Examining the Effects of Wastewater Infrastructure on Puget Sound Near-shore Water Quality Across a Gradient of Urbanization

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A dissertation

submitted in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

University of Washington

2014

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Program Authorized to Offer Degree:

Interdisciplinary Program in Urban Design and Planning

University of Washington

Abstract

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As shorelines develop, wastewater infrastructure systems are designed to simultaneously support urban development and protect human and ecosystem health from sewage contamination. The ability to effectively manage coastlines in an urban setting depends on understanding the interactions between human and biophysical systems, and to incorporate that information into policy and planning decisions that support regional water quality goals. Past research has linked the contamination of coastal and estuarine ecosystems to upland land use, as well as centralized and decentralized wastewater systems. Missing from this research is an evaluation of how urban development relates to alternative wastewater infrastructures and the links between coastal water quality, wastewater infrastructure and patterns of urbanization. My research sought to systematically assess alternative wastewater infrastructures across an urban gradient and to assess the relationships between wastewater disposal type, land use-cover pattern, and near-shore water quality. I evaluate the spatial characteristics of parcels with sewers vs. onsite septics in sub-watersheds and link wastewater type to urban patterns to answer two questions: (1) How are

alternative wastewater infrastructures spatially distributed across an urban gradient? (2) How do different wastewater infrastructures relate to land-use and land-cover patterns? At a larger landscape-scale, I relate indicators of near-shore water quality to wastewater infrastructure and land use-land cover patterns to address a third question: (3) How does near-shore water quality relate to wastewater infrastructure and urban development patterns?

This research relies on a three-part approach that uses quantitative measures of wastewater patterns, landscape characteristics, and microbial conditions for shellfish growing areas. To answer the first question, I quantify and compare spatial measures of parcels on two types of wastewater systems. I address the second question by relating land-use and land-cover pattern (composition and configuration) to wastewater type (septic vs. sewer). I answer the third question by combining spatial information about land-use, land-cover and wastewater in near-shore basins to assess how these factors influence water quality in shellfish growing areas.

The results from the study in the Puget Sound support previous findings that suburban sub-basins with moderate amounts of development contain significantly higher counts and densities of residential parcels with onsite-septics than urban or rural counterparts. However, I did not find septic density to be a significant predictor of fecal coliform (FC) in shellfish growing areas; the number of septics was only moderately related to FC. The total amount of high intensity urban land cover was the single best predictor of near-shore water quality. I found significant associations between wastewater treatment type and the composition and configuration of land cover. On average, Puget Sound basins with 20% of their area or more covered by high urban land cover are more likely to be dominated by parcels on a sewer system.

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Acknowledgements

For those that have travelled the long and lonely journey that is the dissertation, you understand that it would be impossible without those significant anchors in life, past and present to keep you pressing along. First and foremost, I would like to thank my husband, Nathan for enduring this long journey with me, keeping me fed and clothed, for his unfaltering support even during my darkest hours, and above all, for being an amazing father to our beautiful daughters, Kaya and Nadia. Without him, I know this project would never have come to fruition. I thank my parents, Diane and Christian Spirandelli, for their unconditional love and for instilling in me this life-long curiosity. To Kaya and Nadia, you are a daily joy and reminder of what really matters in life.

I am incredibly indebted to my advisor, Marina Alberti, who re-invigorated my early interests in urban ecology, and who, through patient guidance, mentoring, and a tenacious quest for excellence inspired my interdisciplinary and scholarly pursuits. I would also like to thank my committee members Elaine Faustman and Mary Ruckelshaus for their infectious enthusiasm. Jan Wittington deserves a special thank you for going the extra mile and for keeping her streak alive by helping me land a tenure track job. I also want to thank Michael Brett for his vital insights and for keeping it real.

I consider myself extremely fortunate to have journeyed through the PhD at the University of Washington. I drew inspiration and motivation from many students, faculty, friends and related community members over the years as a student of the Interdisciplinary Program in Urban Design and Planning and a member of the College of Built Environments. Past and present colleagues of the Urban Ecology Research Lab were, and continue to be, sources of inspiration, including Michal Russo, Karis Tennesson, Julia Michalak, Tracy Fuentes, Vivek Shandas, and Adrienne Greve. I am especially thankful for my very close friends, Anna Tamura and Ken Yocom, who helped me see the humor in the most absurd of circumstances, and for teaching me to fly-fish.

I would like to acknowledge NOAA and the Joint Institute for the Study of the Atmosphere and Ocean (JISAO), which funded much of this research and Mark Plummer, Northwest Fisheries Science Center. Lastly, I would like to thank my colleagues and friends at the University of Hawai`i at Manoa. Their unwavering support helped me reach the finish line.

Chapter 1: Research Summary

1.1. Introduction

Many of the world's coasts are becoming increasingly urban. Fourteen of the world's seventeen largest cities are located on coasts. Two-fifths of cities with populations between 1 million and 10 million people live on the coastline. Further, a vast majority of coastlines are developing at a rate higher than population growth and in the form of low-density peri-urban settlements (Beach, 2003; Small & Nicholls, 2003). In the United States, landscape change associated with urbanization has been significant in the last several decades and is also expected to continue (Crosset, Culliton, Wiley, & Goodspeed, 2004). Trends in coastal development across the planet point to the transformation of sensitive near-shore areas that contain high biodiversity and affect critical ecosystem services (Seto, Fragkias, Güneralp, & Reilly, 2011; Barbier et al., 2010).

Urbanization threatens coastal ecosystem health by affecting the structure and function of near-shore ecosystems. Urban development changes upland landscapes, alters bio-physical processes, transforms biogeochemical cycles, and decreases nursing grounds for fish and shellfish (Emmett et al., 2000; Grimm, Grove, Pickett, & Redman, 2000; Leopold, 1968; Vitousek, 1997). These dramatic changes in turn affect the capacity of near-shore areas to deliver essential services to communities and populations that depend upon them for their health, livelihood, and well-being. Near-shore ecosystems provide a number of valuable benefits to humans, including raw materials, food, coastal protection, erosion control, water purification, nutrient cycling and the maintenance of fisheries (Barbier et al., 2010). On the West Coast of the United States, the value of salt marshes' support for recreational fishing alone was estimated at $981 per acre. These highly prized landscapes are polluted, altered and lost due to human related activities in the upland draining watersheds. Moreover, urban development and the human use of coastal areas is associated with increased incidence of water-borne disease from contact with polluted water and the consumption of contaminated seafood (Stewart et al., 2008).

West Coast estuaries typify this situation. Estuaries in the Puget Sound of Western Washington, in particular, have been developing rapidly with some of the highest population densities in the country (Emmett et al., 2000). As human development has increased along the Puget Sound coastline, areas formerly approved for commercial and recreational shellfish harvesting have been closed due to microbial contamination (Glasgoe & Christy, 2004). For over 150 years, Pacific Northwest tidelands and near-shore areas served as productive farm beds for oysters, clams and mussels. Shellfish are prized for their economic return, as a reliable source of protein, and as a cultural icon and resource. The shellfish industry adds an estimated $270 million a year into the region's economy, bringing jobs to over 3,200 people, primarily in coastal communities. While near-shore areas and beaches of estuaries provide many benefits to humans, the harvesting and consumption of shellfish is most dependent on a healthy, functioning ecosystem that provides clean, safe water. The ability of coastlines to accommodate future populations and maintain critical ecosystem functions for shellfish is intimately linked to how we plan, design and manage the upland watersheds.

A major goal of urban ecology is to understand the dynamics of cities as human-dominated ecosystems that evolve over time as a result of a multitude of interactions between ecological and human systems (Alberti et al., 2003; Collins, Kinzig, Grimm, & Fagan, 2000; Grimm et al., 2000). Because human and ecological factors are inextricably linked, urban ecologists believe urban ecosystems should by studied and managed in an integrated manner. From a broad perspective, urban areas are conceived to include not only biological and physical features, but also built and socio-economic attributes. However, scholars of urban ecosystems recognize that simply linking human related decisions to the ecological or visa-versa in an additive manner fails to explicitly represent the processes through which humans affect or are affected by the urban environment. Further, without the use of more integrated models of urban ecosystems, management and planning strategies aimed at reducing the impacts of human related activities will fail because they do not reflect key socio-ecological interactions that are important drivers of change (Alberti, 2008; Pickett et al., 2008).

1.2. Complexity and Hierarchy in Urban Ecosystems

During the past 15 years, several urban ecology schools have articulated a more integrated approach for the understanding of urban ecosystems (Alberti et al., 2003; Pickett et al., 2001; Grimm et al., 2000). Through conceptual models that embrace a “complex systems” paradigm, scholars from these schools aim to test hypotheses regarding the relationships between human and ecological patterns and human and ecological functions. Although each model varies in levels of integration between systems, each approach conceives of urban ecosystems as dynamic open systems that evolve through feedback loops, non-linear dynamics, and self-organization. Each model also draws on landscape ecology to represent the spatially heterogeneous pattern of built structures and land use activities interspersed with natural land cover. This highly variable landscape emerges from the interactions between socio-economic and bio-physical pattern and processes at multiple spatial and temporal scales (Alberti, 2010).

A key property of complex systems and urban ecosystems is emergence, where complex interactions generate emergent behaviors that are difficult to infer from studying individual components separately (Gunderson & Holling, 2001; Allen & Starr, 1982). Another structural attribute of urban ecosystems is hierarchy. Complex systems are made up of a series of subsystems nested within a larger subsystem. For example, in urban coastal environments, coastal watersheds are considered both an individual ecosystem and composed of smaller watersheds. Each level of the subsystem is understood as semi-autonomous, i.e. each sub-watershed is formed from a set of interacting variables that share similar speeds and geometry (e.g. low order streams, location and density of built infrastructure). Each level interacts with the next higher, coarser, and slower level through the movement of material (e.g. water, energy) or information. Phenomena at each level have their own emergent properties and different levels may be coupled through feedback relationships. To improve our understanding of large-scale environmental change, we must explicitly represent the interactions between local decisions and local scale processes. A key challenge in understanding these dynamics is how the landscape structure in the form of alternative patterns of development emerges from a multitude of human and biophysical interactions across multiple scales to affect ecosystem function. Therefore, scale is key understanding these interactions (Alberti, 2005).

Urban planners and ecologists alike have long theorized that different patterns of urban development effect ecological conditions (Howard, 1989; Jenks, Burton, & Williams, 1996; Lynch, 1981; Sukopp, 1990). Urban ecologists hypothesize that patterns of urbanization control ecosystem dynamics through complex interactions and feedback mechanisms that link urban activities and their spatial organization to land cover and environmental change (Alberti, 2005).

A major objective of empirical studies studying urban ecosystems is to identify underlying mechanisms and interactions that link urban development patterns to ecosystem dynamics. While numerous studies in the past decade have documented the link between urban development and ecological condition (Alberti, 2008; Luck & Wu, 2002), we still know very little about the interactions of urban development that affect ecological dynamics and are relevant to the long-term ecological integrity of a region. One area understudied is the role that infrastructure plays in both the evolution of settlement patterns and in their effect on the environment in urbanizing regions (Alberti, 2010; Monstadt, 2009).

1.3. Infrastructure in Urban Ecosystems

The transformation of cities and the development of human settlements can be linked, in part, to the transformation and transformative power of infrastructure (Neuman & Smith, 2010). Consistent with its Latin pre-fix, *infra*, meaning below, and *structure,* denoting the process of building, the emphasis of infrastructures in cities has focused on the constructed material and networked elements that facilitate the transport of goods and people, the provision of water, the disposal of society's waste, the provision of energy, and the transmission of information within and across communities. The National Research Council (1987) adopted the term "public works infrastructure" to refer to both the functional roles of networked highways, streets, water supply pipes, wastewater management, solid-waste treatment and disposal, telecommunications, electric power generation, and the combined systems these elements comprise (p.4). A more comprehensive understanding of infrastructure spans not only facilities and networked systems but also the operating procedures, management practices, and development policies that interact together with society's demand and the physical world. In summary, infrastructure in cities, (i.e.

urban infrastructure) is defined as a complex system of networked facilities, services and institutions that support land development and human settlements.

Historically, urban infrastructure has played a key role in both abetting urban growth and improving urban conditions for city inhabitants. At the turn of the 19th century, transportation infrastructure in the form of railroads and ports facilitated large-scale rural to urban migrations, vastly changing the relationship between cities and their hinterlands. As populations grew in metropolitan areas, cities exceeded the capacity of natural processes to support the waste of urban households. During an era of urban reforms that swept cities across England, Germany, and the United States, a new model for integrating a network of infrastructure systems produced the progressive Memphis Plan and sanitary sewers in dozens of cities. These connected, gravity-fed piped wastewater systems were instrumental in alleviating foul unsanitary conditions, while also providing early demonstrations of positive relationships among infrastructure, urban landscape structure, and human health (Melosi, 2000). Planned infrastructure became the beacon of the progressive city, linking urban prosperity with infrastructure and physical improvement (Neuman & Smith, 2010). The relationships among infrastructure, city planning, and hygiene remained central to the principles of plan-making in the early 20th century with an emphasis on urban waterways, drainage, water supply, parks, street layout, transportation and railways. However, as Neuman and Smith (2010) trace, the burgeoning planning profession began to distance itself from urban infrastructure in response to a tide of changes in cities including the rise of zoning, an emphasis on administration and the control of private property, as well as the popularization of the single occupancy car. City plans and planners were less occupied with spatial patterns, physical urban form, and infrastructure location and design. The authors argue that the interest of planning professionals and urban scholars in infrastructure waned in deference to other disciplines, but its revival may be key for sustainable urban development given infrastructure's tremendous capital demands, its rapidly deteriorating urban stocks and impacts on the environment (Graham & Marvin, 2002; Neuman & Smith, 2010).

Urban ecology scholars have also called on researchers to disentangle the role of infrastructure in the complex interactions between human and ecological processes in urbanizing regions (Alberti, 2008; Pickett et al., 2008). Cities are understood as highly heterogeneous landscapes made up of a complex pattern of built up and natural patches (Alberti, 2005; Pickett et al., 2001). As a complex and self-organizing system, the urban spatial structure evolves as the result of numerous locally made decisions from top and bottom-up processes and by many adaptive agents (Alberti & Waddell, 2000; Pickett, Cadenasso, et al., 2008). Infrastructure is a defining feature of the urban landscape. However, little is known about the role that infrastructure plays in the dynamics and evolution of urban ecosystems. Urban infrastructure such as roads and drainage networks have been characterized as important human sources of heterogeneity introducing sharp geometries into the urban structure (Alberti, 2005). However, we know very little about the patterns of urban development associated with different infrastructure types. Nor do we understand the ecological trade-offs at different scales accompanying infrastructures. In studying the interactions between human and ecological processes, we need to consider that infrastructure may influence socio-economic and biophysical factors at various levels with important feedbacks. Identifying these underlying mechanisms that link urban patterns to ecosystem function may be key to devising effective strategies that minimize ecological impacts of urbanization.

Few studies have systematically examined alternative wastewater infrastructure systems (centralized and decentralized) and their relationship with human settlement patterns. Only with the exceptions of Walsh et al. (2004) and Harrison et al. (2012) have both infrastructure types been studied, but neither fully explores the relationship of different infrastructures with land use or other land development patterns. In the urban geography and economics literature, there has been some effort to associate wastewater disposal type with patterns of development in relation to externalities such as development costs, the location or timing of development (Speir & Stephenson 2002; Suen 2005), or indicators of sprawl (LaGro, 1998). Most of these studies examine each system separately and none of them evaluate the relationship between wastewater type and landscape structure. An improved understanding of the differential effects of alternative wastewater infrastructures and patterns of urban development on ecosystems requires an investigation of the spatial location and development pattern of wastewater systems using measures that can easily be quantified and that are relevant to planners. Further, in order to examine how each system interacts with landscape structures to alter ecosystem functions, we need more information about how each system relates to patterns of land use and land cover.

1.4. Conceptual Framework Linking Coastal Patterns, Processes, and Wastewater to Near-shore Ecosystem Function

In Figure 1.1, I adapt a conceptual framework developed by Alberti et al. (2003) for studying urban ecosystems to analyze the impacts of coastal patterns and processes on near-shore ecosystem function and human well-being. Changes in land-use, land cover patterns (forest cover, paved surfaces, grass and shrubs) and decisions associated with wastewater infrastructure are driven by both socio-economic (population growth, infrastructure investments, land use policy) and biophysical (topography and climate) factors. These in turn control natural processes, such as runoff and nutrient cycles. As we alter the patterns of the landscape, we also alter our soils, leaving legacies that affect biological processing and ecosystem functions that ultimately support human health and well-being.

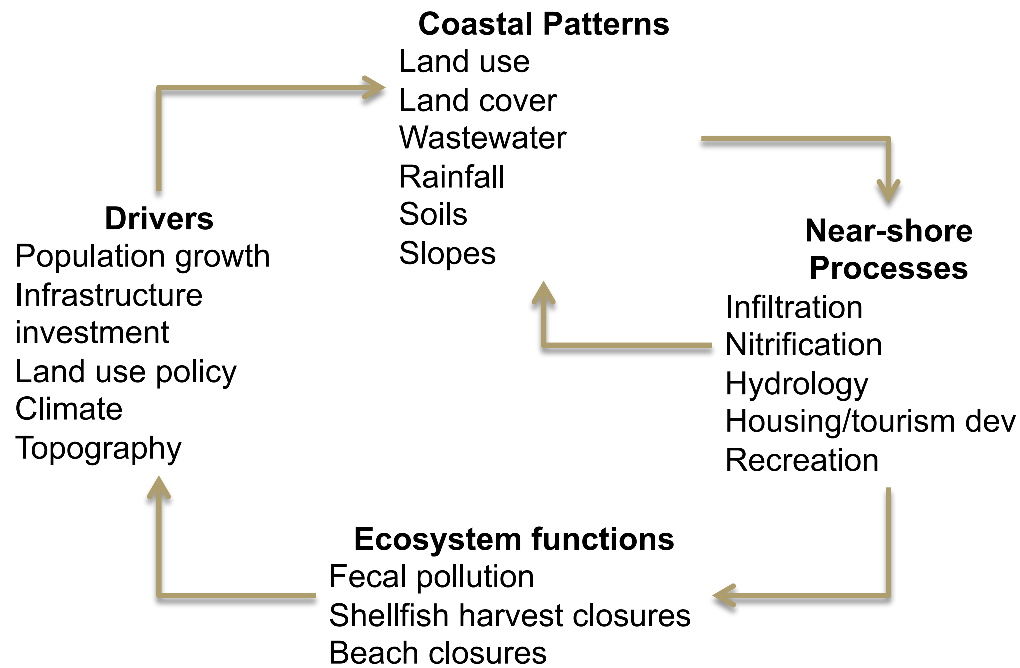


Figure 1.1: Linking coastal patterns to near-shore ecosystem function

1.5. Research Goals

My research aims to expand our understanding of the complex interactions that link human and ecological patterns to human and ecological functions in coastal watersheds in two specific ways: (1) by explicitly studying the spatial arrangements of wastewater infrastructures and their relationship with urban development patterns; and (2) exploring the role that wastewater infrastructures play in mediating the impacts of urbanization on ecosystem functions. In ecology, ecosystem function is defined as the ability of the earth's processes to sustain life over a long period of time. While there are a variety of measures and indices of ecosystem function (for example, nutrient cycles, energy flows, species interactions and primary productivity), for the purpose of my study, I use fecal coliform as an indicator of near-shore ecosystem function, linking upland watershed health to near-shore water quality, human health and well-being.

A second goal of my research is to tease out the role that wastewater infrastructure plays in mediating the impacts of urban development patterns on human health and ecosystem function in coastal systems. Most of the research focusing on the impacts of coastal development on watershed hydrology and coastal water quality emphasize the impact of individual land-based stressors associated with human development and activities. Studies suggest that land use characteristics can have an effect on fecal coliform densities in coastal receiving waters. Studies by Mallin et al. (2000) and Kelsey et al. (2004) point to urban land uses and the percent of impervious cover in a basin as important variables associated with densities of fecal coliform. Past research linking the condition of ecosystems to urbanization is inconclusive about the role that wastewater plays in supporting the needs of coastal communities and the health of aquatic systems (Hatt, Fletcher, Walsh, & Taylor, 2004; Kelsey, Porter, Scott, Neet, & White, 2004; Lipp, Farrah, & Rose, 2001; Mallin, Williams, Esham, & Lowe, 2000; Young & Thackston, 1999; Weiskel & Howes, 1996; National Research Council, 1993). Some research shows both centralized and decentralized systems help alleviate the impacts of urbanization up to a certain density of housing or population (Young & Thackston, 1999; Weiskel & Howes, 1996). Other studies suggest that decentralized wastewater such as septic tanks are a major source of fecal contamination even in rural environments (Hatt et al. 2004; Lipp, Farrah, & Rose 2001). However, we know very little about the ecological effects of wastewater type and the spatial structure of land cover or land use.

These goals to improve our understanding of the complex interactions between human-ecological processes are pursued using the urban ecology framework (Figure 1.1), which provides several critical advancements in the understanding and management of coastal and near-shore ecosystems. First, by more fully integrating humans into coastal ecological research, there is greater potential for establishing relevant ties between wastewater engineering, planning and coastal research. Second, an urban ecology framework explicitly frames the research within a dynamic system where human and natural processes are tightly coupled and trade-offs exist between human and ecological functions. Finally, a fully integrated framework of human and biophysical processes allows researchers to make better predictions and inform policy-makers about how these interactions and ecosystem functions might change under future scenarios. My research applies an urban ecology framework to explore two aspects of human-natural interactions in coastal watersheds: (1) the relationship between wastewater infrastructure and landscape development patterns; and (2) the role of alternative wastewater infrastructures in coastal ecosystems.

1.6. Research Questions

Wastewater infrastructures and technologies are highly engineered systems. They are designed to mimic biogeochemical processes critical for the treatment of human waste. For nearly two centuries advances in wastewater engineering and technologies have greatly improved coastal conditions by mitigating urban sources of pollution (Burian, Nix, Pitt, & Durrans, 2000; National Research Council, 1993). As such, they perform an important function in cities, supporting human settlements at a variety of densities while protecting human health, subsistence practices, cultural resources, as well as key marine ecosystems. There are several wastewater treatment systems and related strategies that have been implemented in the United States. These have been categorized as either centralized, where all wastewater is collected and conveyed to a central plant for treatment and disposal, or decentralized, where the wastewater is treated and disposed of onsite (Burian et al., 2000; Melosi, 2000). Across an urbanizing coast, a variety of wastewater technologies exist from onsite septic systems and cluster septic systems to centralized sewer systems. This makes wastewater and their related disposal and collection systems an excellent object of study for the investigation of urban infrastructure, associated landscape patterns and role in urbanizing coastal areas.

Using an urban ecology approach, I link biophysical and socio-economic factors to ecological conditions in the near-shore environment. Specifically, I study the spatial arrangement of landscape elements and wastewater infrastructure and relate those to indicators of near-shore ecosystem health. I focus on the water quality conditions in near-shore areas for the growing and harvesting of shellfish. Shellfish growing areas are sensitive to contamination from human and animal feces. Since oysters, clams, mussels and other bivalve molluscan shellfish filter plankton and other particles from the shoreline environment, they can accumulate disease-causing pathogens and micro-organisms. As a result, shellfish are commonly implicated in disease outbreaks. Environmental contamination threatens the livelihoods of commercial fishermen and local populations that rely upon shellfish as a major dietary source and use it for customary traditions (Judd et al., 2005; Lipp, Farrah, et al., 2001). This research examines whether the type of wastewater infrastructure mediates the impacts of urban development on near-shore water quality conditions in shellfish growing areas. By focusing on wastewater infrastructure and urban patterns in near-shore watersheds, this study asks three questions:

(1) How are alternative wastewater infrastructures spatially distributed across an urban gradient?

(2) How do wastewater infrastructures relate to land use and land cover patterns?

(3) How does near-shore water quality relate to wastewater infrastructure and urban development patterns?

This research relies on a three-part approach that uses quantitative measures of wastewater patterns, landscape characteristics, and microbial conditions for shellfish growing areas. The first part of the research uses parcel scale measures of spatial patterns of wastewater infrastructure. I assess spatial metrics of two types of wastewater systems – parcels on central sewers and parcels served by onsite septic systems. The second part uses spatial metrics of urban development patterns, including land use patterns and land cover patterns to examine the relationship between wastewater disposal type and surrounding development. The third part combines measures of development patterns and wastewater patterns in near-shore basins to assess how these factors influence water quality in shellfish growing areas.

1.6.1. Research Setting: Puget Sound Near-shore

The Puget Sound near-shore is an ideal setting to study the connections between upland development patterns, wastewater infrastructure and near-shore water quality. While the Puget Sound has experienced some of the highest rates of population growth, the continued vitality of the region is inextricably linked to the health and quality of the marine waters, streams and watersheds. Serious concerns over the decline of the estuary prompted the previous Governor of Washington, Christine Gregoire to enact legislation in 2007 to create the Puget Sound Partnership. The Puget Sound Partnership was created in response to the growing awareness that decades of urban growth across the Seattle metropolitan region were threatening the very sources of it's prosperity. These threats included damage to critical shoreline habitat, the rapid decline in species populations, the closure of shellfish beaches, and the death of fish species due to low-dissolved oxygen levels. In some ways the story of rapid urbanization in the Puget Sound is not unique. The Puget Sound is the second largest estuary in the United States characterized by its unique semi-enclosed, glacial fjord. A rich and biologically diverse estuary, the Puget Sound supports more than 100 species of sea birds, 200 species of fish, 15 marine mammals, hundreds of plant species and thousands of invertebrates (Ruckelshaus & McClure, 2007).

The Puget Sound has over 4,000 km (2,500 miles) of marine shorelines. The majority of these shorelines are coastal bluffs composed of erodible gravel, sand, and clay deposited by glaciers over 15,000 years ago (Shipman, 2008). The shallow near-shore area of the Puget Sound is a critical zone that links terrestrial and freshwater environments to the marine environment. Terrestrial-aquatic exchanges of water, sediment, and nutrients are fundamental processes that support critical ecosystem functions in these areas, such as shellfish production, habitat for marine birds, rearing and migration of Chinook salmon, and many other services. The Puget Sound shorelines also support valuable services to the many communities and individuals that live there and visit the beaches. Harvest of Puget Sound farmed shellfish (clams, mussel, geoduck, oyster, and scallops) has ranged from 3.8 million pounds in 1970 to 11.4 million pounds in 2008 (Northern Economics, Inc., 2010). Shellfish is particularly important to tribal groups and Asian Pacific Island communities whose traditional diets and reliance on subsistence fishing and harvesting involve an intimate connection with the near-shore (Judd et al., 2005). For all of these communities, the importance of maintaining near-shore ecological conditions is critical.

Currently, there are an estimated 4.5 million people living in the surrounding 12 counties of the Puget Sound with roughly 1.5 million of those people living in cities and small towns directly adjacent to Puget Sound waters (WA. Office of Financial Management, 2013). It is projected that population will increase to nearly 5 million people by 2040 in the four most populated counties of the central Puget Sound (King, Snohomish, Pierce, and Kitsap) (Puget Sound Regional Council, 2013). Given estimates of population growth, environmental planners, scientists and citizens face important challenges moving forward: (1) monitoring and assessing the relationship between urban development and near-shore ecosystem conditions; and (2) incorporating information about the trade-offs associated with alternative wastewater infrastructures.

1.6.2. Research Outline

This dissertation research is presented in 5 chapters. Following this introduction, Chapter 2 presents a systematic study of wastewater systems across a gradient of coastal urbanization. In this chapter, I conceptualize a range of wastewater disposal systems from centralized to decentralized systems as a collection of alternative wastewater infrastructures. I hypothesize that patterns of alternative wastewater infrastructures vary with urbanization in complex and non-linear ways. I use spatial measures to characterize centralized versus decentralized wastewater treatment types at the parcel-scale. Chapter 3 builds on this study and examines the relationship between wastewater treatment type and patterns of land use and land cover. I use a logistic regression model to explore the relationships between wastewater treatment types (septics vs. sewers) and urban landscape patterns. The role of alternative wastewater infrastructure in mitigating the impacts of urbanization on shellfish growing areas is investigated in Chapter 4.

Chapter 5 synthesizes the findings on alternative wastewater infrastructures, discusses the implications for urban ecology, and identifies future directions in research.

Chapter 2: Spatial Patterns of Wastewater Infrastructures Across a Gradient of Urbanization: A Study of the Puget Sound Region

ABSTRACT

Wastewater is a leading cause of water contamination in urbanizing coastal regions and a key contributor to the loss of near-shore ecosystem function. Previous studies examining the impacts of urbanization on coastal ecosystems have identified both sewers and septics as leading stressors. However, little is known about the relative impact of wastewater disposal types associated with patterns of urbanization. This article examines patterns of alternative wastewater infrastructures in urbanizing watersheds across a metropolitan coastal region and discusses the implications for environmental land use planning and wastewater management. This study incorporates a landscape scale approach to examine sewage disposal types (sewer and onsite septic systems) across a gradient of urbanization in the Puget Sound Region (WA). Findings from the study show that patterns of wastewater infrastructure represent a complex arrangement of residences on septic and sewer systems particularly in suburban watersheds. This study points to the trade-offs associated with wastewater infrastructure decisions and a basin's level of urbanization, and the implications for coastal ecosystems.

2.1. Introduction

Population growth and land use change are key drivers that alter coastal ecological conditions. Waste from urbanizing areas, as well as urban land use activities are leading contributors to water pollution impacting near-shore ecosystem function. As watersheds and shorelines urbanize, an array of wastewater treatment systems are built to simultaneously support urban development and protect human health by controlling the release of potentially harmful pollutants. For the most part, centralized wastewater infrastructure as an end of pipe solution to many water quality problems has improved coastal water conditions (National Research Council, 1993). However, despite this improvement, non-point sources of pollution rank among the top sources of contamination and are of significant concern with respect to the transport of pathogens into the marine environments (Stewart et al., 2008; Mallin, 2006; Environmental Protection Agency, 2002). The U.S. Environmental Protection Agency (EPA) recognizes both central sewer systems and onsite septic systems as equally important sewage disposal options, particularly across a range of urbanizing environments, each providing cost-effective alternatives to process wastes, protect ecosystems and human health (Environmental Protection Agency 2002).

Evidence from previous studies suggests that sewer systems and onsite septics are both associated with the contamination of coastal and estuarine ecosystems (Holland et al., 2004; Mallin & Esham, 1999; Weiskel & Howes, 1996; National Research Council, 1993). However, the empirical data for understanding how wastewater disposal types and urban development relate to the health of coastal ecosystems are limited. For example, we do not know if there is a link between the sewage system type (i.e., sewers vs. septics), surrounding urban development, and coastal water quality. On a more fundamental level, we know very little about the locational determinants of different sewage disposal types or how they are spatially distributed across urban, suburban or rural environments. Without examining patterns of alternative wastewater infrastructures across a region we cannot assess the cumulative impacts of wastewater disposal associated with urban development and the potential risks of watersheds inability to process wastes. Understanding the spatial determinants of alternative wastewater infrastructures across a region is critical to provide planners and decision makers with the necessary information for managing land use and making wastewater choices in line with regional water quality goals.

In this paper, I analyze and characterize spatial patterns of two alternative wastewater disposal types (sewer vs. septics) across a gradient of urbanization in the Puget Sound region in Washington State. This paper has two primary objectives: (i) to quantify parcel level patterns of alternative wastewater infrastructures; and (ii) assess patterns of alternative wastewater infrastructures in coastal sub-basins across a gradient of urbanization. I discuss how wastewater patterns vary across a large coastal metropolitan region and the implications for environmental land use planning and wastewater management. The overarching goal of this study is to contribute to evidence-based regional land use planning and wastewater management (Krizek, Forysth, & Slotterback, 2009) with an assessment of sewage patterns across the Puget Sound..

