099**
RdsTDA						RdsTDA	4.89E-04	2.88E-04	0.404	1.698	**0.096**
						(Constant)	-0.741	1.320		-0.561	0.577
LNA	12	0.618	0.602	2	5.89E-11	LNA	-0.161	0.093	-0.444	-1.729	**0.090**
ResIC						ResIC	0.291	0.211	0.354	1.379	**0.174**

Table 10. Bivariate linear regression between independent variables and the natural log of residual flow. Sorted by decreasing R^2 value.

		Model Summary			Model Components			
Category	Variables Entered	R Square	F	Sig.	Constant	b1	Beta	t
Lacunarity	Parcels With Roads Lacunarity 1000	0.635	86.868	0.000	6.292	-5.967	-0.797	-9.320
	Roads Lacunarity 1000	0.620	81.680	0.000	3.795	-3.775	-0.788	-9.038
Ratios	Ratio of Commercial to Residential Total Developed Area	0.620	81.471	0.000	-3.081	4.039	0.787	9.026
	Ratio of Commercial to Residential Impervious Cover	0.615	79.924	0.000	-3.013	0.917	0.784	8.940
	Ratio of Developed Parcels to Road Total Developed Area	0.609	77.850	0.000	-5.086	1.364	0.780	8.823
Total Developed Area	Road Total Developed Area	0.601	75.322	0.000	-3.391	9.39E-04	0.775	8.679
	Parcels With Roads Total Developed Area	0.601	75.309	0.000	-2.965	1.87E-04	0.775	8.678
Edge Density	Parcels With Roads Edge Density	0.601	75.183	0.000	-4.830	0.041	0.775	8.671
	Road Edge Density	0.613	79.238	0.000	-3.577	0.022	0.783	8.902
	Roads Total Edge Contrast Index	0.595	73.554	0.000	-5.449	0.069	0.772	8.576
Impervious Cover	Roads Impervious Cover	0.600	75.149	0.000	-3.386	1.34E-07	0.775	8.669
	Residential Impervious Cover	0.594	73.246	0.000	-2.997	0.633	0.771	8.558
	Watershed Impervious Cover	0.588	71.365	0.000	-2.818	4.34E-08	0.767	8.448
Other	Loss of Natural Areas	0.603	75.883	0.000	1.033	-0.281	-0.776	-8.711
	Roads Length	0.601	75.322	0.000	-3.391	9.39E-07	0.775	8.679

with the natural log of residual flow. The results of these tests are seen in Table 10. All ofthe bivariate models tested were found to be significant. The table is arranged to group similar metrics.

Conclusions

The results of this chapter present an interesting conundrum. Twenty-nine variables were selected to represent changes in the quantity and configuration of development within the watershed over time. Some of the variables representing non-spatial quantity were subsets of other quantity variables and were expected to exhibit less explanatory power than the superset. Other variables represented spatial configuration and were loosely tied to measures of quantity. These were expected to complement the non-spatial variables and provide additional explanatory power.

The biggest surprise in this section was how strongly correlated all of the variables were to each other and to the dependent variable. Of the twenty-nine variables, only one, RdsMPI, had a Pearson's correlation value to residual flow less than 0.50 in absolute terms. Only two were below 0.60. Between independent variables, the lowest correlation value was 0.43.

The correlations between the independent variables made it impossible to develop a more detailed model of the relationships between development and streamflow. Although this study could not separate the spatial and non-spatial characteristics of the development, considerable evidence was provided establishing that spatial configuration plays a role in the observed changes in streamflow. If the spatial configuration of development was not responsible for some portion of the observed changes in streamflow, then the metrics which focused entirely on the quantity of development would have exhibited larger zero-order correlation values with residual flow. This was not the case.

By focusing on the variables which exhibited stronger relationships to residual flow than WIC, we may better understand what aspects of configuration are most important. When discussing configuration, it is easy to focus entirely on the spatial distribution of development and the metrics designed to discern the distribution. However, even the direct measure of quantity of development was observed in several ways and each was not equal in predicting changes in streamflow. Quantity and configuration are key aspects of development and how each of those changed over time has effected the way water moves through this study area. Each of the top 15 metrics is examined in the following paragraphs.

Figure 32 shows how all of the final variables predict the number of days greater than expected, the numerator for residual flow by decade. The findings for all of the metrics were very similar with the exception of PWRED and only in the last decade. This anomaly is discussed below. Although all of the metrics, both spatial and non-spatial had similar results in Figure 32, these are influenced by the total amount of development within the watershed. By plotting the predicted number of days of streamflow above expected on a per unit basis, the effects of total development can be controlled. These are plotted and discussed below.

WIC is considered the baseline for studying changes in development. WIC consists of all impervious cover and makes no distinctions about the source – whether

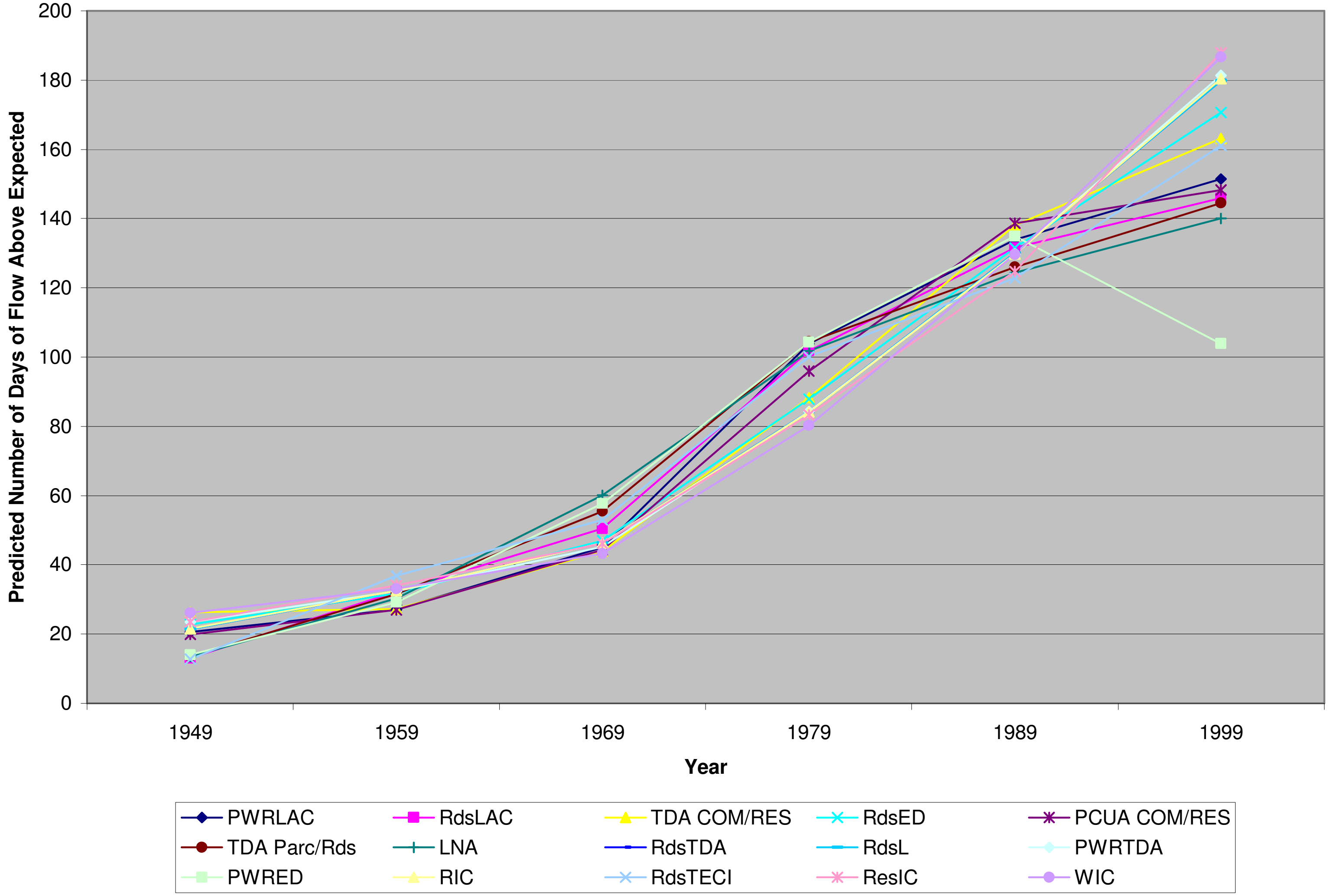


Figure 32. Number of days greater than expected by year of observation as predicted by each independent variable using the parameters in Table 10.

residential, commercial or roads. It also makes no distinctions between ratios of impervious cover and total developed land for different land use types. Figure 32 shows that the impact of WIC decreases over time on a per-unit basis except for the last two decades of the study.

Two steps were necessary to generate Figure 32, and all subsequent per-unit graphs. The first step was to solve the linear regression using the formula:

$$\mathrm{Ln}(rf) = \mathrm{b}_0 + \mathrm{b}_1 t$$

where b_0 and b_1 were the appropriate coefficients in Table 10, t was the measured spatial or non-spatial metric at those the five points in time, and rf was the residual flow. The second step was to convert the predicted value to a per-unit value. The dependent variable, residual flow, was in a natural log form, so the exponent of the first value was calculated.

$$rf = \exp(\ln(rf))$$

Recall that residual flow is the ratio of days above expected to the days below expected, and that the entire year (365 days) is comprised of days above and days below expected flow for any given rainfall experienced that year. This resulted in the residual flow ratio which was converted to days above using the formula:

$$DaysAbove = \frac{365rf}{1+rf}$$

where rf is residual flow. The result was the number of days annually expected to be greater than the regression line between daily precipitation and daily streamflow. To convert this to a per-unit basis, *DaysAbove* was divided by the measured value of the independent variable for that year. Each per-unit plot is accompanied by the scatterplot of *DaysAbove* versus the measured value for the metric for the given year.

ResIC, as a subset of WIC, was not expected to have a higher correlation to residual flow than WIC. Although the differences are slight, this finding suggests that one of the other subsets of impervious cover is skewing the results for WIC. Looking back at Figure 14, one should note the similarities between ResIC and RdsIC. In stark contrast is ComIC, which demonstrates a non-linear curve over time. Because the test for a relationship between impervious cover and residual flow is assumed to be linear (and residual flow was transformed with a natural logarithm to make it so), the problem lies in the non-linear nature of ComIC.

On a per-unit basis, ResIC behaves similarly to WIC, although the impacts of WIC are much greater (see Figure 33). Although the correlation to the dependent variable is higher, it is obvious that impervious cover from residential development has a minor influence on streamflow due to WIC on a per-unit basis. Although roads have the least amount of total impervious cover, RdsIC has the highest per-unit influence on residual flow. If the relationship between impervious cover and streamflow cannot be best explained by quantity, it must have an element of configuration.

Although per-unit changes in impervious cover have been variable over time, all enter a growth phase in the 1970s, a trend that continued through the end of the study period.

