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Research Paper

Assessing Rain Garden Placement through Hydrological Modeling in the Puget Sound Region

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Green Stormwater Infrastructure (GSI) is built to intercept stormwater runoff and mitigate peak flows and stormwater pollutants before reaching surface waters. A rain garden is a type of GSI comprising a plant-soil system in which water retention and pollutant mitigation are maximized through infiltration and storage. Proper placement of rain gardens within the watershed is crucial to maximizing their effectiveness. The Lower Puyallup River Watershed in South Puget Sound, Washington, United States, consists of the primarily residential areas of Puyallup, Washington, United States, and Tacoma, Washington, United States. Preventing water quality impairment is essential because the streams and rivers in the watershed are critical habitat for salmon that return for spawning. The study's objective was to develop a framework to identify suitable sites for rain gardens in an urbanizing watershed and assess the adequacy of the method through hydrological modeling. An indexing approach to identify Hydrologically Sensitive Areas (HSA) was adopted, in which we considered the topography, runoff contributing area, soil depth, and hydraulic conductivity. The Topographic Wetness Index (TWI) and Soil Water Storage Capacity (SWSC) were computed to obtain the Hydrologic Sensitivity Index (HSI). Hydrological modeling of various conceptual hillslopes was conducted using a physically based Water Erosion Prediction Project (WEPP) model, and simulated runoff was computed under varying slope and soil property combinations. HSI values were calculated based on the simulated hillslope properties, and the relationship between HSA and runoff generation was assessed. Areas considered infeasible per criteria specified by state and county regulations were removed, and the HSI was classified based on suitability for the construction of rain gardens. The moderate HSI range (9.1 – 15.6) was deemed most suitable for rain garden placement in the study area. Most suitable sites were identified, providing a practical, scalable, and transferrable tool for prioritizing rain garden placement for stormwater runoff management at the watershed scale.

Keywords Green Stormwater Infrastructure (GSI), Hydrological modeling, Stormwater runoff, WEPP

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Highlight

An indexing approach based on variable source area hydrology was evaluated through hydrological modeling and used to prioritize placement of rain gardens.

1. Introduction

Impervious surfaces in urban areas hinder infiltration, reduce evapotranspiration (ET), and increase the rate and quantity of runoff (Tsihrintzis and Hamid 1997; Walsh et al. 2012) to receiving systems. Runoff emanating from roads, parking lots, and roofs carries various chemicals, including nutrients, organic pollutants, microplastics, and heavy metals such as lead, zinc, and copper (Tsihrintzis and Hamid 1997; Björklund et al. 2018), that can adversely impact downstream water quality (Paul and Meyer 2001; Müller et al. 2020). For example, toxic stormwater runoff was found to be the cause of increased mortality of juvenile coho salmon in small urban streams around Puget Sound, Washington, United States (Sandahl et al. 2007; McIntyre et al. 2018). More specifically, Tian et al. (2021) showed that an oxidative product (6PPD-Q) in stormwater derived from the breakdown of car tires was the causative toxicant for coho salmon mortality in urban streams in the Puget Sound.

1.1. Green Stormwater Infrastructure (GSI)

Stormwater pollution can be mitigated by slowing and retaining runoff and treating its associated pollutants (Taguchi et al. 2020). Green Stormwater Infrastructure (GSI) comprises Best Management Practices (BMPs) that intercept and provide treatment of polluted urban runoff (Grumbles 2007; Chini et al. 2017; Taguchi et al. 2020). There are several types of GSI practices, such as green roofs, permeable pavements, bioretention systems, and rain gardens (WSDOE 2019). Each of these practices aims to incorporate or promote ecosystem processes in the mitigation of stormwater impacts on receiving systems. The terms "rain garden" and "bioretention systems" are used interchangeably across much of the United States. However, in the State of Washington, there are some critical differences between the 2 practices according to the Washington State Department of Ecology (WSDOE), which provides oversight of stormwater regulations in the state. Rain gardens are typically smaller than bioretention systems and are usually non-engineered, often utilizing native soils, whereas bioretention systems rely on specially designed soil media that meet specific standards and are constructed according to engineering guidelines (Bertolotto and Clark 2017). The focus of this study is exclusively on the smaller rain gardens. Rain gardens are a type of small-scale GSI that serve as a stormwater sink comprising a plant-soil system in which water retention is enhanced through infiltration and storage (Martin-Mikle et al. 2015; Shuster et al. 2017; Taguchi et al. 2020). Rain gardens collect runoff from nearby rooftops, yards, sidewalks, and parking lots (Taguchi et al. 2020).

Rain gardens might be considered mini-ecosystems that remove pollution from the influent stormwater using natural hydrologic, physicochemical, and biological processes, which reduce contaminant loads through sedimentation, adsorption, microbial breakdown, and plant uptake (Woodward et al. 2009; Winston et al. 2010). The effectiveness of rain gardens depends on their design, construction, and placement on the landscape (Shuster et al. 2017). Critical parameters for rain garden design include the drainage area contributing to runoff and the soil properties where the rain garden will be constructed (WSDOE 2019). If the rain garden is not sized or located correctly, runoff from the contributing drainage area could overwhelm it, limiting its performance and causing flooding and pollution downstream (Guo et al. 2021). Soils with adequate permeability and storage capacity are essential to maximizing rain gardens' performance (Jennings 2016; Shuster et al. 2017). Soils of extremely high permeability offer a shorter contact time for pollutant treatment. In contrast, those of low permeability impede infiltration and could generate more runoff, leading to a rain garden's failure (Shuster et al. 2017). Another critical factor is the strategic placement of GSI (Martin-Mikle et al. 2015). Ideally, a site-appropriate GSI practice could be installed in every lot that generates runoff for stormwater remediation. However, many factors, especially the cost of GSI installation and maintenance, prevent widespread installation. Therefore, it is essential to identify those hydrologically appropriate locations in a watershed that most effectively intercept and infiltrate stormwater runoff.

1.2. Placement of GSI

Shojaeizadeh et al. (2021) developed a tool using Storm Water Management Model (SWMM) to strategically place GSI at a sub-basin scale, optimizing for flow and pollutant reduction while minimizing cost. SWMM's hydrological and water quality capabilities were combined with performance, cost, and optimization frameworks to identify optimal GSI placement. Similar approaches using SWMM and optimization have been employed (Macro et al. 2019; Wu et al. 2019). Guo et al. (2021) used the Water Erosion Prediction Project (WEPP) model to evaluate GSI efficiency in Austin, Texas, United States. Hillslopes producing the most soil loss were identified for implementing GSI practices, including native trees, permeable pavement, rain gardens, and detention ponds. GSI reduced average annual runoff by 15% to 56%, with native trees performing best (54% to 56%). While these approaches rely on hydrological models, modeling expertise, advanced computing, and extensive datasets, there is a need for more straightforward methods using readily available data. Such methods simplify the application process, making them more accessible for natural resource managers and planners, even in smaller cities and communities with limited resources.

1.3. Hydrologically Sensitive Area Approach

A simplified approach to prioritizing locations for GSI is identifying hydrologically sensitive areas (HSAs), which are those areas within a watershed that are more prone to generate runoff (Walter et al. 2000; Bueno and Alves 2017). This approach originated from the variable source area hydrology method proposed by Kirkby and Beven (1979). Qiu (2009) used an indexing method to identify HSAs by calculating 2 indices. The first index, the Topographic Wetness Index (TWI), accounts for the effects of slope steepness and runoff contributing area. The second index, the Soil Water Storage Capacity (SWSC), is a function of soil saturated hydraulic conductivity and soil depth modified by percent impervious areas. Subtracting SWSC from TWI yields the Hydrologic Sensitivity Index (HSI). Then any area is considered a Hydrologically Sensitive Area (HSA) if its HSI value exceeds a defined threshold (Qiu et al. 2020).

Qiu et al. (2020) examined various topographic index thresholds for delineating HSAs in New Jersey, United States, and found that the appropriate threshold varied from one region to another in the study area. As such, different thresholds have been used in different studies to identify HSAs, e.g., 10 standard deviations (Qiu 2009), 9 standard deviations (Bueno and Alves 2017), and 1.5 standard deviations greater than the mean (Martin-Mikle et al. 2015).

