

Article

## Patterns of Wastewater Infrastructure along a Gradient of Coastal Urbanization: A Study of the Puget Sound Region

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Academic Editor: Andrew Millington

Received: 6 September 2015 / Accepted: 11 November 2015 / Published: 23 November 2015

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**Abstract:** The aim of this paper is to explore patterns of wastewater infrastructures (sewers vs. septic tanks) in urbanizing watersheds across a coastal metropolitan region. This research combines an urban-rural gradient with spatial metrics at the patch and watershed scale (proportion of parcels on a treatment system, septic density, lot size and percent imperviousness) to analyze wastewater patterns in the Puget Sound, WA, USA. Results show that most urban residential parcels are hooked up to a sewer, although there remain urban residences on a septic tank with small lots. I find a complex arrangement of wastewater treatment in suburban watersheds representing a patchwork of parcels on sewers and septic tanks. Sewers dominate in total numbers, while the density of septic tanks is highest in this portion of the urban gradient. Lot size decreases from rural to urban; however, it varies depending on the type of wastewater treatment system. In urban watersheds, lots on septic tanks are significantly smaller than lots in suburban and rural watersheds and of a similar size compared to lots on sewers. I also find a significant difference in the amount of impervious surfaces in watersheds dominated by sewers vs. septic tanks. In the urban portion of the gradient, the amount of paved surfaces in parcels with septic tanks is also similar in level as parcels with sewers. I discuss how these patterns emerge from the interplay of biophysical, socio-economic and technological factors and how different regulatory regimes for septic tanks and sewers may further induce these patterns.

**Keywords:** urban patterns; wastewater infrastructure; septic tanks; sewers; coastal urbanization

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## 1. Introduction

Coastal areas in the United States and in the world are experiencing some of the highest rates of population growth and land use change [1,2]. Coastal urbanization introduces new sources of pollution [3] and transforms natural landscapes [4–6], which effects the structure and function of coastal ecosystems [7,8]. As a result, urbanization and the human use of shoreline environments are associated with increased incidence of water-borne diseases from contact with polluted water and the consumption of contaminated seafood [9,10].

The treatment of sewage is critical for urban development, the protection of coastal water quality and ecosystem health. As shorelines urbanize, centralized and decentralized wastewater infrastructures are built to control the release of pathogens, viruses and other potentially harmful pollutants. Centralized wastewater infrastructures collect sewage from multiple sources and transport it through a network of sewers and pumps to be treated by a central plant before discharging effluent to surface and/or groundwater. Decentralized wastewater systems, also known as onsite wastewater treatment systems (OWTS), collect and treat wastewater from individual homes, clusters of homes and subdivisions at or near the point of waste generation [11]. Most OWTS consist of a septic tank and soil absorption field, although a range of alternative treatment technologies exist to process wastewater on site [12]. Since the passage of the Clean Water Act (1972) and subsequent environmental policies, sewers and wastewater treatment plants have improved coastal water conditions [13]. Despite this improvement, sewage and non-point sources of pollution continue to be leading causes of coastal contamination [9,14,15]. Studies identify pollutants from failing septic tanks, leaky sewer pipes, wastewater treatment plants and domestic and wild animal feces in stormwater run-off [16–18]. Efforts to formulate prevention measures are complicated by disagreements over leading stressors at the watershed scale. For example, there is evidence that septic density in watersheds with low amounts of urban development lead to contamination in coastal waters [19,20]. In suburban areas, urban land cover, impervious surfaces and septic density are also found to positively correlate with fecal pollution [21]. Other research has documented higher sewage contamination in sewered watersheds with urban development compared to unsewered watersheds with septic tanks and similar high levels of development [22]. Some suggest the effect of sewers and impervious surfaces can offset the gains achieved in controlling pollution from septic tanks [17,23]. These studies highlight the need to better understand how wastewater treatment systems (for example, sewers *vs.* septic tanks) relate to urban development patterns and coastal ecosystem function. A first step in understanding this relationship is to examine how wastewater infrastructures relate to the built environment and surrounding landscape patterns across a range of urbanizing environments. This paper addresses this first step by evaluating patterns of wastewater infrastructures and discusses the interacting socio-economic and bio-physical factors that influence their geographic location, patch attributes and the urban landscape patterns associated with different systems across an urbanizing coastal region.

To assess the spatial patterns of wastewater infrastructures, quantitative spatial analysis methods are needed. Among several approaches, an urban-rural gradient along with landscape analysis is useful for studying changes in patterns across urbanizing landscapes [24,25]. Researchers have used urban-rural gradients to represent a continuum of urban intensity and to study the ecological effects of urbanization [25–27]. Urbanization gradients also serve as a framework for assessing interactions

among landscape patterns, built infrastructure and ecosystem processes [28]. In this study, I employ a coastal urban gradient combined with landscape pattern metrics to characterize spatial patterns of alternative wastewater infrastructures across watersheds in the Puget Sound, WA, USA. I measure spatial patterns at the patch scale by extracting parcel-level characteristics regarding sanitation system, lot size and estimating parcel density and impervious surfaces for watersheds dominated by different wastewater systems. I investigate two wastewater treatment systems, sewers and septic systems, and address three research questions related to their location, patch attributes and associated landscape pattern: (1) How does the proportion and density of parcels on wastewater treatment systems vary across an urban gradient? (2) How does the lot size of parcels on different treatment systems change across the gradient? (3) How does the wastewater treatment relate to patterns of imperviousness? Identifying spatial patterns of wastewater infrastructures is an important step to understand how alternative development patterns relate to wastewater treatment. Understanding how wastewater infrastructures are distributed and relate to surrounding development across a coastal region is also 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.

## 2. Patterns of Wastewater Infrastructure

Scholars of ecology and urban planning have called on researchers to disentangle the role of wastewater infrastructure in the link between spatial patterns of urbanization and ecological processes [28,29]. Cities are highly heterogeneous landscapes made up of a range of development types and a mosaic of built-up and natural patches [26,30]. Alternative patterns of development contain different land uses with diverse arrangements of vegetation, impermeable surfaces and other land covers, with parcels that vary in size, shape and density [25,31]. Infrastructure is a defining feature of the urban landscape. Roads, drainage networks, sewers and septic systems introduce new geometries and land cover surfaces into the urban spatial structure [26,32,33] with consequences for hydrologic flows, nutrient cycling and aquatic ecosystems [16,17,29,34]. While it is clear that the degree of human impact on the landscape depends on the level and pattern of urban development, it is not clear what role wastewater infrastructure plays in mediating the impacts of urbanization on ecosystem functioning.