Despite the variability in all IC metrics per unit, when the amount of development is considered, the results are exponential growth in every category (Figure 34). The steepness of the curves relays the intensity of the hydrologic response to the various forms of impervious cover. It should not be assumed that the hydrologic response would

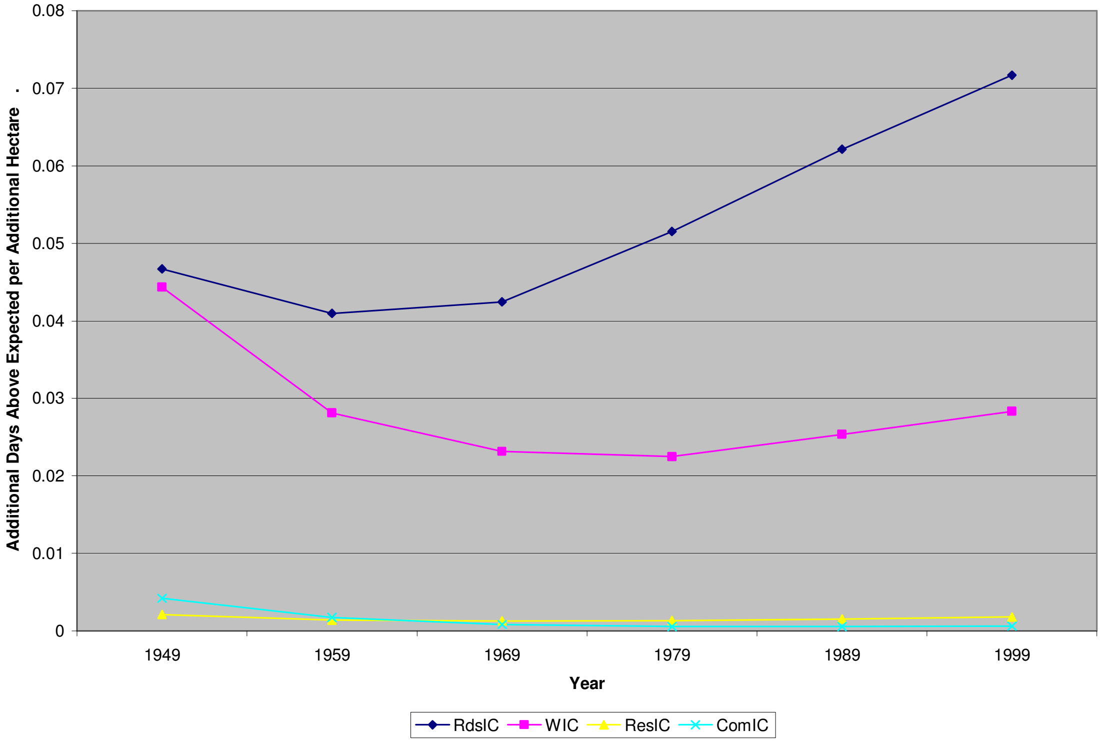


Figure 33. Number of days greater than expected streamflow per hectare of impervious cover for residential, commercial, roads and the watershed by year.

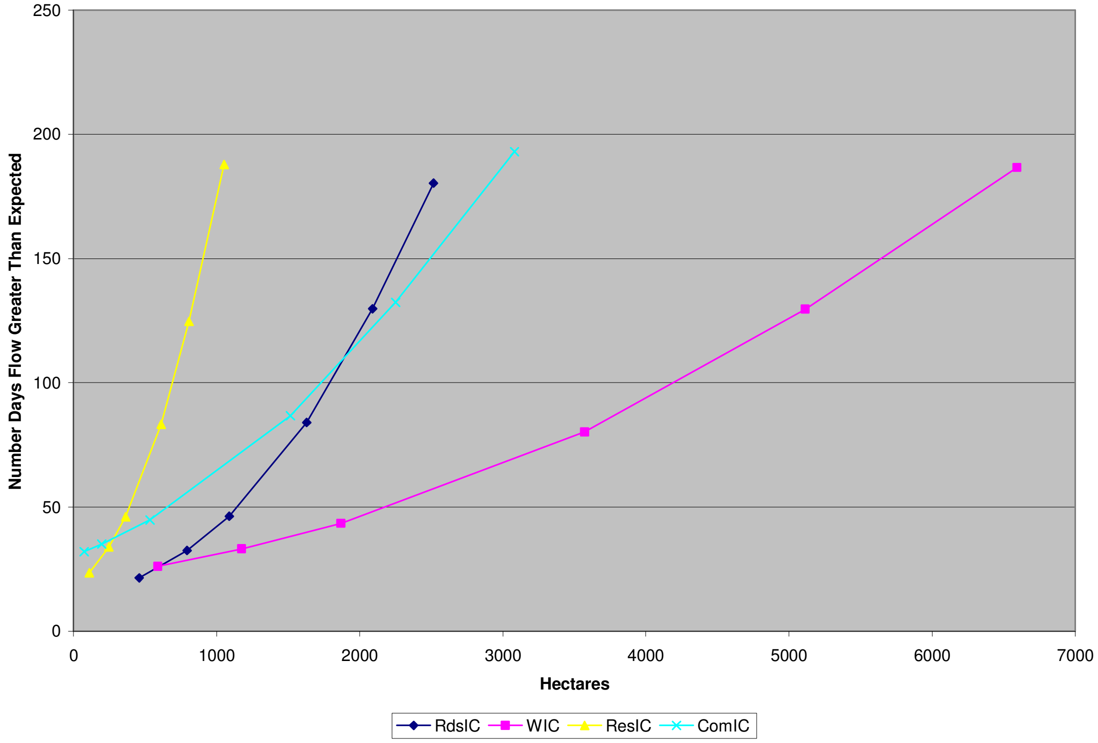


Figure 34. Scatterplot of impervious cover versus number days flow greater than expected for residential, commercial, roads and the watershed.

be the same if development only occurred in one category and not the others. The terms are interactive and the effects of each are cumulative. However, this plot does show the relative amounts of impervious cover and the measured streamflow response as residual flow above expected. This graph shows that even during periods when the per-unit response was decreasing, the response per additional hectare of impervious cover was exponential in nature.

The total edge contrast index (TECI) is measured as a percentage of the total amount of edge. As a function of the total edge, TECI is sensitive to patch size, the type of adjacent patches, and the total amount of the focal patch. RdsTECI was purposely configured to relay information about the amount of road edge adjacent to developed parcels while ignoring undeveloped land. In this case, RdsTECI ranged from just over 30% in the beginning of the study to nearly 80% at the end.

In Figure 35, the number of days of streamflow higher than expected per RdsTECI increases over time. This indicates the watershed is becoming increasingly sensitive to the creation of additional roads. As seen in WIC, the relationship between RdsTECI and the number of days greater than expected is exponential (Figure 36). The amount of interaction between road edges and developed parcels has a stronger correlation to residual flow than WIC on its own and may be the component which explains the higher correlation between RdsIC and residual flow.

RdsED on a per-unit basis (Figure 37) behaves differently than RdsTECI because RdsED also accounts for the interaction between roads and undeveloped landscape. During the first two decades of the study, the relationship between RdsED and per unit residual flow remains relatively flat, but increases for the final three decades. This change

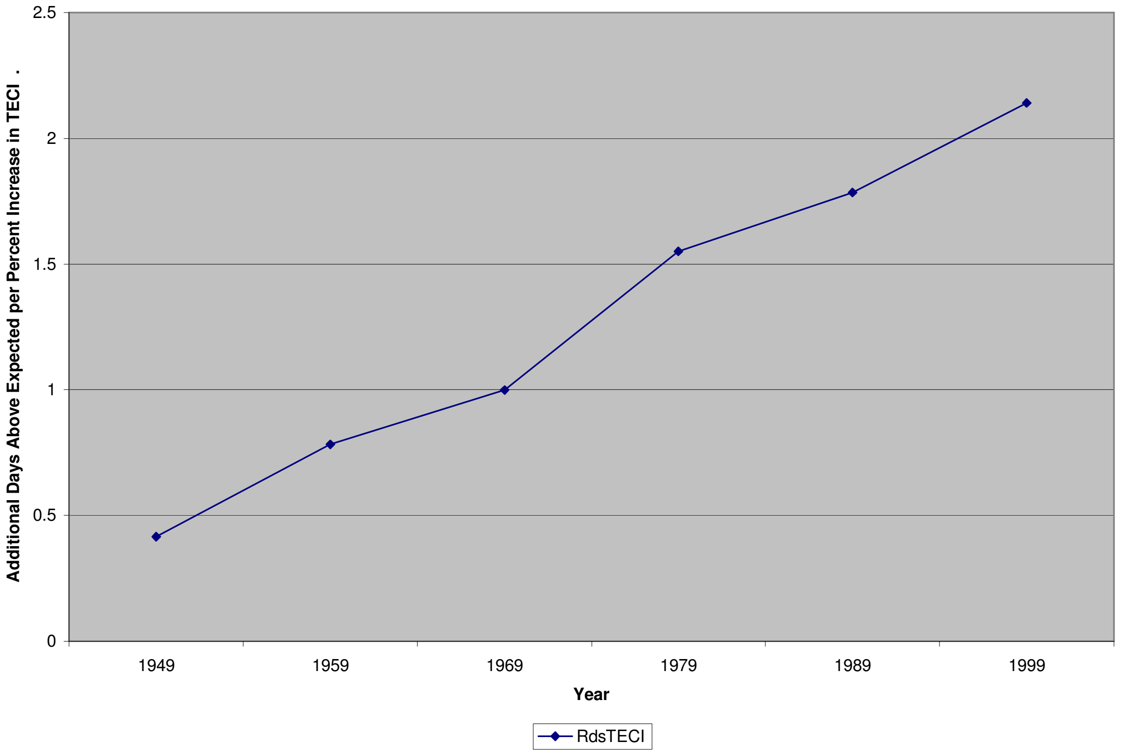


Figure 35. Number of days of flow greater than expected per percent increase in RdsTECI by year.