Mahat et al. (2024) used the HSA approach to identify suitable locations for bioretention systems in the Lower Puyallup River Watershed of the South Puget Sound region in western Washington State. The study involved ground-truthing, including soil sampling and analysis, infiltration tests, and visual assessment of the suitability of identified locations for bioretention systems. The findings indicated that areas with high HSI values were more prone to surface ponding and runoff, and HSI was an effective indicator of the potential for runoff generation. Mahat et al. (2024) recommended prioritizing areas with high HSI for siting bioretention systems.

1.4. Rationale and Objectives

Various approaches exist for siting GSI practices and evaluating their effectiveness, but their use is limited by low spatial resolution, high cost, or a steep learning curve (Jayasooriya et al. 2014; Dovel et al. 2015; Martin-Mikle et al. 2015). There is a need for simplified methods, such as the HSA approach, that can render a quick assessment and decision support (Ahiablame et al. 2012). Studies on the siting of GSI practices have focused primarily on the eastern and central United States. Mahat et al. (2024) were among the first to apply this approach to identify suitable locations for bioretention systems, a large-scale GSI, in the U.S. Pacific Northwest. Mahat et al. (2024) recommended that future efforts be devoted to evaluating the HSI indexing method based on the HSA approach by comparing it with hydrological modeling results.

This study focuses on adapting the HSA principle for proper siting of smaller-scale GSI practices, especially rain gardens with fewer construction restraints. We build on the methodology of Mahat et al. (2024) to identify optimal locations for rain gardens. Rain gardens are designed to function as mini ecosystems, and ecological engineering principles apply to their design, installation, and maintenance. A decision-support tool that identifies optimal locations for these ecologically engineered systems on the landscape is critical to their effective function and to the practice of ecological engineering. Further, we make the first effort (to our knowledge) to relate the HSI and runoff generated to a physically based hydrologic model. Therefore, the research objectives of this work were to (i) identify optimum locations for small-scale GSI practices, specifically, rain gardens, in the Lower Puyallup River Watershed, based on the HSI method; and (ii) assess the adequacy of the method through hydrological modeling using the WEPP model.

2. Methodology

2.1. Study Area

The Lower Puyallup River watershed was selected as the study area as it is one of the fastest developing areas in the South Puget Sound region (Figure 1). The watershed measures 128 km^2 and comprises several cities, including Puyallup and Tacoma in Pierce County, with approximately 60% residential area (WSDOE 2018). The study area is most commonly underlain by glacial sediment deposits called the Vashon Till, which overlays sedimentary and volcanic bedrock deposits (Welch et al. 2015). Impervious areas account for 29% (USGS 2021) of the watershed area. High-density development is concentrated in the central and northwestern sections, encompassing downtown Puyallup, South Hill, and Tacoma. Natural parks and wilderness areas are interspersed with forests throughout the watershed, while

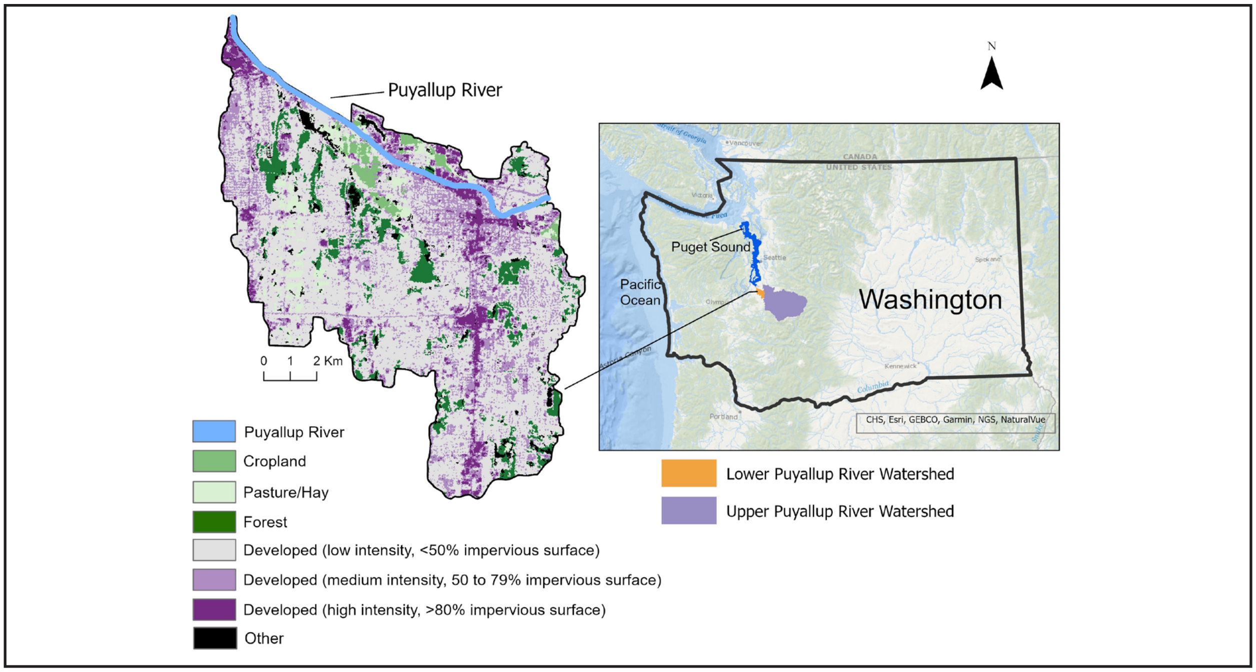

Fig. 1. Land use and land cover map of the Lower Puyallup River Watershed in South Puget Sound (ArcGIS Pro map data: CHS, Esri, GEBCO, Garmin, NGS, NaturalVue).

agricultural fields are situated in the northern Puyallup River floodplains. Wetlands, forests, parks, and water bodies are also scattered across the watershed. Several tributaries containing salmon spawning habitats flow south to north and join Puyallup River along the northern boundary of the watershed, draining directly into Puget Sound. The watershed contains multiple aquatic habitats to which Chinook and coho salmon return for spawning during the rainy season (Reinelt 2013). These species are susceptible to harm from toxic stormwater (French et al. 2022). There is a critical need to develop planning tools at the landscape level to help mitigate the harm stormwater poses to aquatic ecosystems.

The area exhibits a mediterranean climate characterized by warm summers and wet winters. The average annual precipitation of the area is 992 mm, and the average daily temperature is 10.5 °C based on long-term (1914 – 2022) weather records (NOAA 2023). Elevation ranges from –9 m to 200 m above mean sea level, with the lowest elevations and flattest terrain associated with the Puyallup River valley in the north, ascending to the watershed's South Hill region to the south and central regions (Figure 2a). The predominant soil is Kapowsin gravelly loam, which is moderately deep, permeable, and primarily found in the central part of the watershed (NRCS 2023). Shallow, less permeable soils occur in the west-central part of the watershed, while deep, highly permeable soils are found in the southern part (Figure 2b, 2c; NRCS 2023).

2.2. Data Sources

All the data used in this study were compiled from publicly accessible sources (Table 2) and geospatial analysis was conducted using ArcGIS (ESRI [date unknown]). The LiDAR (Light Detection and Ranging) elevation data were of 1.8-m (6-ft) resolution (WDNR 2021). Soil data were extracted from the SSURGO database (NRCS 2023). The impervious area layer was derived from National Agriculture Imagery Program (NAIP) imagery (USGS 2021). Areas unsuitable for rain gardens per United States Environmental Protection Agency (EPA) and state ordinances (WSDOE 2019; Table 1) were extracted from the Pierce County (2021) website.