2.2. Alternative wastewater infrastructures

The term "alternative wastewater infrastructures" is used in this paper to refer to all wastewater treatment approaches that vary from conventional centralized systems to decentralized onsite septics and cluster systems. The term also entails the collection of all infrastructures found in a region that are involved in processing "wastes" including sewer mains, laterals, pumps, and manholes, as well as septic tanks, drainfields, seepage pits, mounds, and constructed wetlands (Environmental Protection Agency, 2002; Tchobanoglous, Burton, Stensel, & Metcalf & Eddy, 2003). Wastewater collection, treatment, and disposal are three basic components involved in all wastewater treatment systems, and together make up the alternative wastewater infrastructures of a region. These systems have been historically treated separately, even pitted against one another as centralized vs. decentralized, where one wastewater treatment technology is preferred over another based on cost, site conditions, level of development, and environmental impacts (Massoud, Tarhini, & Nasr, 2009; Pinkham, Magliaro, & Kinsley, 2004). In the U.S., this separation is reflected in different regulatory policies for each system with oversight by different managing agencies. For example, central wastewater treatment plants operate under permits regulated by the Water Quality Act (1972) and managed by the EPA, whereas septics are managed by the Department of Health and operate under county health codes. As a result, wastewater issues are treated separately by different planning, engineering, and environmental regulatory communities who focus on separate parts of one system both in practice and scholarship. In this study, alternative wastewater infrastructures intentionally include the assemblage of systems that collect, treat, and dispose of wastewater, including the multitude of agents responsible for managing the disposal systems.

2.3. The need for a systematic assessment of alternative wastewater infrastructure systems

In a 1989 study of the impacts of private sewage systems in Wisconsin, Hanson and Jacobs (1989) describe the lack of a systematic assessment of environmental, aesthetic, and land use impacts of private onsite sewage systems both in Wisconsin and in the United States. A critically limiting factor was the lack of well-organized, statewide sewage databases. Over twenty years later, the literature shows a continued deficiency in statewide or regional level assessments of wastewater treatment systems, private or public, their locations and their impacts. A notable exception is a recent study by Harrison and others (2012) in which the authors describe the spatial pattern of residences on septic and sewer systems across the metropolitan Baltimore region. A major challenge for regulators and policy makers assessing wastewater disposal options for urban development and water quality is the decentralization of rules, plans, and management among multiple state and county institutional actors, as well as local utilities and residential actors. As a result, information regarding the location, age, and maintenance of these systems is diffused and stored in numerous formats including electronic databases and hard copy paper. A first step in understanding the role of alternative wastewater infrastructures in supporting coastal water quality is to develop a systematic assessment of sewage disposal types across a range of urbanization.

2.4. Urbanization and coastal water quality

Coastal areas in the United States and in the world are experiencing some of the highest rates of population growth (Crosset et al., 2004; Small & Cohen, 2004). Rapid urbanization has a dramatic impact on ecosystem health by introducing new sources of pollution (National Research Council, 1993), disrupting hydrological systems (Arnold & Gibbons, 1996; Burton & Pitt, 2001; Leopold, 1968), decreasing critical nursing grounds for fish and shellfish (Emmett et al., 2000), and modifying the nitrogen cycle (Costanza, 1995; Vitousek, 1997). As a result, the increase in urbanization and the human use of shoreline environments are associated with increased incidence of water-borne disease from contact with contaminated water and the consumption of contaminated seafood (Shuval, 2003; Stewart et al., 2008).

Studies examining the relationship between urbanization and coastal water quality are split in identifying key environmental stressors. Some studies have shown that the increase in coastal pollution is associated with an increase in impervious surfaces in sewered watersheds, while others have identified the density of septic systems as the key driver of coastal water contamination (Hatt et al., 2004; Kelsey, Scott, Porter, Thompson, & Webster, 2003; Lipp, Kurz, et al., 2001). These studies underscore the confounding pollution problems caused by urban development including stressors from sewers, septics, and stormwater runoff (National Research Council, 2009). The effects of sewers and stormwater drainage networks can offset the gains achieved in controlling pollution from septics (Hatt, Fletcher, et al., 2004; Walsh, 2004). While such conversions can achieve marked improvements in community sewage treatment, they may facilitate new allied stressors. For example, Young and Thackston (1999) documented higher fecal bacteria concentrations in sewered and densely developed watersheds than in unsewered watersheds with similar levels of development.

2.5. Wastewater disposal types in coastal regions

In many cities of the developed world, the provision of sewers and wastewater treatment plants is often one of the first actions taken to manage pollution in urbanizing catchments. In the United States, treatment plants operate under approved permits to discharge permissible concentrations of pollution into designated receiving waters. Many older cities and suburbs combine stormwater runoff, residential wastes, and industrial wastewater into the same pipe, all to be treated by the sewage treatment plant. During periods of heavy rainfall or snowmelt, the wastewater volume can overwhelm the system and produce what is known as a "Combined Sewer Overflow Event" or a CSO event (Mallin et al., 2000). CSO events can be a significant, although rainfall driven source of pollution. For example, Seattle and King County, with more than 120 combined sewer overflow outfalls, discharge an average of about one billion gallons per year of untreated sewage, stormwater and industrial wastewater into the Puget Sound (Susewind, 2011). Newer suburbs separate their sewer and stormwater pipes. These systems, known as separated sewer-stormwater systems (SSS), collect the residential and industrial wastewater in sewer pipes while run-off from roads, rooftops, and other paved surfaces is collected and diverted into stormwater pipes and drained into receiving waters (Walsh, 2000).

Onsite wastewater treatment systems, also known as onsite septic systems (OSS) serve an important role in protecting human health in watersheds by removing or treating pathogens, nutrients, and Biological Oxygen Demand (BOD) in human waste (NRC, 1993). The EPA estimates that up to 30% of all urban and suburban households in the United States are on a septic system (Environmental Protection Agency, 2002). In a 1997 report to Congress, the EPA reported these systems as a viable and economical option for the treatment of waste at the source and in a decentralized manner (Environmental Protection Agency, 1997a). A conventional onsite septic system consists primarily of a septic tank and a soil absorbing drainage field. Septic tanks settle and remove the settleable solids, while the drainage field partially treats remaining nutrients and pathogens through adsorption, filtration, and infiltration into underlying soils. However, OSS can fail because of poor installation, maintenance, hydraulic over-capacity, pollutant overloading, and/or unsuitable soils (Environmental Protection Agency, 1997a). In addition, they can be located in sensitive areas such as shellfish growing areas or in densities too high to be supported by the assimilative capacities of the soils (EPA 2002). In un-sewered urban areas, overflow from septics may enter surface waters via sub-surface flow, and this pollution will act separately from the effects of urban runoff (Walsh, 2000). Recent published studies link the density of septic systems to bacterial contamination and increased nutrient loads (Hatt et al., 2004; Kelsey et al., 2003; Lipp, Kurz, et al., 2001).

2.6. Spatial pattern of wastewater disposal types

Land use and infrastructure systems are intricately related (Berke, Godschalk, & Kaiser, 2006). However, while the transportation-land use link has been well established (Kelly, 1994), comparatively little attention has been paid to landscape development patterns associated with different sewage disposal types (Curtis et al., 2008). Choices in wastewater infrastructure are driven by patterns of population growth and economic activities, as well as by socio-economic and biophysical constraints (Leung, 2003). These human and natural determinants influence spatial patterns of wastewater types and the landscape-level patterns across a variety of urbanizing environments, from dense urban areas to expansive ex-urban and rural areas.

Figure 2.1 presents a conceptual framework that links the human and natural drivers of wastewater decisions in the Puget Sound to landscape determinants of wastewater types, and to their spatial distribution and pattern. The spatial pattern indicates a site-scale pattern; the parcel's location on an urban to rural gradient and the parcel scale patterns associated with different wastewater disposal types. A landscape determinant refers to the surrounding urban landscape patterns at a neighborhood or sub-watershed scale.

Soils are a key physical constraint on the location and siting of on-site septics, as well as depth to the water table (Berke et al., 2006). Siting conditions are also regulated by local sanitary health codes that constrain residences with septics to particular lot sizes and residential density with codes varying widely across local jurisdictions. As a result, onsite septics are commonly perceived to only serve scattered rural or low-density suburban areas. However, changes in technology might facilitate the installation of septics at higher densities

(Curtis, 2008). In their study examining the influence of urbanization on stream pollutants in the Dandenong Ranges of southern Australia, Hatt et al. (2004) found septic tanks sparse in basins of low and high urban development, but more abundant in the moderately urbanized basins. LaGro (1998) described the landscape morphology of residential areas with onsite septics in Ozaukee County, Wisconsin, within the Milwaukee metropolitan statistical area. The findings report rural residential patches are generally small in area and contribute to the dissection of the rural landscape.

Cost is also a major constraint on the choice of a wastewater type. Because of the cost of sewage, new developments and the subdivision of land with sewers are constrained by site location (Urban Land Institute and Miles 2007). The planning literature indicates that sewer infrastructure costs are sensitive to development patterns (Burchell, 2005; Real Estate Research Corporation., 1974; Speir & Stephenson, 2002; Windsor, 1979). Centralized wastewater systems are understood to better serve urban areas and achieve higher economies of scale in compact urban areas because dispersed patterns require longer sewer mains and can be much more costly to local governments and residents (Burchell, 2005).

Land use policies also constrain the choice in wastewater infrastructure. Different states and regions in the United States have adopted policies that aim to focus development where thereis existing infrastructure (Martin, Pendall, & Fulton, 2002). These policies either mandate it through the use of urban growth boundaries or incentivize it by targeting state spending for public infrastructure, such as sewers within designated areas. For example, in 1995, Washington adopted its Growth Management Act (GMA), that directs all new development within urban growth boundaries to be on a public sewer system. Maryland approved its Priority Funding Area (PFA) program in 1997 to encourage local governments to focus new development within specific PFA areas. The effectiveness of these policies is uncertain. In a recent study of five counties surrounding Baltimore, Maryland, Harrison et al. (2012) found that since the passage of the law, new development with onsite-septics has occurred inside PFAs.

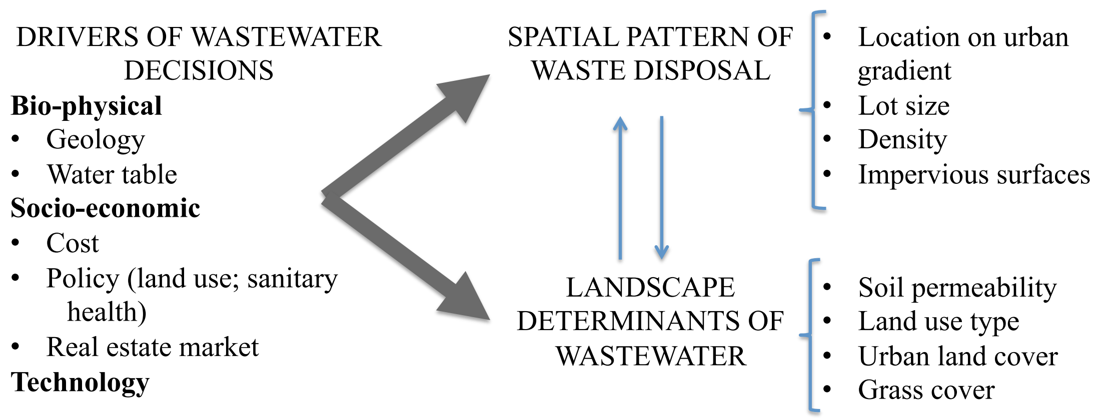


Figure 2.1: Conceptual framework for the spatial pattern of wastewater infrastructure

2.7. Approach

For this study, I posit that the spatial patterns of wastewater infrastructures vary across a gradient of urbanization in complex and non-linear ways. While we might expect the number of parcels on sewer systems to increase linearly with urbanization, the opposite may not hold true for septic systems. Previous research at the watershed scale has shown that the density of septic systems does not decrease with urbanization (Hatt et al. 2004). In addition, while previous studies on urban landscape patterns have shown parcel lot size to decrease with urbanization (Luck & Wu, 2002), this development pattern has not been discriminated by wastewater treatment type. Parcel lot size may vary across the gradient but in different ways;

the cost of sewers constraining lot size while sanitary codes imposes larger lot sizes for septic drainfields. In this study, I hypothesize that parcels on sewers are primarily in urban areas, on small lots and with high amounts of impervious surfaces. I expect septics, on the other hand to be primarily in rural areas as well as in suburban areas with low amounts of impervious surfaces, with varying lot sizes and at varying densities.

To test these hypotheses, I characterize patterns of wastewater infrastructures primarily by their site-level spatial features and analyze these at the basin-scale. I describe how wastewater disposal types are distributed across an urban to rural gradient. I use the parcel as the unit of analysis and quantify spatial patterns of parcels that use two types of wastewater disposal, sewer and onsite septic. I measure parcel lot size, parcel density and percent impervious. This study's primary objective is to describe their spatial pattern and distribution across an urban-rural gradient.

I organize this study around three research questions:

(1) How are alternative wastewater treatment types spatially distributed across a gradient of urbanization?

(2) How does the average parcel lot size of coastal basins vary across a gradient of urbanization, and does it vary differently for parcels on septics vs sewers?

(3) How is the density of onsite septics distributed across a gradient of urbanization?

(4) How do patterns of wastewater infrastructure relate to measures of urbanization?

2.8. Study Area and Data Description

2.8.1. Study Area

I focus this empirical analysis of alternative wastewater infrastructures in seven counties of the Puget Sound basin, including: Snohomish, King, Pierce, Thurston, Kitsap, Mason, and Jefferson counties. Several characteristics of this region make it ideal for this study. The population of the Puget Sound region is among the fastest growing in the United States. The rapidity and scale of urban development and associated wastewater needs has resulted in a mixture of wastewater choices, presenting a unique opportunity to assess their spatial arrangement across the urban landscape.

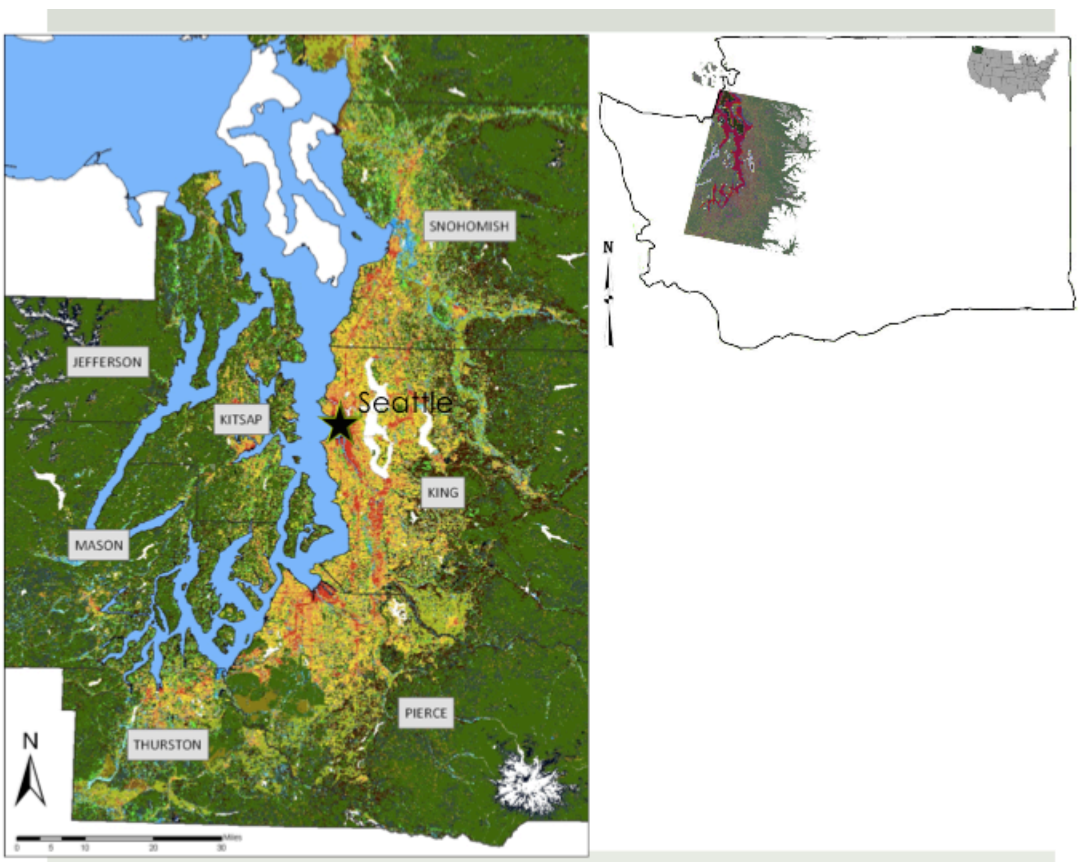


Figure 2.2: Puget Sound, WA. Estuary

The Puget Sound estuary (Figure 2.2) including the Hood Canal is classified as a fjord created as a result of glaciation (Emmett et al., 2000). The large and deep Puget Sound estuarine system encompasses many smaller estuaries that mix saltwater from the Pacific Ocean with fresh water draining from surrounding upland watersheds. The estuary has relatively high annual freshwater inflows and gross primary productivity, understood to contribute toward its high biological activity. Puget Sound shorelines are home to a large diversity of benthic invertebrates, many of which are native, including bivalves, mollusks, and sea urchins. Perhaps most recognized, the Puget Sound estuary plays a vital role in the life history of many salmonid fish species.

Population growth in Washington emulates a national trend. The state is ranked fourth in leading U.S. coastal population growth with most people settling around the shores of the Puget Sound (Crosset et al., 2004). Rapid urbanization around Puget Sound coasts is a leading driver of urban land use development and land cover change. To accommodate these growing populations, coastal areas have rapidly transformed into suburban and urban environments with pollution impacting the health and ecosystem function of the estuarine environment.

2.8.2. Sampling of coastal basins across an urban gradient

I randomly selected 90 coastal basins from a spatial database previously created by the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP). This database contains small-scale coastal basins all draining into the Puget Sound. The data was developed to support research on human induced changes and ecosystem decline along Puget Sound's shoreline (Puget Sound Nearshore Ecosystem Restoration Project, 2009). I stratify the selection of basins by ‘urban’, ‘suburban’, and ‘exurban/rural’ according to a constructed urban-rural gradient. Building on a gradient approach developed by Alberti (2008), I develop a gradient analysis of the Puget Sound that explicitly takes into account urban centers in port-cities, population densities, and slopes. I use GIS data on population from the US Census, slopes from a digital elevation model (DEM) and location of urban centers from the Puget Sound Regional Council. I randomly extract 10,000 data points from each layer and log transformed each layer. Using Principle Components Analysis, I re-express the layers as a linear combination and into an urban-rural index. Eigenvectors from the first component (PC1) were used to construct the index, which retained 74% of the variation of the original data (Table 2.1). I subsequently partition the urban to rural index into four classes ‘urban’, ‘suburban’, ‘exurban/rural’, and ‘wildlands’ based on the distribution of 2006 CCAP Washington State land cover data from NOAA’s Coastal Change Analysis Program (C-CAP) (National Oceanic and Atmospheric Administration, 2006). I selected cut-off points for each gradient class by observing the distribution of land cover across the gradient index values (Figure 2.3). I initially determined the break point between urban and suburban based on the peak in the light urban land cover (blue line in Figure 2.3). However, within this distribution of light urban there is a second small peak in heavy urban land cover. Using high resolution digital orthophotos, I observed high-density land uses such as major office complexes (e.g. Microsoft) classified as suburban. Therefore, I determined the break between urban and suburban based on the second peak of light urban. The break between suburban and rural was determined by the peak of the pasture land cover. And the break between rural and wildlands was determined based on the transition between mixed-forest cover and coniferous forest where wildland represents a dominant alpine coniferous forest. I field checked each break point for accuracy using high-resolution digital orthophotos (1-meter resolution) (United States Department of Agriculture 2006). Each basin was subsequently classified according to one of the gradient classes, where 50% or more of the basin's area was dominated by one of the first three gradient classes (Figure 2.4).

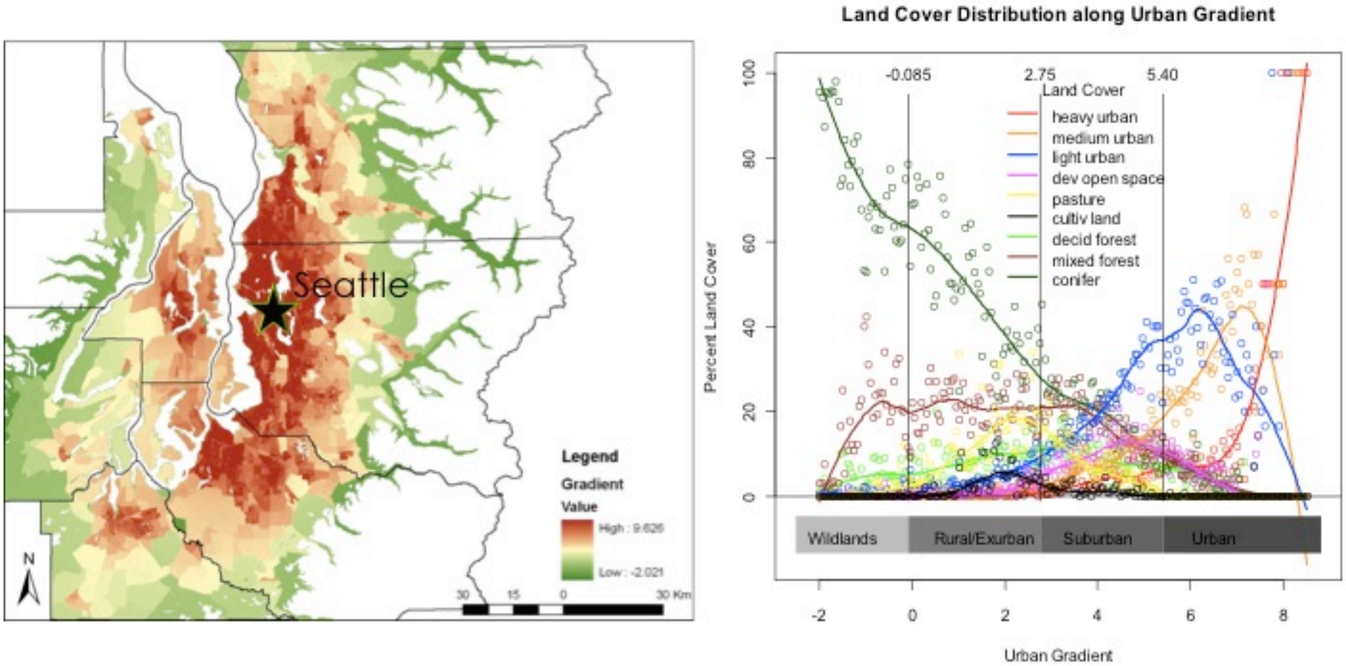


Figure 2.3: Map of the urban gradient with land cover distribution. Gradient index is from 10 (most urban) to -2 (wildlands)

	PC1	PC2	PC3
Population density	**0.91**	-0.06	0.40
Slope	**-0.03**	0.98	0.21
Distance to urban centers	**-0.40**	-0.21	0.89

Table 2.1: Eigenvectors obtained from the covariance matrix.

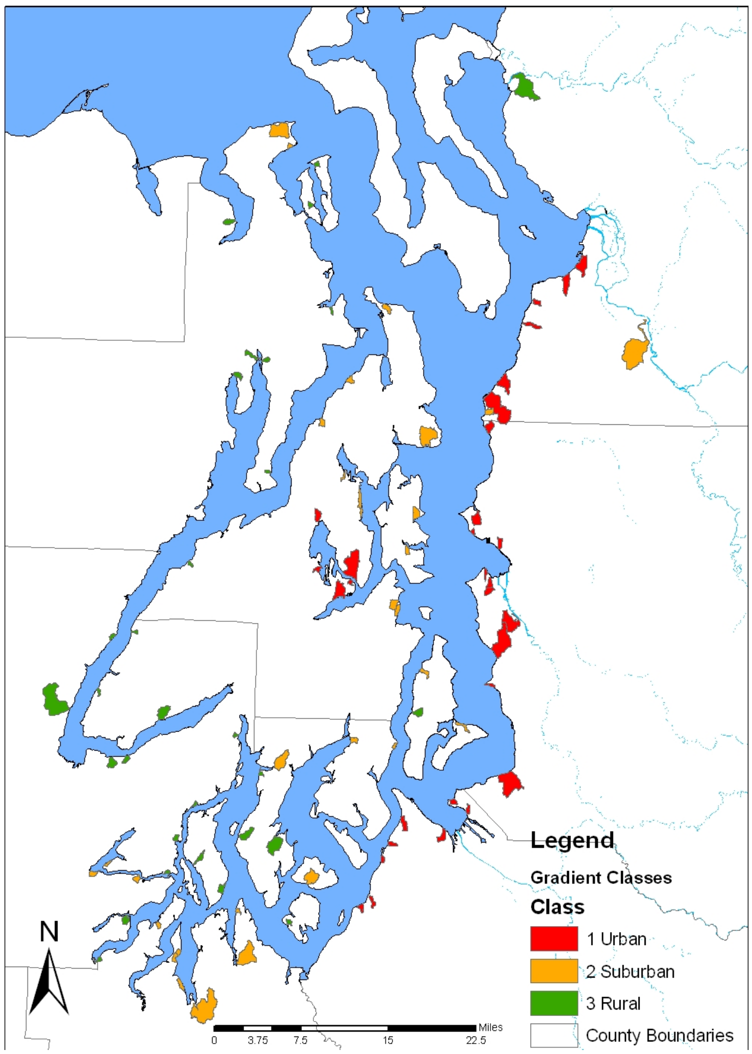


Figure 2.4: Total of 90 Coastal basins classified as urban (30), suburban (30), and rural (30).

2.8.3. Wastewater Disposal Types

To characterize the spatial distribution of wastewater disposal types, I compile data on parcel with onsite septics or hooked up to a central sewer system. I collected the data from numerous county and city agencies including departments of health, tax assessors, public works and city service departments (Table 2.2). Most data on estimated parcels on septic systems originated from local health department permitting records or tax assessor's offices. Data on known parcels hooked up to a sewer system originated from either property assessments by local tax assessor offices or from CAD drawings by local public works departments. The resolution of the data ranged from point address locations, sewer line locations to parcel level. To generate a map of estimated parcels on either a septic system or sewer system, all data were converted to parcel polygon maps where estimated locations were geo-mapped using ESRI's ArcGIS 9.3 software and associated with the tax assessor's parcel information using a common parcel Id number. Data about wastewater with address or point locations were intersected with parcel polygon data. Data with sewer line information were buffered by 50 feet and intersected with all parcels except with 'Undeveloped' parcel land uses. I used data about wastewater locations from several sources to triangulate and estimate locations. All estimated locations were spatially joined with the Washington State Parcel Database and associated with land use development types (Rogers, Cooke, & McLaughlin, 2010). The geo-referenced dataset is a compilation of all county tax assessor parcel databases into one unified database. The parcel data characterizes current land uses with 90 land use classes. I collapsed these land uses into 11 general land use classes and assigned each parcel on a wastewater disposal type with a land use type.

Table 2.2: County data sources of sewer and septic location information

County	Disposal Type	Department	Data Sources for location estimations	Resolution	Extent	Year
King	Septics	Dept. of Natural Resources and Parks	County Health "As Builts" database with parcel identifier	parcel	County	2010
	Septics	Dept. of Assessments	Assessor's Parcel property information	parcel	County	2012
	Sewers	Dept. of Assessments	Assessor's Parcel property information	parcel	County	2012
Snohomish	Septics	Surface Water Management	Tax Assessor and Health Department	parcel	County	2010
	Sewers	County Assessor's Office	Appraiser's of property	parcel	County	2011
Pierce	Septics	Dept. of Health	Health department, property sales, inspection reports	point locations	County, unincorporated	2010
	Septics	Tacoma Public Works	Access database with estimated property addresses from distance from sewer mains, sewer bills, smoke test and permit records	property location	Tacoma	2012
	Sewers	Pierce GIS Services	Sewer mains and private lines; sewer basins	sewer lines	County, unincorporated	2012
	Sewers	Tacoma Public Works	Sewer mains and private lines CAD data	sewer lines	Tacoma	2012
Thurston	Septic	Thurston GeoData Center	Tax Assessor property information	parcel	County, unincorporated	2011
	Sewer	Thurston GeoData Center	Tax Assessor property information	parcel	County, unincorporated	2011
	Septic	City of Olympia	City Public Works	parcel	City of Olympia	2010
	Sewer	City of Olympia	City Public Works	parcel & sewer lines	City of Olympia	2010
Kitsap	Septic	Kitsap County Health District	Department Access database of permit and inspection records	parcel	County	2010
	Sewer	Kitsap County Wastewater	Sewer permits database	Parcel	County	2010
Mason	Septic	County GIS Department	County GIS Database	Parcel	County	2010
	Sewer	County GIS Department	CAD Sewer lines	Sewer lines	Allyn & Belfair	2010
Jefferson	Septic	Jefferson County Central GIS Services	Permitting data from Jefferson Environmental Health	Parcel	County	2010
	Septic	City of Port Townsend	City database of known septics	Parcel	City of Port Townsend	2011
	Sewer	City of Port Townsend	Sewer mains	Parcel	City of Port Townsend	2011

2.9. Basin Analysis

2.9.1. Wastewater pattern metrics

I computed and assessed five pattern variables at the sub-basin scale using GIS across an urban to rural gradient (Table 2.3). Four measures are pattern variables associated with wastewater treatment: Count of parcels on a wastewater type (the sum of all parcels on either a septic system, sewer system, or no system), proportion of parcels on a wastewater type (the total number of parcels on a septic or sewer system divided by the sum of parcels on a wastewater type), parcel lot size (area of lot), and the kernel density of parcels on a septic system. One metric, percent impervious is a measure of urbanization. The percent area covered by impervious surfaces is strongly correlated with population density and a well-documented environmental indicator (Arnold & Gibbons, 1996; Brabec, Schulte, & Richards, 2002; Leopold, 1968). As such, the metric is a useful measure of urban development. I extracted an impervious layer from NOAA C-CAP 2006 classified land cover data (National Oceanic and Atmospheric Administration, 2006). The total number of parcels on a wastewater type was summed within each of the 90 sample basins. The proportion of parcels in a basin on a wastewater treatment type was calculated to determine the relative dominance of the wastewater type in the basin. The mean parcel lot size across basins was calculated for parcels on one of the treatment systems (septic/sewer) or on none. The density of parcels on a septic system within each sub-basin was calculated using a kernel density function. Five basins contained parcels without any wastewater treatment.

Table 2.3: Summary of basin wastewater metrics

Basin Metric	*Rational*
Mean Count of parcels on a wastewater type	Assess how the number of parcels on a wastewater type varies across an urban gradient.
Proportion of total number of parcels in the basin on a wastewater treatment type	Determine relative dominance of a wastewater type within the basin.
Average parcel-lot size	Lot size is a constraining factor for both sewer and septic system.
Kernel density of parcels on septic	Proxy for density of septic systems. Density of septics may be an important stressor on the near-shore.
% Impervious	Measure of urbanization

2.9.2. Land use patterns

At the landscape level, sample basins contain a range of different land uses (Figure 2.5a). On average, just under 70% of their area is dominated, by single-family residences and undeveloped lands. While the Puget Sound coastal region is rapidly developing, the coastal shoreline still contains many areas that have not yet been developed. Among the parcels identified as on a wastewater disposal type, a more uneven distribution of land uses is evident (Figure 2.5b). Within each sample basin, I calculated the proportion of parcels on a septic system and the proportion of parcels connected to a sewer system across the 11 land uses. A majority of parcels within sample basins on a wastewater disposal type (on site or sewer) is 'Residential' (87%). The remaining parcels with wastewater services are classified as 'Undeveloped' (5%), 'Services' (including government and educational) (2.8%), 'Trade' (including retail) (1.8%),'Transport/Utilities' (1%), 'Recreation' (1%).