Few studies have specifically addressed development patterns associated with different wastewater infrastructures across an urban gradient. Some studies have examined the geographic distribution of different wastewater treatment systems in particular areas [32,35]. Harrison *et al.* (2012) [36] recorded the location and timing of residential development on sewers *vs.* septic tanks in the counties of the Baltimore region. LaGro (1998) [32] mapped the shape and size of residential parcels on septic tanks in rural Ozaukee County, Wisconsin. Hatt *et al.* (2004) [17] plotted the density of septic systems in suburban watersheds with a range of development using impervious surfaces and found a non-linear relationship. Sowah *et al.* (2014) [21] recorded the amount of impervious surfaces, forest, developed and agricultural land in suburban watersheds with high *vs.* low septic density. No studies, to the author's knowledge, have compared patterns associated with sewers and septic tanks across a range of urbanizing environments. In this study, I posit that spatial patterns of parcels with different wastewater treatment systems vary across a gradient of urbanization in complex ways. For instance, the proportion of sewerred parcels may increase linearly with urbanization, while the opposite may not hold true for

parcels on septic tanks. I expect the variation in lot size across an urban-rural gradient to display unique patterns depending on the wastewater treatment system. I hypothesize that parcels on sewers are primarily in urban areas, on small lots and with high amounts of impervious surfaces. I expect septic tanks, on the other hand, to be found in rural and suburban areas with low amounts of impervious surfaces, varying lot sizes and at varying densities.

### 2.1. Bio-Physical and Socio-Economic Factors

Wastewater infrastructure patterns emerge from the interplay of environmental, economic, technical, socio-cultural and political dynamics at multiple scales that evolve across and within an urban area [37,38]. Bio-physical conditions are a key consideration in the installation of wastewater systems [39]. At the same time, infrastructure decisions are also influenced by economics, sanitary infrastructure policies and public health regulations [37]. I summarize from existing literature key factors focusing primarily on bio-physical constraints, cost considerations and U.S. policy that either limit or induce the installation of sewers and septic tanks at the patch or parcel scale. I link how these factors influence their locations on an urban gradient and influence spatial attributes at the patch scale, namely lot size, density and impervious surfaces. I also discuss the role of technology and social acceptability in the adoption of alternative wastewater treatment systems.

#### 2.1.1. Bio-Physical Factors

Geology, topography and the water table are key constraints to the location, siting and installation of sanitary systems [11]. Local environmental conditions control the location and suitability of septic tanks. Most important are soil permeability and depth to water table [40]. Sites characterized by a high water table, shallow bedrock, too slow or too porous soils are considered unsuitable for septic systems. In areas with marginal soil conditions, larger lots are necessary for adequate drainage and the treatment of nutrients and pathogens. Topography, water availability and the presence of waterways also influences the siting and physical form of both septic tanks and sewer networks.

#### 2.1.2. Sanitary and Infrastructure Policies

Sanitation policies regulate all onsite wastewater systems, including septic tanks, with the primary objective of protecting water quality and public health. Health departments encode siting requirements that include prescriptive rules based on soil permeability, lot size and distance from water sources. Health codes generally require enough space for a drain-field and effective effluent treatment. In the U.S., some have argued that these sanitary codes act as a *de facto* growth control by communities that either exclude entire areas as developable lands or by using them for large-lot zoning [41–43]. As a result of these health codes and underlying environmental conditions, septic tanks are commonly perceived to primarily serve scattered rural or low-density areas. Alternative technologies with more advanced treatment capabilities may facilitate the installation of septic tanks on more marginally-suitable lands and at higher densities [35].

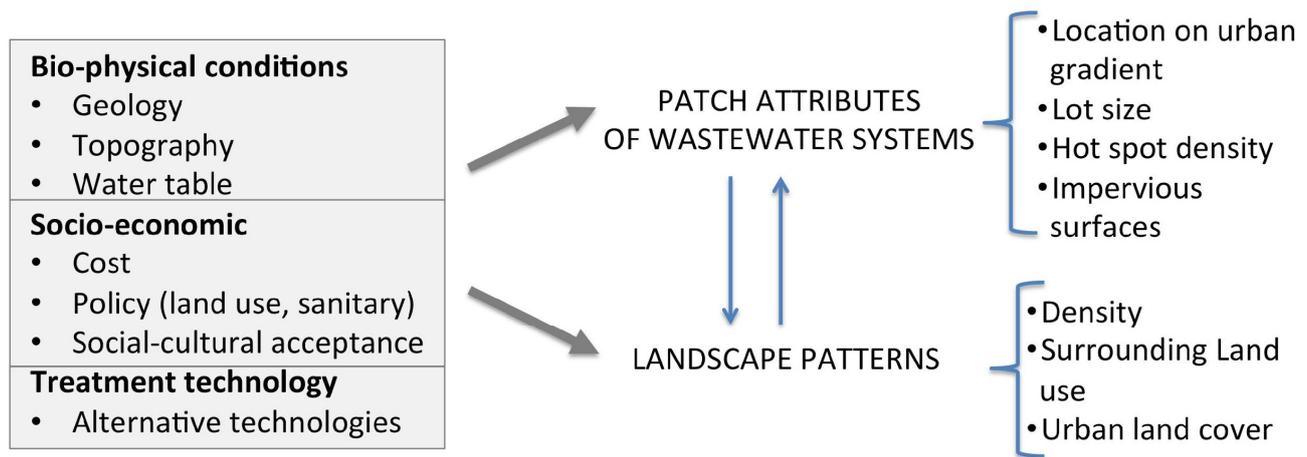
Sanitary infrastructure policies aim to direct development and the extension of sewers. Different states and regions in the United States adopt policies that function as implementation and phasing

mechanisms that aim to promote development in designated areas and to avoid haphazard sewer extensions [44]. These policies either mandate it through the use of urban growth boundaries or incentivize it by targeting public spending for sewers within designated urban areas. For example, local jurisdictions in the United States have employed adequate public facilities ordinances (APFO) designed to link urban development to the extension of a public sewer [44,45]. At the state level, Washington adopted the Growth Management Act (GMA) in 1990, which requires county governments to work with cities to direct urban growth by requiring adequate infrastructure [45,46]. Similarly, Maryland approved its Priority Funding Area (PFA) program in 1997 to encourage local governments to focus all new development within specific PFA areas. The effectiveness of these policies, however, is uncertain. In a recent study of five counties surrounding Baltimore, Maryland, Harrison *et al.* (2012) [36] found that since the passage of the law, a significant proportion of new development with septic tanks occurred inside PFAs.