2.3. Computing Hydrologic Sensitivity Index (λ_{HSI})

Hydrological Sensitivity Index (λ_{HSI}) was computed in ArcGIS (ESRI [date unknown]) using the Digital Elevation Model (DEM), soil depth, saturated hydraulic conductivity, and impervious areas. Slope steepness was computed using the DEM after removing sinks. Grid cells with a slope gradient of zero were assigned a small value of 0.0001 following Qiu (2009). D-infinity algorithm (Jenson and Domingue 1988) was used in ArcGIS to compute the flow direction, flow accumulation, and contributing drainage areas per unit contour length (α) from

Table 1 Data layers used in this study

GIS Layer	Resolution/Format	Source	Citation
Elevation	1.8-m (6-ft) raster	Washington State Department of Natural Resources	(WDNR 2021)
Impervious areas	1.8-m (6-ft) raster	National Agriculture Imagery Program	(USGS 2021)
Unsuitable areas (roads, parks, wetlands, erosion and landslide hazard areas)	polyline/polygon	Pierce County Open Geospatial Data Portal	(Pierce County 2021)
Soil data (depth, saturated hydraulic conductivity)	polygon	United States Department of Agriculture (USDA) Soil Survey	(NRCS 2023)
Watershed boundary, Water bodies	polygon	United States Geological Survey (USGS)	(USGS 2021)

the filled DEM. Topographic Wetness Index (λ_{TWI}) was computed using Equation 1. Soil Water Storage Capacity index (λ_{SWSC}) was computed following Equation 2a. We considered the impact of impervious surface by adjusting the soil depth to the restrictive layer (Equation 2b). The impervious layer was a binary raster of 0 (impervious) and 1 (pervious). Therefore, the "effective" soil depth would become 0 for impervious surfaces. λ_{HSI} was computed using Equation 3, and its spatial patterns and various effects of landscape characteristics were analyzed using raster library in R (R Core Team 2023) and Pandas library in ArcPy (ESRI [date unknown]). All other post-processing was completed using R. λ_{HSI} values were then classified into 5 classes of equal intervals to evaluate their common characteristics in different areas of the watershed.

$$\lambda_{TWI} = \ln\left(\frac{\alpha}{\tan(\beta)}\right) \quad (1)$$

$$\lambda_{SWSC} = \ln(K_s D_m) \quad (2a)$$

$$D_m = D \times I \quad (2b)$$

$$\lambda_{HSI} = \lambda_{TWI} - \lambda_{SWSC} \quad (3)$$

In the equations, α is the contributing area drained per unit contour length (m^2/m), β is the local gradient (radians), K_s is saturated hydraulic conductivity (m d^{-1}), D is the soil depth (m), D_m is modified soil depth (m), and I is the binary impervious surface indicator.

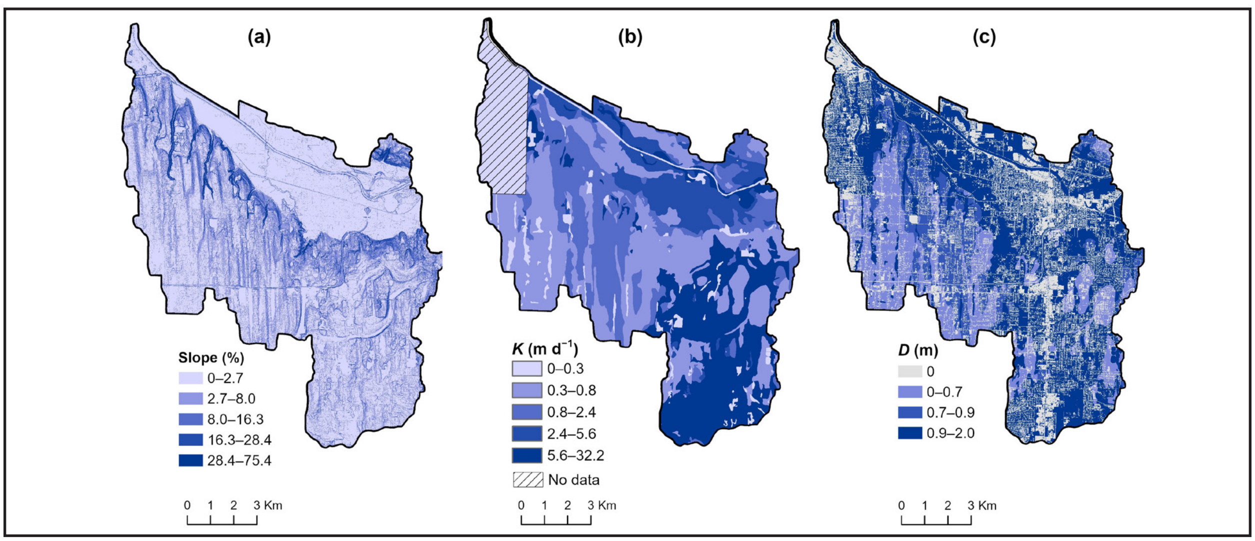

Fig. 2. Slope steepness (a), soil saturated hydraulic conductivity (b), and soil depth (c) in the study area.

2.4. Identifying Areas Suitable for Rain Gardens

Areas within the watershed unsuitable for rain gardens were excluded following engineering criteria provided in federal and state ordinances (WSDOE 2019). These areas included impervious areas, regulated flood plains, wetlands, water bodies (with a 30-m [100-ft] buffer), landslide and erosion hazard areas, parks, and forests.

Engineering criteria for constructing rain gardens primarily concern size (area), soil depth, and saturated hydraulic conductivity (WSDOE 2019). Rain gardens are typically sized to be about 5% of their contributing area at sites where the soil is deeper than 2 m (6.7 ft), and saturated hydraulic conductivity ranges from 0.18 m d^{-1} to 5.5 m d^{-1} (PCSWM 2015). The maximum size of a rain garden was set as 140 m^2 (1,500 ft^2) after consulting with professionals, and the maximum contributing area as 2,800 m^2 (30,000 ft^2), following the state and county engineering guidelines (PCSWM 2015; WSDOE 2019). Areas not meeting the engineering requirements were excluded from consideration. The maps of λ_{HSI} were converted from grid- to lot-scale using a 30 m × 30 m (100 ft × 100 ft) "fishnet" by computing the mean of the λ_{HSI} values falling in the range of each lot-scale area. Hydrological analysis (Section 2.6) was conducted to assess the relationship between λ_{HSI} and runoff generation. Last, areas at varying levels of suitability for rain garden placement were identified.

2.5. Adjustment to λ_{HSI}

Impervious areas affect the movement of stormwater runoff in various manners. Residential driveways may be constructed with little change to the natural landscape and minimal effect on runoff flow paths. Large-scale industrial and commercial development is subject to state stormwater management regulations where stormwater infrastructure may alter natural flow paths, e.g., stormwater runoff is collected and removed through storm drains. To account for the potential disruptive effects of impervious areas on natural drainage pathways, we assumed 2 cases: (i) flow was not disrupted by impervious areas, and (ii) flow was disrupted by impervious areas, such as roads, buildings, and parking lots. In the second case, we adjusted flow accumulation using weighting factors (0 for impervious areas and 1 for pervious areas) to obtain new maps of λ_{TWI} and λ_{HSI}, to fully account for the disruptive impact of impervious areas. The 2 scenarios correspond to 2 extreme cases: one where impervious areas are assumed to have no effect on surface runoff and natural flow pathways, and the other where flow is disrupted (e.g., runoff intercepted and removed with underdrains). In reality, impervious surfaces, without any stormwater mitigation practices implemented, are likely to increase and speed up surface runoff, and GSI or grey infrastructure for stormwater management is not installed on all areas covered by imperious surfaces. Figure 3 shows the