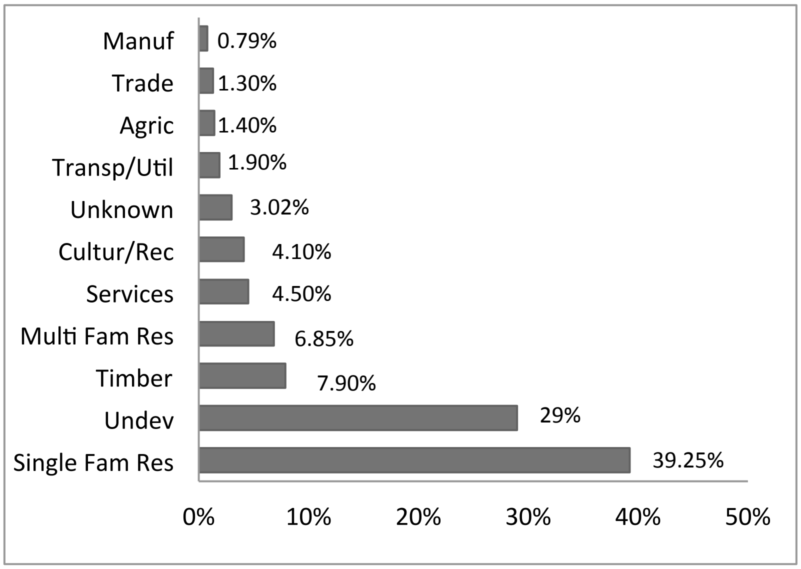


Figure 2.5a: Proportion of land use across all parcels in sample basins

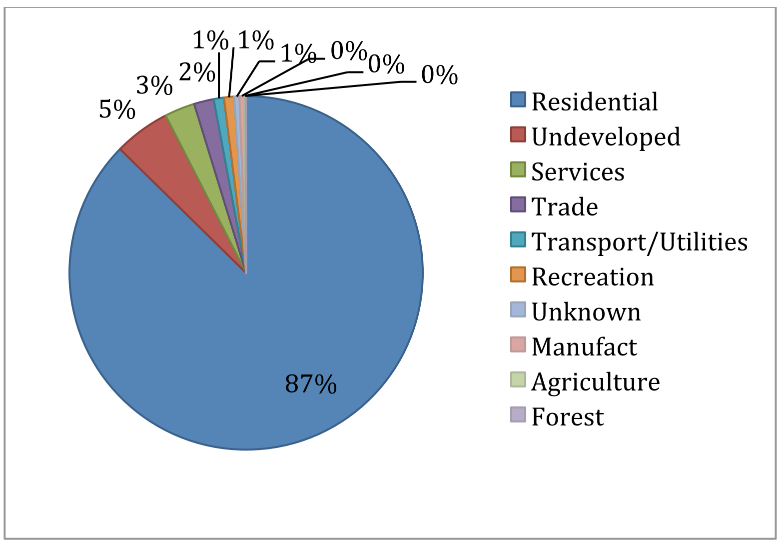


Figure 2.5b: Land use attributes of known parcels in sample basins on septic or sewer

Because the majority of parcels on a wastewater type are dominated by residential development, I extract the residential sample parcels for further analysis. I use several non-parametric tests to assess differences across groups. The Kruskall-Wallis rank sum test allows the assessment of group differences without assuming a normal distribution. In addition, I use ANOVA and scatterplots to examine differences in basin patterns and check for relationships with measures of urbanization. The mean count of parcels on wastewater and the mean percent imperviousness were log transformed to account for normality assumptions.

2.10. Results

The majority of residential parcels in the Puget Sound are hooked up to a central sewer system (>85%) with the remaining residences using a septic system to process household wastes. An overwhelming majority (>95%) of residential households hooked up to the sewer system are located in the most urban portion of the coastal urban gradient. The remaining coastal urban residences use onsite septics. By contrast, an estimated 38 percent of suburban coastal residences use onsite septics to process their household wastes. Rural households (>94% of rural parcels) mostly use septic systems.

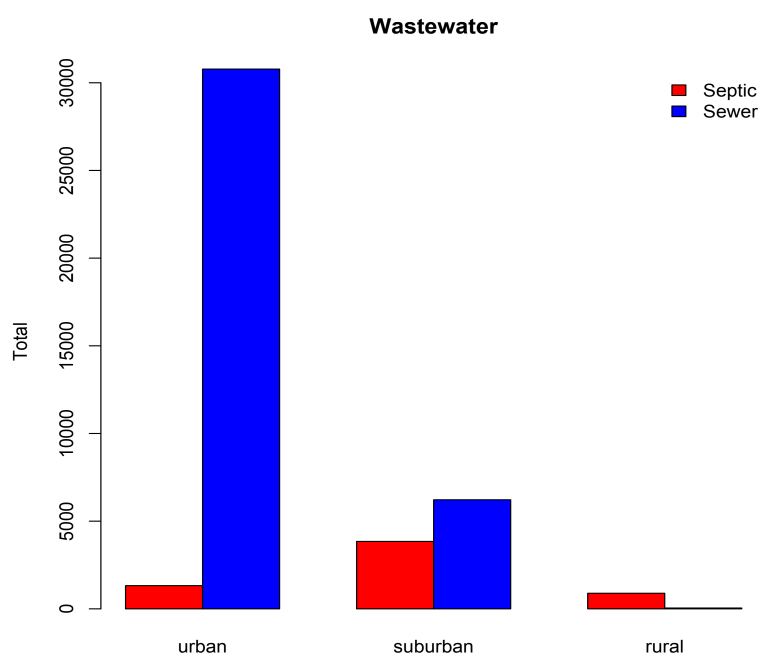


Figure 2.6: Count of parcels on a wastewater treatment type

Table 2.4: Count of parcels on a wastewater treatment type

	Urban	Suburban	Rural		Total
Septic *(n)*	1323 (4%)	3845 (38%)	889 (94%)		6057 (13.5%)
Sewer *(n)*	32305 (96%)	6220 (61%)	47 (6%)		38572 (86%)
Total *(n)*	33628	10065	936		44629

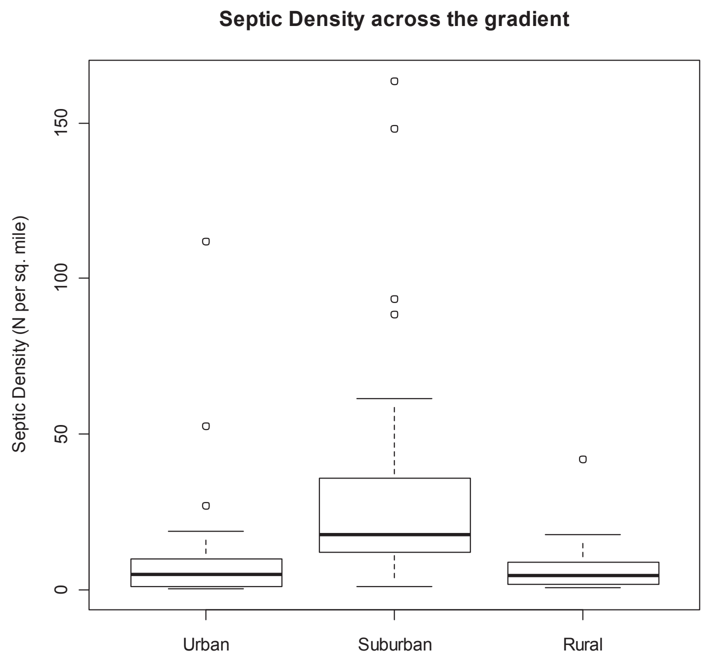


Figure 2.7: Density of parcels on septic systems across the urban gradient

The total number of parcels on a wastewater treatment type across the three urban gradient classes decreases with distance from the urban core (Figure 2.6). This is not surprising, as we would expect the total count of parcels to decrease from urban to rural communities. However, when the data is partitioned between parcels on septics and parcels on sewers, the parcel count on sewer decreases from urban to rural, whereas, the parcel count of septics is largest in suburban basins (n=3845), followed by urban basins (n=1323), and rural (n=889) (Table 2.4).

The density of parcels on a septic system displays a similar trend across the urban to rural gradient (Figure 2.7). The density of septics is higher, on average, in suburban basins (35±40 parcels/mi^2) compared to urban basins (10±22 parcels/mi^2) and rural basins (7±8 parcels/mi^2). Results from a one-way ANOVA revealed the density of parcels on septics differed significantly among all gradient classes, $F(2, 76) = 15.7, p=<0.001$.

Table 2.5: Average parcel lot sizes

	Urban			**Suburban**			**Rural**		
	ALL	SEPTIC	SEWERS	ALL	SEPTIC	SEWERS	ALL	SEPTIC	SEWERS
Mean (acre)	0.32	0.50	0.30	0.94	1.37	0.32	4.07	2.8	0.30
Sd	1.5	2.8	1.21	4.22	3.07	2.10	9.72	5.3	0.20

The average lot size of all coastal basins regardless of wastewater treatment increases with the urban gradient (Table 2.5). However, the average lot size of sewered parcels is 0.3 acres across all urban, suburban, and rural basins. There is some variation in sewered lot sizes within urban basins (0.3 ± 1.21 acres) and suburban basins (0.3 ± 2.10 acres), but very little in rural basins (0.3 ± 0.2 acres). The average lot size of parcels on a septic system is smallest on average in urban basins (0.5 ± 2.8 acres) compared with suburban (1.37± 3.07 acres) and rural basins (2.8±5.3 acres).

Impervious surfaces across all sample basins ranged between 0 – 70% imperviousness. An average of 40% of urban basin areas were covered by impervious surfaces (Figure 2.8). Suburban basins contain a more moderate average of roughly 15% imperviousness. Rural basins contained low percentages of imperviousness, ranging mostly in the single digits. Basins dominated by sewers showed relatively high amounts of impervious surfaces across all urban, suburban and rural sub-basins (>20%). The amount of impervious surfaces observed in urban sub-basins dominated by septic systems was in the range of 23-45% imperviousness whereas suburban basins contained just under 10% imperviousness. A positive, although weak, relationship was observed between the log of percent impervious and the log of parcels on a wastewater treatment type (r^2=0.34, p<0.001). When the data is partitioned across the urban gradient, this relationship is stronger in the suburban basins (r^2=0.56, p<0.001). This suggests that in suburban basins, as the count of parcels on wastewater treatment (sewer or septic) increases so does the amount of impervious surfaces. This relationship was not observed for the data partitioned by basins dominated by septics vs. sewers.

(a) %Impervious all parcels (b) %Impervious sewer parcels (c) %Impervious septic parcels

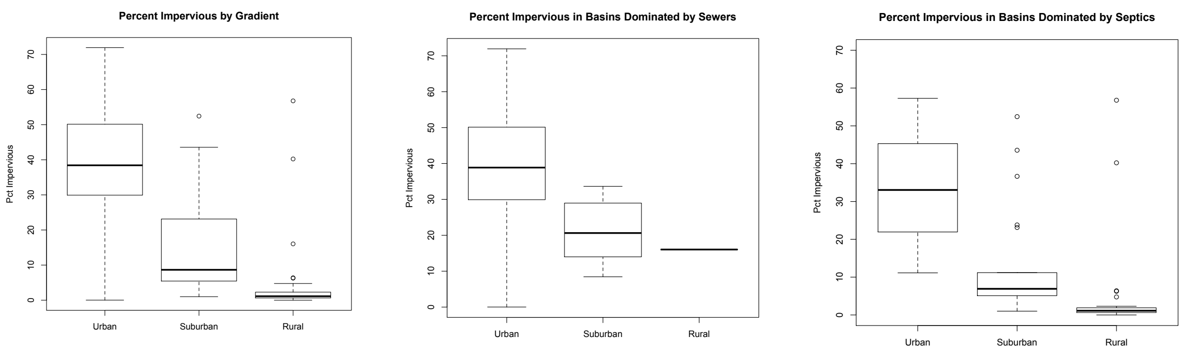
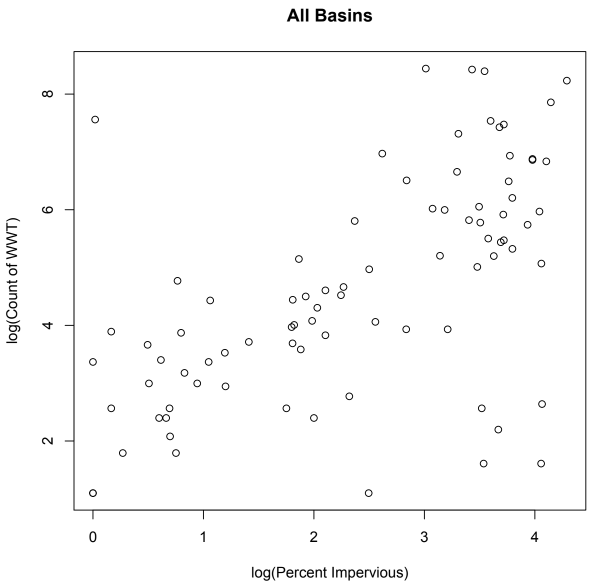
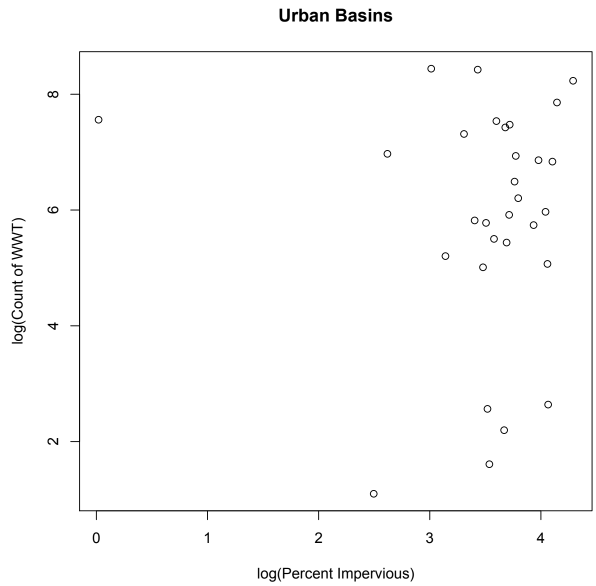


Figure 2.8: (a) Percent impervious across all basins; (b) and (c): Percent impervious partitioned by sewer and septic dominated parcels.

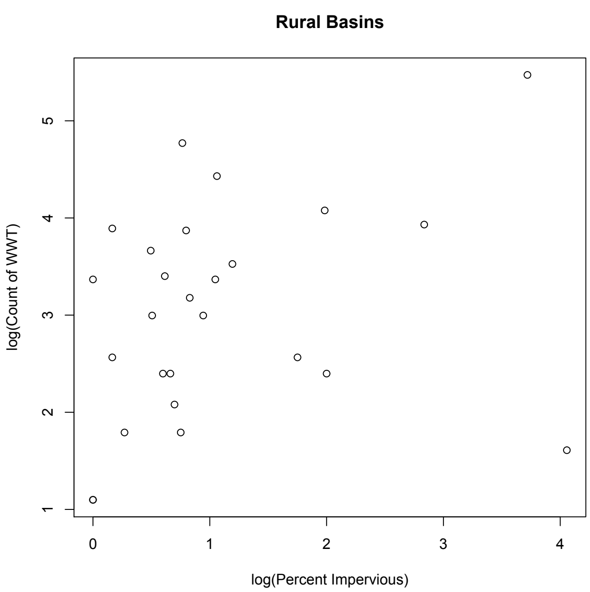
(a) Log (WWT) and log (impervious) across **ALL** basins



(b) Log (WWT) and log (impervious) across **URBAN** basins



(c) Log (WWT) and log (impervious) across **RURAL** basins



(d) Log (WWT) and log (impervious) across **SUBURB** basins

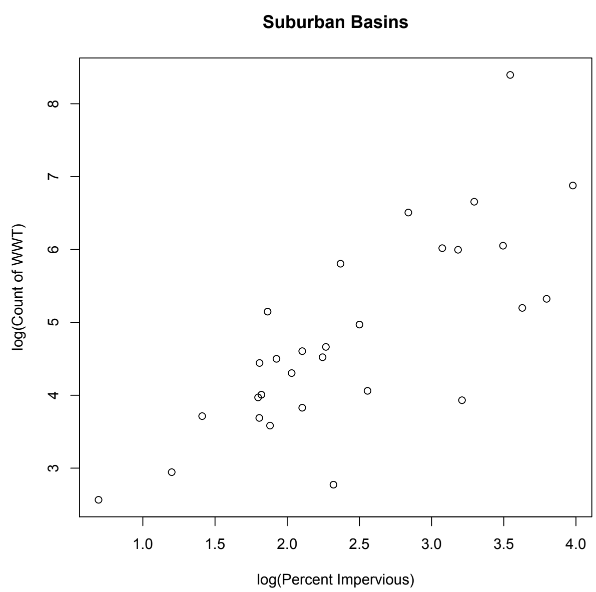


Figure 2.9: Log of parcels on (WWT) and log (imperviousness) in (a) ALL basins, (b) URBAN basins, (c) RURAL basins, (d) SUBURBAN coastal basins

2.11. Discussion

As wastewater treatment is a vital service for processing household wastes, it is not surprising to find residential land uses dominating the overwhelming majority of parcels on a wastewater disposal system. In the Puget Sound, coastal urban basins dominate parcels hooked up to a central sewer system. As the Puget Sound coast urbanizes, the provision of sewers is an important service to households in these areas. This is reflected in the Washington State Growth Management Act (GMA), which mandates all new development within designated urban growth boundaries to be connected to a public sewer system. Yet, there remain some residential parcels on septic systems in these same heavily urbanized coastal environments. These parcels may be older and represent households previously on septic systems before sewers were installed, although without additional information on the dates of when the homes were built, it is difficult to know for sure.

While parcel lot size seems to be heavily influenced by the urban gradient regardless of wastewater treatment type, lot sizes of sewered parcels are smaller at just under a third of an acre than parcels on septics whether in urban, suburban or rural coastal environments. Lot sizes may be constrained to this small size because communities that can afford to hook up to sewers may do so by dividing their few developed parcels to smaller lot sizes.

Cost of infrastructure may be the most constraining factor for lot sizes particularly for installing and extending sewer mains. Berke and others (2006) assert that the cost of sewers is a critical limiting factor of urban development. Smaller lot sizes in sewered parcels may also reflect the development constraints placed by the Washington State Growth Management Act (GMA).

However, establishing the role of the GMA on wastewater infrastructure would require more research to determine whether these areas are composed of new residences built after the act was established in 1995.

In this study, the majority of residential parcels with onsite septics were in the suburban portion of the urban gradient. Parcels on septic systems are also in relative abundance in urban basins. The mean lot sizes of these parcels on septics are also, on average, smaller in urban and suburban coastal basins than in rural basins. In the past, local health departments in the Puget Sound were responsible for specifying minimum lot areas. Only recently has the state of Washington codified minimum lot areas for single-family residences (Washington Administrative Code (WAC) Chapter 246-272A, 2007). Despite these local health codes for residences on septic systems, other urban processes, such as the real estate market and the GMA, may be at play controlling development with septics. As Harrison et al. (2012) documents, in Maryland, since the passage of the state's smart growth legislation in 1997, development in urban areas that use septic tanks has grown significantly, and in some cases inside priority sewer funding areas (Harrison et al., 2012). This may be of concern since septic systems require sizeable leach fields for the microbial processing of wastes. In the Washington Administrative Code, the minimum lot area is specified between 0.3 – 0.5 acres depending on the soil type for residences on a public water supply system (WAC., Chapter 246-272A, 2007). Results from this study found urban and suburban residential parcels on septics with less than the minimum lot area. For residences in coastal sub-basins, if the lot size is too small for the hydraulic capacity of the leach field, particularly if the underlying soils are less permeable, the result may be treatment failure. This is of particular concern when households are located within close proximity to sensitive coastal ecosystems such as shellfish.

The amount of impervious surfaces covering a watershed sub-basin is a key indicator of urban development impacts on receiving waters (Arnold & Gibbons, 1996). Urban and suburban sub-basins contained the highest percentages of impervious surfaces, however, the relative dominance of sewers vs. on site septics influences the distributions and amounts. This study found moderately high average amounts of impervious surfaces (between 20%-40%) across all urban, suburban, and rural sub-basins on sewers. By contrast, urban sub-basins on septics contained markedly higher average amounts of impervious surfaces (>35%), an amount that some studies have shown to impact coastal ecosystem functions and services (Holland et al. 2004; Mallin et al. 2000). Their suburban and rural counterparts displayed much lower averages of impervious surfaces. This result points to the possibility that while impervious surfaces may be a leading urban stressor to Puget Sound ecosystems, and hence important indicator of coastal ecosystem function, it's relationship to coastal water quality may not be linear. The choice in wastewater infrastructure may influence the differential effects of impervious surfaces across the urban gradient. In this study, impervious surfaces may be the leading stressor in the most urbanized sub-basins regardless of wastewater disposal type. Although, the high amounts of impervious surfaces in urban basins dominated by septics may further exacerbate the effects of small urban lot sizes.

A unimodal relationship was observed between the density of parcels on septics and the urban gradient. In other words, suburban residential parcels on septic systems were not only more abundant, they were also located in higher densities. Septics in urban basins and rural basins were observed to be sparser, on average, than septics in suburban basins. Several suburban coastal basins had some of the highest densities of septics. In addition, within these suburban basins, the density of septics was highest in the moderately impervious basins (between 10-30% imperviousness). This finding is consistent with the results from the study by Hatt and others (2004). In this study, suburban sub-basins with the highest septic tank density also had the highest concentrations of nitrogen in streams. The U.S. EPA recognizes the relative negative impacts of septic systems based on how densely packed they are, and classifies them as low, medium, and high risk to groundwater contamination due to the number of septics in an area (EPA, 1977). In 1977, the EPA determined low risk to be <3.8 septic systems per kilometer squared, medium risk to be 3.8–15.4 systems per kilometer squared, and high-risk to be >15.4 systems per kilometer squared. In this study, localized densities of septic systems within areas with moderately high amounts of impervious surfaces may be hot spots of nutrient loads via sub-surface and surface flows (Walsh, 2004).

In the United States, more people live and work in the suburbs than in cities. "Sprawl", a well-recognized form of development has been characterized as a scattered, low-density development of residential housing and commercial strips (Ewing, 1997; Jabareen, 2006). This type of development has been associated with more driving, poor water quality, more carbon emissions, and other environmental costs. The link between wastewater treatment type and urban growth has reinvigorated the attention of recent researchers and policy-makers who view septic systems as encouraging development on the urban fringe in the form of leap-frog development particularly in the wake of growth management policies (Harrison et al., 2012; Newburn &

Berck, 2011a). Heimlich and Anderson (2001) state that suburban and ex-urban development represents two fundamentally different types of urban development based on wastewater disposal: suburbia relies on access to sewer and small residential lots, rural development on the other hand, is not constrained by collective sewers and therefore relies on septic systems and hence larger lot sizes (Heimlich & Anderson, 2001). This study seems to contradict this assumption as it shows that septic systems are distributed across a variety of urban, suburban, and rural environments, however are most abundant in moderately urbanized suburban coastal basins.

Another motivating factor for controlling septic systems along with sprawl is to better manage coastal water quality. The key assumption to this proposal is that septic systems are associated with more coastal pollution than sewers. While a number of studies have shown the detrimental effects of poorly sited and designed septic systems or at too high in densities for the assimilative capacity of coastal ecosystems, sewer systems have also been shown to negatively impact coastal water quality (Mallin, Johnson, & Ensign, 2008; Hatt et al., 2004; Young & Thackston, 1999). There is a lack of studies that compare the influence of both sewers and septics on indicators of coastal water quality and ecosystems. Their residential patterns, environmental stressors and related effluents generated are not homogenous. While the impacts of septics in urbanizing basins may primarily impact sub-surface loads because of the reduction of biological processing, sewers primarily affect direct discharge loads. Furthermore, the impacts of septics are diffuse in nature and may increase slowly over time, happening without notice. Sewer-related impacts are much more concentrated, punctual and quickly recognized.

2.12. Conclusion

This study found two wastewater disposal types (sewers and septics) distributed across a range of urbanizing coastal basins in the Puget Sound. Urbanization involves a complex set of urban and environmental processes including the subdivision of residential land, the conversion of land uses, and the replacement of vegetation with impervious surfaces (Alberti, 2008). This study found unique residential development patterns associated with septic and sewer systems across a range of coastal environments. Sub-basins in rural and ex-urban Puget Sound coastal areas are dominated by large-lot parcels on septic systems with low amounts of imperviousness. By contrast, sewers and small lot parcels dominate coastal urban basins.

The pattern of sewage disposal in suburban coastal sub-basins of the Puget Sound is more complex possibly representing a landscape in flux. While sewers still dominate in total numbers, the relative abundance and density of septic systems is significantly higher in this portion of the urban gradient. Imperviousness, a well-studied indicator of environmental quality increases linearly only in suburban basins as the total number of parcels on either wastewater treatment type increases. The highest amounts of impervious surfaces are found in sub-basins dominated by sewers regardless of where they are on the urban gradient. Suburban sub-basins dominated by septics, on the other hand, contain much lower amounts of impervious surfaces compared to their urban counter-parts.

Development pressures in suburban coastal basins add new subdivisions by converting entire landscapes, reducing lots sizes and adding impervious surfaces to accommodate new roads, houses, and other paved uses. The density of septic systems is highest in coastal suburban basins. This study does not implicate septic systems per-se as the leading stressor to Puget Sound coastal ecosystems, but rather cautions that the suburban pattern of sewage disposal may be reaching a threshold for its ability to process wastes with detrimental effects to ecosystem functions (Environmental Protection Agency, 1997a; Gold et al., 2001). Due to the multiple processes driving urbanization, sewage disposal patterns emerge undetected until coastal ecological conditions reach a threshold of degradation signaling a need to switch to a central sewer system. While concerns for the quality of the coastal environment calls into question whether to extend sewer mains, replace decentralized septic systems and/or build a new wastewater treatment plant, the tradeoffs are not well understood. High proportions of urban land cover associated with sewers may replace grass, forest and other land cover associated with septic systems. However, more research is needed to explore the relationship between sewage disposal types, their landscape determinants and coastal ecosystem health.

Chapter 3: Relationship between urban landscape patterns and wastewater infrastructure in the Puget Sound Region, WA

Abstract

Land use patterns and urban infrastructure are intricately linked (Berke et al., 2006). However, while the relationship between transportation and patterns of urban development has been extensively studied (Kelly, 1994), relatively little attention has been paid to wastewater treatment systems. This paper explores the connection between urban landscape patterns and wastewater infrastructure. Urban landscape patterns relate to the composition and configuration of land use and land cover. In this paper I develop a logistic regression model to examine the relationship between wastewater treatment types (septics vs. sewers) and patterns of land use and land cover across urbanizing sub-basins in the Puget Sound. I find significant associations between wastewater treatment type and the composition and configuration of land cover. On average, Puget Sound basins with 20% of their area or more covered by urban land cover are more likely to be dominated by parcels on a sewer system.

3.1. Introduction

Coastal environments are attractive places for people to live, play, work, navigate and experience nature. They are also highly productive areas for local communities and economies. Fish and shellfish harvesting, for example, are key activities that support subsistence and income generation for coastal residents. A thriving marine-based commercial industry supports jobs, generates revenue, draws tourists, and supplies an important local source of protein. Marine harvest is also a significant part of the local culture and heritage of a place, and provides a meaningful spiritual basis for local tribes. As a result, coastal areas in the United States and in the world are experiencing some of the highest rates of population growth (Crosset et al., 2004;

Small & Cohen, 2004; Wilson & Fischetti, 2010) and urban land expansion (Seto et al., 2011). Watersheds draining into West Coast estuaries, particularly the Puget Sound, also have some of the highest population densities in the country (Emmett et al., 2000). The provision of critical urban services like wastewater infrastructure allows for the transformation of these lands for human use while protecting environmental health. At the same time, landscape change associated with coastal development is of great concern to the health of coastal ecosystems. The conversion and fragmentation of coastal landscapes are understood to increase sources of pollution (National Research Council, 1993), alter hydrological processes (Booth & Jackson, 1997), reduce habitat for native fish and shellfish (Emmett et al., 2000), and modify biogeochemical processes (Vitousek, 1997). As a result, important resources and species critical to coastal communities are increasingly at risk of decline and extinction.

Alarming rates of coastal ecosystem decline have triggered a number of watershed studies examining the impacts of coastal development patterns on downstream microbial water quality and ecosystem health. The outcomes of these studies are mixed and unresolved. Some studies show that the increase in coastal pollution is associated with an increase in the amount of urban land uses and impervious surfaces in sewered and non-sewered watersheds (Hatt et al., 2004; Walsh, 2000; Young & Thackston, 1999). Other studies identify the density of septic systems as the key environmental stressor (Lipp et al. 2001; Kelsey et al. 2003).

In many parts of the world and the United States, households depend upon septic tanks to treat and dispose of wastewater. In a 1997 Response to Congress, the United States Environmental Protection Agency (US EPA) concluded that “[a]dequately managed decentralized wastewater systems are a cost-effective and long-term option for meeting public health and water quality goals, particularly in less densely populated areas." However, research has shown that failing and poorly maintained septic systems may be an important and chronic pollutant source to surface water, groundwater, and nearshore waters (Withers, Jordan, May, Jarvie, & Deal, 2013). Dense areas with septic systems may also present a high risk of contamination to receiving coastal waters and consequently impact public health (Lipp, Farrah, et al., 2001).

3.2. Patterns of urban development and wastewater infrastructure

The study of land use change (also referred to as "land change science") is concerned with the study of land use and land cover, and their change over space and time (Seto & Shepherd, 2009; Turner, Lambin, & Reenberg, 2008). The use of remotely sensed data together with biophysical and socio-demographic information allows researchers to observe and measure changes in land, understand these changes as a coupled human-natural system, and model spatial dynamics of land use change effects on ecosystem function (Pickett et al., 2011). Urban landscapes exhibit unique spatial patterns involving a diversity of human activities and natural habitats. Urban ecologists conceptualize changes in patterns of land use (e.g. housing densities) and land cover (e.g. amount of vegetated areas) as both a *driver* and a *product* of socioeconomic interactions (e.g. real-estate) and biophysical (e.g. hydrology) processes (Pickett et al., 2008; Alberti et al., 2003; Grimm et al., 2000). These interactions are understood to be dynamic, nonlinear, and often path-dependent, implying that present and future patterns of land use are determined by past and present outcomes. The urban landscape is represented as a dynamic mosaic of patches that form, develop, and disappear across space and time in response to human and biophysical drivers (Cadenasso & Pickett, 2008; Wu & David, 2002).

In the past decade, the relationship between patterns of urbanization and environmental conditions has emerged as an important research topic in urban planning (Alberti, 1999; Guhathakurta & Gober, 2010; Jabareen, 2006). Attention has grown around the structure of the landscape, form of the built environment, patterns of land use and types of land cover. Numerous arguments are made around the most appropriate and beneficial patterns of development mostly focusing on the influence on automobile use, human health, resource consumption, the preservation of agricultural lands and ecosystems. Urban planning practice also now considers the environmental implications of present and future development patterns, usually in models expresses as ‘smart growth’ and ‘new urbanism,’ which tend to emphasize higher building densities and mixed land uses at the metropolitan scale. They also focus on street pattern, block size and form, lot configuration, park layouts and public spaces, and the use of impervious surfaces at the neighborhood and block scale. However, there remains considerable disagreement over the environmental performance of such pattern attributes (Alberti, 1999; Jabareen, 2006).

Historically, planners and urban theorists have sought to understand how cities evolve and why they develop with particular settlement patterns (Geddes, 1915, Mumford, 1961, Lynch, 1981). In the past several decades, the role of infrastructure has gained prominence as an important factor influencing the mix, density and shape of development. Once in place, urban infrastructures, can be difficult to reverse, leading to a path dependency with regard to urban growth, resource consumption patterns, and human activities associated with urban land use. Following the completion of the interstate highway system and the suburbanization of cities, the land use-transportation connection has received particular attention from researchers and practitioners alike (Waddell, 2011). Theories of the relationship between land use and infrastructure are understood as a two-way interaction (Alberti 2008; Seto & Shepherd 2009). Patterns of land use, such as the present mixture and density shape infrastructure-related patterns and infrastructure decisions influence land use patterns. For example, in the realm of transportation, high residential density is known to have an inverse relationship with automobile distance travel, although this effect may only be marginal (Ewing and Cuervo, 2010). Conversely, choices in transportation systems influence patterns of urban development (Waddell, 2011). While the majority of studies examining the link between infrastructure and patterns of land use focus on the influence of transportation systems, wastewater infrastructure has received far less attention (Curtis et al., 2008).

In the United States, there are an estimated 21,594 municipal wastewater treatment plants that provide wastewater collection, treatment, and disposal service to 226.4 million people, roughly 75% of the population (US EPA, 2008a). The US EPA reports that according to the American Household Survey, nearly one in four households depends on individual septic systems (also referred to as an onsite systems) or small community cluster systems to treat their waste (US EPA, 2008b). Septic systems are implemented in up to 30% of all U.S. residential households, and up to 50% of all residences in suburban and rural towns (EPA, 2002). In some states such as Massachusetts, these numbers are much higher. In Chapter 2, I reported that most residential wastewater (over 85% of households) in the Puget Sound is serviced by a central sewer system. However, I also found over 43% of all suburban and rural households served by onsite septic systems.