### 2.1.3. Economic Factors

Cost is also a major constraint [47]. Cost constrains the location of sewers and the conversion of old septic systems to sewers. The planning literature indicates that sewer infrastructure costs are sensitive to development patterns [48–51]. Sewer systems are more economically efficient and achieve higher economies of scale in compact urban areas with small lots. Dispersed patterns with larger lots require longer sewer mains and incur higher costs to local governments and residents [51]. Cost also influences the ability for households to convert older septic systems to sewer. This constraint might explain why many older neighborhoods in the U.S. still contain legacy septic systems that were built decades ago or even earlier during the postwar era, when suburban developments proliferated [43]. In the city of Olympia, in Thurston County, WA, for example, there are nearly 2000 septic systems in the city's sewer service area, many of which were installed before public sewers were constructed [52]. According to a study by the Olympia Wastewater Utility, the estimated cost to convert a home on a septic system to a public sewer can range from \$4000 to \$36,000 in construction expenses alone, depending on proximity to existing sewers [52].

While these factors are important for the selection of wastewater treatment, it is also vital to recognize the significant influence of the social, cultural and political context within which treatment decisions are made [53]. Some communities reject proposals to construct sewers, even as a solution to mitigate failing septic systems, based on the concern that sewers enable high density development and spiraling utility costs [35]. At the same time, household preferences for rural and suburban living and development pressures for additional housing creates a market demand for development beyond existing sewer systems. Figure 1 presents a conceptual framework that links the interplay of socio-economic, biophysical and technological factors to the location and spatial pattern of wastewater infrastructures. This framework identifies and organizes factors that determine the location, patch attributes and distribution of wastewater treatment systems across a region. The “patch attributes of wastewater systems” specifies parcel characteristics, such as a parcel's location on an urban-rural gradient, lot size, density and amount of impervious surfaces. “Landscape patterns” refer to the surrounding urban matrix of the built environment at a neighborhood or sub-watershed scale.



**Figure 1.** Conceptual framework of the regional-scale pattern of development associated with wastewater infrastructure, adapted from Spirandelli (2014) [54].

### 3. Materials and Methods

The approach I describe here builds on urban gradient studies [24] and previous research quantifying urban landscape patterns [25,26,55]. A commonly-used technique to characterize urban gradients has been the transect approach, which defines a linear distance from the urban core to the rural outskirts [25,56]. This approach assumes a monocentric model of the region, where a central urban core is surrounded by concentric rings of development. The Puget Sound coastal region is not made up of one major urban center, but instead of several urban centers and ports, including Seattle, Everett, Tacoma and Olympia (Figure 2). In contrast to the transect approach, I build off an approach developed by Alberti (2008), to construct a more complex urban gradient that explicitly takes into account social and natural processes driving coastal urban development. To quantify spatial patterns of wastewater infrastructures across an urban gradient, I estimate and summarize select parcel-scale spatial attributes most relevant to alternative wastewater infrastructures. Namely, I quantify the number of parcels on a wastewater system, lot size, “hot spot” septic density and percent imperviousness, and summarize these at a sub-watershed scale (Table 1). I use a coastal urban gradient to examine differences and change in patterns across a metropolitan coastal region and in relation to urban development.

#### 3.1. Study Area and Data Description

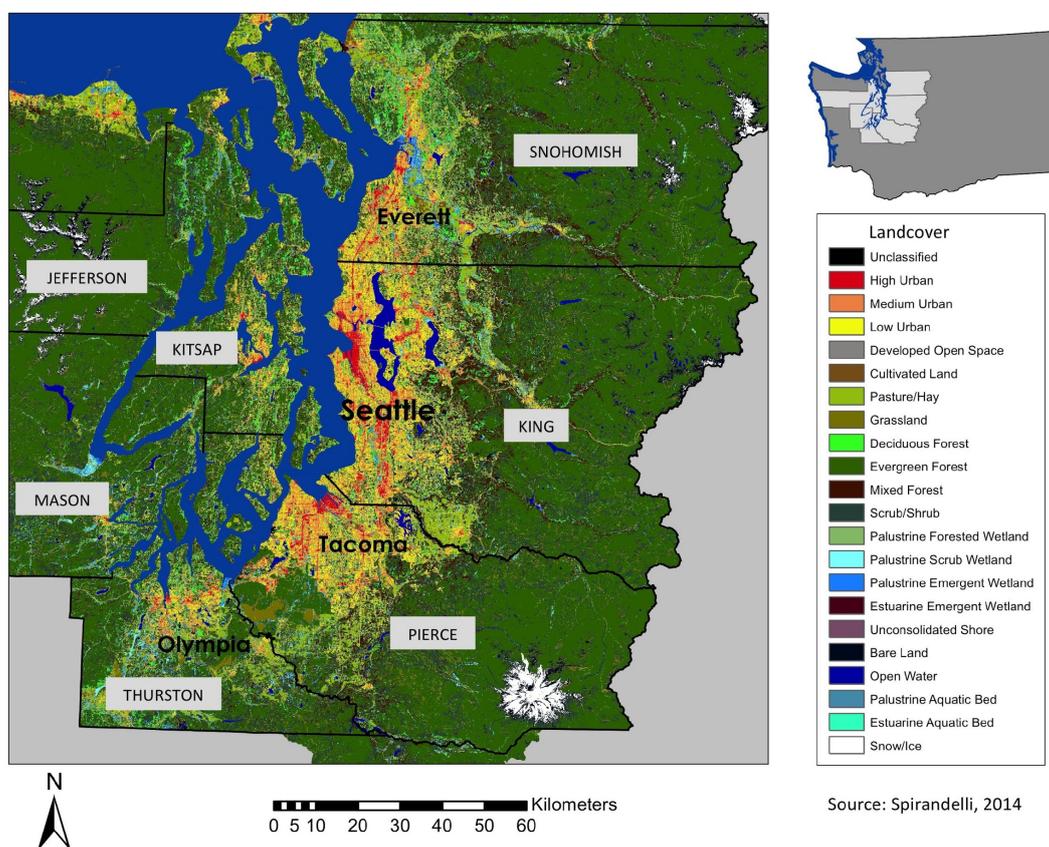
##### 3.1.1. Study Area

The Puget Sound metropolitan region is located in Western Washington and comprises 12 counties in total, of which this study focuses on seven with varying land uses and population density (Figure 2). The underlying geology and soil types in the Puget Sound region are mainly the result of the last glacial period, roughly 15,000 years ago [57]. The majority of watersheds in the region are dominated by poorly-drained glacial till and moderately well-drained glacial outwash soil types.