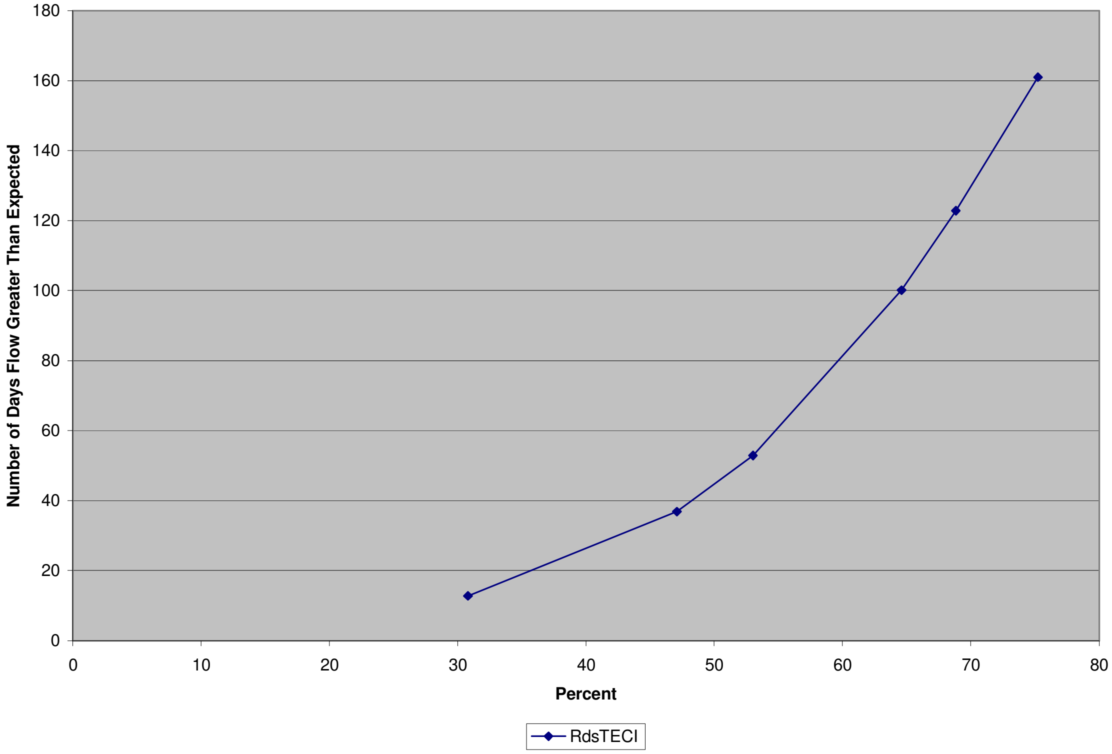


Figure 36. Scatterplot of number of days of flow greater than expected versus RdsTECI by year.

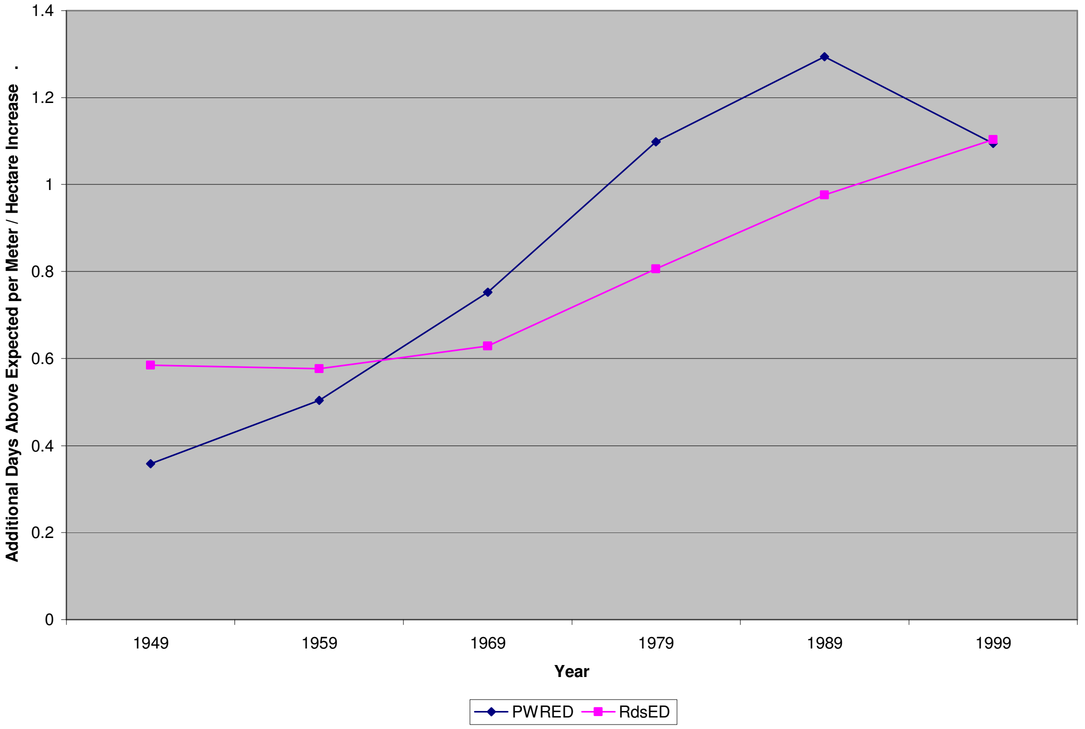


Figure 37 Number of days greater than expected streamflow per meter/hectare increase in edge density by year for roads and parcels with roads.

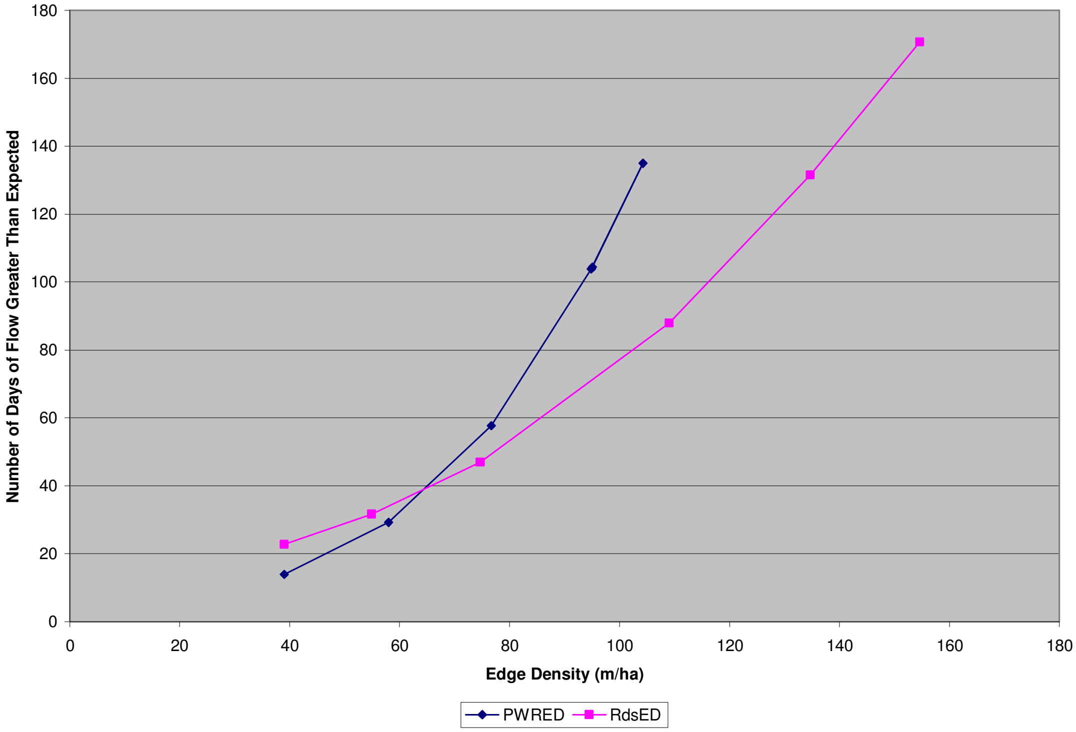


Figure 38. Scatterplot of number of days flow above expected versus edge density for roads and parcels with roads.

in relationship occurs at the same time the number of days of residual flow greater than expected increases for RdsTDA in Figure 37 and the length of the roads. It is evident that RdsED is affected by the total amount of road development.

PWRED is good example of why caution is necessary when interpreting the results of the spatial metrics. When the per-unit influence of PWRED drops, it has a strange effect of the scatterplot in Figure 37. The lower edge density seen in 1999 is calculated to result in fewer days of streamflow greater than expected. However, residual flow is, in fact, higher in 1999 than in 1989. The observed decrease in PWRED is due to the consolidation of patches, but happens as total impervious cover is increasing. Any spatial metric that might change direction as total cover increases should be used with caution.

Residual flow per unit is less sensitive to changes in PWRED. However, residual flow per unit for PWRED shifts increases throughout the study period until the patches start merging at the end of the study period. As the PWR patches merge, the patches are larger and have fewer edges, so the decrease in the residual flow per unit of PWRED was not unexpected. Despite sensitivity in the per-unit measures, there is still an exponential relationship between total PWRED and residual flow as well as RdsED and residual flow (Figure 38).

The effects of total developed area on a per-unit basis are not as strong for PWR as they are for roads (Figure 39). The initial decrease observed in both occurs as the number of patches in watershed increases over time. After 1972, when continued growth connects the smaller patches, the influence of both measures of TDA on a per-unit basis increases as well. RdsTDA has a greater influence per unit and shows greater increases

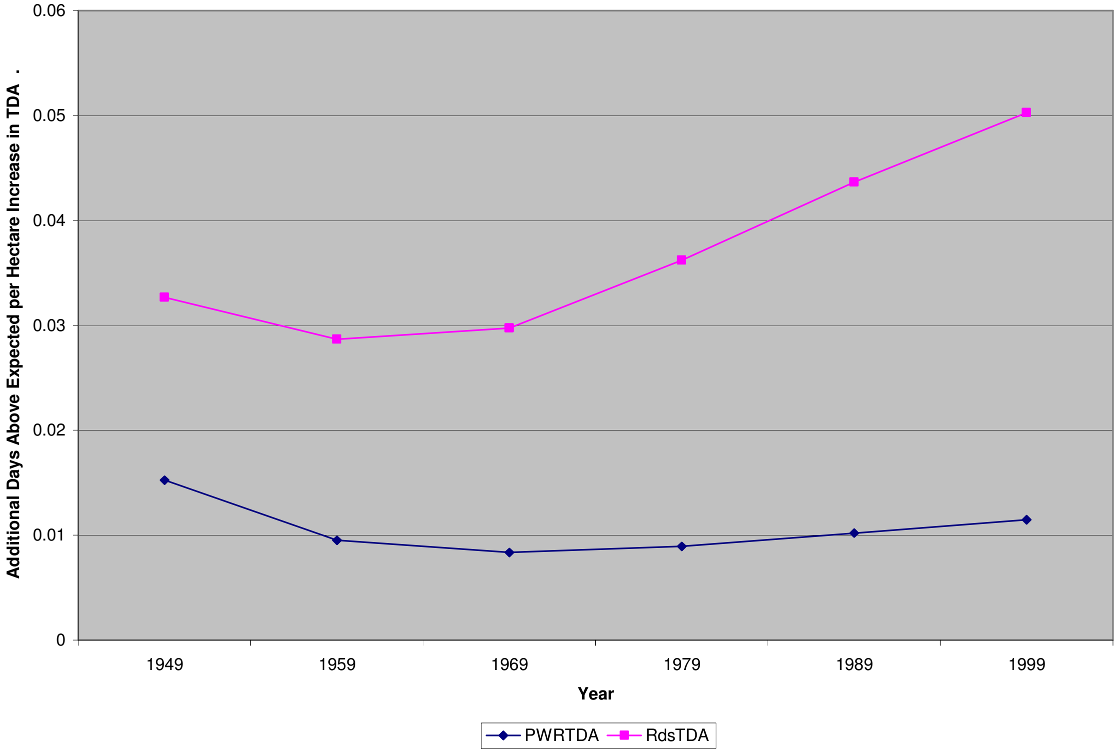


Figure 39. Number of days greater than expected streamflow per hectare increase in TDA by year for roads and parcels with roads.