Population growth and the expansion of urban areas increase the demand for wastewater services, in the form of both collection sewer systems and onsite septic systems. Site conditions and cost are the primary factors influencing use and implementation of each treatment type. Theoretically, onsite septic systems can only be used in suitable soils and at low densities and are generally found in scattered rural or low-density suburban areas (Berke et al., 2006). Sewer systems, on the other hand, are assumed to only serve urban land uses because they achieve higher economies of scale in high-density developments (Hanley & Hopkins, 2007).

Several studies focus on the relationship between central sewer systems on land use and development patterns. These studies either associate the location and timing of development with sewer expansion (Hanley & Hopkins, 2007) or the economic costs of providing public infrastructure in relation with different patterns of development (Burchell, 2005; Speir & Stephenson, 2002; Real Estate Research Corporation, 1974). Housing or population density is commonly used to characterize development patterns. In a recent study, Suen (2005) measured the physical characteristics of residential development patterns in urban areas of Iowa at the block scale and related them to infrastructure cost. This study finds that the cost of providing infrastructure decreases with an elongated rectangular shape of parcels, providing more efficient parcel shapes in subdivisions (Suen, 2005).

Other studies examine decentralized wastewater treatment type and their location at a county or sub-county scale (Harrison et al., 2012; Curtis, 2008; Hatt et al., 2004; LaGro, 1998). These studies focus primarily on the link between decentralized, private wastewater systems with residential development patterns. In the most comprehensive landscape study to date, LaGro

(1998) describes the landscape context of rural residential areas on three types of private sewage systems (conventional septics, alternative systems, and holding tanks) within the Milwaukee metropolitan statistical area. In this study, residential patches on these systems are generally small in area (48% of patches on 1.0 ha or smaller) with straight edges that form shapes ranging from complex polygons to simple rectangle and squares. By measuring fractal dimensions of residential patches and the percentage of the patch perimeter adjacent to other land uses, LaGro (1998) shows that rural residential development contributes to the "dissection" and "perforation" of the surrounding agricultural landscape.

Siting constraints, sanitary health codes, and zoning are thought to restrict septic systems to sparse rural environments (Berke et al., 2006). Curtis et al. (2008) observed in Wilson County, Tennessee decentralized systems on recently converted land to residential land use on formerly zoned agricultural lands. The design, siting, and implementation of conventional onsite systems have traditionally been based on prescriptive requirements (Environmental Protection Agency, 2010). Most counties and jurisdictions specify the type and depth of soils that must be present. They might also require mandatory setbacks from high water tables, wells, surface waters, and sensitive ecosystems. However, different states and counties codify siting constraints within local health regulations. In the previous chapter, I found in a sample of urban and suburban coastal basins, parcels on central sewer systems have significantly smaller residential lots than parcels with onsite septics. Onsite septics are associated with larger lots. This is not surprising as septic drain-fields require additional lot space to process waste. Sanitary health codes regulate minimum lot areas for parcels on septics. Technological advances such as sand filters and mound systems, however, have been shown to discount siting constraints, allowing septics to be installed anywhere (Curtis, 2008; Hanson, Jacobs, Ham, Leonard, & Simmons, 1989; LaGro Jr, 1998).

Hatt and others (2004) examine the relationship between the density of septic tanks and urbanization in coastal basins of the Dandenong Ranges in Southern Australia. In their study, they find septic tanks to be sparse in basins with low and high amounts of impervious surfaces, but in higher density in basins with moderate amounts of urban land cover. Similarly, in the previous chapter, I found higher densities of septic systems in suburban coastal basins of the Puget Sound compared to urban and rural basins. In another recent study in Maryland, Harrison et al. (2012) associate wastewater treatment type with the age of development across four counties with varying amounts of urbanization both inside and outside of designated urban growth boundaries. They find that despite the implementation of the state's Preferred Funding Area (PFA) policy that targets sewers in designated urban areas, newer developments in these areas were more likely to be on septic systems.

Table 3.1: Summary of theory and empirical studies linking land use to wastewater type

Direction	**Factor**	**Effect on**	**Theory and observed impacts**	**References**
Land use -> wastewater	Location	Type	Distance from urban centers influences wastewater type	Burke et. al., 2006
	Cost	Type	Higher density leads to lower cost for sewers	Real Estate Research Corp., 1974; Suen et al., 2005; Speir and Stephenson, 2008.
	Land use policy	Type	Urban land uses constrained to sewers	Harrison et al., 2012
wastewater -> land use	Site conditions	Development density	Low residential development	La Gro, 1998; Curtis et al., 2008
		Location	Poor site conditions influence location	Burke et al., 2006.
	Technology	Development densities	Technological advances for septics can increase density	Hanson et al., 1989; Curtis et al., 2008
	Residential	Landscape configuration	Septics lead to dissection of ag lands	La Gro, 1998

3.3. Study Objectives and Approach

Previous studies generally focus on either the distribution of wastewater infrastructure or the cost of providing wastewater infrastructure in relation to different patterns of development at the metropolitan or community level. Land use, residential parcel density, or residential parcel shape is used to characterize development patterns associated with a wastewater type (LaGro, 1998; Hatt et al., 2004; Suen, 2005). Density of septic systems or the geographic location of a residential parcel on a wastewater type is commonly used to measure wastewater provision (Hatt et al., 2004; Curtis, 2008; Harrison et al., 2012). This study builds on previous research on landscape development patterns and the previous chapter on patterns of alternative wastewater infrastructures in the Puget Sound region to test and generate hypotheses about the relationships between land use and land cover composition and configuration, and wastewater infrastructure.

For some time, watersheds have been used by landscape ecologists, urban ecologists, hydrologists and more recently by urban planners as an integrative tool and a scale of analysis for examining information about biological, physical, and social attributes of different patches across a landscape (Alberti, 2008; Pickett et al., 2011). This study identifies micro-scale spatial patterns of land use, land cover, and wastewater infrastructure aggregated at the sub-basin watershed scale. I examine associations among land use - land cover attributes and wastewater infrastructure across an urban-rural gradient. The urban-rural gradient paradigm is used as an organizing framework (M. McDonnell et al., 1997) for examining complex urban spatial structure and for describing varying states of urbanization, such as 'urban', 'suburban', and 'rural'. As such, it is an effective approach for assessing patterns of urban development and their associated wastewater infrastructures.

I posit that the dominance of a particular wastewater type in urbanizing coastal watersheds is significantly influenced by three pattern variables: land use composition, land cover composition, and landscape configuration. I distinguish between land use attributes associated with the use of land parcels (e.g. single-family residential use, undeveloped use) and land cover representing the type of cover on the land (e.g. urban land cover, forest cover). Landscape configuration is characterized by the aggregation of urban land cover and fragmentation of vegetation. I differentiate two alternative types of wastewater infrastructure, onsite septic systems and central sewer systems, as dominating coastal areas at the sub-basin scale.
This study focuses on three specific questions:

1) How do patterns of land use vary across basins dominated by different wastewater treatment types?
2) How do patterns of land cover composition and configuration vary across basins dominated by different wastewater treatment types?
3) Are there development patterns associated with the dominance of a wastewater disposal type (septics vs. sewers) in coastal sub-watersheds?

The overarching hypothesis of this study is that a particular type of wastewater infrastructure in coastal watersheds is significantly associated with the composition and configuration of land use and land cover. Specifically, I define three hypotheses:

1) Basins dominated by sewers contain significantly larger proportions of urban land use and land cover than basins dominated by septics.
2) Basins dominated by septics contain significantly larger proportions of forest cover than basins dominated by sewers.
3) The likelihood that a wastewater treatment type (septic vs. sewer) dominates a coastal watershed is associated with the basin's land use and land cover composition and configuration.

I have developed a three-step analytical process: (1) based upon previous studies of nearshore conditions in the Puget Sound and the literature on development patterns and wastewater infrastructure, I select landscape metrics that I hypothesize are relevant to a wastewater treatment type; (2) I use non-parametric t-tests and stepwise logistic regression to reduce the set of variables to those associated with basins dominated by septic vs. sewer; and (3) I use statistics and develop a model to test my hypotheses.

3.4. Study Methods

To carry out this study, I develop an explanatory model of 85 coastal basins in the Puget Sound region dominated by two different wastewater treatment types: septic systems and sewer systems. I use a landscape analysis approach developed within landscape ecology to quantify human settlement patterns in terms of land use composition, land cover composition, and land cover configuration. I combine remote-sensing data and parcel-scale land use and wastewater information and use cross-sectional analyses to compare different watersheds across a gradient of urban development. First I identify and classify 90 sub-basins as dominated by septics (OSS) vs. sewers (CWW) across a previously developed coastal urban to rural gradient. I then characterize and quantify land use and land cover pattern metrics in the coastal basins. I examine differences in landscape patterns between basins dominated by two wastewater types (OSS vs. CWW). I use binomial logistic regression to associate wastewater treatment type with landscape patterns of land use and land cover.

For the purposes of this study, I chose a local (neighborhood) basin scale for my focal of analysis. The local near-shore basin serves as an appropriate scale of analysis because it allows me to define basins dominated by a wastewater treatment type and analyze the patch-work of land uses and land covers. This scale also allows me to capture as much variation as possible in wastewater dominance across an urban-rural gradient. On average, basins were 1.69 km^2 (420 acres) but some basins were as small as 0.3 km^2 (74 acres) and as large as 10.8 km^2 (2668 acres). Urban, suburban and rural basins do not have significantly different areas ($\chi^2 = 5.8$, df= 2, p<0.06). I used a stratified random sampling scheme to select 90 coastal sub-basins across seven urban to rural counties. Sub-basins were previously classified according to the urban-rural gradient developed in Chapter 2.

I also previously identified parcels as being served by either onsite septics or central sewers. From this parcel-level data, I identified basins as being dominated by either septics or sewers based on the proportion of parcels within the basin that are on septics vs. sewers (Figure 3.1). If the proportion of parcels on one of the wastewater treatment types within the basin (septic vs. sewer) was over 51%, then the basin was categorized as being dominated by that type. Table 3.2 shows the number of basins dominated by septics (OSS) or sewer (CWW) systems and their distribution across urban, suburban and rural environments. A total of 47 basins from the sample are dominated by septic systems (OSS) and 38 basins are dominated by sewers (CWW). Five basins did not contain any parcels on a wastewater treatment type.

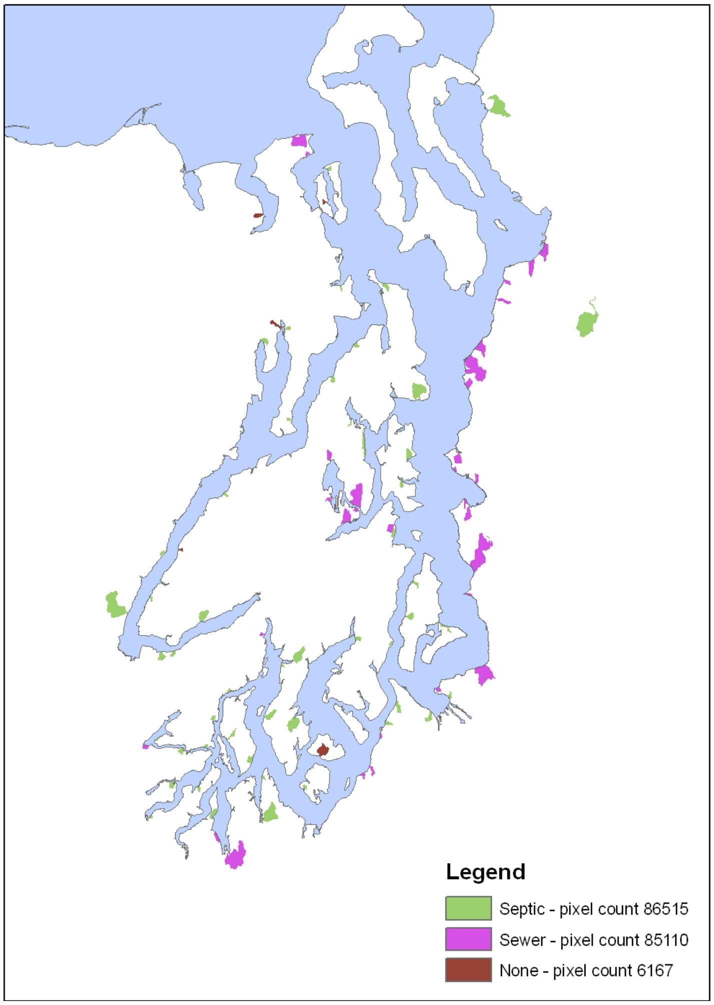


Figure 3.1: Distribution of 90 coastal basins in Puget Sound classified by wastewater treatment dominance

Table 3.2: Count and total area of basins dominated by wastewater disposal type across urban gradient

Basins on WWT	Urban	Suburban	Rural	total
Septics (OSS)	0	22	25	47
Sewers (CWW)	30	7	1	38
No WWT	0	1	4	5
Area in Km^2				
Min	0.35	0.31	0.30	0.3
Max	8.0	10.8	9.1	10.8
Average (± st. dev)	1.94±2.15	1.87±2.6	1.26±1.96	1.69±2.24

3.4.1. Data Sources

Information regarding land use data was obtained from the Washington State Parcels database version 2009 (Rogers et al., 2010). The parcels database is a vector based geo-referenced dataset of polygons from county tax assessor's data received from Washington counties between May – November 2009, and processed by the Rural Technology Initiative at the University of Washington. Each county dataset was normalized by removing geometry duplicates by flattening and aggregating parcels. During the process, each parcel was given a unique identifier also used to link to a tax assessor database including land use, assessor's land price. The assessor data represent current land uses in each basin, as compared to zoning, which refers to potential future uses. Each county's coding system is calibrated and re-coded to create a unified system of 90 land use classes. The 90 classes were collapsed into 11 basic land use codes.

The land cover data were derived from the 2006 Washington State land cover dataset from NOAA's Coastal Change Analysis Program (C-CAP). The Coastal Change Analysis Program produces a nationally standardized database of land cover and land change information for coastal regions of the United States (National Oceanic and Atmospheric Administration, 2006). The NOAA C-CAP dataset comprises of 22 different land cover types classified from Landsat Thematic Mapper (TM) satellite imagery. These landcover types were identified as important indicators of coastal ecosystems. These classes include 4 classes of developed land with varying intensities based on the amount of land area that is covered by concrete, asphalt, constructed materials, vegetation or other cover. Vegetated crop areas are classified by two agricultural crop types, three forest land types, grasslands, and scrub lands. There are four barren land types, six wetland types, and open water or submerged land types. The resolution of the data is limited by the Landsat data, which have a 30-meter pixel size (spatial resolution). Therefore, the minimum mapping unit is 30 meters x 30 meters (900 square meters, or 0.22 acres). The accuracy of the data meets an 85% overall accuracy specification, meaning 85 out 100 times we expect the C-CAP classification to be correct (National Oceanic and Atmospheric Administration, 2006).

3.4.2. Landscape Metrics

I use several measures of landscape composition and configuration (Table 3.3). I measure land use composition by the percent of land use. Land use patterns in the basins were compiled and quantified by intersecting parcel data from the Washington State Parcels database using ESRI's ArcGIS 10.0 software to determine the percentages of land use types in each basin. I measure land cover composition by the percent of a land cover type within each basin as classified by the C-CAP land cover map. I use FRAGSTATs software v.4.2 to estimate two land cover configuration metrics: the *Aggregation Index* (AI) and *Clumpy Index* (CL) (McGarigal & Marks, 1995). These two configuration metrics are similar in that they are both measures of dispersion however they are calculated differently. AI equals the number of similarly classed neighboring pixels (or "like adjacencies") involving the corresponding class, divided by the maximum possible number of like adjacencies of that class. CL is a similar index except that it separates the configuration of the class from the area of the class. As such, CL provides an index of the fragmentation of a land cover type that is not confounded by changes in its area. The Clumpy Index (CL) equals the proportional deviation of the proportion of like adjacencies involving the corresponding land cover class from that expected under a spatially random distribution.

Table 3.3: Landscape Metrics

Variable Name	**Equation**	**units**
Percentage of Land Use Percentage of total basin area comprised of a land use type	$PLAND = P_i = \frac{\sum_{j=1}^{n} a_{ij}}{A}(100)$	%
Percentage of Land Cover Percentage of total basin area comprised of a land cover type	$PLAND = P_i = \frac{\sum_{j=1}^{n} a_{ij}}{A}(100)$	%
Aggregation Index Equals the number of like adjacencies involving the corresponding land cover class, divided by the maximum possible number of like adjacencies involving the corresponding class; multiplied by 100.	$AI = \left[\frac{g_{ii}}{\max \rightarrow g_{ii}}\right](100)$	Index measured from 0 – 100
Clumpy Index Equals the proportional deviation of the proportion of like adjacencies involving the corresponding land cover class from that expected under a spatially random distribution.	$Given\ G_i = \left[\frac{g_u}{(\sum_{k=1}^{m} g_u) - \min e_i}\right]$ $CLUMPY = \left[\begin{matrix} \frac{G_i - P_i}{P_i} for\ G_i < P_i \ \&\ P_i < .5, else \\ \frac{G_i - P_i}{1 - P_i} \end{matrix}\right]$	Index measured from -1 to 1

3.4.3. Land use

Sample basins dominated by wastewater treatment contain primarily single-family residences and undeveloped land uses. Figure 3.2 shows the distribution of land uses in total amount of percent land area across all sample basins. Land uses within sub-basins show differences in average amounts across basins dominated by either sewers or sewers (Figure 3.3).

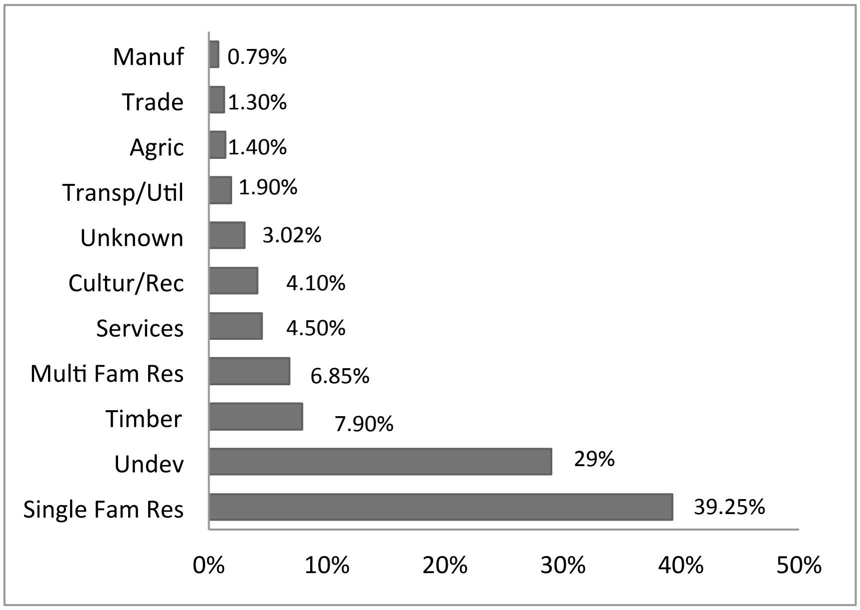


Figure 3.2: Proportion of land use across all sample basins

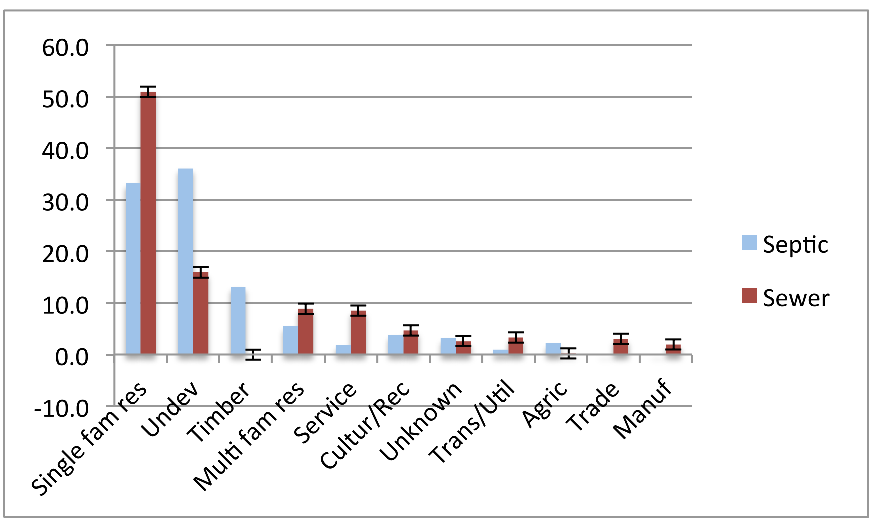


Figure 3.3: Proportion of land use across basins dominated by either septic or sewer

3.4.4. Land cover

On average, roughly 25 % of all sample basin areas were covered by evergreen forest. There is, however a substantial amount of variation in evergreen forest across all basins (Table 3.4). Another 24% of basin areas are comprised of deciduous forest, mixed forest, and scrub/shrub. Urban developed land cover makes up roughly 45% of all basin areas. According to NOAA's C-CAP classification, just over 50% of this class is made up of low urban and open space land cover (National Oceanic and Atmospheric Administration, 2006). This class represents low intensity developed areas containing a mixture of vegetation and constructed paved materials, with constructed materials making up 49 percent or less of the total area. The remaining urban land cover is comprised of heavily developed landscape with most of the areas (over 50%) covered by asphalt, pavement, and concrete materials. The 'High' and 'Medium' developed land typically includes heavily built-up areas with large constructed surfaces in urban, suburban and rural areas with single-family and multi-family housing. Grassland, described as dominated by graminoid or herbaceous vegetation with generally greater than 80 %of total vegetation, covers an average of 2% of basin areas. These areas are not subject to intensive management (NOAA, 2006). Cultivated lands and pasture lands together make up less than 1 percent of basin areas, on average.

Table 3.5 shows the distribution of mean percent land cover across basins classified as dominated by septic system or sewer system. Basins dominated by septics contain between 3% - 88% of evergreen forest with an average of over 40%. Sewered basins contain between 0% - 43% with an average of 6.5%. There are also significant differences in averages of deciduous and mixed forests between basins dominated by septic versus sewers, however the ranges are not as dramatic (a range of roughly 35% for septics vs 23% for sewers). Similarly, urban development dominates these basins differently. On average, basins dominated by septics contain just over 1% of high and medium urban land cover. Sewers on the other hand, contain on average nearly 9% and 28%, respectively. Septic dominated basins contain more low urban land cover, with an average of nearly 9% and nearly 5% developed open space. Basins dominated by sewers also contain a high amount of low urban land cover. On average, they contain nearly 34% of low urban land cover, and among all basins dominated by sewers, the basin with the minimum amount of low urban land cover is 15%.

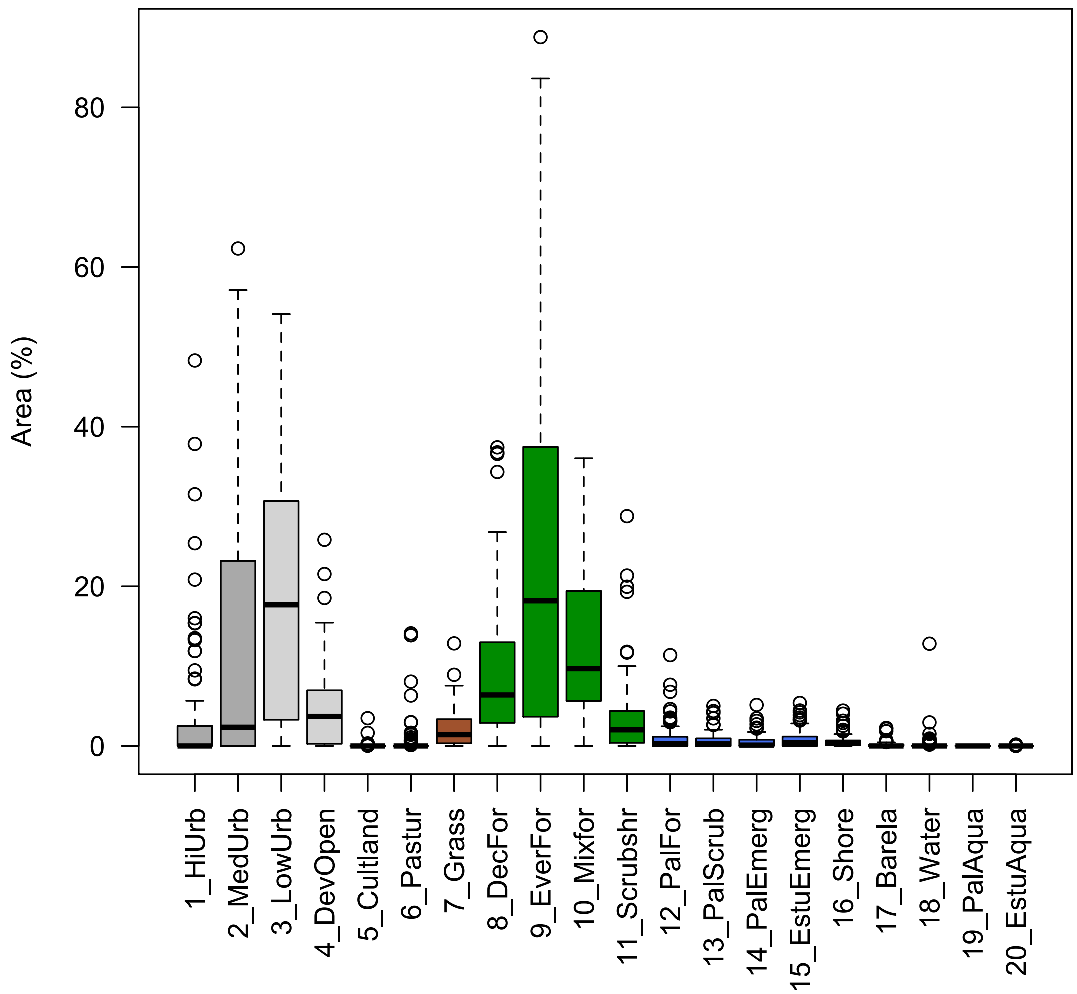


Figure 3.4: Box plots of percent land cover across all 85 sample basins

Table 3.4: Mean percent land cover across sample basins

LC CLASS	Land Cover Description	Mean %LC	St. dev. %LC
1	Developed - High Urban	3.98	8.71
2	Developed - Medium Urban	13.01	16.17
3	Developed - Low Urban	20.09	16.61
4	Developed- Open Space	4.85	5.37
5	Cultivated land	0.07	0.42
6	Pasture/Hay	0.86	2.79
7	Grassland	2.23	2.45
8	Deciduous forest	9.26	9.11
9	Evergreen forest	25.38	26.38
10	Mixed forest	12.48	9.25
11	Scrub/shrub	3.60	5.04
12	Palustrine forested wetland	1.03	1.86
13	Palustrine Scrub/shrub	0.70	1.08
14	Palustrine Emergent wetland	0.53	0.90
15	Estuarine Emergent wetland	0.88	1.21
16	Unconsolidated shore	0.59	0.85
17	Bare Land	0.17	0.41
18	Open Water	0.28	1.43
19	Palustrine Aquatic Bed	0.00	0.00
20	Estuarine Aquatic Bed	0.00	0.02

Table 3.5: Mean percent land cover across sample basins dominated by septics or sewers

	Septic, *n=47*				Sewer, *n=38*			
	mean	**sd**	**min**	**max**	**mean**	**Sd**	**min**	**max**
Developed - High Urban	0.14	0.64	0	4.31	8.74	11.39	0	48.29
Developed - Medium Urban	1.06	2.61	0	13.58	27.8	13.39	1.59	62.32
Developed - Low Urban	8.87	10.25	0	52.15	33.97	11.74	15.27	54.1
Developed- Open Space	4.78	6.79	0	25.83	4.93	2.85	0.28	10.65
Cultivated land	0.12	0.56	0	3.48	0	0.01	0	0.04
Pasture/Hay	1.43	3.64	0	14.11	0.15	0.54	0	2.99
Grassland	3.44	2.55	0	12.85	0.74	1.2	0	5.4
Deciduous forest	10.97	10.29	0	37.41	7.14	6.95	0	26.22
Evergreen forest	40.59	25.93	3.18	88.8	6.57	9.28	0	43.54

Mixed forest	17.35	8.95	2.81	36.04	6.45	5.18	0	20.48
Scrub/shrub	5.88	5.79	1.25	28.79	0.78	1.13	0	5.4
Palustrine forested wetland	1.51	2.29	0	11.38	0.44	0.85	0	3.55
Palustrine Scrub/shrub	1.15	1.27	0	5.02	0.15	0.25	0	0.95
Palustrine Emergent wetland	0.81	1.1	0	5.14	0.18	0.35	0	1.42
Estuarine Emergent wetland	0.84	1.18	0	5.39	0.92	1.26	0	4.44
Unconsolidated shore	0.47	0.73	0	4.04	0.73	0.97	0	4.43
Bare Land	0.24	0.52	0	2.26	0.09	0.18	0	0.71
Open Water	0.34	1.87	0	12.81	0.21	0.52	0	2.95
Palustrine Aquatic Bed	0	0	0	0	0	0	0	0
Estuarine Aquatic Bed	0	0.02	0	0.12	0.01	0.03	0	0.18

Land cover classes were consolidated and collapsed from 20 classes to six classes. All forest classes were collapsed as one. The developed class was divided between High Urban and Low Urban such that High Urban and Medium Urban form one urban class (‘High Urban’), and Low Urban and Developed Open Space make up the second urban class (‘Low Urban’). Grassland was kept as a separate class while ‘Cultivated land’ and ‘Pasture/Hay’ were collapsed into one ‘Agriculture’ class. All remaining classes were collapsed into ‘Other.’ Mean percentages of land cover across sample basins were re-calculated for these six land cover types (Figure 3.5). Sample basins with wastewater treatment (n=85) contain primarily forested land cover (44.6%) followed by low urban (27.4%) and high urban (19.6%). Their distributions, however, differed significantly across basins dominated by septic systems vs. sewer systems. Figure 3.6 shows that basins dominated by septic systems contain on average 50% more forest cover compared to basins dominated by sewers.