In 2010, there were just under 4 million people residing in the region, and it remains one of the fastest growing coastal areas in the United States [1]. The state is ranked fourth in leading U.S. coastal population

growth, with most people settling around the shores of the Puget Sound. Rapid urbanization in the region is the leading driver of land cover change. To accommodate growing populations, coastal areas have rapidly transformed into suburban and urban environments, with land-based pollution impacting the health and ecosystem function of the estuarine environment. The rate and scale of urban development and associated wastewater needs has resulted in a patchwork of wastewater treatment, which presents a unique opportunity to examine their spatial configuration across an urban-rural gradient.

In 1990, Washington State established the Growth Management Act (GMA) that directs all new development within urban growth boundaries. The GMA requires fast growing counties and their cities to develop comprehensive plans and to designate urban growth areas (UGA), with all new developments inside those boundaries to be connected to a public sewer system. However, counties can approve the installation of septic systems on either new developments or subdivisions within urban areas subject to the evaluation by the local health department [58]. Local health officers establish, for example, a minimum lot size based on soil conditions and water supply (private well vs. public).

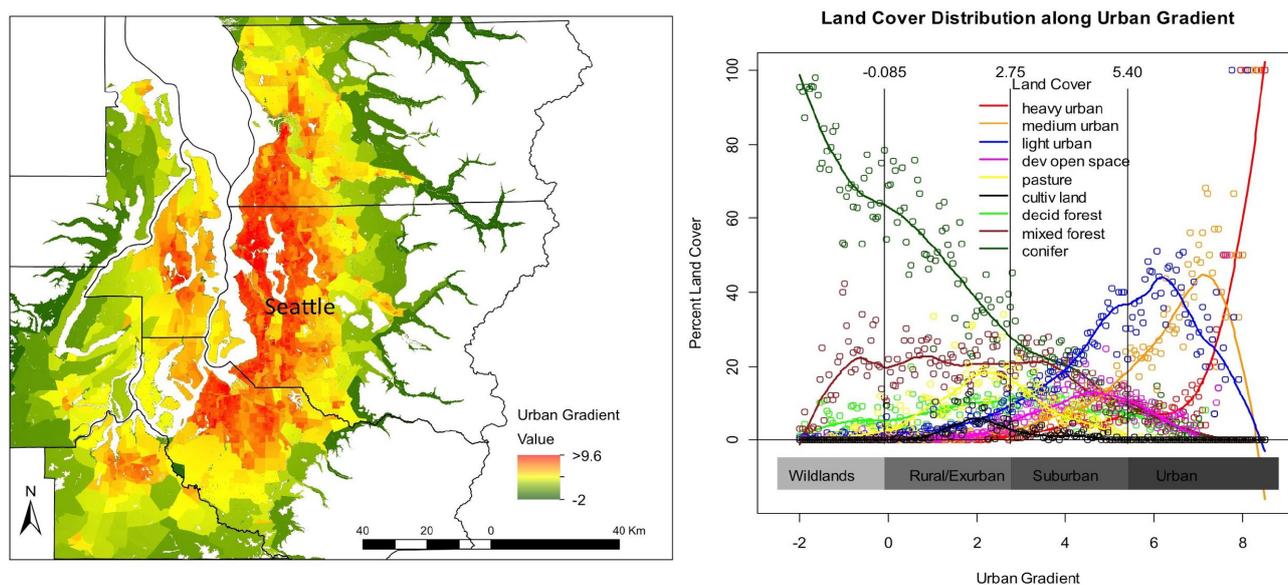


**Figure 2.** The study area includes seven counties of the Puget Sound, WA, estuary.

### 3.1.2. Sampling of Coastal Watersheds across an Urban Gradient

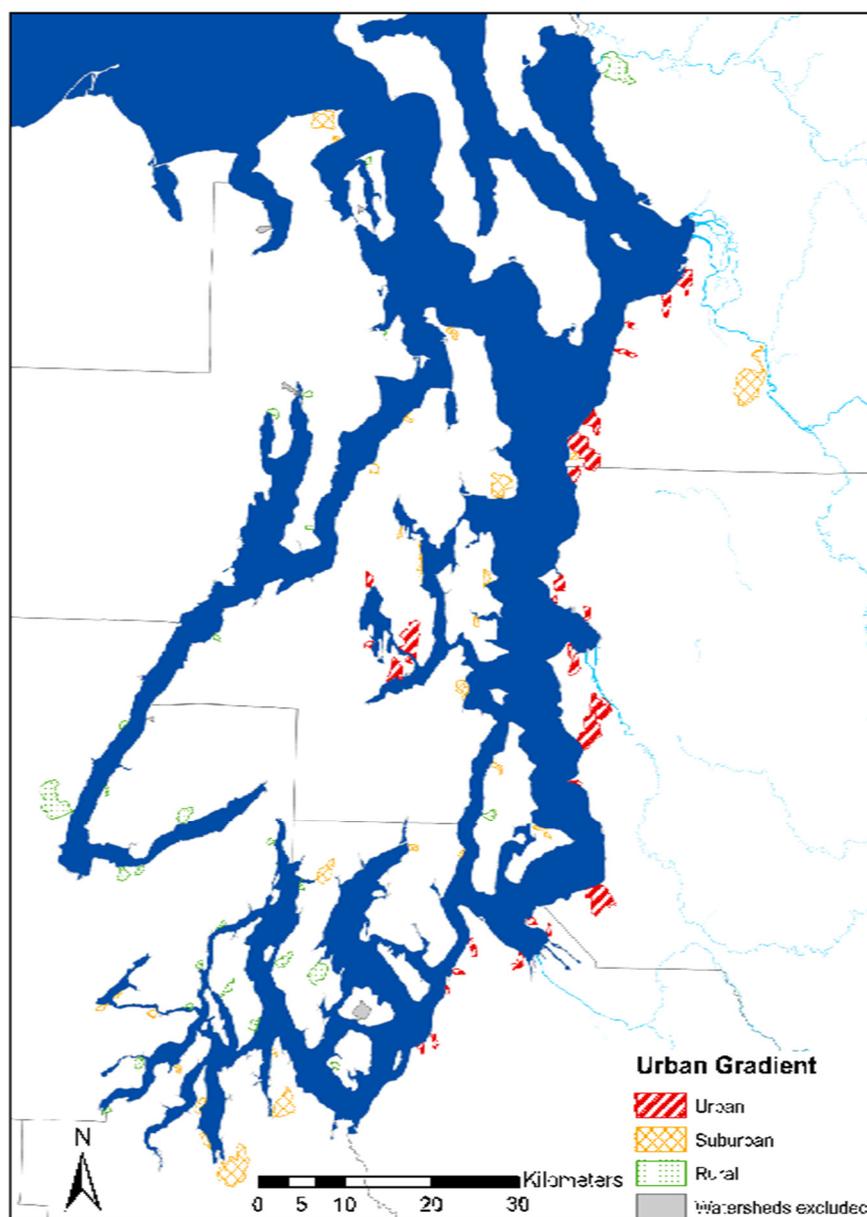
Coastal watersheds were selected from a spatial database developed by the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP). This database contains small watersheds draining upland areas directly into the Puget Sound. The data were developed to support research on human-induced changes and ecosystem decline along Puget Sound’s shoreline [59].