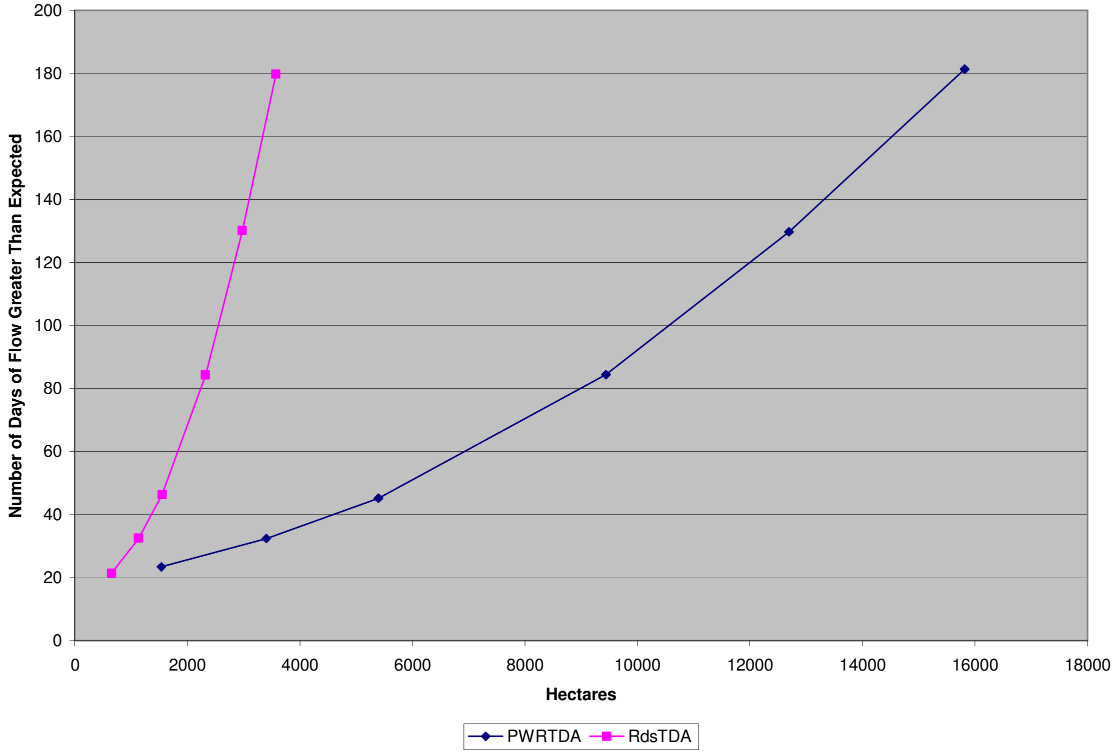


Figure 40. Scatterplot between number of days of flow greater than expected by total developed area for roads and parcels with roads.

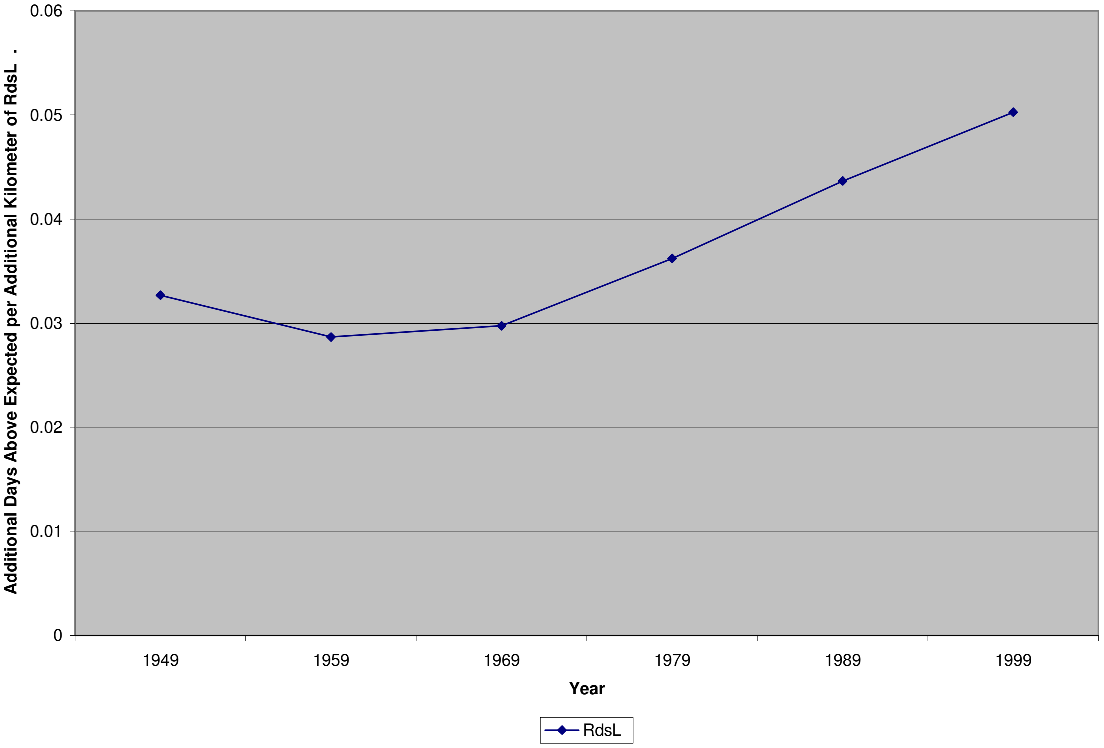


Figure 41. Number of days greater than expected streamflow per kilometer of road length by year.

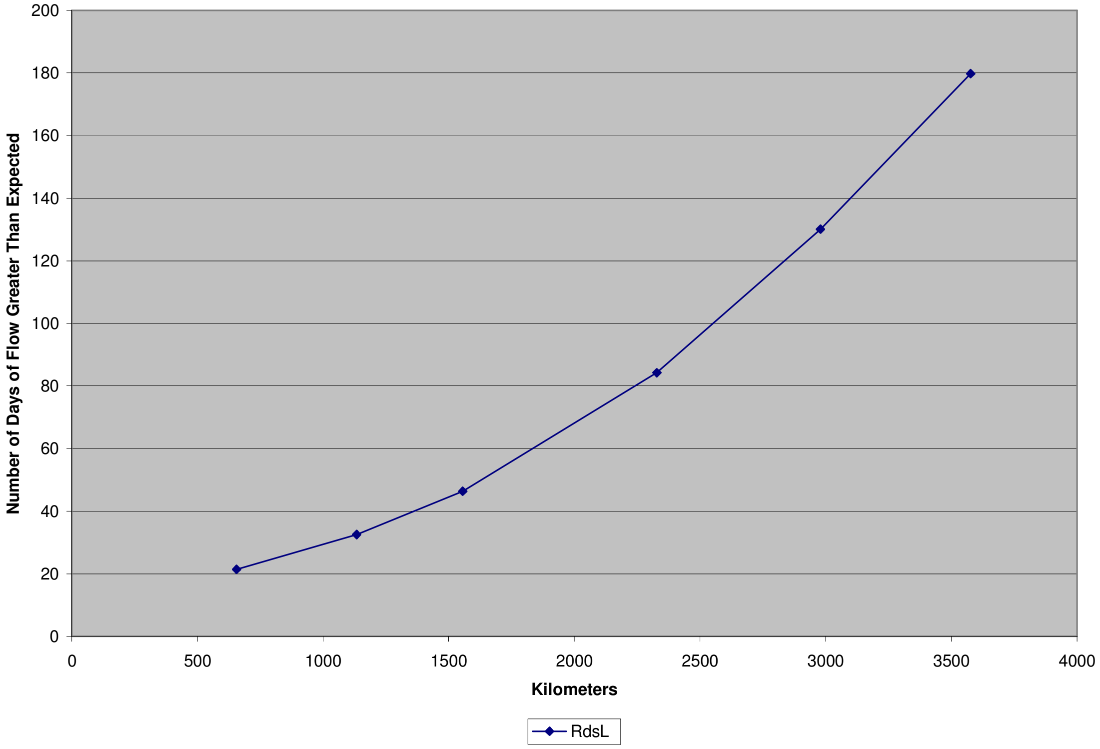


Figure 42. Scatterplot of number of days greater than expected streamflow versus road length.

over time, a pattern also reflected in the measure of road length. As in other measures, a scatterplot of the TDA metrics shows that despite per-unit decreases, the total amount of development creates an exponential relationship to residual flow (Figure 40). Comparisons between the TDA for roads and PWR can be quite informative. The chart clearly shows how much additional road area was developed to serve a given level of parcel development and the associated expected flows.

In Figures 41 and 42, the number of days of streamflow greater than expected is plotted per unit road length and versus total road length, respectively. Days above decreases per unit road length during the first decade, but increases exponentially thereafter. The per-unit effects are overwhelmed by the total amount of road built and the increasing length of the road network is related to exponential increases in streamflow.

The loss of natural areas has been highly correlated to streamflow despite the relatively small portion of the landscape occupied by natural features. On a per-unit basis to LNA, it is no surprise that the number of days of streamflow greater than expected increases over time (Figure 43). Losing natural areas that serve to mitigate flow should result in increased amounts of streamflow. On a total amount lost, the relationship between LNA and number of days above expected streamflow is exponential as well. It should be recognized that Figure 44 is an inverse relationship because greater amounts of natural areas will serve to mitigate flow.

It should also be noted that the estimates here are based on conservative measures of natural areas. The true area influenced by each prairie pothole could not be measured with the technique used for this study. Also, newly forested areas were not accounted for in this study. The older forests were primarily located in the riparian zones or

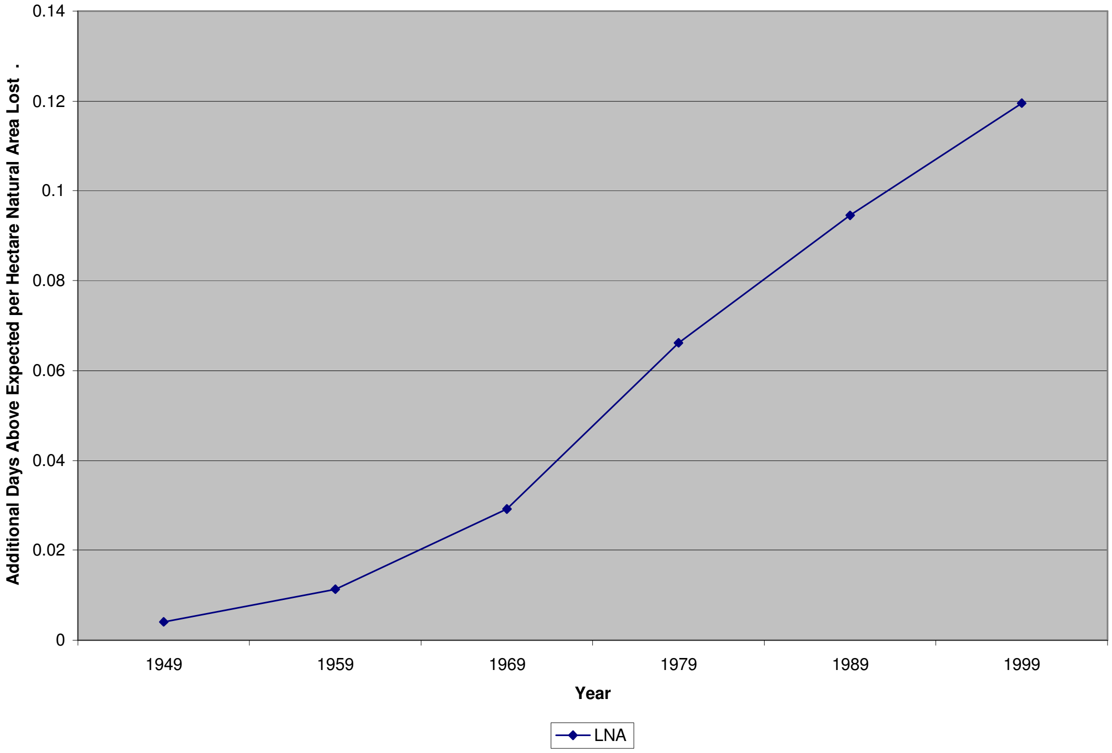


Figure 43. Number of days greater than expected streamflow per hectare natural area lost by year.