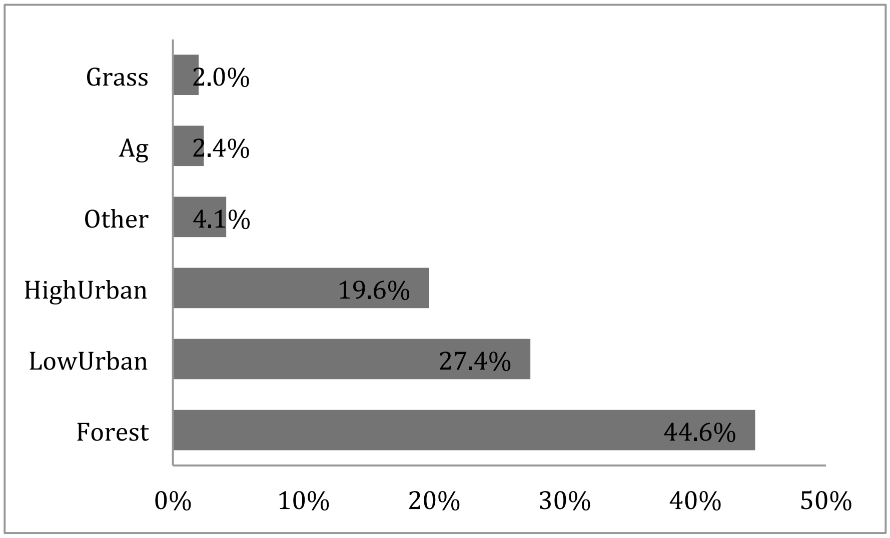


Figure 3.5: Proportion of land cover across all sample basins

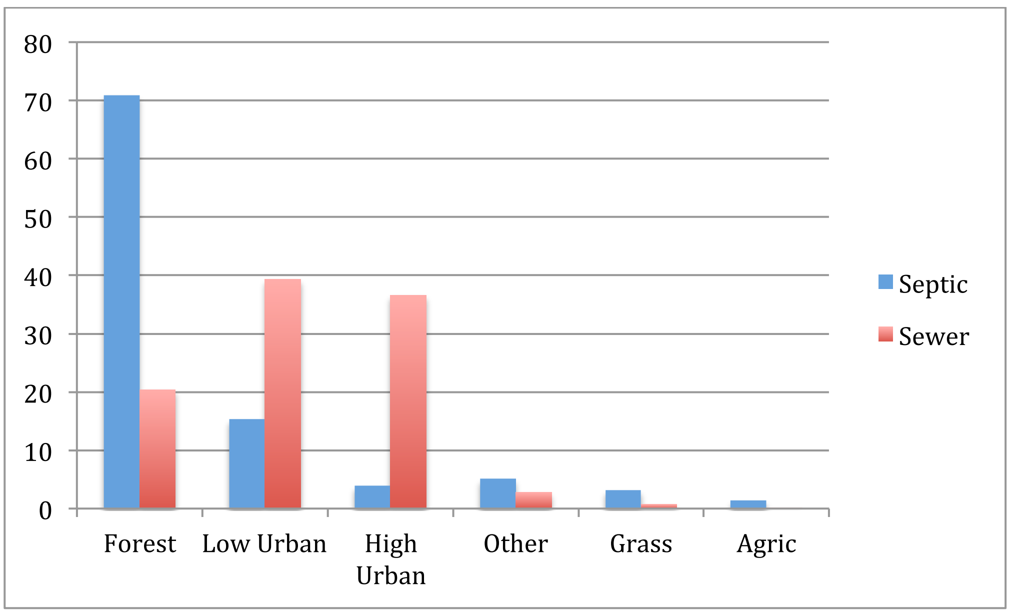


Figure 3.6: Mean percent land cover for basins dominated by either septic or sewer systems

3.4.5. Analysis Methods

Data analysis was based on non-parametric t-tests and binomial logistic regression. To examine differences in the amounts of land use and land cover across basins dominated by either septic systems or sewer systems, I use the Kruskal-Wallis non-parametric test. This test was chosen because the sample populations are independent, come from unrelated populations, and do not follow a normal distribution.

To test whether a wastewater treatment type is associated with the development patterns in the sub-basins, I use binomial logistic regression. The outcome variable, wastewater type, is a coastal basin being dominated by onsite septic systems (OSS) or a central sewer system (CSS), where 1 = OSS and 0 = CSS. Because the independent variables are not normally distributed and therefore fail the assumption of normality, a binary logistic model is used to estimate wastewater type given a set of landscape patterns across an urban gradient (Hosmer & Lemeshow, 2000). The logit model (Logit (P) = Log [P / (1-P)]) is defined as:

$$logit\left(\pi(x_i)\right) = \ln\left(\frac{\pi(x_i)}{1-\pi(x_i)}\right) = \alpha + \beta_i + \cdots + \beta_j x_{ji} \qquad (1)$$

where the term within the brackets is the odds of an event occurring. In the example above this would be the odds of a basin being dominated by OSS. The logistic regression is carried out with a binomial generalized linear model in R version 3.01 in the Macintosh environment.

I tested logistic models to fit the data and to test the research hypothesis regarding the relationship between the dominance of wastewater type and a basin's pattern of land use and land cover. All variables were individually evaluated for significance and assessed for collinearity. Since I know that urban land cover is an important variable for sewer systems, I developed a hierarchical model starting with percent High Urban land cover and tested the significance of entering other composition and configuration variables.

Some variables are highly correlated (Figure 3.7). Single Family Residential (SFR) is positively correlated with Low Urban (0.75) and Services is positively correlated with High Urban (0.64).

Among land cover classes, forest cover is negatively correlated with High Urban (0.84) and Low Urban (0.80). Forest cover is also positively correlated with Undeveloped (0.6). In addition, the composition variable of % High Urban was highly correlated with its Aggregation Index (Figure 3.8). I did not include these correlated variables together in the models.

The results of fitting the univariable logistic models are given in Table 3.7. This table shows (1) the estimated slope coefficient(s) for the univariable logistic regression model containing only this variable; (2) the estimated standard error of the estimated slope coefficient; (3) the estimated odds ratio, which was obtained by exponentiating the estimated coefficient; (4) the 95 confidence interval (CI) for the odds ratio;(5) the likelihood ratio test statistic, *G*, for the hypothesis that the slope coefficient is zero; and (6) the significance level for the likelihood ratio test. Since the Clumpy Iis between -1 and +1, a change of 1 point in the estimated coefficient is not meaningful. Therefore, an odds ratio was calculated for a 0.1 point index for the clumpy variables (CL Forest, CL High Urban, CL Low Urban, and CL Grass). Several variables are not significant, namely *Clumpy Forest*, *Aggregation of Low Urban*, and *Clumpy Low Urban,* and were excluded from all subsequent models.

I systematically added variables one at a time and assessed each variable's importance based on the statistical significance of the coefficient for the variable and whether it produced an improvement in the Akaike's Information Criterion (AIC). I assessed each landscape variable type separately. First I assessed the land use variables, followed by the land cover composition variables, and the configuration variables. I began each model by including the variable that has the highest odds ratio (Table 3.7). In the case of land use, this is the %Services. In the case of land cover composition, this is %High Urban cover. I used a significance level $p<0.15$ as a cutoff for individual coefficients to allow for variable entry into the model (Hosmer and Lemeshow, 2000). Hosmer and Lemeshow (2000) discuss how a lower significance level may be too restrictive and exclude important variables into the model. Using this cut-off, I excluded %CultRec, %Uknown, %Agriculture, and CL Forest. I also excluded variables from entering the model that were highly correlated with variables in the model. I assessed the best model using Akaike's Information Criterion (AIC). In R, the AIC is defined as: -2 [maximized log-likelihood] + 2 [number of parameters].

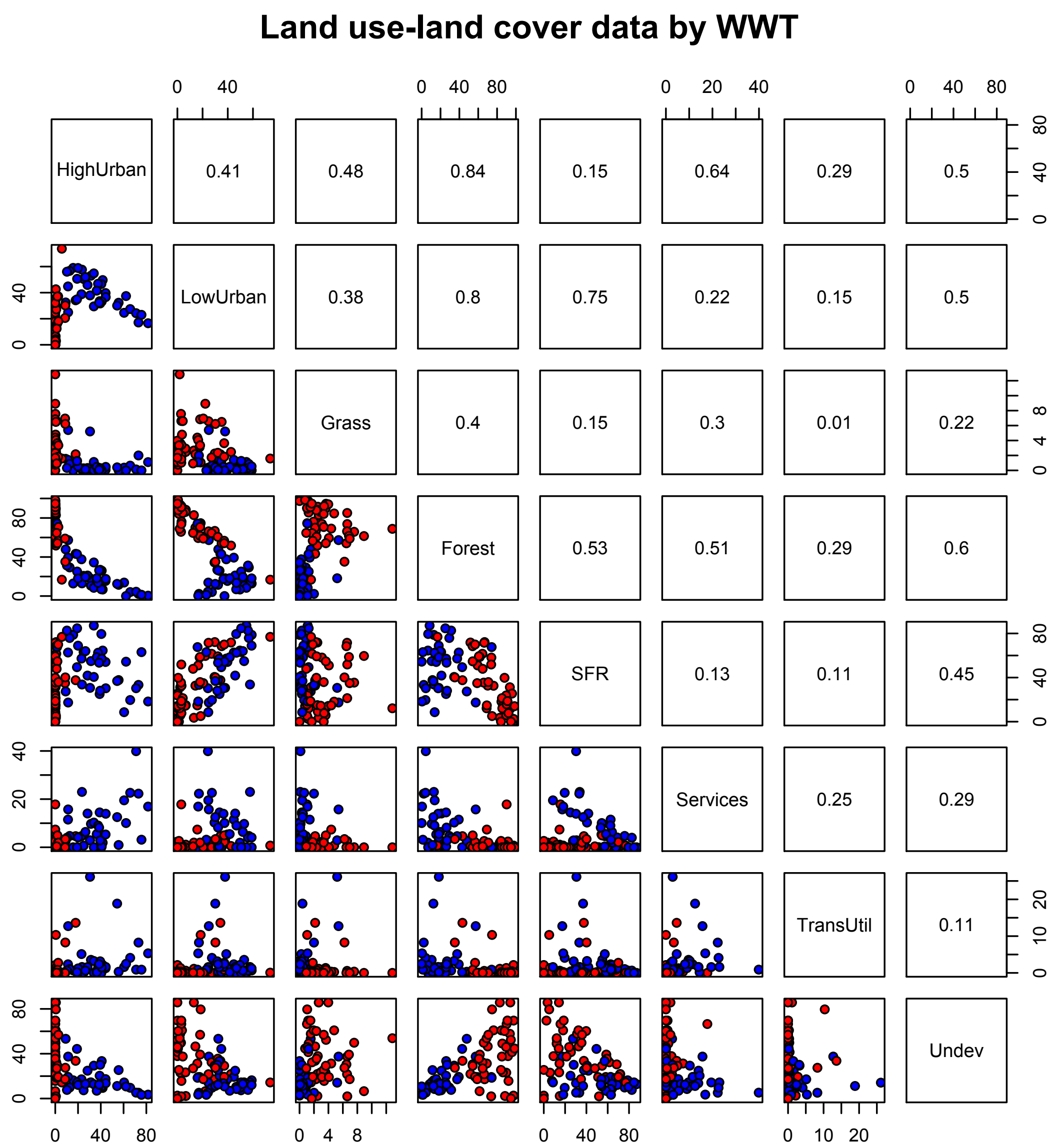


Figure 3.7: Scatterplots and correlation coefficients of proportional land use-land cover composition. Red points are basins dominated by septics, blue points are basins dominated by sewers.

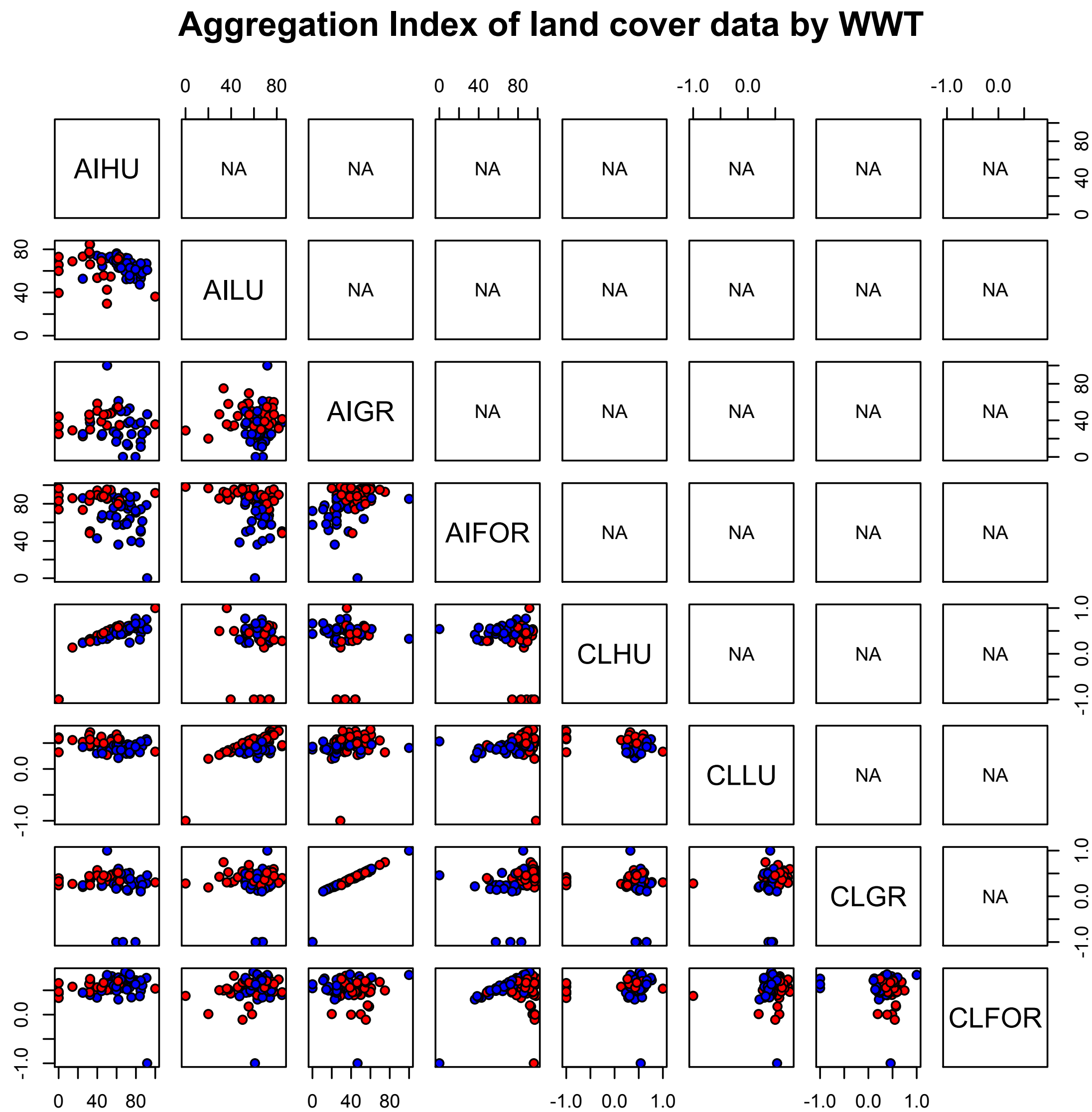


Figure 3.8: Scatterplot of landscape configuration variables

3.5. Results

This section begins by characterizing the relationship between land use and land cover in the 85 basins. I then describe differences in land use and land cover across basins dominated by either septic systems or sewer systems (Table 3.6), and results of the logistic regression models.

3.5.1. Land use and Land cover

The 85 sub-basins represent residential land use ranging from 0% residential in rural areas of Mason and Jefferson Counties to over 80% in the most urban areas of King County, Snohomish, and Kitsap counties. The distributions of land cover across basins by land use type show a complex relationship between land use and land cover (Figure 3.9). Some land uses are dominated by one land cover type. For example, lands designated for timber use are dominated by forest cover (>95%). Conversely, urban land cover dominates parcels classified as trade including commercial and trade activity (100%). Over 70% of parcels classified as 'undeveloped' are covered by forest. However, nearly 20% of the remaining parcels are covered by low urban and high urban land cover. Residential parcels exhibit a heterogeneous pattern of land cover: 47% of the area occupied by single family residences (SFR) is covered by low urban, 31% by forest, 15% by high urban, nearly 2.5% by grass and 1.5% by agriculture. Lands occupied by multi-family residences are covered by nearly 20% more urban land cover and half the amount of forest cover as their single-family counterparts.

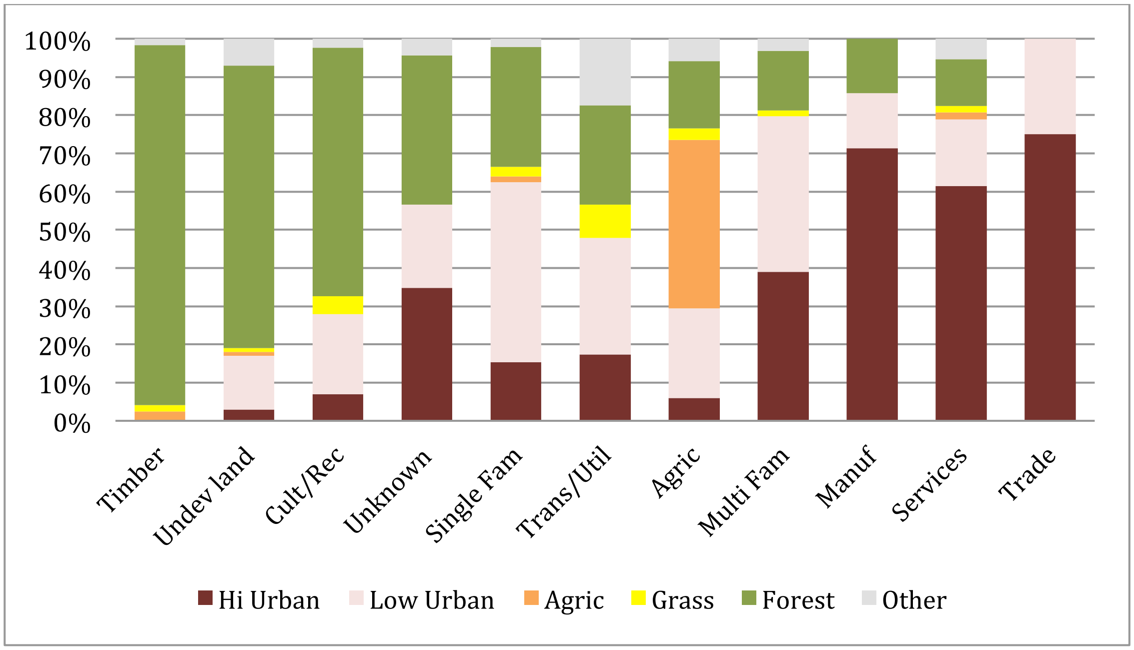


Figure 3.9: Proportion of land cover by land use type

Basins dominated by central sewer systems and onsite septics were evaluated for differences in land use and land cover composition. Results from non-parametric T-tests show that differences in average amounts of land use and land cover are significant (*P*<.001) between basins dominated by the two disposal types, except for the land uses classified as unknown and agriculture (Table 3.6). Averages in agriculture land cover also did not very significantly between basins on septics vs. sewers. Basins dominated by sewers contain, on average, 50% (± 21) single-family homes (SFR) and nearly 9% (± 8) multi-family homes (MFR). By contrast, septic-dominated basins contain 32% (± 23.7) SFR and 5% (±7.7) MFR. Basins dominated by septics contain significantly less land uses associated with urban activities, namely land use activities associated with retail, services, trade, cultural activities, transportation, utilities, and manufacturing (Table 3.6). Basins with septics also contain significantly less urban land cover. By contrast, basins with septic systems contain significantly more undeveloped land uses and timber, as well as forested cover and grass cover.

Basins dominated by sewers vs septics also contained significantly different configurations of land cover. Sewer dominated basins contained significantly higher aggregation of high urban land cover and significantly lower aggregation of forest cover than their septic dominated counter-parts. Similarly, basins dominated by septics contained significantly higher aggregation of grass cover than the sewered basins. The aggregation of low urban cover was not significantly different between the two wastewater treatment groups ($p=0.11$). Differences in the mean Clumpy Index for forest cover and high urban cover were not significant ($p=0.015$). This may be because the Clumpy Index normalizes for the total proportion of the land cover thereby reducing bias in the estimate of the aggregation index (McGarigal & Marks, 1995).

Table 3.6: Mean % land use and % land cover for basins dominated by septics vs. sewers (85 basins total

Land use	Septic Mean %	Septic Std	Sewer Mean %	Sewer std	W	Two-sided p-value	One-sided p-value
Single fam res (SFR)	32.3	23.7	50.1	21.5	516	0.0008	0.0004
Undev	37.2	22.4	16.6	11.2	1081	<0.0001	<0.0001
Multi fam res (MFR)	5.3	7.7	8.8	8.2	530	0.0013	0.0006
Service	1.3	2.9	8.5	8.8	319	<0.0001	<0.0001
Cultur/Rec	3.1	12.4	5.4	6.5	413	<0.0001	<0.0001
Trans/Util	0.9	2.7	3.1	5.3	328	<0.0001	<0.0001
Trade	0.0	0.1	2.9	5.8	264	<0.0001	<0.0001
Unknown*	3.2	14.5	2.6	3.7	665	0.063	
Manuf	0.0	0.0	1.8	4.1	517	<0.0001	<0.0001
Agric *	2.4	5.6	0.2	0.9	1033	0.11	
Timber	14.3	20.8	0.0	0.0	1349	<0.0001	<0.0001
Land cover	**Septic Mean %**	**Septic Std**	**Sewer Mean %**	**Sewer std**	**W**	**Two-sided p-value**	**One-sided p-value**
High Urban (HU)	1.20	3.16	36.54	20.54	13	<0.0001	<0.0001
Low Urban	13.65	15.66	38.90	12.65	192	<0.0001	<0.0001
Agric*	1.56	3.92	0.15	0.54	1115	0.016	0.008
Grass	3.44	2.55	0.74	1.20	1616	<0.0001	<0.0001
Forest	74.79	18.21	20.94	16.24	1732	<0.0001	<0.0001
Other	5.37	4.85	2.73	2.62	1242	0.002	0.001
Agregation Index	**Septic Mean**	**Std**	**Sewer Mean**	**Std**	**W**	**Two-sided p-value**	**One-sided p-value**
Agg HU	38.21	25.29	67.15	15.87	127.5	<0.0001	<0.0001
Agg LU*	58.1	17.75	64.5	7.93	654	0.22	0.11
Agg Grass	44.7	12.6	31.9	20.43	952	0.0005	0.0002
Agg Fores	88.5	8.84	66.7	19.04	1549	<0.0001	<0.0001
Clumpy Index	**Septic Mean**	**Std**	**Sewer Mean**	**Std**	**W**	**Two-sided p-value**	**One-sided p-value**
Clump HU	0.13	0.63	0.48	0.13	273	0.015	0.007
Clump LU	0.48	0.27	0.41	0.07	1214	<0.0001	<0.0001
Clump Grass	0.42	0.12	0.19	0.45	977	0.0007	0.0003
Clump Forest	0.45	0.30	0.56	0.30	600	0.015	0.007

* Results from Wilcoxon-Mann-Whitney test reveal that we cannot reject the null hypothesis that the percent of land use and land cover in basins dominated by septics vs sewers are identical ($P<0.05$).

3.5.2. Landscape pattern and wastewater dominance

Wastewater dominance in coastal basins of the Puget Sound region can be distinguished using land use and land cover pattern metrics. The pattern metrics selected are useful to describe the composition and configuration of urban development in the 85 sub-basins. The logistic regression models show that landscape composition and configuration are useful predictors of wastewater dominance. A number of patterns metrics are significantly associated with wastewater treatment type (Table 3.7).

Results from the univariate logistic regressions examining wastewater type and land use reveal that four predictors are significantly related to wastewater dominance ($p<0.05$) (Table 3.7). These variables are %Services ($p=0.0003$), %SFR ($p=0.001$), %TransUtil ($p=0.04$), and %Undevelop ($p<0.0001$). Among the land cover composition measures, the only variable that is not significant is %Agriculture ($p=0.19$). Several landscape configuration variables are significantly related to wastewater type, including the aggregation index of high urban land cover ($p=0.0001$), forest cover ($p<0.0001$), and grass cover ($p<0.0001$). In addition, the Clumpy Index of high urban ($p=0.03$) and grass ($p=0.016$) were found to be significant predictors of WWT.

In the sample of 85 basins, multiple logistic regression was performed to estimate the relationship between dominance of sewers and land use and land cover pattern metrics. The results from multiple logistic models (Tables 3.7 through 3.9) indicate that the best model for predicting the dominance of sewers is the proportion of High Urban land cover ($p<0.001$), AIC = 26.11 (Model 9 in Table 3.8). The adjusted OR of sewer dominance associated with one percent increase in high urban cover is 1.47 (95% CI 1.22 to 1.93). As the percentage of basin area covered by High Urban land cover increases, sub-basins are more likely to be dominated by sewers. In probability terms, this ratio indicates that for every increase in the percent of High Urban land cover, the probability that a basin is dominated by sewers increases by about 147%. Figure 3.10 shows a plot of the logistic regression between High Urban and WWT. This plot shows that the probability that a basin is dominated by sewers increases to nearly 100 percent when 20% or more of the basin's area is covered by high urban. In fact, for a basin with 20 percent of its area covered by high urban land cover, the predicted odds that it is dominated by septics is extremely low at 0.009 (=exp(-4.69)).

The change in deviance (2.957) when adding Grass cover to Model 9 is not significant at the 0.1 level. In other words, adding Grass does not significantly improve Model 9. However, grass cover comes close to be significant ($p=0.14$). In this model, the adjusted odds ratio associated with a one percent increase in grass cover is 0.6 (95% CI 0.24 to 2.06), suggesting that the presence of grass cover in a basin decreases the odds that it is dominated by sewers.

Several land use models were examined (Table 3.8, Models 1-8). The best land use model for estimating wastewater dominance, was the proportion of parcels classified as Service, proportion Undeveloped, and proportion of Single Family Residences (Model 7). The estimated odds ratio between WWT and Service is 1.37 (95% CI 1.18 to 1.66) when adjusting for the amount of area with parcels undeveloped and with single-family residences.

Three variables referring the aggregation of land cover were examined together. These were the aggregation index of high urban, forest and grass cover (Table 3.9, Models 12-15). The Clumpy Index was excluded from any of the models because the variables were either found to not be significantly related to wastewater (Table 3.6) or the variables that were significant were highly correlated with the Aggregation Index.

I tested whether adding land use information to the urban land cover improved predictive power of high urban land cover on its own. None of the variables did, although Single Family Residences (SFR) was on the border (p=0.18) and the overall model performed marginally (AIC = 27.054). However, this model did not perform as well as the model with High Urban land cover and Grass cover.

I also tested the aggregation index of High Urban to see if adding this variable improved the explanatory power of High Urban land cover. Twenty-five basins contained no data for the aggregation of High Urban land cover, therefore the null degrees of freedom reduced to 60 (see Table 3.7). This makes sense since an Aggregation Index of zero or more requires proportional land cover data of that class > 0. Twenty-two basins (out of 85) do not contain any high urban land cover. This model did not perform as well (AIC = 27.412) and the AI High Urban variable is not significant (p>0.8). The aggregation of high urban land cover is highly correlated with % High Urban (0.73). I also tested how strong of a predictor urban land cover is if I only examine basins classified as suburban (n=29) and rural (n=26) according to the gradient classification. Again, the percent of high urban land cover was the most significant predictor (p<0.01) for whether basins were dominated by sewers. The estimated logit was g(OSS)=-3.63 + 0.328 * High Urban, and the estimated odds ratio (OR) was exp(0.328)=1.37

Table 3.7: Results from univariate logistic regression models

Variable	n	df	(β)	SE (β)	e^{β} (odds ratio)	95% CI	Wald's z	P>|z|
Land use								
% SFR	85	83	0.0335	0.0105	1.03	(0.014, 0.055)	3.23	0.0012 **
% MFR	85	83	0.05	0.03	1.05	(0.002, 0.128)	1.9	0.056.
%Services	85	83	0.30	0.08	1.34	(0.163, 0.491)	3.63	0.0003**
%CultRec	85	83	0.024	0.02	1.02	(-0.02, 0.085)	0.952	0.34
%TransUtil	85	83	0.183	0.092	1.19	(0.037, 0.405)	1.99	0.046*
%Uknown	85	83	-0.00506	0.0217	0.99	(-0.06, 0.03)	-0.25	0.8
%AgResExtr	85	83	-0.34	0.19	0.74	(-0.872, -0.076)	-1.79	0.073.
% Undevelop	85	83	-0.07159	0.018	0.93	(-0.11, -0.04)	-3.92	<0.0001***
%Timber								
%Manuf						fitted probabilities 0 or 1		
%Trade								
Land cover composition								
% Forest	85	83	-0.1204	0.0254	0.88	(-0.18, 0.08)	-4.732	<0.0001***
% HighUrban	84	83	0.382	0.101	1.47	(0.22, 0.63)	3.773	0.0001***
% LowUrban	85	83	0.1079	0.0223	1.11	(0.07, 0.16)	4.836	<0.0001***
% Grass	85	83	-1.2311	0.295	0.29	(-1.88, -0.72)	-4.163	<0.0001***
%Other	85	83	-0.21	0.08	0.80	(-0.398, -0.07)	-2.645	0.008**
%Agric	84	83	-0.479	0.367	0.61	(-1.47, -0.07)	-1.305	0.192
Land cover configuration								
AI Forest	83	82	-0.148	0.03	0.86	(-0.22, -0.09)	-4.331	<0.0001***
CL Forest	84	82	1.5202	1.018	4.57	(-0.18, 3.84)	1.493	0.1354
AI High Urban	59	58	0.07	0.019	1.07	(0.037, 0.113)	3.66	0.0002***
CL High Urban	60	59	2.76	1.3	15.91	(0.88, 6.18)	2.11	0.034*
AI Low Urban	79	77	0.0366	0.019	1.03	(0.002, 0.077)	1.932	0.0534.
CL Low Urban	79	77	-3.10	1.89	0.044	(-7.1, -0.026)	-1.641	0.10.
AI Grass	73	72	-0.054	0.018	0.94	(-0.093, -0.02)	-2.96	0.003**
CL Grass	74	73	-4.32	1.81	0.013	(-8.23, -1.40)	-2.390	0.0168*

*** p<0.001 ** p<0.01 * p<0.05 . p<0.1

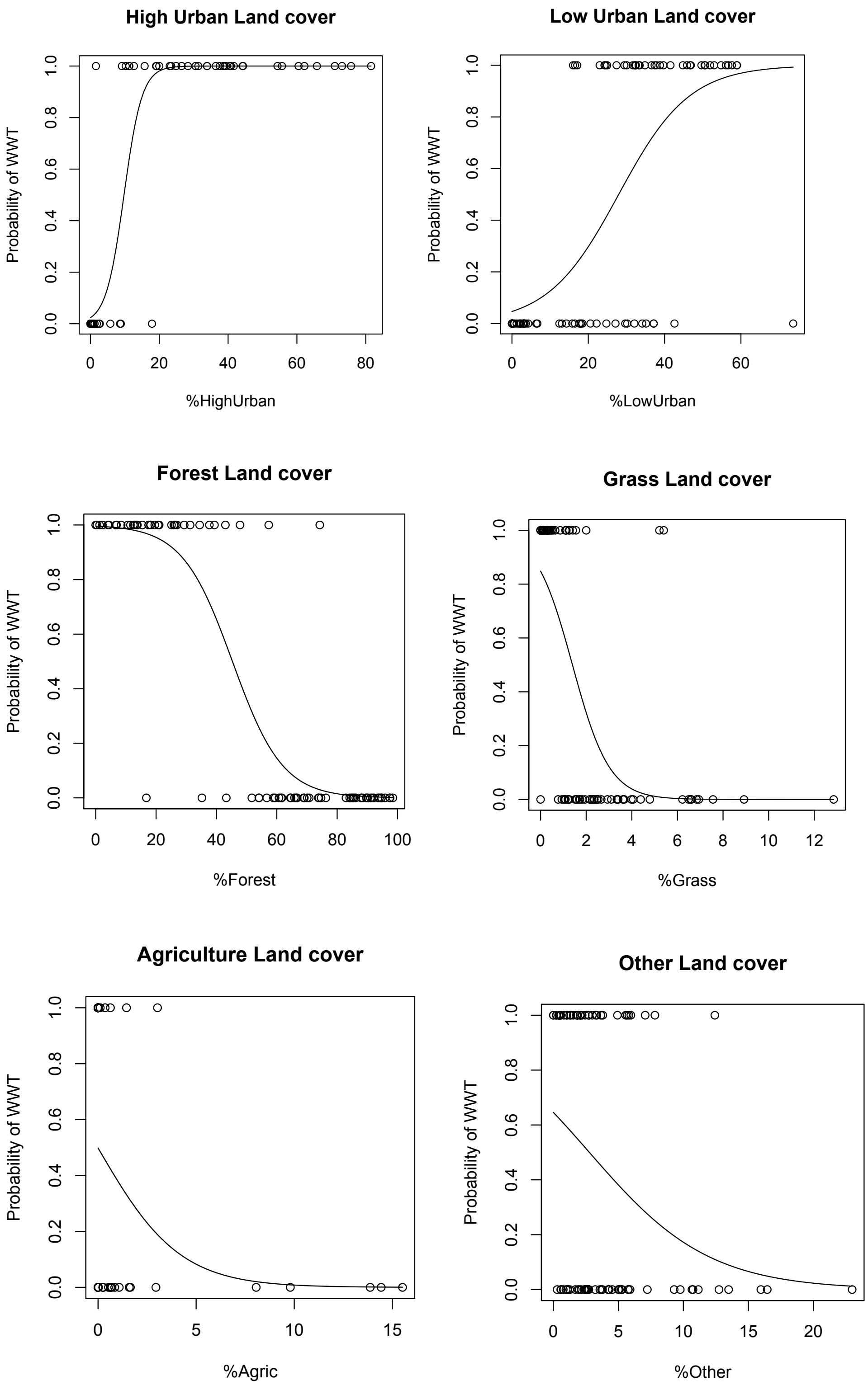


Figure 3.10: Distribution plots of logistic regression between WWT ~ land cover variables