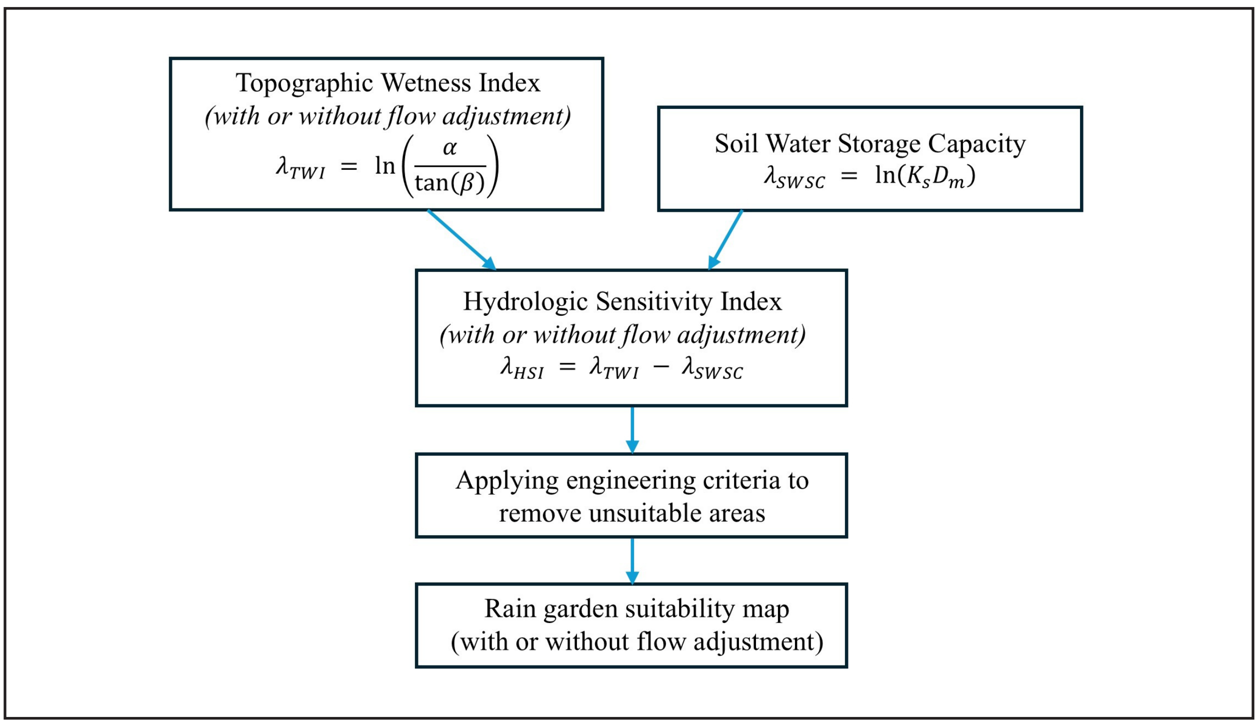

Fig. 3. Schematic identifying suitable areas for rain gardens with the option for flow adjustment due to impervious areas.

framework and steps to identify suitable areas for rain gardens, with options for flow accumulation adjustment.

2.6. Hydrological Analysis

We applied the WEPP model (hillslope version 2012.8) to quantify water balance and assess runoff in relation to λ_{HSI}. WEPP is a physically based, distributed-parameter, and continuous- simulation model for hydrology and water erosion (Flanagan and Livingston 1995). WEPP simulates major hydrological processes, including runoff, infiltration, ET, subsurface lateral flow, and deep percolation (Flanagan and Livingston 1995). WEPP has been used extensively to simulate hydrological processes in croplands, rangelands, forestlands, and urban settings (Greer et al. 2006; Dahal et al. 2022; Guo et al. 2021; Dobre et al. 2022). It requires climate, slope, soil, and management inputs and uses the Overland Flow Element (OFE) as the smallest hydrological response unit to represent a unique combination of slope, soil, climate, and management settings.

A conceptual hillslope was designed with 3 OFEs comprising the top, middle, and toe of a hillslope (Figure 4). We used the observed precipitation and temperature from the weather station within the watershed (McMillin Reservoir, Puyallup, WA; USC00455224; 47.13556°, −122.25611° [NOAA 2023]) and other climate inputs, such as wind speed and direction, dew-point temperature, and solar radiation, generated by CLIGEN, an auxiliary stochastic weather generator (Nicks et al. 1995). Ten-year (2012 – 2021) simulations were performed to capture the interannual variations in weather conditions and their impact on water balance.

The soil inputs were built based on the properties of the Kapowsin gravelly loam, the predominant soil series within the study watershed (NRCS 2023). The slope steepness and lengths were varied while all other properties (including soil depth and saturated hydraulic conductivity) were fixed, and multiple simulations were conducted to assess the topographic effects on runoff generation (Table 2). Similarly, the soil depth and saturated hydraulic conductivity were varied while the slope steepness and length constant were fixed to determine the effect of soil characteristics on runoff generation (Table 2). Bromegrass was used as the representative vegetation for all scenarios based on watershed delineated through WEPP cloud (Lew et al. 2022) and associated land use and cover for the study area. The vegetation growth parameters were defined following Flanagan and Livingston (1995).

To assess the effect of developed areas on runoff, we evaluated 2 scenarios: ground surface paved or an underdrain installed for the top OFE of the hillslope. The scenario of paved ground surface represented the case where the upslope area was covered by an impervious surface with saturated hydraulic conductivity set at zero and no plant transpiration. The underdrain scenario represented the case where the flow is taken away from the natural flow path, mimicking fully effective stormwater mitigation. The 2 scenarios for the upslope area would have different effects on runoff generation of the downslope areas along the hillslope. Hydrological Sensitivity Index (λ_{HSI}) was then computed for all scenarios with combinations of varying hillslope properties, and

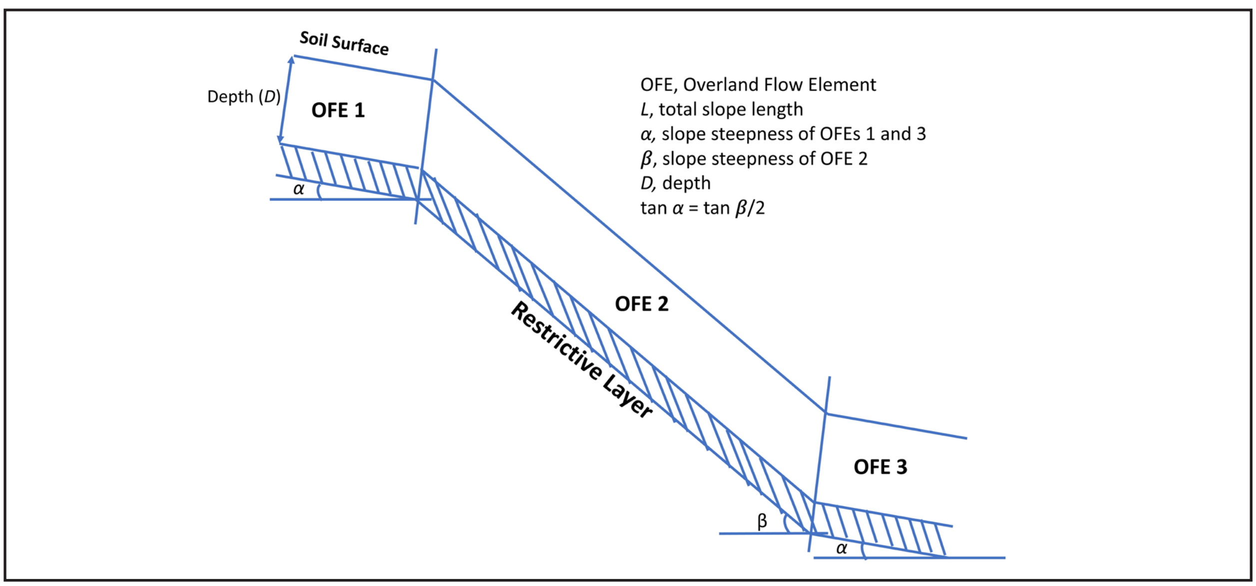

Fig. 4. Conceptual hillslope comprising 3 (top, middle, toe) Overland Flow Elements (OFEs) for hydrological analysis.

Table 2 WEPP-simulated scenarios with combinations of varying hillslope characteristics (slope length and steepness) and soil properties (depth and saturated hydraulic conductivity)

Varying Slope Characteristics		Varying Soil Properties	
Fixed D = 1.0 m and K = 0.48 m d^{-1}		Fixed tan β = 0.075 and L = 100 m	
Slope Steepness (tan β)	Slope Length (L, m)	Soil Depth (D, m)	Saturated Hydraulic Conductivity (K, m d^{-1})
0	25	0.5	0.12
0.075	50	1.0	0.24
0.15	100	1.5	0.36
	200	2.0	0.48
			0.60

a correlation (at significance level α = 0.05) between the λ_{HSI} values and WEPP-simulated runoff was computed.

3. Results and Discussion

3.1. Distribution of λ_{TWI} and λ_{SWSC}

The λ_{TWI} values ranged from −0.2 to 30, with high-λ_{TWI} areas distributed across the watershed near depressions, wetlands, and the end of flow paths (Figure 5a). High-λ_{TWI} areas also clustered at lower elevations in the northwest of the watershed. High λ_{TWI} values correspond to large contributing areas and low slope steepness, both being key factors for elevated runoff. Conversely, areas with low λ_{TWI} values, and thus low potential for runoff, were at the central, moderately to highly sloping part of the watershed. The λ_{SWSC} ranged from −3.4 to 4.2, with higher values more common for the southern part of the watershed because of the deeper soils, the larger saturated hydraulic conductivity of the soils, or both (Figure 5b). The areas with high λ_{SWSC} values tend to have effective infiltration and adequate storage to negate runoff generation.