I stratified the watersheds by “urban”, “suburban”, “rural/exurban” and “wildlands” using a constructed urban-rural gradient (Figure 3). Adapting Alberti’s (2008) methodology, I develop a coastal gradient that explicitly takes into account urban centers and port cities, population density and slope. I use publically-available GIS data on population from the 2000 U.S. Census, slopes derived from a digital elevation model (DEM) and location of ports and urban centers from the Puget Sound Regional Council. I randomly extracted 10,000 data points from each layer and log transformed each layer. Using principle components analysis, I re-expressed the layers as a linear combination and into an urban-rural gradient index. Eigenvectors from the first component (PC1) were used to construct the index, which retained 74% of the variation of the original data. The final gradient index was mapped and expressed as a range from 10 representing areas that are most urban to  $-2$  representing wildland areas. The continuous gradient was subsequently partitioned into four discrete classes, “urban”, “suburban”, “rural” and “wildlands”, using the distribution of 2006 C-CAP Washington State land cover data from NOAA’s Coastal Change Analysis Program (C-CAP) [60]. I selected cut-off points for each gradient class by visually observing the distribution of land cover across the gradient index values (Figure 3). Break points were determined between urban and suburban classes based on the peak distribution of light urban land cover. I field checked land uses, such as major office complexes, with lower density populations and classified these as suburban. The break between the suburban and rural/exurban class was determined based on the distribution of pastureland and cultivated land across the two classes. The break was identified between the two classes at just below the peak of the pastureland and near the trough of the cultivated land. The break between rural and wildlands was determined based on the transition between mixed-forest cover and coniferous forest where wildlands represent a dominant alpine coniferous forest. Identifying appropriate break points between classes was an iterative process visually comparing class break locations (e.g., division between “urban” and “suburban”) on the gradient map with areas of known land uses using high-resolution digital ortho-photos (1-meter resolution) [61].



**Figure 3.** Map of the urban gradient with land cover distribution. Gradient index ranges from 9.6 (most urban) to  $-2$  (wildlands). Source of map and graph: Spirandelli, 2014 [54].

All PSNERP watersheds were classified as either “urban,” “suburban” or “rural” using the gradient map. Watersheds in the “wildlands” portion of the gradient were excluded from the study, since the objective of this project was to identify parcels on wastewater treatment systems in urbanizing watersheds. A choropleth map was created (Figure 4) by intersecting the PSNERP watersheds with the gradient map and classifying each watershed based on the amount of area dominated by one of the three classes. If fifty percent or more of the watershed’s area was dominated by one of the gradient classes, it was labeled as such. For example, if a watershed contained 60% “urban”, 25% “suburban” and 15% “rural,” it was classified as an urban watershed. A stratified random sampling routine was employed to select 30 urban, 30 suburban and 30 rural watersheds [62].



**Figure 4.** Location of 90 sampled coastal watersheds across the study area. Each watershed was classified as urban (30 watersheds), suburban (30 watersheds) and rural (30 watersheds). Five watersheds were removed from the sample because they lacked wastewater treatment.

### 3.2. Watershed Analysis

#### Spatial Metrics

Data records with information about parcels on a septic or hooked up to a sewer system was collected from local public agencies, including county departments of health, tax assessors, public works, utilities and city service departments. Details on data sources, location information and year collected are provided in the Supplementary Material. Wastewater treatment location data were spatially joined with the Washington State Parcel Database [63]. I calculated five spatial metrics at the parcel scale and summarized them at the sub-watershed scale (Table 1). Four measures are patch attributes of parcels on a wastewater treatment system, either septic or sewer. The first two measures are the number of parcels and the proportion of parcels in a watershed on a sewer or septic tank to determine the relative dominance of residences on a treatment system. Parcel lot was extracted from the Washington State Parcel Database. I calculated lot size because it may be a constraining factor with regard to the choice in treatment type [40,50]. The fourth metric identifies “hot spots” of septic intensity using a kernel density estimate (KDE) in ESRI’s ArcGIS Spatial Analyst 9.3. The KDE uses a quadratic function to produce a smooth density surface of points over space by computing point intensity as density estimation [64]. I calculated clustered “hot spots” using a radius of 1 kilometer around points of known septic tanks. The fifth metric, percent impervious, is a measure of urbanization. The percent area covered by impervious surfaces is strongly correlated with population density and is a well-documented environmental indicator [5,6,65]. Previous studies have shown that impervious surfaces increase run-off volumes, enhance the transport of pollutants and alter biogeochemical processes that cycle nutrients [66–68]. As such, the metric is a useful urban development pattern. I derived information on imperviousness for parcels on a wastewater treatment type using classified Landsat TM data from NOAA’s C-CAP 2006 land cover data [60]. The mean percent impervious was extracted for parcel location with either a septic system or sewer.

I use several non-parametric tests to assess differences across groups. The Kruskal–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 watershed 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.