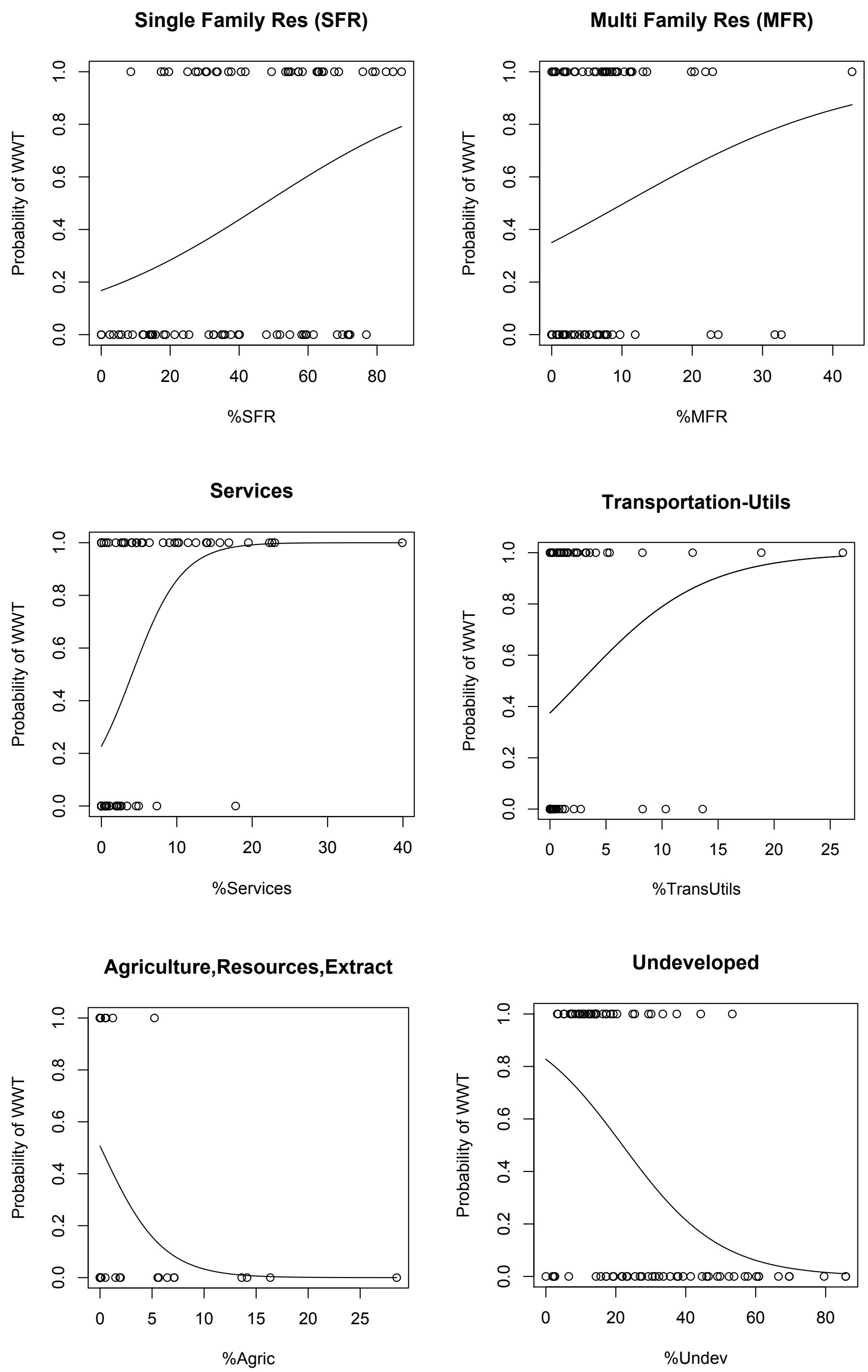


Figure 3.11: Distribution plots of logistic regression between WWT ~ land use variables

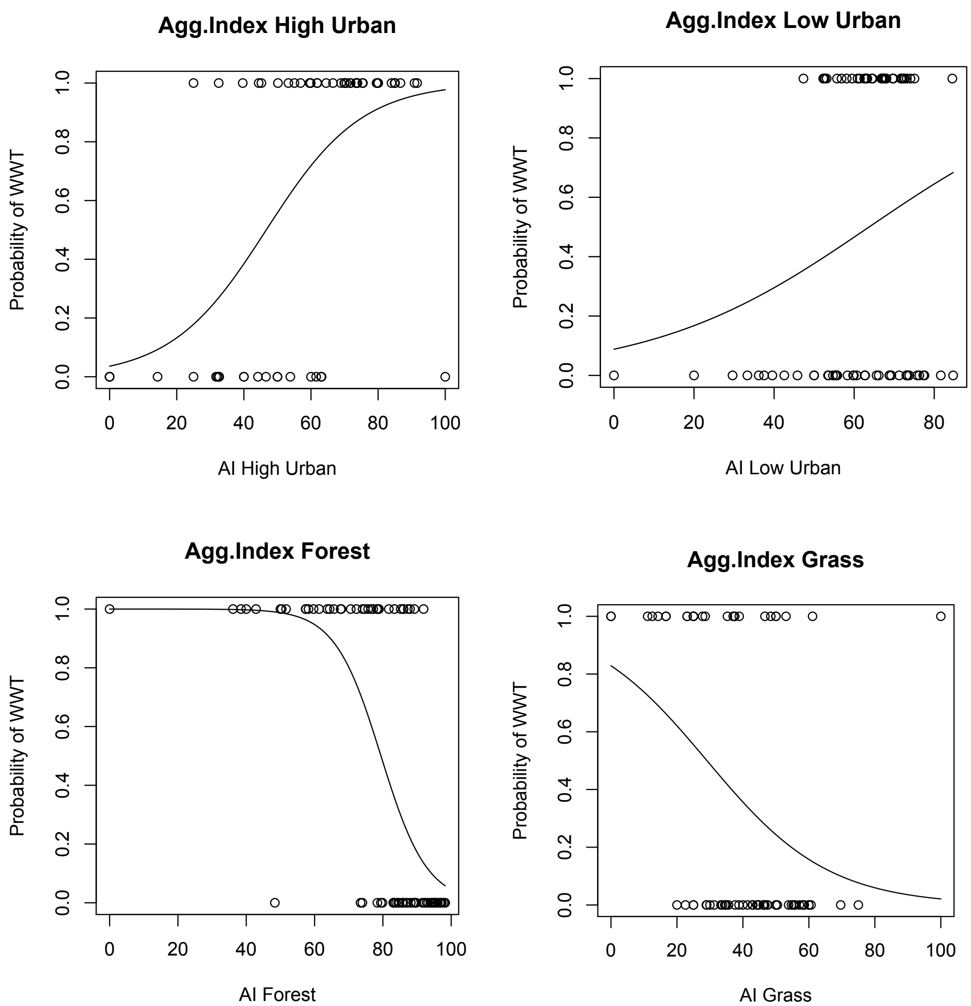


Figure 3.12: Distribution plots of logistic regression between WWT ~ Aggregation Index of land cover

Table 3.8: Models with beta values for land use composition explanatory variables for wastewater dominance (model shaded in grey performed the best)

	Model 1				**Model 2**				**Model 3**			
Variable	(β)	SE (β)	Wald (z)	**P>|z|**	(β)	SE (β)	Wald (z)	**P>|z|**	(β)	SE (β)	Wald (z)	**P>|z|**
Intercept	-1.22	0.324	-3.78	<0.00	-1.28	0.33	-3.85	<0.00	-0.99	0.33	-2.94	<0.00
% Services	0.30	0.083	3.6	<0.00	0.28	0.083	3.39	<0.00	0.32	0.09	3.36	<0.00
% TransUtil					0.06	0.07	0.84	0.3				
%AgResExtr									-0.35	0.20	-1.70	0.09
%Undev												
%MultiRes												
%SFR												
Null deviance	116.88											
Residual dev.	86.36				85.57				79.92			
df	83				82				82			
AIC	90.36				91.57				85.92			

	Model 4				**Model 5**				**Model 6**			
Variable	(β)	SE (β)	Wald (z)	**P>|z|**	(β)	SE (β)	Wald (z)	**P>|z|**	(β)	SE (β)	Wald (z)	**P>|z|**
Intercept	0.55	0.53	1.027	0.3	0.78	0.56	1.37	0.16	0.51	0.58	0.087	0.37
% Services	0.27	0.07	3.54	<0.00	0.28	0.08	3.33	<0.00	0.27	0.07	3.5	<0.00
% TransUtil												
%AgResExtr					-0.32	0.22	-1.42	0.153				
%Undev	-0.07	0.02	-3.3	<0.00	-0.06	0.02	-3.2	<0.00	-0.07	0.02	-3.30	<0.00
%MultiRes									0.006	0.04	0.14	0.88
%SFR												
Null deviance	116.88											
Residual dev.	69.49				64.63				69.9			
df	82				81				81			
AIC	75.9				72.83				77.92			
	Model 7				**Model 8**							
Variable	(β)	SE (β)	Wald (z)	**P>|z|**	(β)	SE (β)	Wald (z)	**P>|z|**				
Intercept	-2.07	1.21	-1.7	0.08	-4.26	1.01	-4.2	0.00				
% Services	0.31	0.08	3.81	<0.00	0.33	0.08	4.1	0.00				
% TransUtil												
%AgResExtr												
%Undev	-0.05	0.02	-2.09	0.03								
%MultiRes												
%SFR	0.043	0.016	2.64	0.00	0.06	0.01	3.72	<0.00				
Null deviance	116.88											
Residual dev.	60.47				65.13							
df	81				82							
AIC	**68.47**				71.13							

Table 3.9: Models with beta values for land cover composition explanatory variables for wastewater dominance

	Model 9				**Model 10**				**Model 11**			
Variable	(β)	SE (β)	Wald (z)	**P>|z|**	(β)	SE (β)	Wald (z)	**P>|z|**	(β)	SE (β)	Wald (z)	**P>|z|**
Intercept	-3.73	0.89	-4.15	0.00	-2.39	1.11	-2.15	0.03	-4.27	1.17	-3.6	0.00
%HighUrban	0.38	0.10	3.77	0.00	0.38	0.11	3.31	0.00	0.32	0.11	2.84	0.00
%Grass					-0.51	0.35	-1.45	0.14				
%LowUrban									0.02	0.03	0.9	0.3
%Other												
Null deviance	116.88											
Residual dev.	23.0				20.11				22.28			
df	83				82				82			
AIC	27.07				26.11				28.28			

	Model 12											
Variable	(β)	SE (β)	Wald (z)	**P>|z|**								
Intercept	-3.67	1.16	-3.15	0.001								
%HighUrban	0.38	0.10	3.73	0.001								
%Grass												
%LowUrban												
%Other	-0.01	0.15	-0.08	0.9								
Null deviance												
Residual dev.	23.07											
df	82											
AIC	29.07											

Table 3.10: Models with beta values for land cover configuration explanatory variables for wastewater dominance

	Model 13				**Model 14**				**Model 15**			
Variable	(β)	SE (β)	Wald (z)	**P>|z|**	(β)	SE (β)	Wald (z)	**P>|z|**	(β)	SE (β)	Wald (z)	**P>|z|**
Intercept	-0.02	0.13	-0.2	0.8	0.14	0.197	0.747	0.46	1.78	0.19	9.04	<0.00
Agg Index High Urban	0.01	0.002	5.45	<0.00	0.01	0.002	4.63	<0.00				
Agg Index Grass					-0.005	0.003	-1.43	0.156				
Agg Index Forest									-0.01	0.002	-6.98	<0.00
Null deviance	13.93				12.32				20.7			
Residual dev.	9.2				7.9				12.98			
df	58				47				82			
AIC	63.83				58.1				87.52			
	(25 obs. deleted due to no data)				(35 obs. deleted due to no data)							

3.6. Discussion

Past research in planning, geography, and urban economics suggests that different wastewater infrastructure types are associated with alternative patterns of urban development (Suen, 2005; Hatter et al., 2004; Speir & Stephenson, 2002; LaGro, 1998; Real Estate Research Corporation, 1974). My research sought to build upon past findings and explore whether coastal basins dominated by different wastewater treatment types vary in the composition of land uses and the amount and arrangement of land covers. This study also sought to investigate what patterns of land use and land cover are associated with wastewater treatment.

As hypothesized, the results from my study found that basins dominated by septics vs. sewers contain significantly different types and amount of land uses and land covers. Coastal basins on septics are characterized mostly by single family residences, undeveloped land uses, and timber activities. Sewer dominated basins also contain high proportions of single family residences, but they also contain significantly more proportions of land uses associated with commercial and industrial activities, such as services, retail, trade, manufacturing and transportation-utilities. Urban land cover distributions were also significantly different in basins dominated by sewers vs. septics. Basins that are dominated by parcels hooked up to a sewer system contain on average over 35% of their basin area covered by high urban land cover. Conversely, basins dominated by septic systems contain on average just over 1% of their area covered by high urban land cover. Instead, these septic basins contain a very large proportion of their area (>75%) with forest cover.

This study also found differences in the arrangement and configuration of the landcover. Basins dominated sewers contained significantly more urban land cover that was clustered together.

Conversely, the fragmentation of forest cover indicated by the aggregation index of forest was significantly higher in basins dominated by sewers. This was a surprising result as the literature on septics seems to suggest that they are a driver of sprawl (LaGro, 1998; Speir & Stephenson, 2002). However, these results of the aggregation index may have been biased by the larger proportion of land cover in the basins. The Clumpy Index which normalizes for the proportion of a land cover type in an area did not find a significant difference in the fragmentation of forest between septics and sewers.

Results from the multiple logistic regression models show that the composition of urban land cover, particularly high intensity urban land cover is the best predictor for the dominance of a wastewater treatment type in coastal watersheds of the Puget Sound. Even among suburban and rural basins, high urban land cover is the best predictor for wastewater treatment type.

This outcome may be a result of scale economies. Sewer systems are more efficiently built by providing capacity to serve all land uses at build out, rather than by adding capacity as needed (Hanley & Hopkins, 2007). Further, sewer costs go up (and therefore development costs) with the size of lots and distance from existing service (Newburn & Berck, 2011b). Across an urbanizing metropolitan region, a complex mixture of built-up development patterns including parking lots, mixed-use activities, and low-density single-family homes with lawns interact with multiple forms of wastewater infrastructure. This study finds sewer systems are more likely than onsite septic systems to be associated with high amounts of urban land cover. In fact, results show that for basins with 20% or more of its area covered by high intensity urban land cover, the likelihood that that basin is dominated by septic systems is zero. As a result, for basins in urban, suburban, and rural coastal areas alike, high intensity urban land cover is a strong predictor for sewer provision. Once in place, urban infrastructures like sewers are difficult to reverse and their longevity leads to a path dependency with regard to urban landscape patterns and associated ecological impacts.

The strong association between urban land cover and wastewater treatment type points to the urban pattern trade-offs accompanying wastewater infrastructure decisions. While onsite septic systems are found in urban, suburban, and rural environments with varying amounts of low urban land cover, grass and forest cover, a switch to a sewer system is more than likely accompanied by heavy urban land cover. Urban land cover is well-documented as a lead stressor in coastal ecosystems, altering the hydrology of a watershed basin and adding new sources of contaminants (Brabec et al., 2002; Burton & Pitt, 2001; Mallin et al., 2000; Booth & Jackson, 1997). The conversion of landscapes to high intensity land uses with large amounts of impervious surfaces affects the amount of pollutants in storm water and the ability of the landscape to attenuate pollutants. More intense uses create more sources of pollutants and larger proportions of impervious surfaces lead to greater volumes of run-off. At a watershed scale, the total amount of impervious area is an important indicator of coastal water pollution

This study did not find the configuration of the landscape to be an important factor for explaining wastewater dominance. The Aggregation Index and the Clumpy Index may not be the best variables to measure differences in the configuration of the urban built-up landscape. At the sub-basin scale, this variable is highly correlated with the composition of urban land cover. This finding underscores the need to understand the aggregation of residential patterns using other associated indices in order to understand the relationship with wastewater treatment type.

3.7. Conclusion

This study investigated the relationship between patterns of land use, land cover, and wastewater infrastructure based on the dominance of parcels on private onsite septics and public sewers in urbanizing coastal basins of the Puget Sound region. It provides a means for exploring the link between urban development patterns and wastewater disposal type. The empirical analysis of 85 coastal sub-basins reveals that a higher percentage of urban land cover in urban, suburban, and rural basins tends to be associated with parcels served by sewers. This study also demonstrates an approach to evaluate the association between development patterns and different wastewater treatment types across an urban-rural gradient.

Across an urban region, a variety of wastewater infrastructures serve a complex pattern of intermixed high and low-density built-up areas. Although some studies have addressed the relationship between urban development patterns and wastewater infrastructure, none has asked directly how patterns of urban development relate to central sewer vs. decentralized onsite septic systems. Most studies on development patterns and wastewater associate patterns focus on one system or another. This analysis reveals that although urban development patterns are heterogeneous in their spatial pattern, the choice in wastewater infrastructure may be an influential factor homogenizing the landscape with important environmental implications. One of the challenging problems environmental land use planners and coastal resource managers face is the consequential impacts of infrastructure choices. It has been well-documented that different types of transportation interact with development patterns to affect transportation choices, travel behavior, and the environment. Comparably little research has been done to understand how wastewater infrastructure choices interact with patterns of urbanization to influence ecological conditions. It is necessary to understand the nature of the relationship between urban development patterns and wastewater infrastructure and their interactions before trying to associate them individually to coastal ecological conditions. Perhaps even more important, this understanding is crucial before local planners or decision-makers choose to invest in one infrastructure type over another.

There are limitations to the application of results. The logistic regression model did not include the influence of soils due to the lack of data across the Puget Sound counties. Soils and soil permeability are an important siting constraint for onsite septics and may be an influential biophysical pattern associated with onsite-septics (Batisani & Yarnal, 2009). In addition, Washington state has had a strong urban growth policy in place since 1995. This policy aims to direct the construction of all new development in urban growth areas on sewer systems. This study did not test the relationship between the age of development and wastewater treatment type, therefore it is hard to know whether the results are because of the urban growth policy. Furthermore, because this case study is in the Puget Sound region, the generalizability of results is limited. Additional research in other parts of the United States, with and without urban growth policies is needed to confirm these results. The methodology adopted in this study, however, can be adopted and applied to other coastal urban areas.

Chapter 4: The Role of Alternative Wastewater Treatment in Mediating the Impacts of Urbanization on Water Quality in Near-shore ecosystems.

4.1. Introduction

In urban areas, the pattern of the built landscape and urban infrastructure modify both the ways that sewage and nutrients get transported and how they are cycled in the environment. Wastewater infrastructure choices influence settlement patterns and land cover composition. In the previous chapter I assessed the landscape patterns associated with wastewater treatment types and found sewers to be more likely associated with coastal areas that contain 20% or more of their area covered by high intensity urban land cover. This study examines the role of alternative wastewater treatment in mediating the impacts of urban development patterns on shellfish growing areas.

It is well established that the replacement of vegetation with impervious surfaces interrupts hydrologic processes (Booth & Jackson, 1997; Leopold, 1968). As a result, the proportion of a watershed covered by impervious surfaces serves as a useful indicator for impacts of pollution (Arnold & Gibbons, 1996). While imperviousness is an important stressor altering hydrologic processes, it does not fully explain the relationship between urbanization and coastal water quality. Urban development also interacts with the built infrastructure thereby altering biogeochemical processes necessary for cycling nutrients leading to the export of excess pathogens, nutrients and toxins to urban estuaries and coasts.

Perhaps most known, understood and controlled are the effects from Combined Sewer Overflows (CSO). These events can be a significant, although rainfall driven and therefore intermittent and "pulsed" source of pollution. For example, Seattle and King County, with more than 120 combined sewer overflow outfalls, discharge an average of about one billion gallons per year of untreated sewage, stormwater and industrial wastewater (Susewind, 2011). Coastal ecosystems such as shellfish growing areas are particularly sensitive to these sudden and large pollution events. As a result, the Washington Department of Health establish closure zones for shellfish harvesting around sewer outfalls and sewage treatment plant operators are required to inform the Department of Health if an event occurs, or if a problem occurs with the treatment system (Washington State Department of Health, 2012).

Urban infrastructures also alter the natural drainage pattern of a watershed. In particular, roads, sewers and stormwater pipes greatly increase the delivery of pollutants to downstream receiving waters acting as a major stressor to marine and freshwater biota. For example, Walsh and others (2004) demonstrate that even at very low levels of imperviousness (<10%), a catchment's drainage connectivity can have devastating effects on stream amphipods (Walsh, 2004).

Decentralized wastewater infrastructure may also play a role in coastal water quality. In un-sewered urban areas, overflow from septic tanks and drainage from cesspools may enter surface waters via groundwater, and this pollution will act separately from the effects of urban runoff (Walsh, 2000). In addition, they can be located in sensitive areas such as shellfish growing areas or in densities too high to be supported by the assimilative capacities of the soils (EPA, 2002). Recently published studies link the density of septic systems to bacterial contamination and increased nutrient loads in coastal waters (Hatt et al., 2004; Kelsey et al., 2003; Lipp, Kurz, et al., 2001). In the Puget Sound, Alberti and Bidwell (2006) examined the relationship between urbanization and nearshore water quality in shellfish growing areas (Alberti & Bidwell, 2006). They examined human settlement patterns in the amount and arrangement of built elements and found the difference in water quality is associated with different amounts and configurations of forest cover. However, among the more urbanized basins, they found a non-linear relationship between patterns of urban land cover and urban connectivity (e.g. roads) with indicators of pollution. They speculated the type of wastewater infrastructure is an important variable interacting with development patterns to control water quality.

In the previous studies, I observed a higher density of septics in more moderately urbanized basins draining into the Puget Sound. I also found high urban land cover positively related with basins dominated by sewer systems. The objective of this study is to identify the mechanism controlling nearshore water quality by assessing the differential effects of septic systems and landscape patterns on water quality for shellfish. This study examines patterns of septic systems and land cover composition in Puget Sound watersheds and their influence on nearshore water quality in shellfish growing areas. This study is organized around two research questions:

(1) Is the indicator of water quality significantly different between basins dominated by onsite septics vs. central sewers?

(2) Do patterns of onsite septics explain additional variability in WQ, in addition to landcover composition?

4.2. Study Approach

I develop an empirical analysis of 20 basins that represent a gradient of urban landscape patterns and alternative wastewater infrastructures (Figure 4.1). Using bacterial contamination as an indicator of near-shore conditions in shellfish growing areas, I develop a cross-sectional analysis across 20 basins to assess what landscape factors, including patterns of wastewater infrastructure best explain water quality conditions in Puget Sound's shellfish growing areas. My hypothesis is that patterns of septic systems explain additional variation in water quality conditions not explained in upland land cover composition.

This study is based on a landscape analysis approach at the watershed scale. By combining remotely sensed data with socio-economic and wastewater infrastructure data, I apply a set of landscape measures to quantify human settlement patterns and their influence of coastal water quality conditions. I analyze patterns of land cover and wastewater infrastructure at the watershed scale and select a set of variables including land cover composition, total number of septics, percent of parcels on a septic system, and septic density. The role of septic systems in mediating the impacts of land cover patterns was evaluated in three steps: (1) examining differences in water quality conditions for shellfish between areas adjacent to upland basins dominated by septics and basins not dominated by septics; (2) definition of the relationship between land cover pattern and onsite septic pattern; (3) assessment of the influence of land cover pattern and septic pattern on water quality. Land cover pattern metrics are sensitive changes in size (Luck & Wu, 2002). Because the watersheds vary in size, an assessment of the influence of these factors on pattern metrics was included in the analysis. Metrics least likely to be sensitive to these effects were chosen.

The analysis focused on one aspect of water quality conditions in shellfish growing areas, total fecal coliforms counts. The Washington Department of Health (DOH) classifies commercial shellfish growing areas as 'approved, 'conditionally approved, 'restricted', and 'prohibited' based on water quality standards and an annual sanitary shoreline survey. This survey includes water quality assessments, pollution source investigations and assessment of rainfall data. The surveys and classification system follow the protocols and standards of the National Shellfish Sanitation Program (NSSP). Bacterial contamination, specifically fecal coliform bacteria, is used as the primary measure of water quality because it signals the presence of human or animal feces and, in turn, the possible presence of pathogenic organisms. Due to the availability of historical data, I use fecal coliform as the best available indicator at this time.

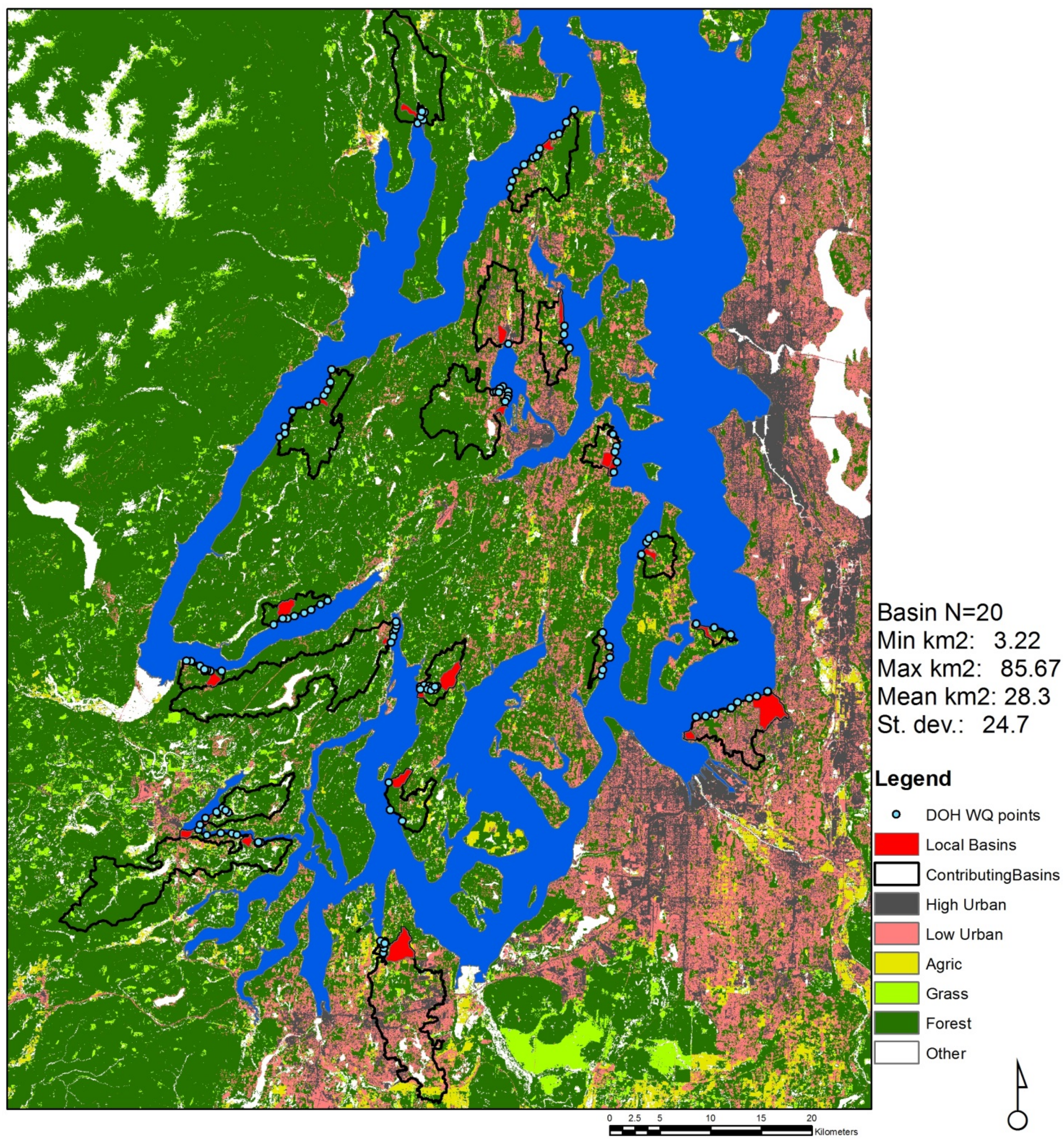


Figure 4.1: Location of watersheds draining directly into Puget Sound commercial shellfish growing areas

4.2.1. Water Quality Data

I collected data from the DOH included all sampling measurements from the Puget Sound area from 2006 through 2008. For the purpose of my analysis, these years were chosen to correspond with the 2006 land cover classification data and to include enough sampling points. The current DOH policy uses a systematic random sampling strategy (SRS) when sampling permanent stations mandated by the National Shellfish Sanitation Program (NSSP). Under SRS, samples are taken at each area at roughly even intervals over time. Conditionally Approved areas are generally sampled 12 times a year. Approved and Restricted areas are sampled 6 times a year. SRS avoids targeting specific environmental factors, such as season, weather, tide, etc. SRS also requires a substantial data set (30 results) to calculate statistics to classify growing areas. As a result, the data represents a wide range of environmental conditions encountered in the growing area. SRS ensures that unbiased, representative data are available for classification (Determan, 2011). However, there were significant differences in the historic length and breadth of data available for each station and each basin. These differences are attributed to changes in sampling schedules or policies, changes in sampling stations, and funding limitations over time.

I standardized the raw fecal coliform data set to represent all sampling stations equally. First, the data set was separated by two hydrographic seasons. The wet season corresponds to months from November to March and the dry season from April to October. Stations without a minimum of 3 samples per season (3 wet-season samples and 3 dry-season samples per year, n=6 per year) were eliminated from the sample. To understand the impacts of seasonal differences in precipitation, I calculated the geometric mean of fecal coliform for both the wet and the dry season separately.

Environmental variables have been shown to have an important influence in explaining part of the variability in fecal coliform across different sites. These include salinity, water temperature, tidal stages, rainfall (Weiskel et al. 1996; Lipp et al. 2001a; Lipp et al. 2001b; Mallin et al. 2001). However the only data recorded consistently was salinity therefore this was the only environmental variable included in the analysis.

4.2.2. Study Areas defined

To assess the role of larger landscape patterns, I delineated larger contributing drainage basins for local near-shore basins used in the previous two studies. I selected basins from the total 90 sample basins that included a shellfish growing area. This reduced my sample size to 23 local basins. I delineated the contributing drainage basins for each of these local basins (Figure 4.1). I used shorelines from the Puget Sound Nearshore Restoration Project (PSNRP) database (Puget Sound Nearshore Ecosystem Restoration Project, 2009) as pour points. I associated water quality data to nearest upland basin using a cost allocation function around each data point in ArcGIS 10.1. This function assigns for each pixel cell a nearest source based on the least accumulative cost over a cost surface. A maximum distance of 1500 meters was assigned around each water quality point. Each cost surface was linked to an upland basin by performing a spatial join between the two spatial data sets. I completed the delineation process in ArcGIS 10.1 using a flow direction based on a 10-meter digital elevation model. The final sample included 20 watershed basins; a few local basins fell into the same watershed because of their proximity to one another. The sample basins are located in six counties of the central Puget Sound, South Sound, and Hood Canal: King, Pierce, Kitsap, Mason, Thurston, and Jefferson.

4.2.3. Land cover patterns

Land cover is related to important terrestrial near-shore functions such as hydrology and nutrient cycling (Leopold, 1968; Walsh, 2005). With the availability of remotely-sensed data, the characterization of land cover patterns and their use in ecosystem studies has grown. Land cover relates to both human activities on the land and responds to varying levels of development (Luck & Wu, 2002). It also has a greater spatial extent and more consistent and objective classification scheme than county tax assessor's land use data or zoning information. Furthermore, it is not limited by political boundaries. Since land cover relates to land use and influences important functions, it acts as an important link to the resilience of ecosystems (Alberti, 2010). While land cover has the advantages of spatial extent and relates well with human and biophysical features, it has some disadvantages. Many of the measures are scale dependent (Wu & David, 2002).