3.2. Distribution of λ_{HSI}

The λ_{HSI} ranged from −3.8 to 28.4, with a median of 5.1 and a standard deviation of 4.1. The 5 equal-interval classes and corresponding percent total areas are presented in Figure 6a and Table 3. Class 2 was predominant, occupying 39% of the study area, while Class 5

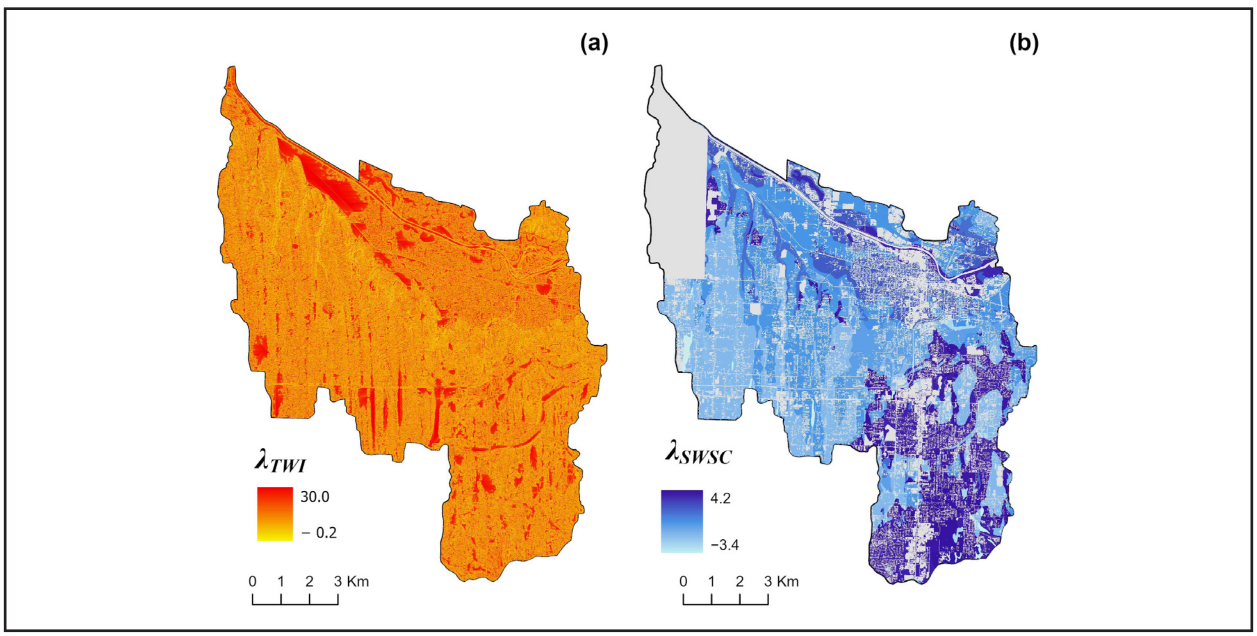

Fig. 5. a) Variation of the Topographic Wetness Index (*TWI*) and b) Soil Water Storage Capacity index (*SWSC*) values within the Lower Puyallup River Watershed.

Table 3 Classes of λ_{HSI} and associated percent total areas

λ_{HSI} Class	λ_{HSI} Value	% Total Area
1	−3.7 to 2.7	14.0
2	2.7 to 9.1	39.0
3	9.1 to 15.6	10.3
4	15.6 to 22.0	1.4
5	22.0 to 28.4	0.1
Other*	-	35.2

*Impervious areas or areas with no soil data

was the rarest, occupying only 0.05%. λ_{HSI} values were skewed toward the right and not normally distributed (W = 0.956, p <0.0001).

Areas with high λ_{HSI} values were concentrated in the central-western portion of the watershed, primarily due to the presence of elevated λ_{TWI} in this part. The low-λ_{HSI} areas were primarily located in the southern part of the watershed, resulting from the combinations of high λ_{SWSC} and low λ_{TWI}. Hydrologic Sensitivity Index (λ_{HSI}) within the study area varies with contributing area, slope gradient, soil depth, and saturated hydraulic conductivity (Figure 7). Generally, λ_{HSI} increases with increasing contributing area and decreases with increasing slope steepness; λ_{HSI} decreases with increasing soil depth and saturated hydraulic conductivity. Thus, the areas with high potential for runoff generation due to topographic conditions but low infiltration capacity and soil storage were highly hydrologically sensitive, with larger chances of stormwater concentration. Conversely, upland areas with steeper slopes and small contributing areas, as well as ample soil storage and infiltration capacity, were least sensitive, with lower chances of stormwater concentration.

3.3. Adjusted λ_{HSI}

Adjusting the effect of impervious areas resulted in a slightly different flow accumulation and λ_{HSI} with minimal change for most areas of the watershed. The differences in λ_{HSI} values, in absolute value, were less than 1 for 61%, between 1 and 4 for 32%, and greater than 4 for 7% of the total watershed area (Figure 8). The minor differences in flow accumulation and λ_{HSI} values after adjusting for impervious areas suggest that, while impervious surfaces can influence local hydrological processes, their overall impact on λ_{HSI} across the watershed may be limited in most cases. Specifically, there was a minimal change (smaller than 1 in absolute value) for 61% of the watershed, indicating that the hydrological sensitivity of the majority of the landscape would remain relatively stable, even with flow disruptions in areas covered with impervious surfaces. Therefore, the HSI method is adequate for much of the watershed area with the current level of urban development. For 32% of the watershed area, for which the differences in λ_{HSI} ranged between 1 and 4, there may be moderate

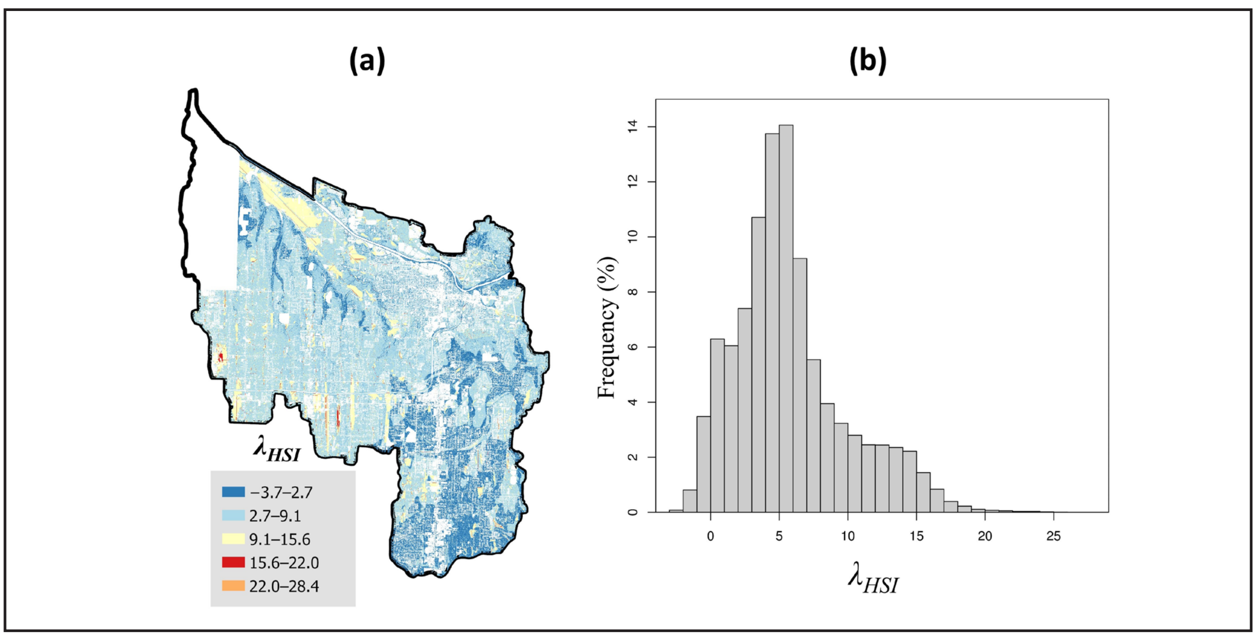

Fig. 6. (a) Hydrologic Sensitivity Index (λ_{HSI}) and (b) frequency distribution for the Lower Puyallup River Watershed.