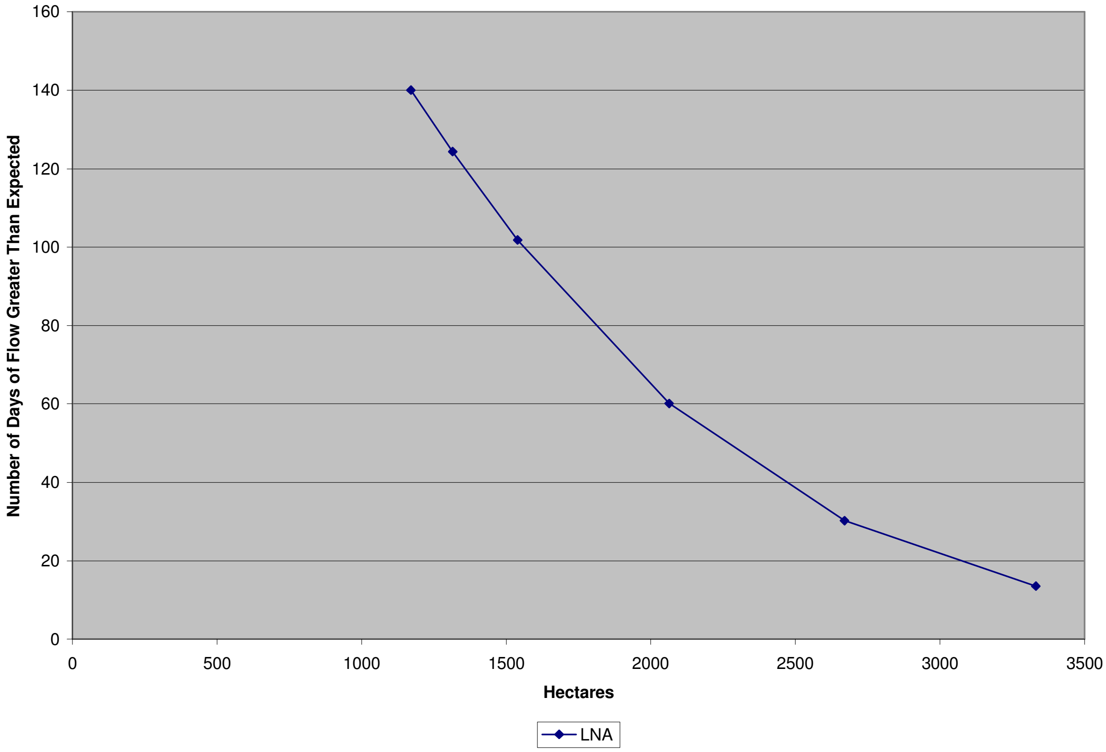


Figure 44. Number of days greater than expected streamflow versus loss of natural areas.

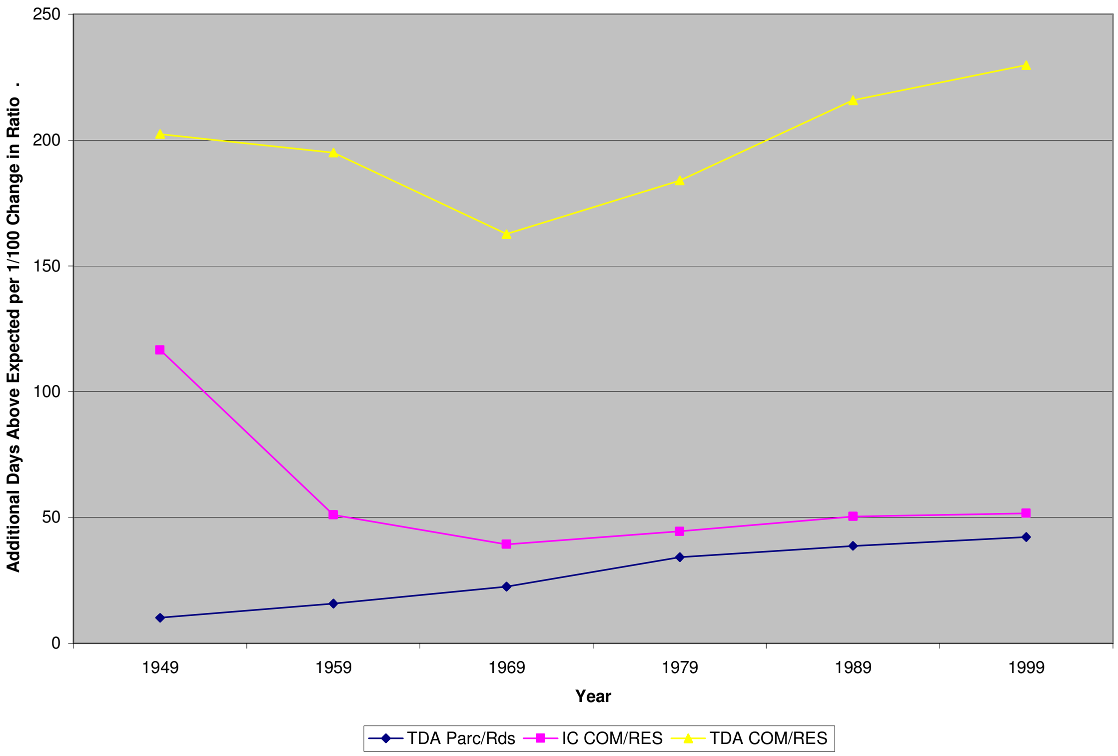


Figure 45. Number of days greater than expected streamflow per 1/100th change in ratio for TDA Parc/Rds, IC COM/RES, and TDA COM/RES by year.

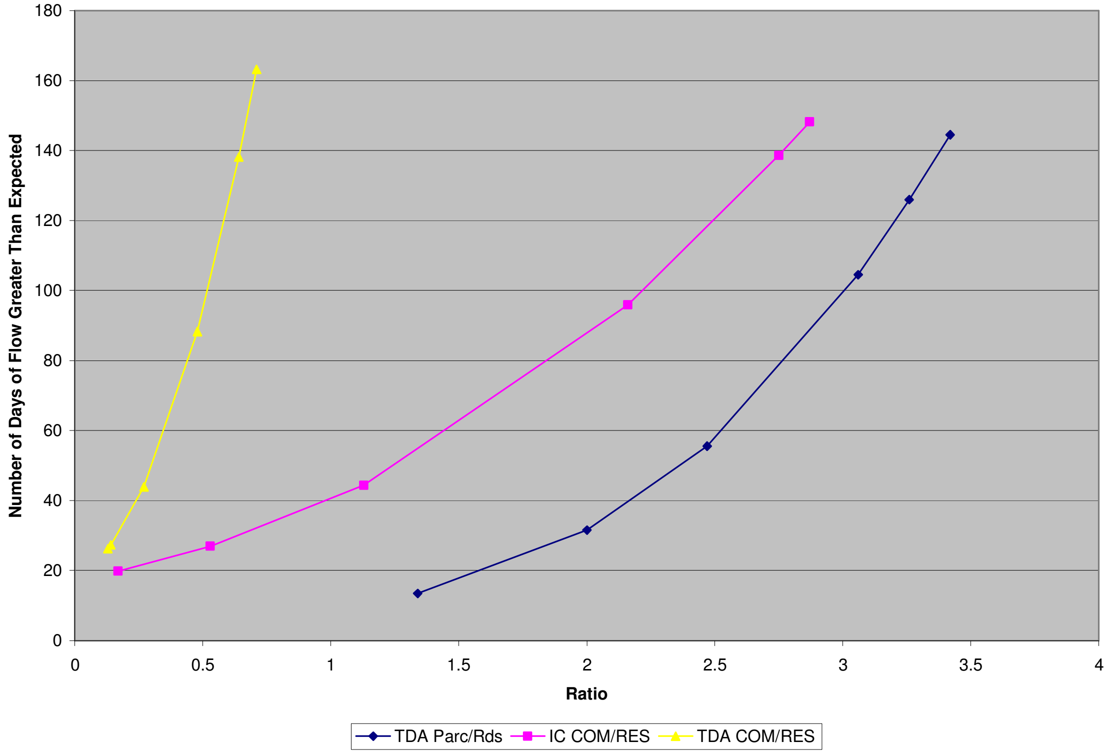


Figure 46. Scatterplot between number of days greater streamflow than expected versus ratios of development for TDA Parc/Rds, IC COM/RES, and TDA COM/RES.

downstream. The new forests were primarily located in headwater areas of the watershed. Because the full influence of the potholes and newly forested areas was not completely accounted for in this study, the results should be considered conservative.

Three different ratios were created in order to understand how the relative amounts of development related to streamflow (Figure 45). The ratio of TDA for all parcels to TDA for roads was thought to a good measure because it accounted for all impervious cover and because of the relative importance of roads in previous tests. Although it had the lowest per-unit effect, this is skewed because the total amounts result in a bigger ratio being divided into the same dependent variable. However, it does show increases in flow per unit over time as the ratio of developed parcels to developed roads increases over time.

The other two ratios focus on the differences between commercial and residential development and can be used to compare the differences in measure of impervious cover and total developed area. IC COM/RES shows a stronger per-unit effect at the beginning of the study. This is quickly reduced but slowly rises after 1969, the same time frame where patches are coalescing into fewer, larger patches. TDA COM/RES behaves a bit differently. Overall, it has a bigger per-unit effect, but this is due to the relatively small differences in TDACOM and TDARes. Overall, TDA COM/RES follows the same pattern seen in IC COM/RES, the same period as the changes seen in the number of patches of development in the watershed.