Land cover pattern was calculated based on a collapsed version of a 2006 23-class, 30-meter C-CAP land cover layer developed by NOAA based on LANDSAT-TM imagery of Washington State (National Oceanic and Atmospheric Administration, 2006). The 23 land cover classes were collapsed into six: high urban (high and medium urban combined), low urban (low urban and open space developed), agriculture (cultivated land and pasture), grass (grass and grasslands), forest (deciduous, evergreen, mixed, and scrub-shrub), other (all remaining classes including wetlands, water, unconsolidated shoreline, and bare land). The six land cover patterns were analyzed for composition. Forest was seen as representing the undeveloped landscape that exists in each watershed. High urban and low urban were seen as potentially different effects on the near-shore due differences in imperviousness across each class. It was also important to separate out any basins with large amounts of agriculture since this could likely be a confounding factor influencing water quality. Percent area of each land cover class was calculated and normalized by the basin area. The NOAA C-CAP data also includes an impervious surface layer, where each 30-meter pixel includes a value representing imperviousness. The values are from 0 to 100, where 0 is completely pervious and 100 is completely impervious. From this layer, the mean and standard deviation was extracted for each basin.

4.2.4. Quantifying On-Site Septic Patterns (OSS)

The spatial measures of on-site septic (OSS) patterns were required to meet three criteria: (1) that they were relevant to planning policy; (2) that the data was available for all parcels in each basin; (3) that they were able to be aggregated over large spatial extents.

Prescriptive guidelines typically set by county health codes tend to focus on lot size and residential density. These codes aim to keep OSS sparse and on larger lots (Curtis, 2008). In 2007, Washington State enacted a state-wide policy for the first time setting minimum standards for lot size for OSS based on the underlying soils and whether the residence is connected to a public source of water or their own individual well. Functioning septics also rely upon regular maintenance and proper operation. Drawing on research from the U.S., U.K. and Ireland, Withers et al. (2013) document that the performance of individual OSS vary widely from site to site mainly because of poor maintenance, improper installation and siting (Withers et al., 2013). In the absence of survey data on household maintenance and operation practices, the age of a septic system may be a good proxy for the maintenance of the system.

I selected four measures of OSS to characterize septic patterns (Table 4.1). The challenge in choosing measures to characterize the watersheds was in the need for a single value for each basin that accurately reflects the presence, arrangement, and management of septics in the basin. Because the values get aggregated across an entire basin, the potential importance of single hotpots of influence are diffused. To represent the overall presence of septics, I chose total number of septics, percentage of parcels that are on a septic system, and the percent area of the basin of parcels on OSS. I used the median percent of parcels as a cut-off point to classify each basin as either septic dominant or non-septic dominant. To characterize the spatial arrangement, I chose mean lot size and the mean kernel density. I did not have adequate data on the age of each septic. Different county and municipal databases record and track septic permits differently. Only Kitsap and Pierce counties tracked the year the permit was granted for the septic system. This maintenance variable was excluded.

Table 4.1: Land cover and septic pattern measures calculated for each watershed

Measure	Method
Percent of landscape	The percentage of pixels within each watershed comprised of the land cover of interest
Mean & standard deviation of Imperviousness	The average and standard deviation of the impervious values extracted from each watershed
Total count of OSS	Total number of parcels within each watershed on a known septic system
Percent of parcels on OSS	The percentage of parcels within each watershed on a known septic system.
OSS Dominance	Percent of parcels of parcels > median is classified as OSS dominant (1)
Mean lot size	The average lot size of parcels on a known septic system
Mean kernel density	The average density of parcels on a known septic system

The 20 watershed basins range from 3.2 to 85.5 km^2 in size (Table 4.2). On average, they contain low percentage of impervious surfaces (7.6% ± 8.8) with a range between 0.6% to 31.5% (Table 4.3). Overall, basins average 69% ± 19 forest cover with septic densities ranging from roughly 3 OSS per km^2 to over 89 OSS per km^2. Ten basins were classified as dominated by OSS and ten were classified as non-dominated.

Table 4.2: Summary of basins, N=20

Basin	Name	Basin scale Wet FC	Dry FC	Area km2	Percent of basin covered by land cover hiurban	lourb	agr	grass	forest	other	Imperv	Septic patterns # Septics	% parcels on septic	OSS domin	lot size acres	density #/ km^2
20072	Hood Canal #1	1.85	1.86	29.52	1.75	14.85	0.27	6.24	74.04	2.86	5.53	2175	83.49%	1	1.97	58.17
20272	Hood Canal #4	1.84	1.93	32.37	0.07	1.50	0.06	3.07	91.40	3.91	0.92	439	64.09%	1	8.53	9.06
20400	Hood Canal #8	2.75	2.18	9.55	0.28	1.30	0.13	3.00	92.00	3.30	0.85	387	83.23%	1	1.37	21.37
20463	Hood Canal #6	3.48	2.32	8.07	0.86	10.97	0.11	2.23	82.61	3.21	4.32	608	50.25%	1	0.94	57.71
21203	Dabob Bay	3.82	2.13	39.84	0.00	1.02	0.00	3.81	88.10	7.07	0.60	117	38.74%	0	8.24	2.89
30039	North Bay	4.24	7.17	85.74	0.44	4.28	0.05	1.95	84.35	8.92	1.69	1709	45.93%	0	0.68	18.45
30146	Vaughn Bay	3.26	4.85	14.15	0.73	5.48	0.56	6.67	78.89	7.67	2.38	212	25.51%	0	3.35	10.07
30406	West Key Peninsula	2.03	1.93	14.69	0.43	5.06	3.15	4.89	79.88	6.59	2.15	474	40.51%	0	1.98	26.45
30629	Oakland Bay	4.02	2.93	19.98	0.14	4.58	0.50	6.00	74.35	14.4	1.72	955	52.76%	1	1.29	31.15
30697	Hammersley Inlet	6.42	3.42	5.29	5.34	24.34	0.73	5.43	54.28	9.88	10.40	375	37.54%	0	1.95	59.62
30742	Hammersley Inlet	8.74	4.06	79.03	0.40	5.40	1.54	6.15	76.78	9.72	1.81	1332	51.41%	1	2.75	15.84
31276	Henderson Inlet	8.75	10.98	74.93	15.52	31.36	6.17	3.65	34.90	8.40	20.04	7347	45.57%	1	3.77	89.53
40145	Dyes Inlet	3.30	2.34	45.44	2.26	10.59	0.07	1.91	79.22	5.94	4.72	1598	58.73%	1	1.57	30.06
40154	Dyes Inlet	7.58	6.45	30.87	15.53	30.18	1.86	1.93	47.97	2.53	19.79	1750	51.52%	1	2.65	49.82
40206	East Passage	2.18	2.80	3.22	0.11	14.24	4.83	5.74	68.14	6.94	3.73	94	30.23%	0	0.68	13.87
40303	Colvos Passage	2.42	2.17	5.11	2.62	24.19	0.37	2.66	67.80	2.35	9.53	403	43.15%	0	0.84	55.77
40320	Yukon Harbor	2.60	2.53	9.79	4.74	38.22	0.34	2.95	49.43	4.31	13.18	1261	44.57%	0	4.25	84.16
40369	Colvos Passage	2.08	1.90	11.11	0.73	16.88	4.13	5.30	71.74	1.23	4.25	234	28.75%	0	0.41	16.76
40572	Poverty Bay	3.41	2.37	32.40	25.77	46.62	0.01	0.41	25.27	1.92	31.53	1555	8.98%	0	1.47	42.12
40615	Port Orchard Passage	2.51	2.19	16.98	6.96	31.50	2.21	3.57	53.29	2.46	13.21	1521	45.59%	1	0.87	66.00

Table 4.3: Summary statistics for water quality and landscape data

	Wet FC	Dry FC	km2	hiurban	lourb	agr	grass	forest	other	Mean Imperv	No. Septics	% parcels on septic	Ave lot size (acres)	density (num per sq. km)
min	1.84	1.86	3.22	0.00	1.02	0.00	0.41	25.27	1.23	0.60	94.00	0.09	0.41	2.89
max	8.75	10.98	85.74	25.77	46.62	6.17	6.67	92.00	14.43	31.53	7347.00	0.83	8.53	89.53
median	3.28	2.35	18.48	0.80	12.61	0.44	3.61	74.19	5.13	4.29	781.50	0.46	1.76	30.61
mean	3.86	3.42	28.40	4.23	16.13	1.35	3.88	68.72	5.68	7.62	1227.30	0.47	2.48	37.94
std	2.22	2.33	25.33	6.90	13.70	1.83	1.81	18.67	3.46	8.27	1580.98	0.18	2.28	25.73

4.2.5. Analysis Methods

Data analyses were based on non-parametric t-tests and linear regression. Since the geometric of fecal coliform is highly skewed to the left, the Mann-Whitney rank sum test was used to test the difference in fecal coliform between basins dominated by onsite septics and basins not dominated by septics (OSS vs. Non-OSS). The data was analyzed separately for wet and dry season. For the regression analysis, pairwise correlations and individual linear regressions were used to examine associations between water quality data, land cover and wastewater patterns. The influence of water salinity and basin size was also evaluated in order to assess the separate influence of land cover composition and on site septics in near-shore water quality (Table 4.4). In the regression analysis, the dependent variable was the geometric mean of fecal coliform and the independent variables were proportion of land cover composition (%LC) and pattern of onsite wastewater (OSS). I develop a series of apriori models to examine what land cover and wastewater variables best explain the variability in fecal coliform. Models are split by wet and dry season to evaluate whether influences among landscape factors differ based on rainfall.

$$FC = \beta_0 + \beta_1 (\%LC) + \beta_2 (OSS) + \varepsilon$$

- FC : Fecal Coliform
- %LC: Proportion of land cover composition
- OSS : Patterns of onsite septics

Table 4.4: Dependent, independent, and control variables for regression analysis

Dependent variable	***Independent variables***	***Control***
Wet seasonal FC	% High Urban	Salinity
Dry seasonal FC	% Low Urban	Basin area
	% Grass	
	% Forest	
	No. of OSS	
	Proportion on OSS	
	Density of septic	
	Lot size	

4.3. Results

4.3.1. Influence of septic dominance on water quality

Wet and dry seasonal fecal coliform data were evaluated for differences between basins dominated by septics and basins not dominated by septics. Results from a Mann-Whitney rank sum test show that differences across basins were not significant for either season (w=34, p-value 0.26 for wet; w=40, p-value 0.50 for dry). As a result, I cannot reject the null hypothesis that the geometric means of FC for basins dominated by septics and basins not dominated by septics have the same mean ranks. A visual inspection of the distribution of ranked means show that basins with higher averages in FC are dominated by septics (Figure 4.2). However, there are also a number of OSS dominated basins with very low averages of fecal coliform.

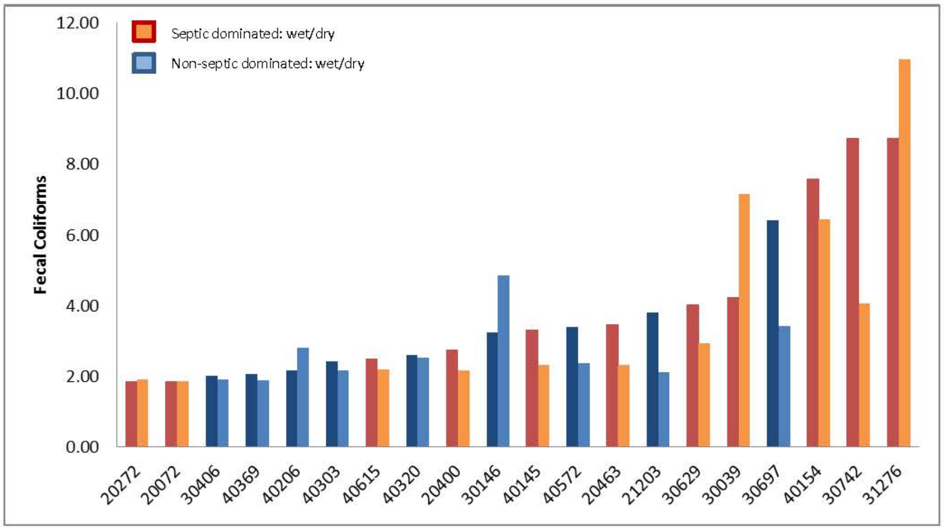


Figure 4.2: Ranked means of fecal coliform for basins dominated by septics and basins not dominated by septics. (Basins dominated by OSS in red/orange, basins not dominated in dark/light blue. Wet seasonal data in dark red & dark blue, dry seasonal data in orange & light blue.)

Pairwise correlations between all water quality and landscape attributes reveal covariance between fecal coliform and landscape variables and among the landscape attributes themselves (Table 4.5). The size of the basin has a strong positive association with fecal coliform. Among the wastewater pattern metrics, the number of septics has the strongest positive association with water quality while high urban and forest cover have the best, albeit moderate correlations with FC. Fecal coliform has a strong negative association with salinity during the wet season but less during the dry season. The density of septic systems is positively correlated with % low urban and negatively correlated with % forest. The density of septics was further investigated in relation to land cover patterns using regression analysis.

Table 4.5: Correlation matrix with water quality data and watershed attributes, n=20

	Wet FC	Dry FC	Area	Num Septics	%Parcel Septics	%Area Septics	Septic Density	High Urban	Low Urban	Agric	Grass	Forest	Other	Wet Salinity	Dry Salinity
Wet FC	1	0.69	**0.67**	**0.62**	-0.092	0.541	0.27	**0.30**	0.127	0.28	0.12	**-0.341**	0.54	**-0.659**	-0.606
Dry FC		1	**0.76**	**0.78**	-0.07	0.521	0.31	**0.30**	0.13	0.381	-0.21	-0.296	0.38	-0.461	**-0.397**
Area			1	0.58	0.055	**0.614**	-0.05	0.16	-0.146	0.068	-0.15	-0.012	0.345	-0.522	-0.491
Num Septics				1	0.062	0.798	0.62	0.52	0.371	0.471	-0.11	-0.53	0.164	-0.31	-0.304
%Parcel Septics					1	0.365	0.01	-0.5	-0.524	-0.29	0.27	0.571	0.006	-0.442	-0.496
%Area Septics						1	0.35	0.19	0.024	0.334	0.19	-0.161	0.128	-0.359	-0.409
Septic Density							1	0.5	**0.743**	0.147	-0.12	**-0.719**	-0.049	0.086	0.048
High Urban								1	0.811	0.105	-0.55	-0.882	-0.205	0.089	0.047
Low Urban									1	0.134	-0.4	-0.944	-0.326	0.404	0.351
Agric										1	0.34	-0.284	0.08	0.1	0.115
Grass											1	0.29	0.417	-0.107	-0.118
Forest												1	0.081	-0.216	-0.178
Other													1	-0.599	-0.518
Wet Salinity														1	0.965
Dry Salinity															1

4.3.2. Land cover pattern and septic patterns

There is a relationship between basin landcover attributes and septic patterns. Overall, low urban land cover and forest cover demonstrate linear relationships with the density of septic systems (Figure 4.3). In the case of low urban land cover, increasing the number of septics per square kilometers results in higher amounts of low urban cover. Conversely, an increase in the density of septics results in lower amounts of forest cover. As found in smaller coastal basins in the previous chapter, there is a non-linear relationship between the density of septics and mean imperviousness (Figure 4.4). The density is lowest in basins with low imperviousness (1-5%) and high imperviousness (>20%). Watersheds moderately covered by impervious surfaces (between 5-20%) contain the highest densities of septics with some basins containing over 60 septics per square kilometer.

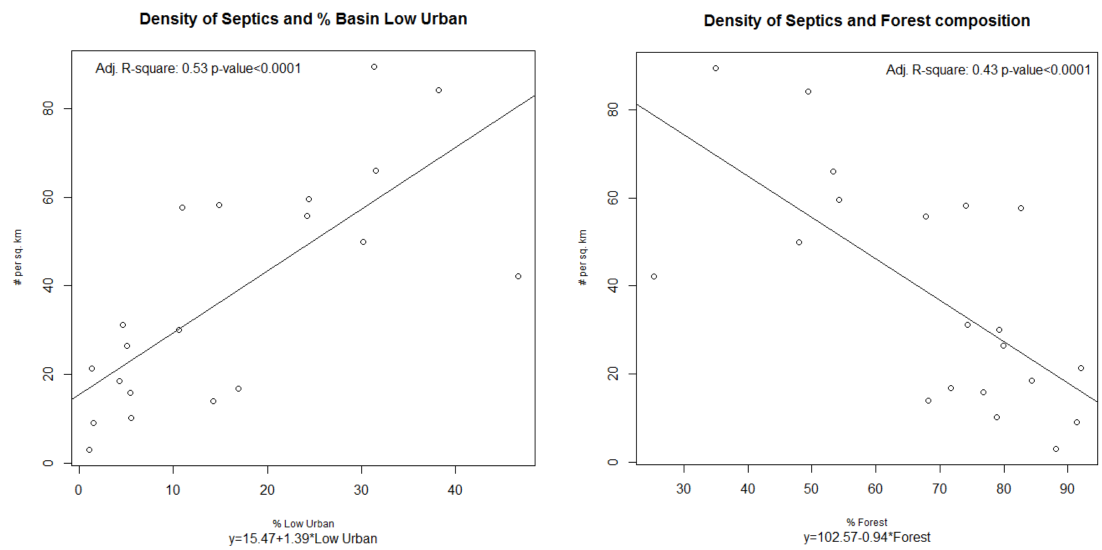


Figure 4.3: Regression results for septic density and land cover composition attributes

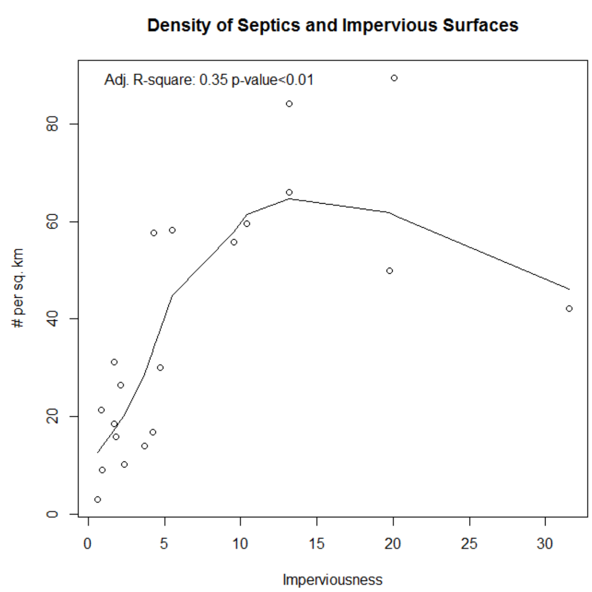


Figure 4.4: Regression results for septic density and mean imperviousness

4.3.3. Fecal coliform

Overall, I found weak results from individual regression analyses between fecal coliform and basin-wide landscape attributes (Table 4.6). Among the land cover pattern attributes, the only significant variables were the proportion of high urban land cover (r^2=0.16, p-value <0.01) and the proportion of forest cover (r^2=0.15, p-value <0.01) (Figure 4.5. These landscape variables were only significant for the wet seasonal data. Among the wastewater variables, the total number of septics was the best predictor of water quality for both wet and dry seasons (Figure 4.6). Several models were tested examining whether the total number of septics in a basin explained additional variability to either the urban land cover or forest cover variables. In all cases, when the total number of total number of septics was added to the model, the land cover variables were no longer significant. Overall, the best-fitted model was for the wet seasonal data and included High urban land cover and average salinity. This predictor model was f(FC)= 10.2+0.15*High Urban – 0.3 *salinity.

Diagnostic tests of the regression models between high urban land cover and fecal coliform reveal two larger outliers in the data set (points 11 and 19 in Figure 4.7). Poverty Bay (40572) has high amounts of urban land cover and above average density of septics but with relatively low FC (Table 4.7). Hammersley Inlet (30742) contains high amounts of forest cover and average numbers of septics, lower than average density of septics but very high fecal coliforms particularly during the wet season (Table 4.2). Results from regression analyses excluding basins 30742 and 40572 suggest the proportion of high urban land cover is a strong predictor of fecal coliform counts, particularly during the wet season (Table 4.6). The relationship also improves between % forest and fecal coliform, again showing a stronger signal during the wet season (adj. r^2=0.35, p-value<0.001) compared to the dry season (adj. r^2=0.16, p-value<0.01).

Table 4.6: Results from linear regressions between FC and landscape variable across all basins (n= 20) and with two basins removed (N=18). Results organized by wet and dry seasonal models.

	All basins, N=20				Two outliers removed, N=18			
	Wet R^2	p-value	Dry R^2	p-value	Wet R^2	p-value	Dry R^2	p-value
% High Urban	**0.16**	**0.084**	0.14	0.1	**0.68**	**0.0001**	**0.44**	**0.002**
% Low Urban	0.03	0.43	0.02	0.5	0.16	0.09	0.06	0.31
% Agric	0.07	0.23	0.12	0.13	0.09	0.2	0.11	0.16
% Grass	0.01	0.9	0.01	0.5	0.05	0.33	0.05	0.36
% Forest	**0.15**	**0.09**	0.1	0.15	**0.39**	**0.005**	0.21	0.058
% other	0.15	0.1	0.08	0.2	0.09	0.2	0.07	0.28
Total num. of septics	**0.34**	**0.006**	**0.47**	**0.0009**	**0.47**	**0.001**	**0.48**	**0.001**
%Parcels on Septics	0.001	0.887	0.01	0.67	0.01	0.67	0.02	0.5
Density of Septics	0.06	0.29	0.04	0.38	0.18	0.07	0.05	0.36
Total Area (km2)	**0.38**	**0.003**	**0.41**	**0.002**	**0.25**	**0.03**	**0.5**	**0.0001**
Wet Salinity	**0.32**	0.01			0.2	0.08		
Dry Salinity			**0.17**	0.1			0.17	0.1

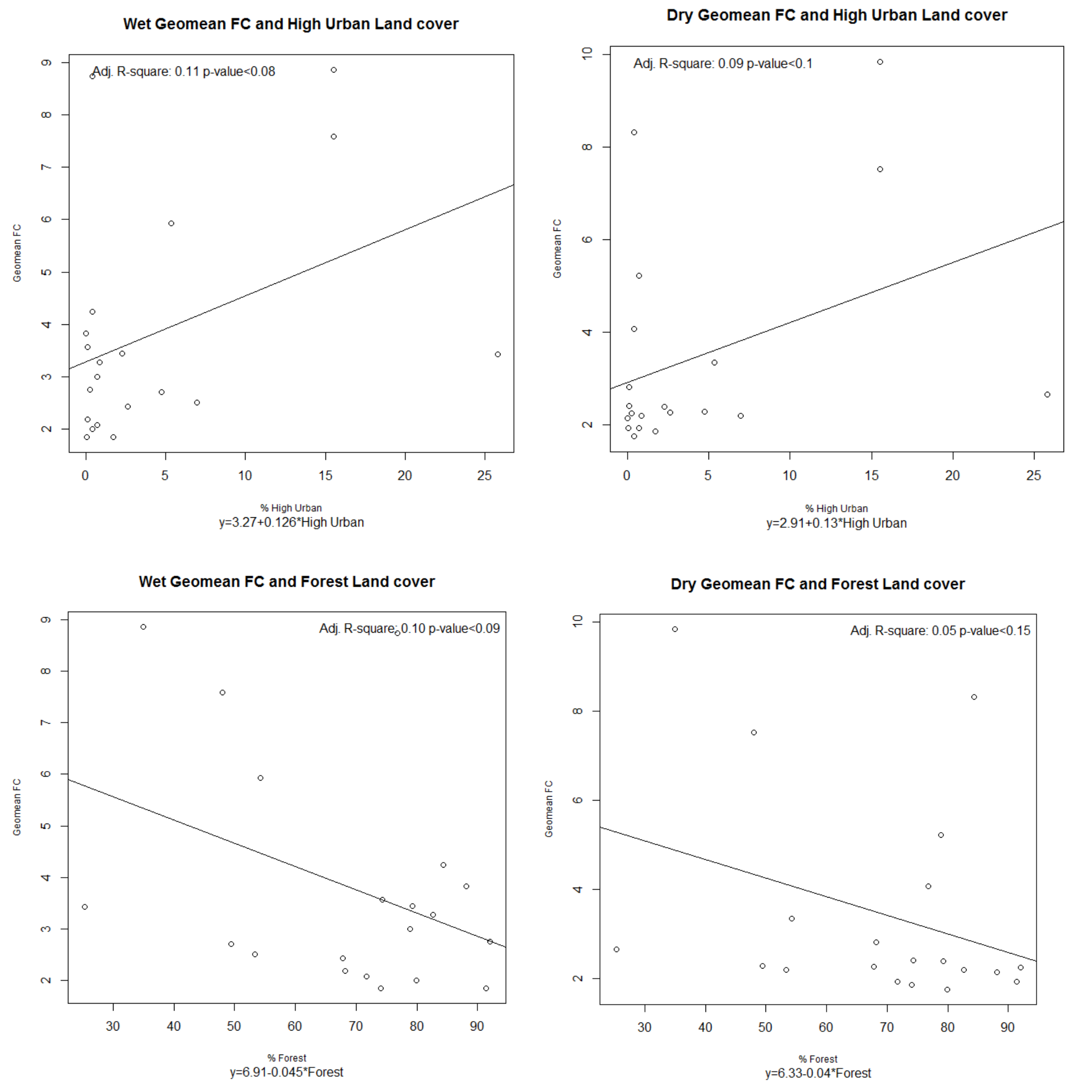


Figure 4.5: Regression plots between fecal coliform and land cover across all basins, N=20

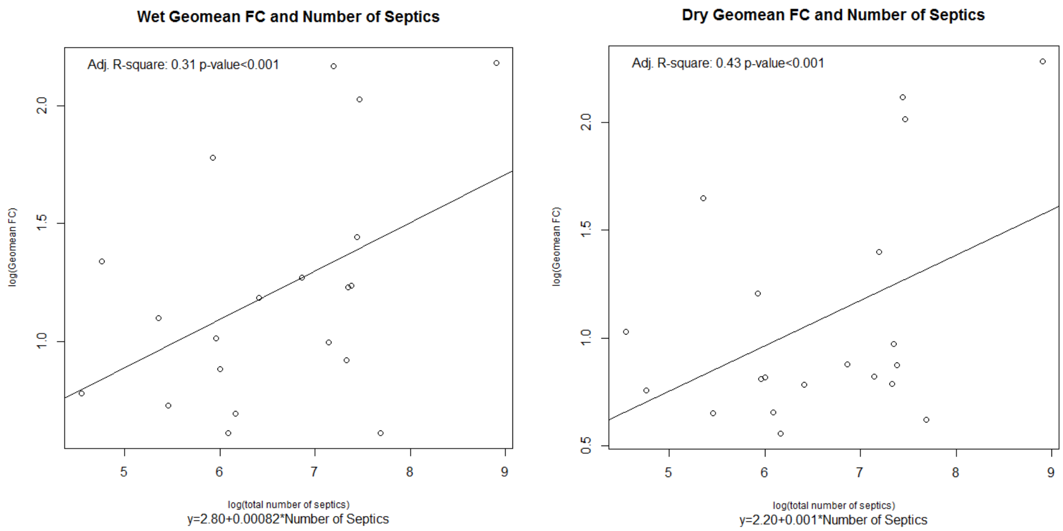


Figure 4.6: Regression plots between fecal coliform and number of septics on a log scale

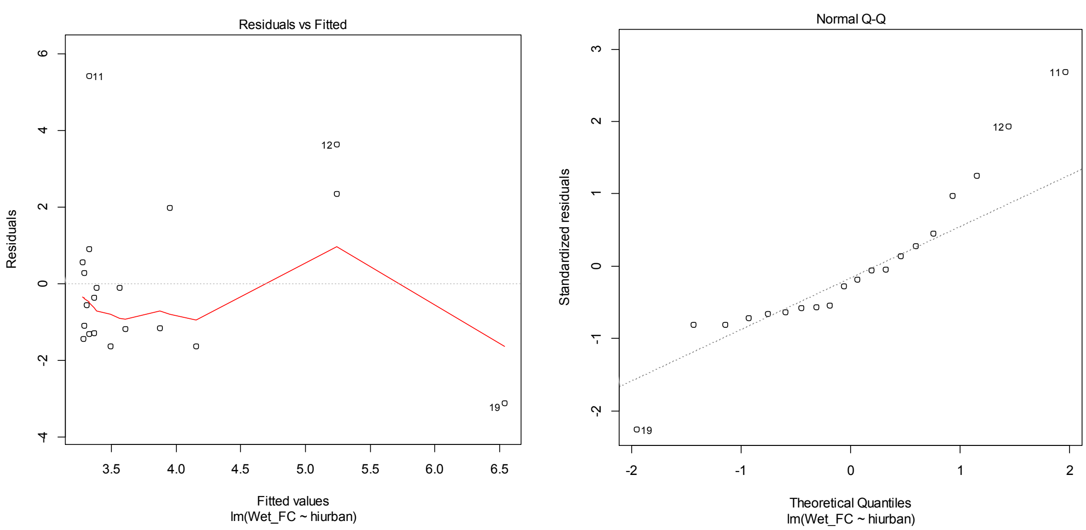


Figure 4.7: Residual vs fitted plot and Q-Q plot for regression between wet fecal coliform and high urban land cover

Table 4.7: Summary information of outliers

	Fecal Coliform		Septics		Impervious	Landcover composition – Percent Area						Basin Area
BASIN	Wet	Dry	Total num.	Density #/km^2	Mean %	High Urban	Low Urban	Agric	Grass	Forest	Other	km^2
Hammersley Inlet (30742)	8.8	4.1	1332	15.8	1.81±7	0.40	5.4	1.5	6.15	76.8	9.7	79.03
Poverty Bay (40572)	3.4	2.4	1555	42.12	31.5±23.5	25.7	46.6	0	0.4	25.2	1.9	32.4

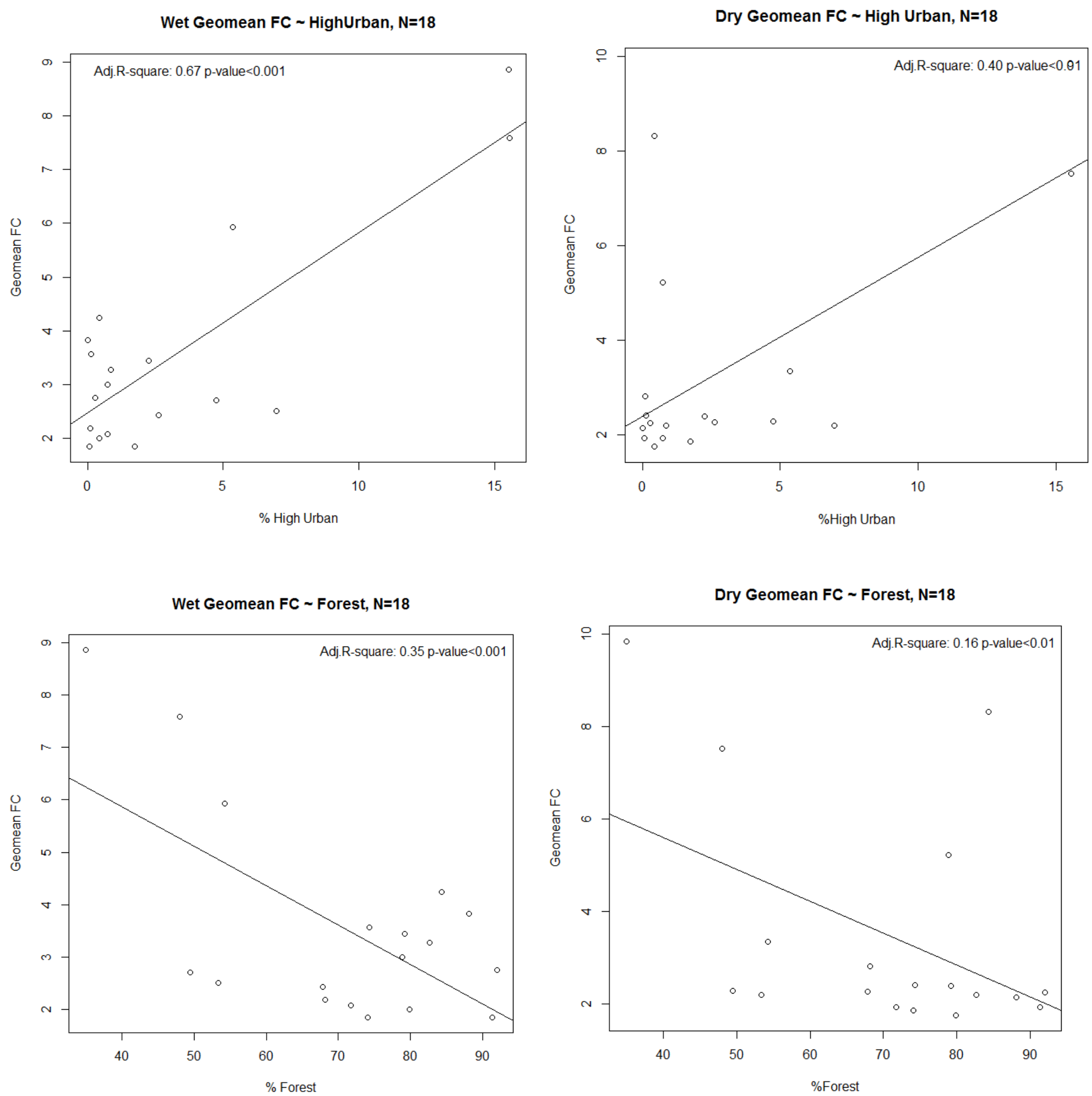


Figure 4.8: Regression plots between fecal coliform and high urban and fecal coliform and forest, outliers excluded, N=18

4.4. Discussion

A major goal of urban ecology is to understand the relationship between spatial patterns of cities and urban ecological processes (Luck & Wu, 2002). How heterogeneous patterns of development transform the underlying structure of the landscape to influence ecosystem function is an ongoing research agenda for many urban ecologists, landscape ecologists and planners. My research sought to explore the role of alternative wastewater infrastructures in mediating the effects of urban development patterns on coastal ecological conditions. The research builds upon past findings that urban land uses (DiDonato et al., 2009; Hatt et al., 2004; Holland et al., 2004) and onsite septic systems (Mallin et al., 2000; Withers et al., 2013; Yates, 1985) have separate and deleterious impacts on coastal ecosystems. No studies to date have explored the mediating role of onsite septics between landscape patterns and coastal water quality.