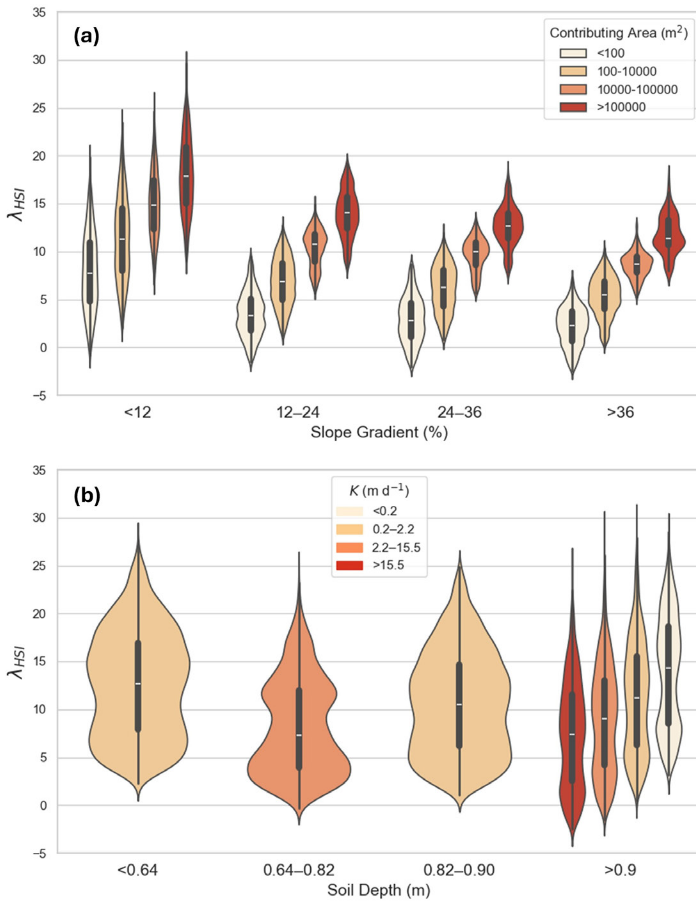

Fig. 7. Distribution of Hydrologic Sensitivity Index (λ_{HSI}) as influenced by (a) contributing area and slope steepness and (b) saturated hydraulic conductivity and depth of soil. The width of the "violin" corresponds to the frequency of data points.

sensitivity to the presence of impervious surfaces. These regions could represent transitional areas where urbanization begins to impact natural flow pathways, but the overall effect is still moderate.

For the remaining 7% of the watershed area for which the differences in λ_{HSI} were larger than 4, impervious surfaces had a more pronounced impact on the natural flow paths. Hence, the hydrologic sensitivity indexing approach may not be as adequate in highly developed areas. In these areas, the natural drainage network is substantially altered due to urbanization and development such that engineered drainage system (pipes, channels, and other infrastructure) must be considered when determining watershed runoff. As such, the indexing method is better suited for identifying hydrologically sensitive areas in regions that have not been heavily developed.

The results from examining differences in flow accumulation due to impervious surfaces highlight the importance of site-specific investigation informed by the λ_{HSI} values. Local factors, such as micro-topography, soil conditions, and other development activities, should not be neglected. Site-specific evaluation complements and strengthens the HSI method, which offers a useful first step in hydrologic sensitivity assessment across large landscapes.

3.4. Hydrological Analysis

WEPP-simulated runoff varied with topographic and soil conditions. In WEPP, ponding water exceeding depression storage is considered runoff. Subsurface lateral flow occurs when the soil water content exceeds field capacity after correcting for entrapped air and is calculated using Darcy's law, dictated by the slope gradient and effective saturated hydraulic conductivity. Consequently, flat areas (0% steepness) do not generate lateral flow, and infiltrated water becomes saturation: excess runoff after filling up soil water storage, as demonstrated in our simulation results (Figure 9). WEPP-simulated runoff decreased with increasing slope gradient and lateral flow,

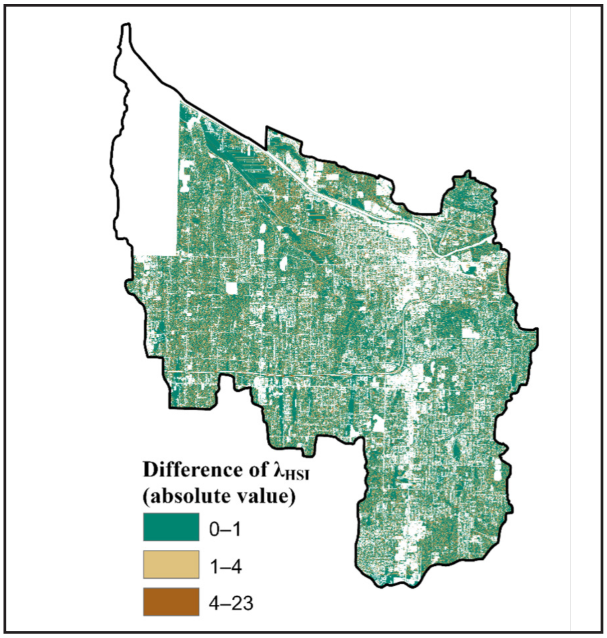

Fig. 8. Difference in λ_{HSI} with or without adjusting for stormwater removal from impervious areas.

and increased with increasing slope length. Changes in ET due to changing slope gradients were minor.

Increasing soil depth in WEPP would allow more infiltration, increasing ET and subsurface lateral flow, resulting in less runoff (Figure 10). Similarly, increasing hydraulic conductivity would augment infiltration capacity and reduce surface runoff.

3.4.1. Influence of Paved Areas and Drainage Infrastructure

The scenario with pavement covering the hilltop (OFE 1) led to an increase in runoff for this area and those downslope (Figure 11) and reduced ET and lateral flow compared to the no-pavement scenario. Higher runoff was because of the low infiltration capacity of the paved area resulting in higher rainfall access during storm events. These results suggest that urban development can exacerbate runoff accumulation at the bottom of the hillslope. This further indicates the applicability of the HSI method in highlighting the need and proper placement of GSI, even when the upslope area is impervious.

With subsurface drains installed for the hilltop (OFE 1) and when runoff is effectively managed at the source, potential runoff would be diverted away, meanwhile reducing other water balance components such as ET and decreasing water accumulation at the bottom of the hillslope. Therefore, if adequate stormwater management infrastructure is installed in upstream developments, the need for stormwater infrastructure downstream will be alleviated.

3.5. Variation of Simulated Runoff with λ_{HSI}

WEPP-simulated average annual runoff was significantly (at $\alpha = 0.05$) positively correlated to λ_{HSI} ($R^2 = 0.93$, $p<0.0001$; Figure 12). Simulated average annual runoff was 44% and 99% lower for the intermediate- and lowest-λ_{HSI} scenarios, respectively, compared to the highest-λ_{HSI} scenario. Generally, areas with the highest λ_{HSI} (Class 4 or Class 5) values have large contributing areas, low slope

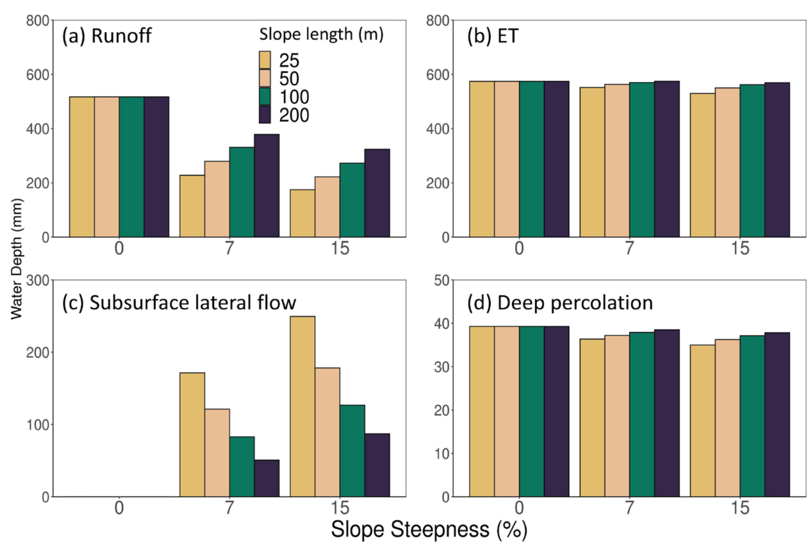

Fig. 9. WEPP-simulated water balance for the conceptual hillslope as influenced by slope length and steepness: (a) runoff, (b) ET, (c) subsurface lateral flow, and (d) deep percolation through the bottom of the soil profile.