Figure 46 gives a clearer picture of how the ratios relate to each other and the changes in above expected flow. All three are exponential curves, but vary in their steepness. Their best value is as a planning tool. For a given number of days greater than

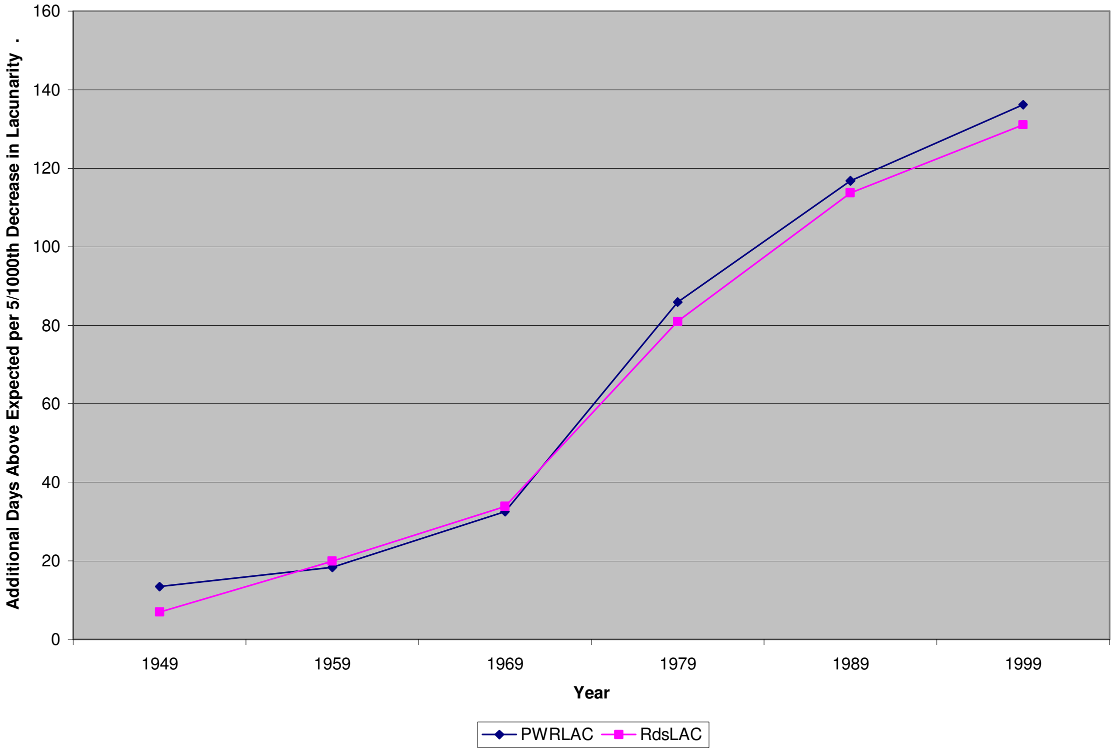


Figure 47. Number of days of greater than expected streamflow due to 5/1000th decrease in lacunarity by year for roads and parcels with roads.

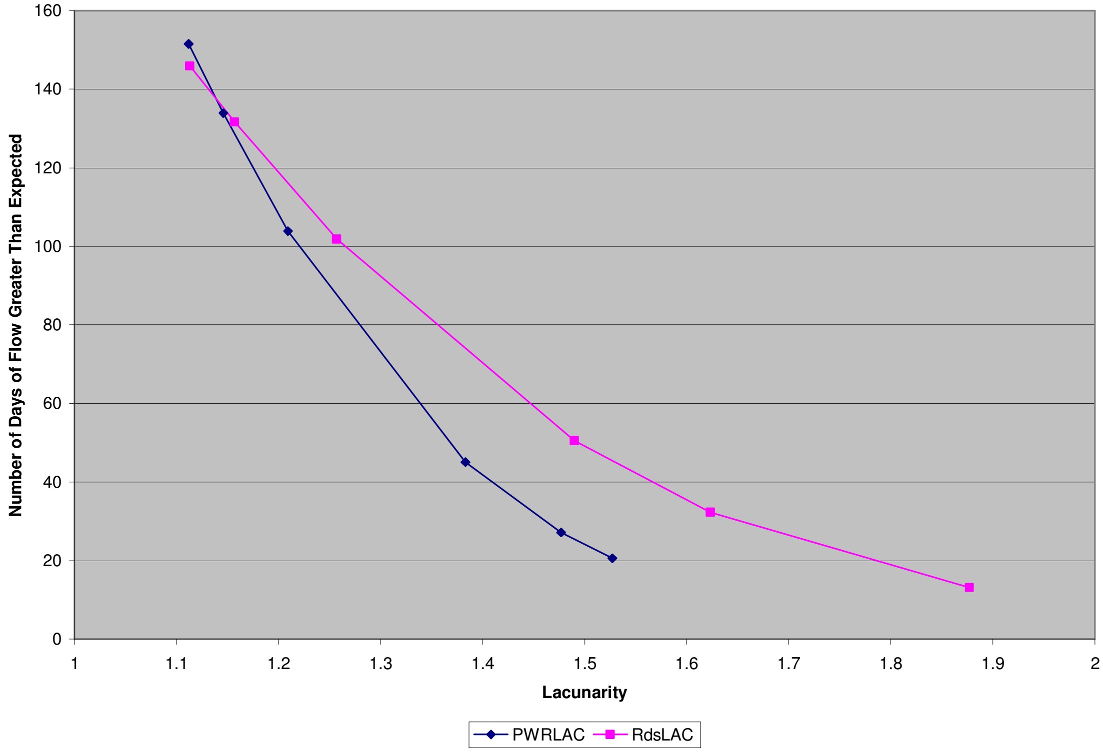


Figure 48. Scatterplot number of days greater than expected streamflow for roads and parcels with roads versus lacunarity.

expected streamflow, the ratios of different types of development are clearly observable. For example, at 100 days greater than expected streamflow, there is twice as much developed area in residential as commercial, but there is over twice as much impervious cover in commercial development as residential, and the total developed area for all parcels is three times that of roads.

Although it is useful to see a snapshot of the watershed conditions at a given point, manipulating the ratios may not reduce residual flow, especially if additional development is required to make the desired change in ratio. Flow shouldn’t be expected to decrease if an additional 1000 hectares of residential impervious cover are added to a watershed to get the IC COM/RES ratio closer to one!

Lacunarity is remarkably similar for roads and PWR on a per-unit basis (Figure 47). Residual flow per unit for RdsLAC and PWRLAC has the same inflection point seen in other metrics. Until the patches started the trend of consolidation after 1972, lacunarity was decreasing at a more rapid rate than streamflow was increasing. After 1972, residual flow was increasing at a greater rate while lacunarity was slowly decreasing over time. This explains the steep curve in residual flow on a per-unit basis. The similarity between residual flow per unit RdsLAC and PWRLAC is a reflection of the similarity between RdsLAC and PWRLAC. Although lacunarity is sensitive to total cover, it is also sensitive to spatial arrangement. Because of the method for generating the time of construction for road segments, road patches and PWR patches were expected to have a high correlation in location.

Figure 48 shows that the greater gappiness measured in roads alone changes the slope of the curve. However, a comparison between the two lacunarity curves reinforces the importance of roads. With the exception of the smallest lacunarity values, for a given lacunarity, roads are expected to have a greater impact in the number of days greater than expected flow. However, one must be cautious in this assessment. The per-unit effects on residual flow are nearly identical. The differences in the lacunarity curves between roads and PWR is due to a lag in time. When PWRLAC reaches a certain lacunarity, RdsLAC will not be expected to reach the same value for several years, thus associating RdsLAC with a higher residual flow value.

CHAPTER VIII

CONCLUSIONS AND DISCUSSION

Study Review

This study has shown that degradation of stream quality as evidenced by changes in streamflow is sensitive to the amount of impervious cover and the loss of natural areas, but is also sensitive to the spatial configuration of development. This study also demonstrates that impervious cover may not be the best measure of historical change. It was found that every measure which could be tested as total developed area or as impervious cover performed better when total developed area was the criterion. It was also found that subsets of total impervious cover were better predictors of change in streamflow than WIC. Focusing solely on total impervious cover ignores the subtle differences in composition and configuration.

Changes in streamflow were particularly sensitive to changes in the amount and configuration of roads. A full third of the best predictors of streamflow were based solely on roads. Although several of the road metrics were based on spatial configuration, the length of the road network within the watershed, which could also be expressed as road density, proved to be an excellent predictor of streamflow. Although other measures of development can provide greater insight, measuring the road network can be done quickly and without great expense, sure to be of value to small planning areas on tight budgets.

The mechanism of the impact of roads is thought to be due to their role in collecting water from large areas of impervious cover and conveying that water to the natural drainage system. This suggests a set of simple planning guidelines: minimize the amount of roads, minimize the connection of roads to developed parcels, and redesign roads so they do not act as a primary transport for water.

The loss of natural areas presented an interesting set of problems within this study area. While much of the change recorded for this watershed was based on public records, the only way to quantify natural areas was through aerial photography. This restricted the study in several ways. First, it restricted the number of time points to those years where aerial or satellite imagery was collected. Second, the measure of natural phenomenon was sensitive to the condition and resolution of the available photography. If the phenomenon was not discernable, it was not recorded. Third, only the loss of natural areas could be quantified annually through an intersection with a more temporally explicit dataset. As measured, the natural areas were only a small portion of the total landscape. Missing was the quantification of their sphere of influence, particularly in the case of the prairie potholes. From hydrological studies we know that each pothole drains the surrounding flats, but measurement was not possible with the available data.

A potential solution to the pothole problem would be obtaining high-resolution elevation data. However, since this is not available historically, its value would be in preserving the remaining hydrology.

Despite these shortcomings, the loss of natural areas proved to be as good a predictor of streamflow as many of the measures based on impervious cover or total developed area. It is expected that these measures would be related because increases in one usually results in decreases in the other. But this information could provide an additional planning tool. By understanding the function of the natural areas within the landscape, development could be restricted in the critical areas and the natural function could be emulated in other developed areas. This is particularly true for the prairie potholes, which acted as local sinks for water.

The ratios of different types of development were also good predictors of change in streamflow for this study. However, changes in ratios may be driven by a single element of the landscape. They also do not convey information about the total amount of development within the landscape. It is feasible for two points in time to have the same ratio of commercial to residential development, but have very different amounts of total development. Although they could provide guidance for planning policy, ratios should not be used without supplemental information.

Lacunarity explained the greatest amount of variance in residual flow this study. Lacunarity is sensitive to both the amount of development and the configuration of that development at different scales. At small scales, it is sensitive to the proportion of the landscape occupied. At medium scales, it is sensitive to the amount of connectivity in the landscape. This sensitivity to scale makes lacunarity a valuable tool, but also makes it difficult to utilize as an independent variable in a regression. It is fortunate that within this study area, lacunarity followed the same general pattern over a variety of scales. As an independent variable, lacunarity produced similar results at all scales tested. However, this should not be assumed to be the case for all landscapes.