This discussion revolves around four findings that contribute to the role of alternative wastewater infrastructure in mediating development patterns on coastal water quality: (1) the role of high urban land cover (2) seasonality (3) the relationship between septic density and imperviousness; and (4) the complex role of onsite septics.

Confirming past research, it is the amount of high urban land cover that best explains water quality conditions for sensitive ecosystems such as shellfish. Despite the fact that basins within my sample contained on average just over 4 percent of their total area covered by high urban land cover, small increases in this land cover type have significant impacts on shellfish growing conditions. Impervious surfaces are a well understood impact on the hydrological function of a basin altering surface flows (Booth & Jackson, 1997; Leopold, 1968). Decreases in vegetation and soil compaction reduce the ability of a watershed to intercept, infiltrate and filter both rainfall and nutrients. However, high urban land cover is also associated with more stormwater and a well-connected stormwater drainage system (Walsh, 2004). Although this study did not estimate the connectivity of the impervious surfaces to the stormwater infrastructure, high urban land cover may serve as a reasonable proxy for the impacts of stormwater run-off. Therefore, in the Puget Sound, the response of water quality to high urban land cover should be expected.

On average, FC concentrations are not significantly different between wet and dry seasons. However, they do tend to be higher during wet season months for basins with higher amounts of urban land cover. This confirms prior research on the role of rainfall and storm events on estuarine conditions (Mallin, Williams et al. 2000; Mallin, Ensign et al. 2001). Mallin and others (2001) examined the role of rainfall on estuarine conditions and found correlations between rainfall events and fecal coliform events in watersheds with higher percentages of impervious surfaces. Shehane et. al. (2005) also reported changes in FC concentrations in streams during changing rainfall patterns suggesting the importance of impervious surfaces interacting with precipitation, particularly after periods of drought (Shehane, Harwood, Whitlock, & Rose, 2005).

It is in coastal basins with moderate amounts of imperviousness that have the highest densities of septic systems. This finding substantiates results from the second chapter regarding the higher than average counts and densities of septics in Puget Sound coastal suburbs. As basins urbanize, the density of septics increases up until a point. After that, basins are urban enough that they might convert to sewers. The average in densities should not, however, be interpreted as uniform across the entire basin. Rather, basins with high densities also have wide spatial variations where some areas contain clusters of septics intermixed by residential development with sewers. It is impossible to know from this research whether these clusters are significant or whether they are influenced by factors such as the year the structure or development was built.

This study did not find a significant difference in fecal coliforms between basins dominated by septics vs. non-septics. Although septics are suspected to be a main factor driving water quality conditions in shellfish growing areas, results from this study did not find enough evidence to suggest that a coastal basin dominated by septics is enough of a determining factor to influence shellfish growing conditions. However, results from the regression model did find the total counts of septic systems within the basin to be a significant variable. Surprisingly, this study did not find the density of septics to be an influential variable. This is surprising because the density of septic systems is thought to be a leading factor in the degradation of coastal conditions. And given that the density of septics were higher in moderately developed basins, it was a surprise to find that this pattern was not a significant variable explaining the water quality conditions for shellfish. However, in their examination of four different urban patterns (total impervious surfaces, connected impervious surfaces, unsealed roads, and septic density) and their association with the stream-dwelling amphipod *A. australis*, Walsh et al. (2004) found septic tank densities did not explain its presence or absence. Instead they speculated the some site-based wastewater systems may be contributing to pollution because of their age and potentially interacting with efficient drainage systems.

Examining the outliers more closely may provide a reasonable explanation for why this might be the case. These outliers show the complexities of on-site septics, their relationship with site specific biophysical conditions, and the socio-ecological dynamics that may influence their ability to function properly.

Hammersley Inlet in the south Puget Sound is a good case in point. The inlet is highly productive for both shellfish and salmonids. Shellfish is both a critical resource to the local economy, a popular recreational activity, and vital food and cultural resources to the local Squaxin tribe. This inlet located near the mouth of Mill Creek (Figure 4.9) is one of the shallowest and narrowest of all inlets in South Puget Sound. The inlet is approximately 6 miles long with an estimated surface area of 2.2 square miles. Mill creek is the major tributary draining Mill creek watershed into the inlet. The basin is roughly 79 square kilometers. On average, the basin contains very low amounts of intense urban cover (less than 1%) and most of the basin is covered by coniferous forest (over 78%). It also has, on average, a low density of septics (15.8 per km^2) well below the average across the entire sample of basins (38 per km^2). Yet it has proved highly sensitive to human impacts; this watershed had five exceedances of the 43/100ml water quality standard for shellfish conditions during the 2006-2008 study period. In 2006, the Washington Department of Health downgraded the shellfish harvest status. A 2011 Water Quality Improvement Report states that sources of fecal pollution are predominantly from nonpoint sources (Washington Department of Ecology, 2011). The Miller Creek watershed is dominated by timber harvest, low-density residential land uses and hobby farms. Miller creek, which feeds Hammersley Inlet is dotted with single family homes on septic systems. The watershed is also characterized by unconsolidated glacial material or compacted till; soils in which on-site sewage disposal systems function poorly. Despite the fact that there are low density septics in the watershed, it may be a few failing systems that are sited on poor soils that act as direct sources of fecal pollution through ground water to the marine waters. A number of factors contribute toward the failure of these systems: their age, poor or improper maintenance, incorrect usage (e.g. use of garbage disposals with them can cause failures), poorly constructed and inappropriate landscaping of the leach field (Environmental Protection Agency, 2010). All of these factors point to the complex socio-ecological dynamics related to onsite-septics and their role as a stressor in coastal ecosystems.

I hypothesize that as the total number of septics increase in a basin, the probability that there will be a few hot-spots of OSS failures also increases. The fact that the total count of OSS was the only significant landscape variable correlated with water quality, it may be that this is simply a proxy for potential problems with existing OSS. However, without information on age of the tank or on the maintenance and upkeep of the system, this is merely a guess. Withers and others (2013) speculate that failing OSS represent a hidden threat to water quality and stressors will be watershed-specific. The complexity of local combinations of soil, geological, and socio-economic factors make it challenging to tease out the relative role of OSS in relation to other urban related stressors on near-shore water quality. However the relative importance of social-economic factors such as a household's ability to pay for upgrades, knowledge about how the system functions and cultural factors may also influence OSS functioning.

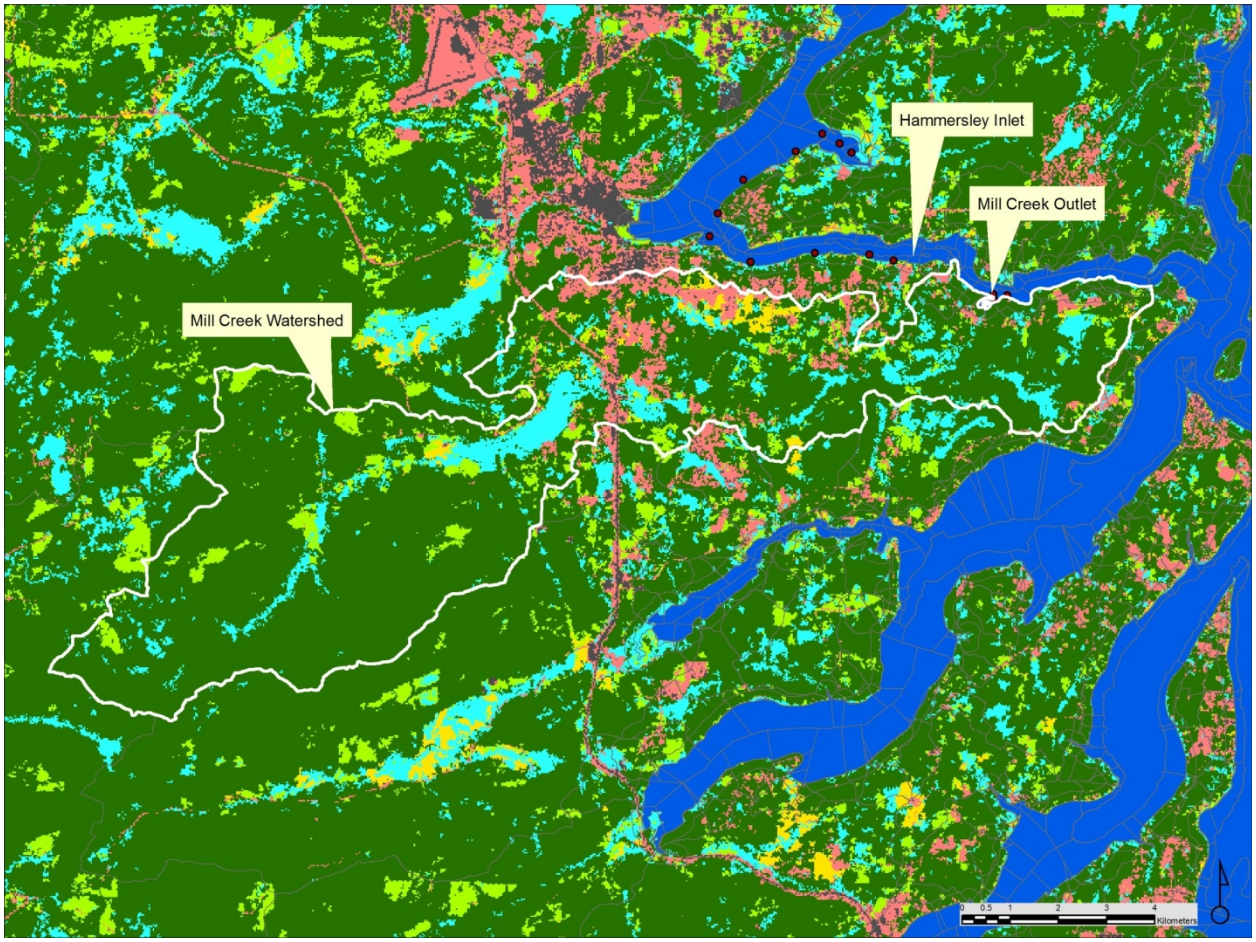


Figure 4.9: Mill Creek Watershed and Hammersley Inlet in South Puget Sound

There are several limitations to the approach used in this study. One challenge is matching the availability of water quality data in shellfish growing areas across the Puget Sound to an urban to rural gradient. This limited my sample size to 20 basins offering few degrees of freedom with which to separate the effects of landscape patterns and wastewater infrastructure. This challenge is found in other space for time substitution studies in urban areas (Carter et al., 2009).

The soil type is not included in the model due to limiting data across a large region. This may be an important confounding variable and more research is needed on this. Age of septic system may also be a key variable not assessed here. In future studies, this may be approximated by using the year built parcel database.

The largest challenge in this study was the small amount of variability in the fecal coliform data itself. This research could be further strengthened by collecting water quality data over time and examining for historical relationships between land cover change, wastewater and water quality. The National Shellfish Sanitation Program does collect WQ data over time, however the objectives of the monitoring program is tailored to the program rather than evaluating the influences of landscape patterns.

Chapter 5: Summary, Lessons Learned, and Future Directions

5.1. Overview

The Puget Sound near-shore is a dynamic environment that connects terrestrial, freshwater, and marine processes. It is also a rich setting where urban development is closely intertwined with near-shore ecosystems and thus provides an excellent setting for applying an urban ecological approach to coastal research. Adopting an urban ecological framework expands the opportunities for examining more explicitly the role of humans in the transformation of these landscapes.

My research sought to expand coastal watershed studies by examining the role of alternative wastewater infrastructures in mediating the effects of urbanization on coastal ecosystems. As such, I use a complex systems paradigm to evaluate the landscape pattern associated with two wastewater disposal types, centralized and decentralized treatment systems, and the ecological trade-offs that emerge. My research used spatial measures to describe the parcel-scale patterns of each system across a gradient of urbanization. Patterns of interest included their location, their abundance, density, and lot size. My research also examined their biophysical trade-offs relating patterns of land use and land cover with each disposal type. These patterns were used in the pursuit of two goals: (1) to examine the relationship between alternative wastewater types and landscape development patterns; and (2) to identify the relative role that alternative wastewater systems play in mediating the effects of landscape patterns on shellfish growing areas.

In this chapter, I summarize the major contributions of my research. The contributions can be organized by methodological advancements, complexity theory and hierarchical urban dynamics, complex systems and uncertainty, and contribution of urban ecological theory to risk management. Within these sections, I identify lessons applicable to a variety of audiences including coastal researchers, shoreline planners and managers, and public health officials. I conclude with future directions for the research.

5.2. Summary of Methodological Contributions

An important step in the conservation of critical near-shore habitats and the goods and services they provide is the identification of the dominant threat with sufficient specificity so that resource managers and planners translate this information into targeted responsive actions. The challenge in teasing out the relative impact of any one land-based stressor on coastal ecosystems is that stressors interact with socio-economic and biophysical patterns and processes at a variety of scales and these interactions produce non-linear and sometimes unexpected outcomes. Near-shore water quality is the result of the upland landscape structures, household behaviors, and social systems of the inhabitants within the geology, climate, hydrology and marine processes. Urban coasts are too complex to assign a single source of stress. However, identifying how the built infrastructure interacts with catchment processes offers insight into the complex ways that coastal urban-ecosystems function. Coastal researchers must aim to better understand how alternatives in wastewater infrastructure interact with the landscape to alter ecosystem functions. But in order to do this, they must integrate their views of these infrastructures as part of a dynamic process of urbanization. My research offers several ways for how we can study alternative wastewater infrastructures.

5.2.1. Spatial patterns of alternative wastewater infrastructures

The first approach is to examine alternative wastewater infrastructures across a gradient of urban to rural landscapes. Past research on the impacts of septic systems or sewers has examined each system separately by examining variables associated with one system or the other. Few studies to date with the exception of Walsh et al. (2004) and Harrison et al. (2012) have assessed both infrastructure types. The Environmental Protection Agency recognizes a wastewater management continuum, wherein a diversity of systems function to collect and process wastes from the household to the municipal scale (Environmental Protection Agency, 1997b). However, unlike other critical infrastructures, such as transportation networks, few of these systems are inventoried and organized into a regional or statewide sewage database. My research sought to systematically assess the spatial patterns of alternative wastewater infrastructures by collecting information at the parcel scale on their location and quantifying their patterns using metrics relevant to county planners and public health officials. These measures included parcel count, density, and lot size. By examining a variety of central and decentralized systems, their location and spatial distribution, researchers in the Puget Sound can begin to understand relative frequencies and distributions in urban, suburban and rural environments. They can also begin to hypothesize how these infrastructure systems interact with landscape structures to affect coastal ecosystem processes.

5.2.2. Definition of a coastal urban gradient

Researchers of urban ecosystems have recognized the challenge of defining what is urban both in conceptual and spatial terms (McIntyre, Knowles-Yanez, & Hope, 2000; Theobald, 2004). McIntyre et al. (2000) suggested using a more explicit quantitative definition that recognizes urban systems as heterogeneous mosaics. An urban to rural gradient is a suitable paradigm for defining an urban ecosystem and for measuring changes across an urbanizing area (M. McDonnell et al., 1997). It also serves as a useful framework for evaluating interactions among landscape patterns, the built infrastructure, and ecological processes (M. Alberti, 2008).

Gradients have been used in both the social and natural sciences to explain differences in land values, social structure (Park et al. 1925), species distributions (Whittaker 1967) and ecosystem function (Vitousek, 2004). Urban gradients have been defined by a distance measure from the central business district or based on aggregate values of population density, total amount of impervious area or housing density (Alberti, 2008). McDonnel and Pickett (1990) used a linear transect beginning in the dense urban core of New York city and ending in the rural outskirts of Litchfield, Connecticut to study changes in forest ecosystem structure and function in relation to varying levels of urban development. However, the urban landscape is far more variegated than these simple measures afford, involving a complex spatial pattern of high density built up patches intermingled with low-density patches and different types of infrastructures.

I adopted an approach based on Alberti (2008) to define a more complex urban gradient based on three socio-ecological variables that influence urban development in coastal environments: population density, slopes, and distance from urban centers and ports. This gradient is based on readily available GIS data and is constructed using Principle Components Analysis. One advantage of this methodology is that it allows researchers to define levels of urbanization that are explicitly separate from metrics used for measuring landscape patterns and structures such as land cover and housing density. This separates the independent variables from the variables used to define the urban gradient, thus avoiding the problem of confounding variables.

5.3. Complexity and hierarchy in urban near-shore ecosystems

By focusing on alternative wastewater infrastructures in the context of urban settlement patterns, the literature on complex systems informs our understanding of hierarchical urbanization dynamics. Urban ecosystems change and evolve over time as a result of socio-economic and bio-physical processes that interact dynamically across multiple scales (Alberti & Marzluff, 2004; Seto et al., 2012). The patterns that emerge across an urban region are the outcomes of multiple local interactions and feedbacks among households, developers, governments and ecological processes.

In chapter 2, I posit that the spatial distribution of alternative wastewater infrastructures vary across a coastal gradient in non-linear ways. One of the most simple, yet important findings of this study is that parcels that are served by onsite-septic systems are found in both higher counts and densities in suburban basins that drain into the Puget Sound near-shore. The planning literature assumes that septics are installed and found mostly in low-density and scattered rural communities (Berke et al., 2006). However, my research substantiates two other recent studies of septic systems across metropolitan regions that also found higher counts and densities in moderately urbanized suburban environments (Harrison et al., 2012; Hatt, Fletcher, Walsh, & Taylor, 2004).

For many communities, an on-site septic system is a more flexible and affordable wastewater management option than extending sewers, laterals and pump stations (Pinkham et al., 2004). The cost of sewers on the other hand can be prohibitively costly to many communities. It may be for this reason alone that communities choose decentralized systems to manage their wastewater. Why they are found mostly in suburban areas may be for two reasons. The first is that these communities were originally scattered rural developments. Some researchers contend that rural development is a fundamentally different typology from suburbia because of its reliance on septics and hence larger lot sizes (Heimlich & Anderson, 2001). Urban development is not a static event, however; it is a process that happens over time both in response to and as a driver of socio-economic interactions and biophysical processes (Alberti, 2003; Grimm et al., 2000; Pickett et al., 2008). Wastewater patterns may be path-dependent, determined by past and present development. In other words, the "suburbanization" of what were once rural communities fills in with developments on sewers in between a patch-work of former rural areas on older septics.

The second reason may be that suburban areas are developing as a patch-work of communities on sewers and onsite septics driven by both top-down and bottom-up processes. Harrison and others (2012) found in their longitudinal study of the Baltimore metropolitan region that septics were installed in new suburban developments despite the fact that these same areas were targeted for priority sewer funding. Land use policies that direct growth in areas with existing sewers are a key driver; however, the socio-economics of wastewater infrastructure may be just as influential. Whether there are more septics in Puget Sound suburban areas as a result of rapid suburbanization of areas formerly on older septics, or because areas are being developed with septics, or both, is hard to know. This would require additional information on the dates of these systems and relating that to surrounding urban land use change.

If an important challenge for ecological scholars and urban planners is to figure out how best to balance human function with ecosystem function in urban ecosystems, then choices in wastewater infrastructure may be a key component. Wastewater service is a necessary, if not essential function of all human settlements. Wastewater systems function by maximizing biological processes to efficiently break down wastes. Choosing among systems involves trade-offs with regards to cost, land use, and wastewater governance (Hanley & Hopkins, 2007; Harrison et al., 2012; LaGro, 1998; Pinkham et al., 2004). The resilience of urban ecosystems relies, in part, on agents in these systems having complete information on the trade-offs associated with wastewater systems and the ecological costs of replacing ecosystem services with human services (Alberti & Marzluff, 2004). My research sought to contribute toward the accumulated knowledge about these trade-offs to help inform wastewater management choices at the community and municipal scale.

A second important finding of my research is that coastal basins dominated by sewers and septics contain significantly different distributions and arrangements of land uses and land covers. This is an important finding because while we might find more septics in Puget Sound suburban areas, the decision to switch to a central sewer system may involve fundamentally different amounts and allotments of land uses and land covers. This research found sewers to be significantly correlated with highly developed urban land cover, urban land uses such as retail, service and commercial uses, the aggregation of high urban land cover, less amounts of forest cover, grass cover and the fragmentation of forests. Given what we know about the relationship between the cost of public infrastructures and development patterns (Burchell, 2005; Real Estate Research Corporation, 1974; Speir & Stephenson, 2002), it is not too surprising to find sewers associated with both the composition and aggregation of high urban land cover. One of the more surprising findings is that basins dominated by sewers are also more likely to have less amounts of forest cover and this forest cover may be more fragmented than basins dominated by septics.

The only research to date examining development patterns associated with wastewater infrastructure found septics to contribute toward the dissection of surrounding agricultural landscape (LaGro, 1998). While additional research is needed to corroborate my findings, this study points to the land cover and related ecosystem service trade-offs associated with central sewers.

5.4. Complexity and uncertainty in urban near-shore ecosystems

For some time, it has been hypothesized that the spatial configuration of urban development influences ecosystem dynamics (Alberti, 1999; Lynch, 1981). This is based on the assumption that different arrangements of the urban structure alter the biophysical structure of the landscape with consequences to the flows of energy, matter, and resources. However, urban landscapes also exhibit rich spatial and temporal heterogeneity. This can make it very challenging to identify the mechanisms that link urban patterns to ecosystem outcomes and induce considerable uncertainty. It has been argued that cross-scale interactions are key factors in driving changes in slow variables that push a system over an ecological threshold (Ernstson et al., 2010).

The distinct patterns of development between septics and sewers may represent fundamentally different development states. These states have important implications for watershed hydrology and the resilience of the coast to future disturbances. Results from my study found urban land cover to be a strong predictor of fecal coliform. The increase in impervious surfaces and replacement of vegetation as a result of urbanization is a well-known stressor of ecosystems (Leopold, 1968). The landscape scale pattern of septics in the Puget Sound complicates the picture. In my research, I hypothesized that the density of septic systems would explain additional variability to land cover composition in the indicator of coastal water quality.

However, I did not find the density of septics to be a significant predictor of fecal coliform counts in shellfish growing areas. While this may have been a result of the low variability of my response variable, other research has found a similar outcome (Walsh, 2004; Withers et al., 2013). Further analysis of the outliers of basins in the Puget Sound points to the complexities of onsite septics and their functional role at a finer scale: the household scale.

At the site scale, onsite wastewater treatment systems perform based on their interactions with the underlying soils, subsurface hydrology, climate and human actions. Soils play a key role in the removal of effluent pollutants before either entering surface or sub-surface waters. Biotic and abiotic factors include soil type, depth of soil horizons, physical and chemical characteristics of the soil and water table depth (Carroll et al., 2006). The mechanism of immobilization of viruses and pathogenic bacteria involve a combination of straining and adsorption (Siegrist, Tyler, & Jenssen, 2000). The treatment capacity also varies with disturbances. For example, large rain events or flooding may release nitrates from septic systems to surface runoff waters and lead to downstream contamination (Weiskel & Howes, 1996).

Households are responsible for the maintenance and operation of individual septics in terms of proper usage, routine cleanings, and appropriate landscaping for drainfields. Individual households are also accountable for replacing old or failing systems. Without regular upkeep and attention, these failing systems become point sources of contamination particularly in areas characterized as more “risky” due to the underlying soils or under certain climatic parameters. However, little is known about the social-ecological dynamics of wastewater management (Withers et al., 2013). For example, we do not know what socio-economic and cultural factors explain wastewater management behaviors at the household scale. At the neighborhood or watershed scale, no studies to date examine whether socio-economic or social structures explain clusters of performance or failures.

5.5. Application of urban ecology theory to risk assessment and management

Urban ecology as a field advocates for the integration of human and natural systems both as a research enterprise and, perhaps more importantly, for strategic decisions related to urbanization, investment in public infrastructures, and supporting important human ecosystem functions for long-term health and well-being. While increasing an integrated understanding between the linkages is important moving forward, local communities, shoreline planners, resource managers, and public health practitioners are challenged with the need to make practical decisions. The risk assessment framework has been identified as a useful approach for assessing and managing the risks of wastewater-related decisions (Carroll et al., 2006).

At *The National Research Needs Conference: Risk-Based Decision Making for Onsite Wastewater Treatment* (EPRI 2000), a series of white papers call for the adoption of a risk-based decision-making framework for assessment and management-related decisions related to the technology, planning and management of wastewater. In the first of the series, Jones et al. (2000) define a high-level integrated framework for risk assessment adopting a risk assessment model across four separate disciplines: engineering, ecology, public health, and socio-economics. The authors present and discuss the use of the risk assessment model for each discipline within the context of decentralized wastewater management decisions including problem formulation, analysis, risk characterization and management. While the framework is useful in laying out analytical steps and considerations in characterizing risks including the uncertainties associated with wastewater decisions, each risk model from the disciplines are treated separately. Within the engineering and ecology disciplines, simple models to more complex hydrological models exist to help characterize risks associated with wastewater technologies. Generally, these estimate and predict different nutrient and pathogen releases at a watershed scale (McCray, Poester, Murray, & Morgan, 2009). There are also models to estimate exposure and health risks associated with contact or consumption of water pollution. While there is discussion about the importance of spatial and temporal scales within each discipline there is a failure to acknowledge the integration of the human and biophysical components at multiple scales.

Integrating an urban ecology framework into the risk assessment framework involves examining the emergent patterns from linked human actions and biophysical processes across space and time at multiple scales. Spatial relationships of elements in the landscape can serve as an important focus for analysis to help understand how human actions modify both ecosystem processes and structures and their impacts on ecosystem functions in coastal shorelines. My study of wastewater infrastructures across the Puget Sound points to the dynamics of these systems across a coastal region and the importance of examining the interacting patterns of land use and land cover with wastewater choices. Considering the larger scale trade-offs in ecosystem functions allows for a more integrated approach for evaluating the risks associated with different wastewater infrastructure choices.

5.6. Future directions

5.6.1. Socio-ecological dynamics of alternative wastewater infrastructures

Urban ecology scholars argue that urban biogeochemistry is distinct from non-urban biogeochemistry because of the unique human controls in urban environments that regulate nutrient export and retention (Kaye, Groffman, Grimm, Baker, & Pouyat, 2006). Important studies emerging from Seattle, Phoenix and Baltimore show complex relationships between bio-physical processes and human processes that may generate unique biogeochemical effects (Groffman, Law, Belt, Band, & Fisher, 2004; Hall et al., 2009; Hutyra, Yoon, & Alberti, 2011). These studies show that alternative patterns of urbanization introduce new sources of nutrients and transform processes (climate, hydrology, and geomorphology) that effect nutrient cycling. Patterns vary both across cities and between cities because of interactions between the local bio-physical context and human actions across multiple scales. For example, some attention has focused on the role of residential lawns in urban nutrient fluxes and found they vary as sources of N and P, and they can act as hot spots for denitrification (Pickett et al., 2008; Raciti, Groffman, & Fahey, 2008). Comparatively little is known about the role of alternative wastewater infrastructures and how they mediate the biogeochemistry across an urban gradient.

I see my future research extending the approach used in this study to explore how patterns of wastewater infrastructures interact with biogeochemical processes to affect nutrient cycling. I would like to build a multi-scalar approach to examine the socio-ecological dynamics of wastewater from household to neighborhood to region. This requires relating nutrient fluxes with household socio-economics, cultural attitudes, and neighborhood attributes. In this way, a better understanding of the mechanisms by which wastewater patterns control nutrient outputs, and the link with social and biogeochemical processes can be explicitly examined and better understood. It is my hypothesis that household attributes such as income and cultural values, and neighborhood factors such as social stratification, housing turnover rate and seasonality may be better predictors of nutrient outputs than aggregate variables of septic numbers or densities. A better understanding of the socio-economics of wastewater management decisions can inform and support fair and socially equitable planning practice and policies.

5.6.2. Climate change

Climate change is recognized to be one of the main challenges to urban infrastructure, urban water, wastewater systems, and water resources in the coming decades (Cutter et al., 2014). Increases in water pollution problems due to warmer air and water temperatures and changes in precipitations patterns are likely to impact water resources with associated impacts to human health and aquatic resources. Extreme weather and disturbance regimes in the form of floods and large storm events are expected to impact water and wastewater infrastructure. Projections of sea-level rise and related inundations that will alter ocean and estuarine shorelines in the future present unique challenges to critical infrastructures on the coast (highways and wastewater treatment plants), as well as decentralized wastewater infrastructures (septics with drainage fields). Future climate variability in the form of droughts are also expected to change the availability of drinking water supplies, but may also reduce the ability of septic systems to process household-scale wastes (Prudhomme et al., 2012).

Despite the increasing understanding of climate change, there still remain questions and considerable uncertainty about the timing and scope of climate change impacts, especially at the local scale where most water, wastewater, and infrastructure-related decisions are made (Rosenzweig et al., 2011). Cities and metropolitan regions are beginning to develop adaptation plans, despite these uncertainties (Cutter et al., 2014). There are questions, however, around how best to adapt, and where to focus investment strategies and planning efforts given that traditional approaches to planning and management, which make assumptions about future conditions based on past climate variation, are no longer tenable (Milly et al., 2008).

There is growing consensus that planning strategies must be robust enough to cope with a wide range of possible conditions and provide flexible opportunities to adjust to a rapidly changing and uncertain future (Grimm et al., 2013; Wilby, 2011). Achieving sustainability and desirable futures will be an ongoing process rather than an end state. In the context of slow moving variables associated with climate change (e.g. sea level rise), it will be important to consider both fairness and the ecosystem service trade-offs of wastewater systems at multiple spatial and temporal scales.

I want to extend my research on wastewater systems and examine their role under alternative climate futures. As there are deep uncertainties related to climate change and other external factors (e.g. population growth, economic developments, new technologies, future policies, and societal perspectives and preferences), my research agenda involves using a collaborative framework that not only includes science-stakeholder processes but also local communities that have intimate knowledge on the dynamics of wastewater across multiple scales. I can see adopting a scenario planning process at a large regional or metropolitan scale involving key decision-makers in water and wastewater utilities, land use policy, conservation agencies, and real-estate development. At a local level, the role of decentralized wastewater infrastructure in a future climate may involve community governance structures that manage, inform, deliberate and monitor their performance and interactions with landscape structure, ecosystem processes and functions. An urban ecology study examining the future resilience of a coastal ecosystem will involve the community to measure the ecosystem health, examine present and future socio-ecological patterns and processes, the role of their wastewater infrastructures and practices, and how these elements interact and reinforce one another.

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