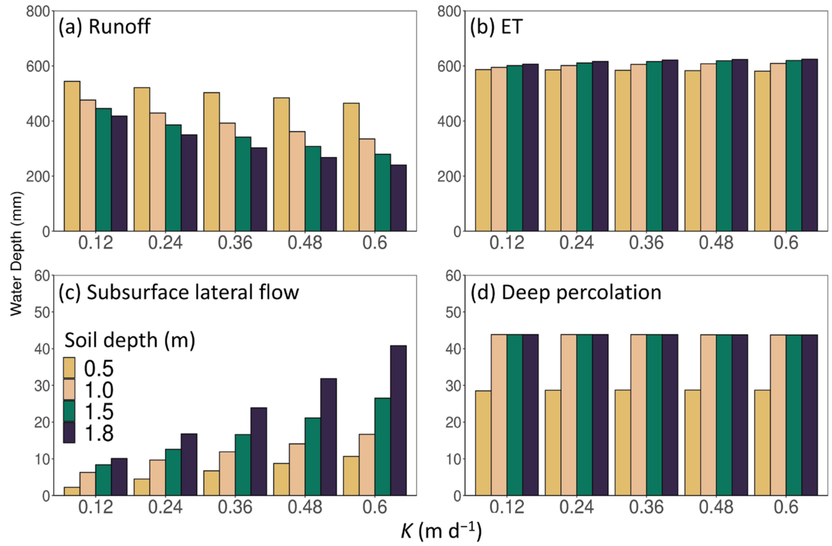

Fig. 10. Water balance of the study watershed as influenced by saturated hydraulic conductivity and soil depth: (a) runoff, (b) ET, (c) subsurface lateral flow, and (d) deep percolation through the bottom of the soil profile.

gradients, shallow soil depths, and low saturated hydraulic conductivity, which tend to produce more runoff. Soils with low saturated hydraulic conductivities and shallow depths impede infiltration and lack water storage. A rain garden is a small-scale GSI that cannot catch all the runoff from a large contributing area. Therefore, placing rain gardens in high-λ_{HSI} areas will be ineffective.

Areas with low λ_{HSI} (Class 1 or Class 2) tend to have low contributing areas, large slope gradients, deeper soils, and higher saturated hydraulic conductivity. When the soil water storage capacity exceeds the topographic wetness, λ_{HSI} becomes negative. Areas with low (or even negative) λ_{HSI} values are "self-sufficient" in receiving runoff and storing infiltrated water and, therefore, do not need additional mitigation by GSI. Hence, the most effective areas for rain gardens are those with moderate λ_{HSI} values (Class 3), where the contributing areas

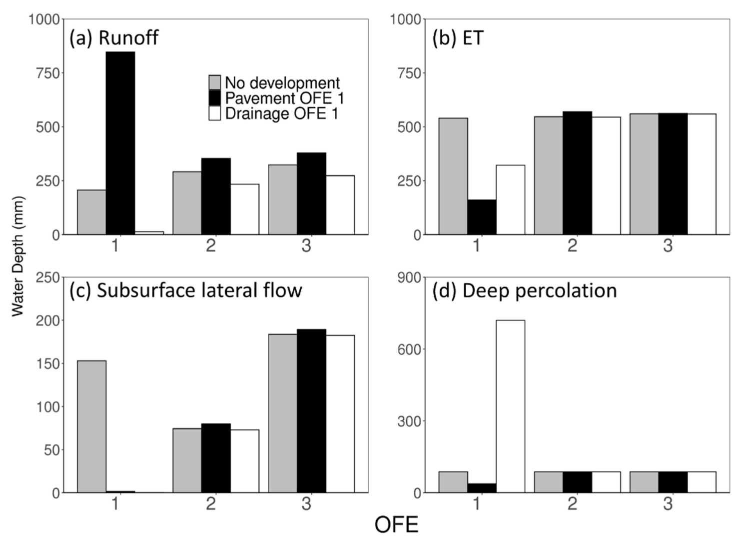

Fig. 11. Water balance of the design hillslope as impacted by pavement and drainage installation at the hilltop: (a) runoff, (b) ET, (c) subsurface lateral flow, and (d) deep percolation through the bottom of the soil profile. Note that ET from the paved OFE 1 comprises only soil evaporation and no plant transpiration.

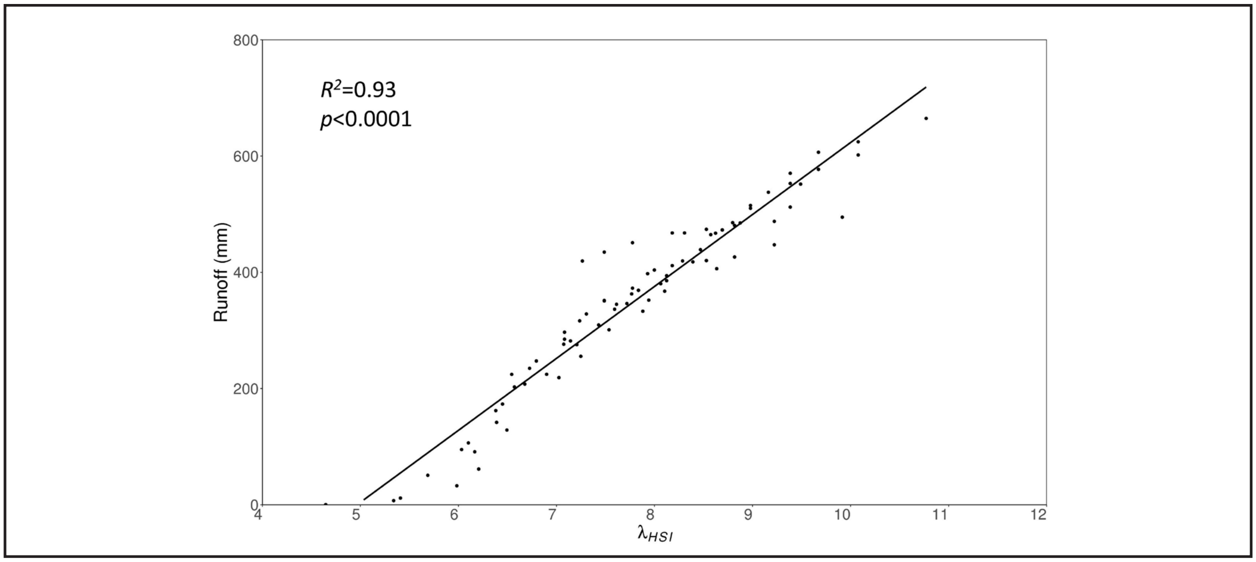

Fig. 12. WEPP-simulated runoff versus Hydrologic Sensitivity Index (λ_{HSI}) (excluding cases with tan $\beta = 0$).

are moderate and the soil depth and hydraulic conductivity are adequate for capturing and storing infiltrated stormwater.

WEPP simulation results revealed an equifinality issue: Various combinations of slope and soil characteristics can result in the same λ_{HSI} value (Figure 12). For instance, other conditions (λ_{TWI} and surface imperviousness) being equal, a soil profile 0.5 m deep with a saturated hydraulic conductivity of 4 m d^{-1} may generate a different amount of runoff from a soil profile 1 m deep with a saturated hydraulic conductivity of 2 m d^{-1} despite having the same λ_{HSI}. The reasons are many. For instance, the effects of soil depth and hydraulic conductivity on runoff generation differ, the former reflecting storage and the latter transmissivity, and both interact dynamically with other factors (patterns of precipitation events and subsurface saturation conditions) in runoff generation. Therefore, it is essential to assess the suitability of rain gardens in areas with similar or identical λ_{HSI} values through on-site evaluation or more process-based hydrologic modeling. Further, the adequacy of λ_{HSI} could be evaluated by examining seasonal variation of soil saturation in areas with contrasting λ_{HSI} values through ground truthing and analysis of remotely sensed images.