**Table 1.** Spatial metrics.

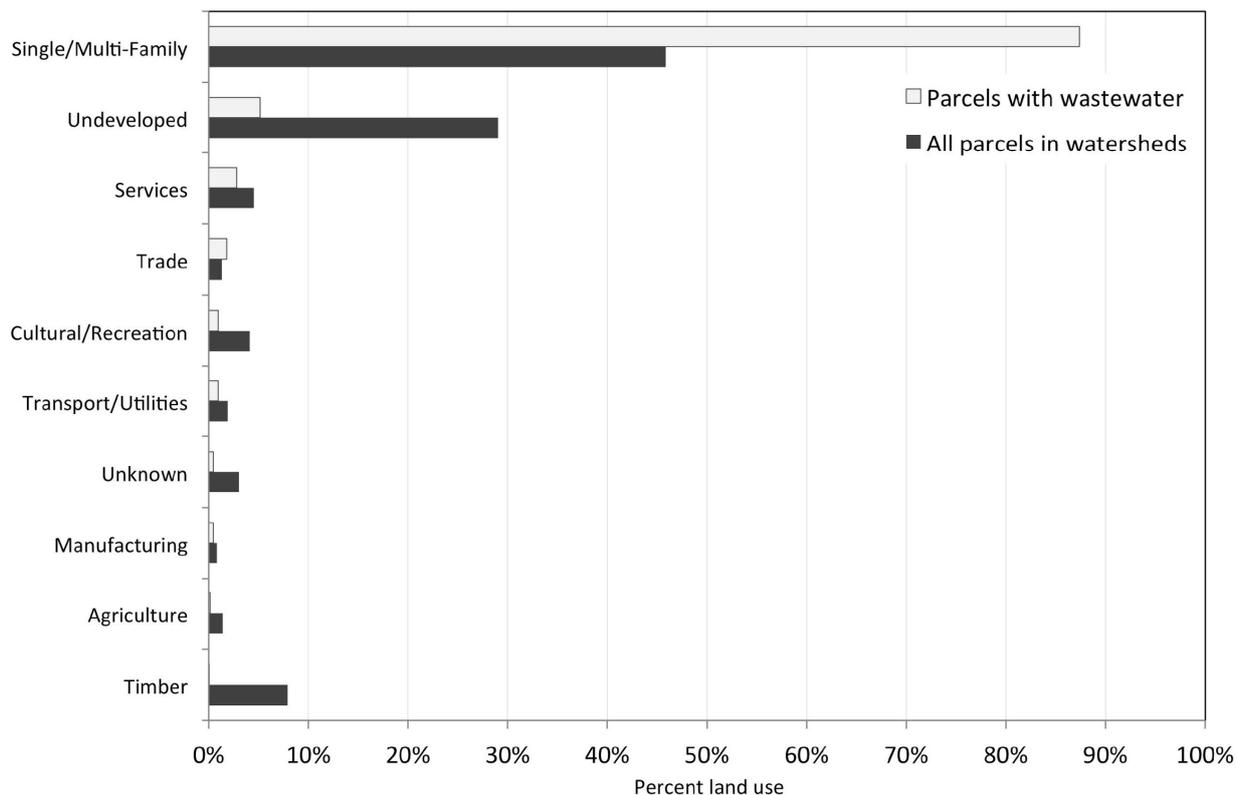
<b>Metric</b>	<b>Description</b>
Mean count of sewers and septic tanks	The sum of all parcels on either a septic system, sewer system or no system
Proportion of parcels on wastewater system	Total number of parcels on a septic or sewer system divided by the sum of parcels on a wastewater type
Mean parcel-lot	Lot size of parcels on sewers and septic tanks averaged across watershed
Kernel density of parcels on a septic system	Proxy for density of septic systems, which may be a stressor on the nearshore
% Impervious	Measure of urbanization

## 4. Results

### 4.1. Coastal Watershed Patterns

Coastal watersheds in the sample are small, roughly 1.7 km<sup>2</sup> (420 acres), on average. Some are as small as 0.3 km<sup>2</sup> (74 acres) and as large as 10.8 km<sup>2</sup> (2668 acres). Watershed area does not vary significantly by gradient classes ( $\chi^2 = 5.8, df = 2, p < 0.06$ ), meaning rural watersheds are not larger than urban or suburban, and urban watersheds are not significantly smaller than their suburban or rural counterparts. The watersheds contain a range of land uses (Figure 5). While the Puget Sound nearshore is dominated by single-family homes, the coastal shoreline also contains many areas that are undeveloped. Among the parcels identified as being on a wastewater treatment type, a more uneven distribution of land use is evident. The bar chart in Figure 5 shows that most parcels on a wastewater treatment system (87%) are residential properties. These residential lands include single-family and multi-family residences. The remaining parcels with wastewater services are on lands classified as “undeveloped”, “services” (including government and educational), “trade” (including retail), “transport/utilities” and “cultural/recreation”. Because the majority of parcels on a wastewater system are dominated by residential development, I extracted these parcels for the subsequent analysis.

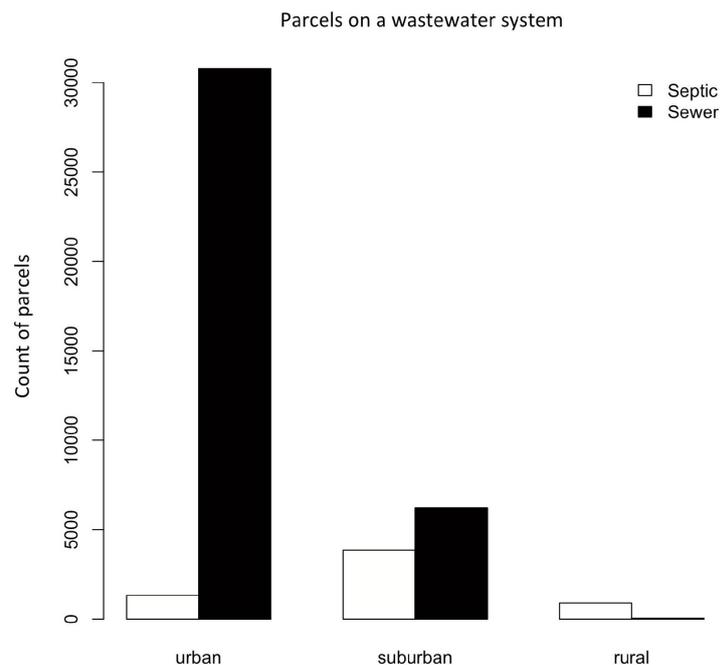
Land use in parcels with wastewater compared with all parcels in watersheds



**Figure 5.** Proportion of land uses in parcels with wastewater treatment (septic or sewer) and the proportion of land uses in all parcels in sample watersheds. Over 87% of parcels with wastewater are single-family or multi-family residential.

#### 4.2. Wastewater Infrastructure Patterns

Across the 85 sampled watersheds, there are a total of 44,629 residential properties either hooked up to a sewer or on a septic system (Figure 6). Most of these residences and the population (86%) are on a sewer system. Figure 6 and Table 2 show the distribution of residential properties on a wastewater treatment system across the gradient. An overwhelmingly majority of urban residences (>95%) are on a sewer system. In the suburban coastal areas, there is a 40:60 ratio of residences on a septic vs. sewer, respectfully. Nearly all rural properties use a septic system.