Lacunarity can be difficult to use as a planning tool. Although it can be described as a measure of the “gappiness” of a landscape, it may be hard to convey that information to an audience unfamiliar with the technique. Lacunarity also does not produce a clear direction for implementing policy. Finally, lacunarity is a measure of the landscape and is not site-specific. One cannot get a lacunarity value for a particular parcel in a landscape. This limits its use to general planning policy instead of a set of site-specific rules.

Many of the variables in this study showed exponential increases during some portion of the study period. This, combined with the exponential growth in streamflow response, shows that the process of development has ever-increasing negative impacts on watersheds. Although some evidence suggests that engineering controls such as detention and retention facilities may reduce the negative impacts of development (CWP, 2003), it is clear that historical development patterns had significant impacts that may not be correctable.

Although a variety of stream quality measures may quantify the environmental impacts of development, streamflow has a particular importance to the built environment. Sustainability of the built environment depends on preventing the impacts of hazardous conditions such as those imparted by excess streamflow. High water events do not need to leave the banks of the drainage system to be hazardous. They have a negative impact on the structure of the drainage system itself.

This study has confirmed the role of impervious cover in the degradation of stream quality, at least in the context of streamflow. It has provided a method for estimating development on an annual basis that does not depend on aerial photography and utilizes databases that are becoming more commonly available. This study has shown that spatial configuration plays a role in the relationship between development and streamflow. Several of the variables in this study may be of use in the development of planning guidelines for development. Of particular interest are the ratios of development types and the density of the road networks, both easy to measure and easy to adapt to planning policy. More complicated measures provide a bit more explanatory power, but may be too complex to be integrated into the planning toolset. Finally, this study has shown that measuring impervious cover alone does not capture all of the effects of development. Quantifying the entire developed area provides a better measure of the changes in the landscape.

Directions for Research

There is a strong need for research on the methods for examining spatial configuration. Inter-correlation between spatial metrics confounded more complex models. Improved spatial metrics or methods for controlling inter-correlation between metrics would enhance modeling efforts. This could produce models which can distinguish between the relative effects of different spatial configuration characteristics.

Several characteristics of the study area also lead to new areas of research. This watershed exhibits homogeneity in soil structure and soils which had characteristics similar to impervious cover. The permeability of the soils and variance in the spatial location of impermeable soils may affect the spatial configuration of development. In turn, development may have drastically different effects on the watershed depending on what type of soil it is located.

This study area is also homogeneous in elevation and vegetative cover. This study made little progress in understanding the effects of vegetative cover and the problem of elevation was ignored.

This watershed was developed without the constraints of tight planning policies. A comparative study between two watershed of similar characteristics but with very different planning policies or developmental controls could reveal much about the efficacy of current planning policies with regards to environmental impacts.

Without any inflow from other watersheds, this watershed is isolated from upstream influences. Repeating this study on a watershed influenced by upstream development or varying climatological conditions could expand our knowledge about development in these areas.

This work shows that spatial configuration influences the impacts of development. Further research could lead to a greater understanding of how the spatial configuration of development impacts our environment. This should lead to new guidelines for development, thus improving the sustainability of our environment.

REFERENCES

Ahern, J., 1995. Greenways as a Planning Strategy. Landscape and Urban Planning 33: 131-155.

Apan, A.A., Raine, S.R., and Paterson, M.S., 2002. Mapping And Analysis of Changes in the Riparian Landscape Structure of the Lockyer Valley Catchment, Queensland, Australia. Landscape and Urban Planning 59 (1) 43-57.

Bhaduri, B., Harbor, J., Engel, B., and Grove, M., 2000. Assessing Watershed-Scale, Long-Term Hydrologic Impacts of Land-Use Change Using a GIS-NPS Model. Environmental Management 26(6): 643-658.

Blaschke, T. and Petch, J., 1999. Landscape Structure and Scale: Comparative Studies on Some Landscape Indices in Germany and the UK. In: Maudsley, M. and Marshall, J. (eds.), Heterogeneity in Landscape Ecology: Pattern and Scale. IALE UK, Aberdeen, 75-84.

Burby, R.J. (Ed.), 1998. Cooperating with Nature: Confronting Natural Hazards with Land-Use Planning for Sustainable Communities. Joseph Henry Press, Washington, D.C.

Burian, S.J., Brown, M.J., and McPherson, T.N., 2002. Evaluation of Land Use/Land Cover Datasets for Urban Watershed Modeling. Water Science and Technology 45(9): 269-276.

Center for Watershed Protection (CWP), 2003. Impacts of Impervious Cover on Aquatic Systems. Ellicot City, Maryland.

City of Houston, 2002. City of Houston Code of Ordinances. Sec. 26-21, Parking Spaces for Certain Types of Occupancies.

Clark, D.E., Novontny, V., Griffin, R., Booth, D., Bartosova, A., Daun, M.C., and Hutchinson, M., 2002. Willingness to Pay for Flood and Ecological Risk Reduction in an Urban Watershed. Water Science and Technology 45(9): 235-242.

Cronshey, R., McCuen, R.H., Miller, N., Rawls, W., Robbins, S., Woodward, D., 1986. Urban Hydrology for Small Watersheds. Technical Release 210-VI-TR-55, USDA Natural Resources Conservation Service, Conservation Engineering Division, Washington, D.C.

Dale, V.H., Brown, S., Haeuber, A., Hobbs, N.T., Huntly, N., Naiman, R.J., Riebsame, W.E., Turner, M.G., and Valone, T.J., 1999. Ecological Principles and Guidelines for Managing the Use of Land: A Report from the Ecological Society of America. U.S. Gov't contract No. DE-AC05-96OR22464.

Fabos, J.G., 1995. Introduction and Overview: The Greenway Movement, Uses and Potentials of Greenways. Landscape and Urban Planning 33: 1-13.

Forman, R.T.T., 1995. Land Mosaics: The Ecology of Landscapes and Regions. Cambridge University Press, Cambrige, UK.

Grafe, V., 1999. Paradise Lost? The Coastal Prairie of Louisiana and Texas. U.S. Fish & Wildlife Service and U.S. Geological Survey http://training.fws.gov/library/Pubs/paradise_lost.pdf.

Griffith, J.A., Martinko, E.A. and Price, K.P., 2000. Landscape Structure Analysis of Kansas at Three Scales. Landscape and Urban Planning 52(1) 45-61.

Gustafson, E.J., 1998. Quantifying Landscape Spatial Pattern: What Is the State of the Art? Ecosystems 1: 143-156.

Hargis, C.D., Bissonette, J.A., David, J.L., 1998. The Behavior of Landscape Metrics Commonly Used in the Study of Habitat Fragmentation. Landscape Ecology 13: 167-186.

Herzog, F. and Lausch, A., 1999. Prospects and Limitations of the Application of Landscape Metrics for Landscape Monitoring. In: Maudslet, M. and Marshall, J. (Eds.), Heterogeneity in Landscape Ecology: Pattern and Scale. IALE UK, Aberdeen, 41-50.

Hey, D.L., 2001. Modern Drainage Design: the Pros, the Cons, and the Future. Presentation at the Annual Meeting of the American Institute of Hydrology. Bloomington, Minnesota. Available at: http://www.wetlands-initiative.org/pdf/modrain.pdf.

Jacob, J.S., Moulton, D.W., and Lopez, R.A., 2002. Texas Coastal Wetlands. Available at: www.texaswetlands.org/prairie.htm

Jennings, D.B. and Jarnigan, S.T., 2002. Changes in Anthropogenic Impervious Surfaces, Precipitation and Daily Streamflow Discharge: A Historical Perspective in a Mid-Atlantic Subwatershed. Landscape Ecology 17: 471-489.

Joerin, F. and Musy, A., 2000. Land Management with GIS and Multicriteria Analysis. International Transactions in Operational Research 7: 67-78.

Karl, T.R. and Knight, W.R., 1998. Secular Trends of Precipitation Amount, Frequency and Intensity in the USA. Bulletin of the American Meteorological Society 79: 231-241.

Landphair, H.C., Klatt, F., 1998. Landscape Architecture Construction, 3rd ed. Prentice Hall PTR, Upper Saddle River, New Jersey.

Lee, K.K., and Risley, J.C., 2002, Estimates of Ground-water Recharge, Base Flow, and Stream Reach Gains and Losses in the Willamette River Basin, Oregon: U.S. Geological Survey Water-Resources Investigations Report 01–4215.

Leitão, A.B. and Ahern, J., 2002. Applying Landscape Ecological Concepts and Metrics in Sustainable Landscape Planning. Landscape and Urban Planning 59: 65-93.

Li, B., Archer, S. 1997. Weighted Mean Patch Size: A Robust Index for Quantifying Landscape Structure. Ecological Modelling 102: 353-361.

Li, H. and Reynolds, 1995. On Definition and Quantification of Heterogeneity. Oikos 73: 280-284.

Linehan, J., Gross, M., and Finn, J., 1995. Greenway Planning: Developing a Landscape Ecological Network Approach. Landscape and Urban Planning 33: 179-193.

Marsden, S.J, Fielding, A.H., Mead, C. and Hussin, M.Z., 2002. A Technique for Measuring the Density and Complexity of Understorey Vegetation in Tropical Forests. Forest Ecology and Management 165(1-3) 117-123 .

Marsh, W.M., 1983. Landscape Planning: Environmental Applications, 3rd ed. John Wiley & Sons, Inc., New York.

McDonnell, J.J., 2003. Where Does Water Go When It Rains? Moving Beyond the Variable Source Area Concept of Rainfall-Runoff Response. Hydrological Processes 17: 1869-1875.

McGarigal, K., Cushman, S.A., Neel, M.C., Ene, E., 2002. FRAGSTATS: Spatial Pattern Analysis Program for Categorical Maps. Computer software program. University of Massachusetts, Amherst. Available at: www.umass.edu/landeco/research/fragstats/fragstats.html.

McMahan, C.A., Frye, R.G., and Brown, K.L., 1984. The Vegetation Types of Texas – Including Cropland. Texas Parks & Wildlife PWD Bulletin 7000-120. Available at: www.tpwd.state.tx.us/admin/veg/.

Mileti, D.S. (Ed.), 1999. Disasters by Design: A Reassessment of Natural Hazards in the United States. Joseph Henry Press, Washington, D.C.

Moglen, G.E. and Beighley, R.E., 2002. Spatially Explicit Hydrologic Modeling of Land Use Change. Journal of the American Water Resources Association 38 (1): 241 – 253.

Pearson, D.M, 2002. The Application of Local Measures of Spatial Autocorrelation for Describing Pattern in North Australian Landscapes. Journal of Environmental Management 64(1) 85-95.

Pitt, R.E. 1987. Small Storm Urban Flow and Particulate Washoff Contributions to Outfall Discharges. Ph.D. dissertation. College of Civil and Environmental Engineering. University of Wisconsin, Madison.

Plotnick, R.E., Gardner, R.H., and O'Neill, R.V., 1993. Lacunarity Indices as Measures of Landscape Texture. Landscape Ecology 8: 201-211.

Raines, G.L., 2002. Description and Comparison of Geologic Maps with FRAGSTATS, A Spatial Statistics Program. Computers & Geosciences 28(2) 169-177.