3.6. Optimizing Placement of Rain Gardens

With areas not meeting the state ordinances and engineering criteria for rain gardens excluded from consideration, 18% of the watershed area could be used for rain gardens (Figure 13). The maps of suitable areas for rain gardens obtained with or without flow adjustment were similar, with differences largely indiscernible. Hence, we show only the suitability map (lot-scale) without adjusting flow accumulation due to the presence of impervious surfaces. For all areas meeting state ordinances and engineering criteria for rain gardens, the suitability was further classified into 3 groups. Based on the reasoning in Section 3.5, areas of the highest suitability ("strongly recommended") for rain gardens had moderate λ_{HSI} values

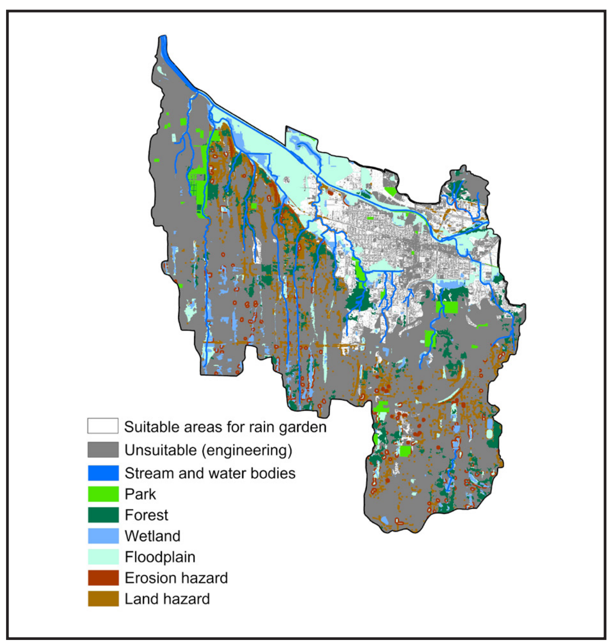

Fig. 13. Suitable areas for rain gardens (in white), Lower Puyallup River Watershed.

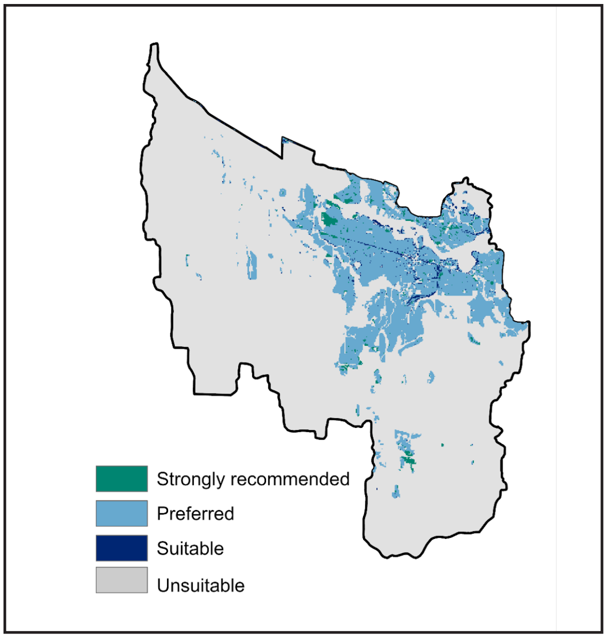

Fig. 14. The suitability of areas for rain gardens (without adjustment to flow accumulation), Lower Puyallup River Watershed.

(Class 3, Figure 14). The areas with one interval of λ_{HSI} larger or smaller (Class 2 or Class 4) were considered of second highest suitability ("preferred") for rain gardens. Areas with the lowest or highest λ_{HSI} values (Class 1 or Class 5) were considered to be of the relatively lowest suitability ("suitable"). The areas most suitable for rain gardens ("strongly recommended") cover 0.98% of the watershed and are unevenly distributed across the watershed, with the majority clustered in the northeastern and north-central parts, particularly in the low-lying areas near the Puyallup River. The "preferred" areas for rain garden installation account for 17% of the watershed, and those "suitable" for rain gardens cover 0.5%. Thus, under the constraint of limited budgets, city planners should first target the "strongly recommended" areas for installing rain gardens because these areas, with moderate λ_{HSI} values, would generate a moderate amount of stormwater runoff that could be effectively infiltrated, retained, and cleansed.

4. Conclusions

In this study we used the HSI approach to identify suitable areas for rain gardens, a small-scale GSI. A mapping tool that enables the most efficient placement of the mini ecosystems that rain gardens epitomize, we believe, is of critical importance to the practicing ecological engineer tasked with the sustainable management of stormwater quantity and quality in urban ecosystems. Our mapping tool incorporates specific hydrologic processes associated with the path that stormwater runoff takes from surface to subsurface, thereby ensuring that rain gardens placed using this methodology are likely to intercept the most stormwater while staying within a rain garden's operating considerations.

The HSI and resultant suitability maps were created with or without flow accumulation adjustment using the impervious surface layer. To evaluate the adequacy of the HSI method, we applied a physically based hydrologic model, WEPP, to a design hillslope. We determined the relationship between potential runoff and λ_{HSI} in multiple scenarios with combinations of varying contributing areas, slope gradients, soil depths, and soil saturated hydraulic conductivity. We also evaluated the effect of development (pavement and subsurface stormwater drain) on runoff. Three levels of suitability for rain gardens were suggested and the corresponding areas were displayed on the suitability map for the study watershed.

Findings from this study demonstrate the appropriateness and effectiveness of the HSI method. The study provides a framework for practitioners and regulatory personnel to optimize the placement of rain gardens. Major conclusions include:

1. For the Lower Puyallup River Watershed, λ_{HSI} ranged from −3.8 to 28.4. The high-λ_{HSI} areas with greater potential for runoff generation were clustered in the central-western flat portion of the watershed. The low-λ_{HSI} areas with lower potential for stormwater runoff were in the southern part of the watershed with steeper slopes and deeper soils.
2. The λ_{HSI} maps with or without flow accumulation adjustment exhibited minimal difference in 93% of the watershed area and noticeable difference in 7% of the area. The HSI framework is, therefore, more adequate in identifying hydrologically sensitive areas in regions that have not been heavily developed, and the framework may be less applicable in fully developed areas.
3. Site-specific investigations remain essential to verifying suitable areas identified using the HSI method. Equifinality issues, inaccuracies in the DEM and SSURGO databases, and changes in hydrological flow paths due to development could cause discrepancies in the λ_{HSI} values, potentially leading to incorrect site selection for GSI. A site visit ensures that local factors, such as micro-topography, soil conditions, and local development activities, are considered.
4. WEPP-simulated runoff was significantly and positively correlated with λ_{HSI}, increasing with the

contributing area and decreasing with hillslope gradient, soil depth, and saturated hydraulic conductivity. Simulated average annual runoff was reduced by 44% and 99% for the moderate- and lowest- λ_{HSI} scenarios, respectively, compared to the highest-λ_{HSI} scenario.

5. When the hilltop OFE was paved, WEPP-simulated runoff increased, leading to a reduction in ET and an increase in runoff from those OFEs downslope compared to the no-development scenario. This result suggests elevated potential for runoff in downstream development areas lacking adequate stormwater infrastructure to manage runoff at its source.
6. When a subsurface stormwater drain was installed at the hilltop OFE, potential runoff was diverted away, decreasing all other water balance components for the site and leading to less runoff in downslope areas.
7. Areas with moderate-λ_{HSI} values are considered the most appropriate for siting rain gardens because these areas do not receive or generate large runoff volumes and have adequate soil storage to receive and retain runoff.
8. Even though 18% of the study area was found to be suitable for rain gardens, approximately 1% of the study *watershed* was deemed most suitable for rain gardens, especially when the resource is limited. These areas are concentrated in the northeastern and north-central parts of the watershed, in the low-lying floodplains of the Puyallup River.
9. Future efforts may be devoted to further corroborating the adequacy of the HSI method by (i) examining seasonal changes in soil saturation through ground-truthing or analysis of remotely sensed images, (ii) comparing results from the HSI method with those from process-based urban hydrologic models, and (iii) integrating with ecologically sensitive periods to prioritize areas closer to aquatic habitats.

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Author Contributions Statement

Conceptualization: AJ, JW; methodology: AJ, JW, MSD, AM; data analysis: MSD; writing original draft: MSD; review/editing original draft: JW, AJ, MSD, AM; investigation: MSD; resources: JW, AJ; data curation: MSD, AM; supervision: JW, AJ; project administration: AJ, JW; funding acquisition: AJ, JW. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Statement

The authors have no conflict of interest to report.

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