**Figure 6.** Number of residential parcels on a sewer system or septic system distributed across the urban gradient.

Consistent with the decline in the number of households, the total number of residential parcels on either wastewater system type decreases with the urban-rural gradient. However, when the data are partitioned between properties with a septic tank and properties on a sewer, the proportion of parcels on a sewer decreases exponentially across the gradient, where 85% of sewer parcels are urban, 15% are suburban and less than 1% are rural. By contrast, the proportion of residences relying on a septic tank is greatest in the suburban portion of the gradient (63%) followed by urban (21%) and rural (14%).

The density of parcels on a septic system displays a similar trend across the urban-rural gradient. The septic density is higher, on average, in suburban watersheds ( $90 \pm 103$  units/km<sup>2</sup>) compared to urban ( $26 \pm 60$  units/km<sup>2</sup>) and rural watersheds ( $18 \pm 20.7$  units/km<sup>2</sup>). Results from a one-way ANOVA revealed that the density of septic tanks differed significantly among urban, suburban and rural watersheds,  $F(2, 76) = 15.7$ ,  $p = <0.001$ .

The average lot size of all residential parcels increases with the urban gradient (Table 2). However, this lot size varies by wastewater treatment type. The average lot of sewer parcels is 0.3 acres across all urban, suburban and rural watersheds. There is some variation in lot size among sewer parcels in urban watersheds ( $0.3 \pm 1.21$  acres) and suburban watersheds ( $0.3 \pm 2.10$  acres), but very little in rural

( $0.3 \pm 0.2$  acres). The average lot size of properties on a septic system is smallest on average in urban basins ( $0.5 \pm 2.8$  acres) compared to suburban ( $1.37 \pm 3.07$  acres) and rural basins ( $2.8 \pm 5.3$  acres).

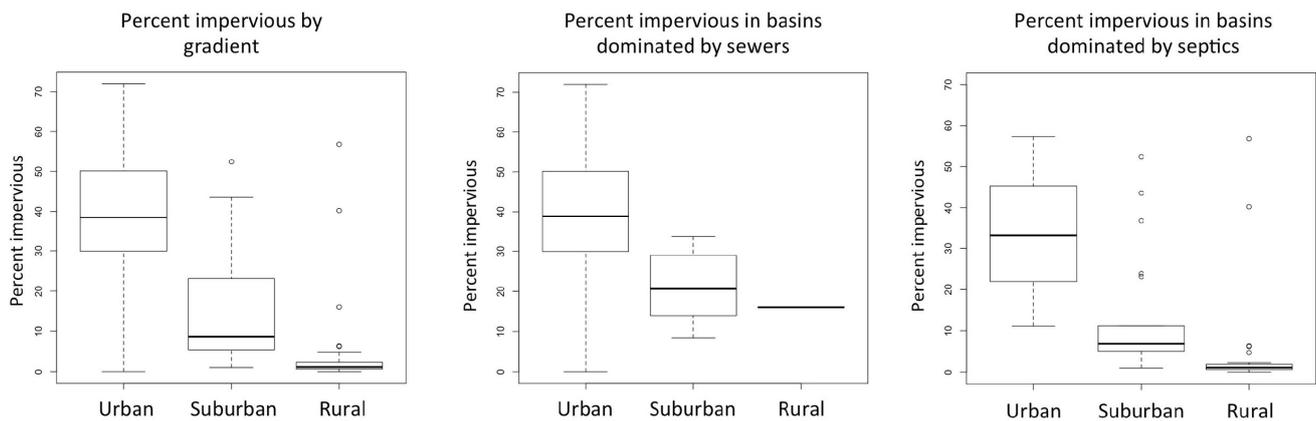
**Table 2.** Summary results of residential wastewater infrastructure patterns across a coastal urban gradient. Data are from Spirandelli, 2014 [54].

Count of parcels	Urban	Suburban	Rural	Total (n)
Septic (n)	1323	3845	889	6057
Percent of total	(22%)	(63%)	(14%)	(14%)
Sewer (n)	32,305	6220	47	38,572
Percent of total	(85%)	(15%)	(0.05%)	(86%)
All parcels on wastewater (n)	33,628	10,065	936	44,629
Population count	Urban <sup>1</sup>	Suburban <sup>2</sup>	Rural <sup>2</sup>	Total
Population on septic	3056	9497	2195	14,748
	(21%)	(64%)	(15%)	(14%)
Population on sewer	74,624	15,363	116	90,103
	(83%)	(17%)	(.001%)	(86%)
Population using wastewater system	77,680	24,860	2311	104,851
Lot size (mean acre)	Urban	Suburban	Rural	
Septic	$0.5 \pm 2.8$	$1.37 \pm 3.07$	$2.8 \pm 5.3$	
Sewer	$0.3 \pm 1.21$	$0.32 \pm 2.10$	$0.3 \pm 0.2$	
All residential parcels	$0.32 \pm 1.5$	$0.94 \pm 4.22$	$4.07 \pm 9.7$	
Septic density (units/km <sup>2</sup> )	Urban	Suburban	Rural	
Mean density	$26 \pm 60$	$90 \pm 103$	$18 \pm 20$	
Mean impervious (%)	Urban	Suburban	Rural	Mean %
Septic dominated				$8 \pm 14$
Sewer dominated				$34.5 \pm 16$
All watersheds	$38 \pm 16$	$13 \pm 16$	$5 \pm 13$	

<sup>1</sup> Population data were estimated using households and persons per household data collected by the U.S. Census American Community Survey, 2013. An average of 2.31 people per household was estimated from the four largest cities in the Puget Sound (Seattle, Olympia, Tacoma and Everett) and used as a multiplier for the urban parcels. <sup>2</sup> An average of 2.47 people per household was estimated from the seven counties in the study area and used as a multiplier for suburban and rural parcels.