Riitters, K.H., O'Neil, R.V., Hunsaker, C.T., Wickham, J.D., Yankee, D.H., Timmins, S.P., Jones, K.B., Jackson, B.L., 1995. A Factor Analysis of Landscape Pattern and Structure Metrics. Landscape Ecology 10(1) 22-39.

Rutledge, A.T., 1998. Computer Programs for Describing the Recession of Ground-Water Discharge and for Estimating Mean Ground-Water Recharge and Discharge From Streamflow Data – Update. U.S. Geological Survey Water-Resources Investigations Report 98-4148: 31-34.

Sanders, R.A., 1986. Urban Vegetation Impacts on the Hydrology of Dayton, Ohio. Urban Ecology 9: 361-376.

Scheuler, T., 1994. The Importance of Imperviousness. Watershed Protection Techniques 1(3): 100-111.

Seppelt, R. and Voinov, A., 2002. Optimization Methodology for Land Use Patterns Using Spatially Explicit Landscape Models. Ecological Modelling 151: 125-142.

Sloan, C.E., 1972. Ground-Water Hydrology of Prairie Potholes in North Dakota. Geological Survey Professional Paper 585-c.

SPSS, 2001. Computer Program for Statistical Analysis. Available at: www.spss.com.

Strom, S. and Nathan, K., 1998. Site Engineering for Landscape Architects, 3rd Ed. John Wiley & Sons, Inc., New York.

Sutherland, R. 1995. Methodology for Estimating Effective Impervious Area. Watershed Protection Techniques 2(1): 47–51.

Szaro, R.C., Sexton, W.T. and Malone, C.R., 1998. The Emergence of Ecosystem Management as a Tool for Meeting People's Needs and Sustaining Ecosystems. Landscape and Urban Planning 40: 1-7.

Tinker, D.B., Resor, C.A.C., Beauvais, G.P., Kipfmueller, K.F., Fernandes, C.I., Baker, W.L., 1998. Watershed Analysis of Forest Fragmentation by Clearcuts and Roads in a Wyoming Forest. Landscape Ecology 13: 149-165.

TNRIS, 2002. Digital data available at: www.tnris.state.tx.us/digital.htm.

U.S. Department of Agriculture (USDA), Natural Resource Conservation Service, 2002. Soil Survey Geographic (SSURGO) Database for Harris County, Texas. Fort Worth, Texas. Available at: www.ftw.nrcs.usda.gov/ssur_data.html.

U.S. Department of Commerce (USDC), 1949-2000. Climatological Data: Texas. National Climatic Data Center, Asheville, North Carolina. Available at: www.ncdc.noaa.gov.

U.S. Geological Survey (USGS), 2001, National Water Information System (NWISWeb) data available at waterdata.usgs.gov/nwis/.

van Lier, H.N., 1998. The Role of Land Use Planning in Sustainable Rural Systems. Landscape and Urban Planning 41: 83-91.

APPENDIX 1

WEIGHTED CURVE NUMBER

In technical release 55 (TR-55), the United State Department of Agriculture outlined simplified procedures for estimating runoff and peak discharges in small watersheds" (USDA, 1986). The method turns rainfall into runoff using a curve number (CN) which represents the conditions of the landscape including soils, plant cover, amount of impervious cover, interception and surface storage. Because curve numbers incorporate many of the watershed qualities which were treated as independent variables in this study, the change in the curve number for this study area was expected to show a strong correlation to residual flow. This appendix describes the steps taken to generate a weighted curve number for this watershed for each year in the study.

The first step was to determine the soil composition and hydrologic soils groups. As originally discussed in Chapter V, soils data was provided in GIS format from NRCS (2000). Over 98% of the watershed was found to be in hydrologic soil group D.

The second step was to determine the appropriate cover. The available vegetation data layers were to coarse in resolution to be of much use. Because the watershed fell into the coastal upland prairie and woods region, a general classification of brush-weed-grass mixture in a poor soil condition was selected. The combination of the vegetation selection, poor soil condition selection and soil type resulted in a general curve number of 83 for 98% of the watershed. The remaining two percent was divided between a better soil condition with a curve number of 78 and impervious cover with a curve number of 98.

The curve numbers were applied to the appropriate soils layers within the GIS, then intersected with the parcels and roads data layer described in Chapter V. The resulting layer contained three pieces of data: 1) the spatial configuration of every parcel and road segment; 2) curve numbers to represent each parcel and road segment in both a developed and undeveloped state; and 3) the date each unit was developed. This combined layer was used to generate annual maps of development for the entire study period. The areas of the parcels and road segments, both developed and undeveloped, were multiplied by the curve number for each year and the products were summed to give the area weighted curve number (WCN) for the watershed on an annual basis.

WCN increased from a minimum of 82.38 in 1949 to a maximum of 86.86 in 2000. This was an average of 0.1% increase per year. To determine whether or not there was a significant change in WCN over time, WCN was compared by decade using the same method presented in Chapter V. The decades were not equally variant, so the Kruskal-Wallis test was performed. WCN was found to have changed significantly (H=48.964, df=4, p=<0.001). Dunn's method revealed significant differences between the 1990s and the 1950s, 1960s and 1970s; between the 1980s and the 1950s and 1960s; and finally, between the 1970s and 1950s.

Having significantly changed over time, WCN was tested for its correlation to the dependent variable, the natural log of residual flow. The Pearson's correlation value was 0.704, too low to be considered for the final analysis.

WCN is an accepted method for estimating runoff and has some advantages over more simplistic measures of development. WCN incorporates soils and cover data, which should improve its accuracy in predicting. The spatial configuration of the landscape is implicit in the model because it depends on the interaction between spatially-explicit variables - soils and land cover. Its relatively poor performance in this study was unexpected, but could be due to several factors. First, the soils in this study were homogeneous and not pervious enough to clearly distinguish them from impervious cover. Second, the cover data was restricted in terms of vegetation and further restricted to a binary condition, developed or undeveloped. Finally, the variability within the soil conditions was unknown.

WCN shows considerable promise, but was limited in its use for this study because of conditions within the study area and limited availability of some data layers.

APPENDIX 2

One procedure for determining the best fit model from a large number of independent variables uses a step-wise series of multi-variate linear regressions to progressively reduce the number of variables until all of the variables within the model are found significant. The procedure begins with all of the independent variables being entered into the model. For each iteration, the variable with the highest significance score above the desired threshold is removed. The regression is repeated with the remaining variables. This process continues until all of the remaining variables are significant at the desired level.

This process is demonstrated below using SPSS 11.0. The dependent variable was the natural log of residual flow. Six coded variables were entered as independent variables. The output from each step is reproduced below. For each step, the variable with the highest Sig. value in the Coefficients table was removed and the regression was performed with the remaining variables. This continued until all of the variables had a Sig. value less than 0.01. The remaining variables were: Var00179, area-weighted mean shape index; Var00202, weighted mean patch size; and Var00347, mean proximity index.

Despite all of the independent variables being found significant, the sign of the coefficient for Var00202 is negative when it should be positive. This is a clear indication of a colinearity problem. This process was utilized exhaustively to determine the best multi-variate linear model between the independent variables and residual flow, but all models were found invalid because of similar colinearity problems.

Regression

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.841[a]	.708	.669	.63293

a. Predictors: (Constant), VAR00507, VAR00347, VAR00179, VAR00396, VAR00202, VAR00504

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	43.717	6	7.286	18.188	.000[a]
	Residual	18.027	45	.401		
	Total	61.744	51			

a. Predictors: (Constant), VAR00507, VAR00347, VAR00179, VAR00396, VAR00202, VAR00504

b. Dependent Variable: LNQAB

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-6.796	1.735		-3.916	.000
	VAR00179	.264	.100	2.618	2.630	.012
	VAR00202	-6.78E-08	.000	-3.164	-2.745	.009
	VAR00347	6.621E-05	.000	1.318	2.900	.006
	VAR00396	197.859	86.764	6.922	2.280	.027
	VAR00504	-1.51E-06	.000	-8.757	-2.012	.050
	VAR00507	1.218E-07	.000	2.152	.930	.357

a. Dependent Variable: LNQAB

Regression

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.838[a]	.702	.670	.63200

a. Predictors: (Constant), VAR00504, VAR00347, VAR00179, VAR00202, VAR00396

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	43.371	5	8.674	21.717	.000[a]
	Residual	18.373	46	.399		
	Total	61.744	51			

a. Predictors: (Constant), VAR00504, VAR00347, VAR00179, VAR00202, VAR00396

b. Dependent Variable: LNQAB

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-7.878	1.286		-6.126	.000
	VAR00179	.287	.097	2.852	2.965	.005
	VAR00202	-6.38E-08	.000	-2.981	-2.628	.012
	VAR00347	6.665E-05	.000	1.326	2.925	.005
	VAR00396	164.971	79.111	5.771	2.085	.043
	VAR00504	-1.01E-06	.000	-5.869	-1.927	.060

a. Dependent Variable: LNQAB

Regression

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.824[a]	.678	.651	.64999

[a] Predictors: (Constant), VAR00396, VAR00347, VAR00179, VAR00202

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	41.887	4	10.472	24.786	.000[a]
	Residual	19.857	47	.422		
	Total	61.744	51			

[a] Predictors: (Constant), VAR00396, VAR00347, VAR00179, VAR00202

[b] Dependent Variable: LNQAB

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-7.258	1.280		-5.668	.000
	VAR00179	.271	.099	2.692	2.732	.009
	VAR00202	-6.95E-08	.000	-3.245	-2.803	.007
	VAR00347	5.459E-05	.000	1.086	2.422	.019
	VAR00396	13.579	9.663	.475	1.405	.167

[a] Dependent Variable: LNQAB

Regression

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.815[a]	.665	.644	.65656

a. Predictors: (Constant), VAR00347, VAR00179, VAR00202

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	41.053	3	13.684	31.745	.000[a]
	Residual	20.691	48	.431		
	Total	61.744	51			

a. Predictors: (Constant), VAR00347, VAR00179, VAR00202

b. Dependent Variable: LNQAB

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-7.789	1.236		-6.303	.000
	VAR00179	.356	.080	3.532	4.462	.000
	VAR00202	-8.17E-08	.000	-3.814	-3.482	.001
	VAR00347	6.702E-05	.000	1.334	3.201	.002

a. Dependent Variable: LNQAB

VITA

Buren Brooks DeFee II, known as “Buck” to family and friends, has taken a truly multi-disciplinary approach to his education. He currently holds a Bachelor of Science degree in marine biology from Texas A&M University (TAMU) awarded in 1994; a Master of Science degree in land development from TAMU awarded in 1998; and is fulfilling his degree requirements for a Ph.D. in urban and regional science from TAMU with this dissertation, to be awarded in 2003. Buck has worked in a variety of fields from medical research to regional planning. His most recent work focused on the application of Geographic Information Systems to solving problems which cross disciplinary, political and physical boundaries. Buck may be reached by mail at 308 Westcott, Houston, TX 77007. He may also be reached by e-mail at aggie@defee.org.