A wide range of impervious surfaces (0%–70%) was observed across all watersheds (Figure 7a). Urban watersheds contain, on average, just over 38% ( $\pm 16\%$ ) of their area covered by impervious surfaces. Suburban watersheds are more moderately developed with an average of 13% ( $\pm 16\%$ ). Rural watersheds contain minimal imperviousness, ranging mostly in the single digits. At the parcel scale, sewered parcels contain an average of over 20% impervious surface coverage regardless if they are in urban, suburban or rural watersheds (Figure 7b). Septic parcels in urban watersheds also contain high amounts of imperviousness, in the range of 23%–45% (Figure 7c). By contrast, septic parcels in suburban watersheds contain, on average, 10% imperviousness. Mean percent imperviousness was averaged across watersheds dominated by septic tanks vs. sewers. Sewer-dominated watersheds contain, on average, 34.5% ( $\pm 16\%$ ) and septic dominated watersheds contain 8% ( $\pm 14\%$ ) impervious surfaces. Among suburban watersheds, sewer vs. septic dominated watersheds contained different amounts of imperviousness ( $21\% \pm 9$  vs.  $13\% \pm 14$ ). A positive, although weak, relationship was

observed between the log of percent impervious and the log of all parcels on a wastewater treatment type ( $r^2 = 0.34$ ,  $p < 0.001$ ). When the data are partitioned across the urban gradient, this relationship is stronger among suburban residential properties ( $r^2 = 0.56$ ,  $p < 0.001$ ). This suggests that in suburban watersheds, as the number of residential parcels on wastewater treatment (sewer or septic) increases, so does the amount of impervious surfaces. When the data are partitioned by septic vs. sewer dominated among suburban watersheds, a positive relationship was observed between the number of septic tanks and impervious surfaces ( $r^2 = 0.41$ ,  $p < 0.001$ ).



**Figure 7.** (a) Percent impervious across all watersheds; (b) percent impervious in sewer parcels; (c) percent impervious in septic parcels. Source of graphs: Spirandelli, 2014 [54].

## 5. Discussion

### 5.1. Proportion and Density of Wastewater Treatment across an Urban Gradient

It has been widely believed that sewers primarily serve urban areas and septic tanks are most prevalent in scattered rural developments [40]. Findings from this study find a more nuanced pattern that such generalizations do not necessarily hold true. I find most urban residences hooked up to a central sewer system; however, there are a remaining, albeit small, number of residential parcels on a septic system in the most heavily-urbanized watersheds. There might be two explanations for this finding. The first is that these are legacy septic tanks installed during a period before sewers were built. Converting these systems has been slow, partly due to the phenomenon of “path dependence”: once a technology is chosen, it is very hard to change, even when it is out of date [37]. The second explanation is that these parcels were developed with septic tanks in urban areas despite existing sewer infrastructure.

The pattern of sewage treatment in suburban watersheds is more complex, representing a patchwork of parcels on sewers and septic tanks. Heimlich and Anderson (2001) state that suburban and rural development represent two fundamentally different types of development based on wastewater treatment: suburbia relies on access to sewer and comprises small residential lots; while rural development relies on septic systems with larger lots [69]. Findings from this study do not support this view. While sewers still dominate in total numbers, the relative number of septic tanks and their density is significantly higher in the suburban portion of the urban gradient. The suburban development pattern in these watersheds contains a mixture of sewers and septic tanks, but with local neighborhoods containing very high clusters of septic tanks, on the order of 6–8 septic tanks per acre.

The high density of septic tanks in suburban areas may be the result of rapid development and increased demand for housing, either in spite of or in response to urban containment policies, such as the Washington Growth Management Act (GMA). Between the period of 1990–2002, the rate of urban development was significantly higher in areas outside of urban growth boundaries than inside across six of the same counties in this study [70]. Whether septic tanks or sewers facilitated this increased rate would require additional information on the year when these different systems were installed. Whatever the role of the Growth Management Act might be, septic tanks may also be a preferred option for developers inside urban growth areas. In Baltimore, for example, since the passage of Maryland's smart growth legislation, development in urban areas that use septic tanks has grown significantly and, in some cases, inside the priority sewer funding area [36]. Harrison *et al.* (2012) [36] explains this may be because the local county government cannot afford sewer expansion and state subsidies are lacking, and/or there is a failure in adequate infrastructure planning.

### 5.2. Lot Size of Parcels with Different Wastewater Treatment

Previous studies have observed lot size to decrease with urbanization, from the rural outskirts to the urban core [25,26]; however, lot size was not discriminated by wastewater treatment system. This study finds residential lots vary in size depending on the wastewater treatment system. A surprising result was the relatively small lot size of urban septic tanks, suggesting that there may be more available area to build with septic tanks than previously thought.

### 5.3. Wastewater Treatment and Patterns of Imperviousness

Previous landscape studies have shown that impervious surfaces and the amount of vegetation varies widely in residential patches and that urban density and the location on the urban gradient influences the distribution [25,26,71]. This study finds a significant difference in the amount of impervious surfaces in watersheds dominated by different wastewater treatment systems. At the patch scale, urban lots on septic tanks contain high amounts of impervious surfaces (>35%), an amount that at the watershed scale can negatively impact coastal ecosystem functions [72,73]. This is of concern, since septic tanks require adequate unpaved area in the yard for a leach-field that can support the efficient processing of effluent. At the watershed level, the suburban watersheds display two distinct patterns. On the one hand, watersheds dominated by septic tanks contain very high densities of septic tanks, but with low amounts of impervious surfaces. By contrast, sewer-dominated watersheds contain high amounts of impervious surfaces.

## 6. Conclusions

The formulation of septic regulations is generally confined to the narrow task of site-scale controls based on bio-physical characteristics and concerns for human health and water quality. As such, these policies fail to address the wider impacts of development patterns associated with septic tanks within and outside areas served by centralized sewer systems. In contrast, planning departments and public agencies develop sewer infrastructure policies that serve as implementation mechanisms for land use planning [44]. Although these policies are designed to direct development and discourage haphazard

development, they also fail to address the proliferation of residences with septic systems in suburbia at very high densities.

If an important challenge for ecological scholars and urban planners is to figure out how best to balance human needs with ecosystem function in urban ecosystems, then understanding the role of alternative wastewater infrastructures may be an important component. The link between wastewater treatment systems and urban patterns 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 sprawl, particularly in the wake of growth management policies [70,74].

This study provides an important step in the examination of urban development patterns associated with sewers and septic tanks at the patch and watershed scale. Yet, much remains to be explored. For example, more research is needed to understand the role that land use policies such as the Growth Management Act play in the distribution and pattern of wastewater treatment across an urban gradient. Additional research is needed to explore the relationship between sewage treatment types and patterns of land use and land cover; for instance, whether the fragmentation of forest and other patterns of sprawl-like development are associated more with septic tanks vs. sewers. Furthermore, an explicit exploration of the relationship between patterns of wastewater infrastructure and watershed ecosystem function is necessary. The pattern of urban development and its associated wastewater infrastructures may be key to devise better strategies to ensure that ecological services support human needs and coastal ecosystems.

## Acknowledgments

The research presented in this paper was partially funded by the United States National Oceanic and Atmospheric Administration (NOAA) and the Joint Institute for the Study of the Atmosphere and Ocean (JISAO).

## Conflicts of Interest

The author declares no conflict of interest.

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