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Restoring the hydrologic response to pre-developed conditions in an urbanized headwater catchment: Reality or utopia?

Olivia Wright[1], Erkan Istanbulluoglu[1], Jim Simmonds[2]

(1)Civil and Environmental Engineering, University of Washington-Seattle, Seattle, WA 98195, USA, contact: owright@u.washington.edu

(2)Water Quantity and Quality Groups Unit, King County, WA

1. Abstract

The conversion of forested areas to impervious surfaces, lawns and pastures alters the natural hydrology of an area by increasing the flashiness of stormwater generated runoff, resulting in increased streamflow peaks and volumes. Currently, most of the stormwater from developed areas in the Puget Sound region remains uncontrolled. The lack of adequate stormwater facilities along with increasing urbanization and population growth illustrates the importance of understanding urban watershed behavior and best management practices (BMPs) that improve changes in hydrology. In this study, we developed a lumped urban ecohydrology model that represents vegetation dynamics, connects pervious and impervious surfaces and implements various BMP scenarios. The model is implemented in an urban headwater subcatchment located in the Newaukum Creek Basin. We evaluate the hydrologic impact of controlling runoff at the source and disconnecting impervious surfaces from the storm drain using rain barrels and bioretention cells. BMP scenarios consider the basin's land use/land coverage, the response of different impervious surface types, the potential for BMP placement, the size and drainage area for BMPs, and the mitigation needs to meet in-stream flow goals.

2. Study Site

The Green-Duwamish Watershed is located east of the Cascade Mountains in Washington and empties into the Elliot Bay of the Puget Sound. Newaukum Creek is a southern tributary in the Green-Duwamish Watershed that flows from the mountains east of Enumclaw into the middle Green River. The catchment of interest is Newaukum Urban located at the headwaters of Newaukum Creek basin, in the city of Enumclaw (Figure 1). The basin is approximately 1 km^2 and is highly developed with 93.5% of the area urbanized (Figure 2) and 70% covered by impervious surfaces (Figure 3).

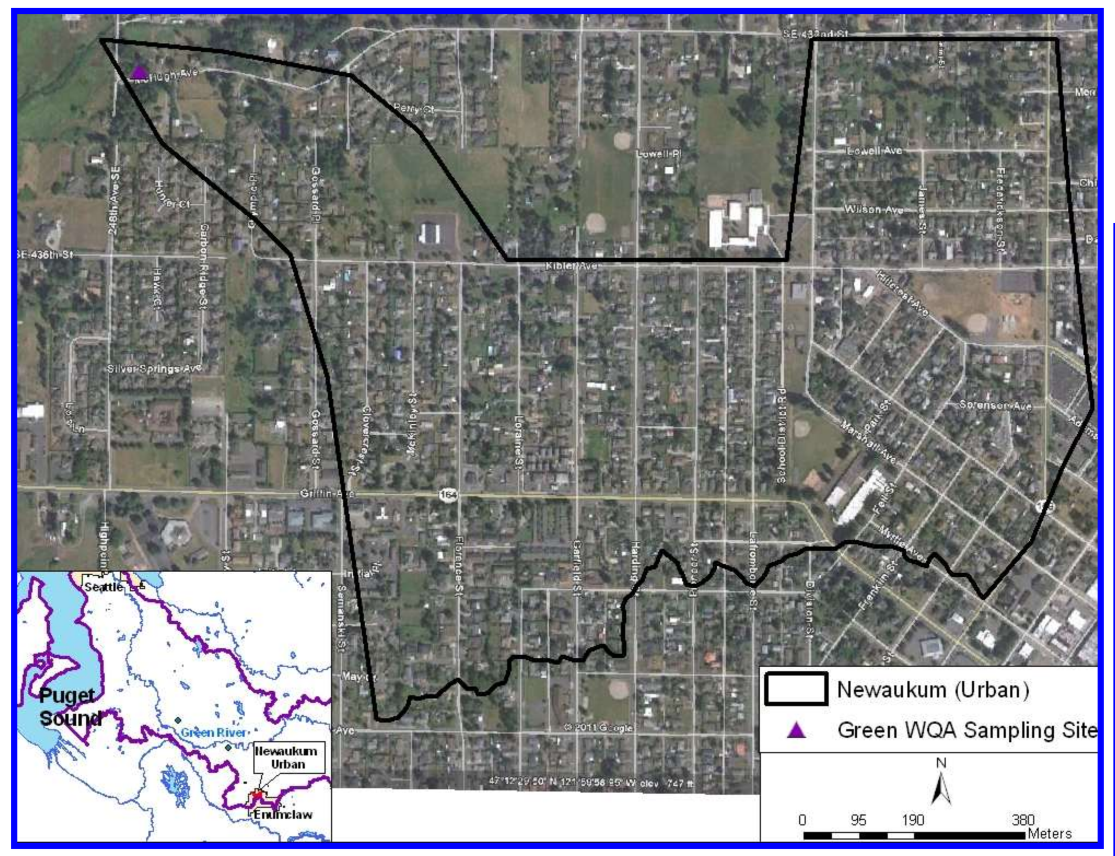

Figure 1. Location map of study area

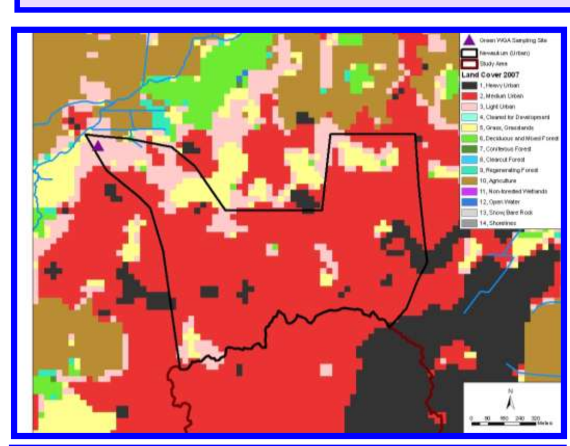

Figure 2. Newaukum Urban Land Cover (King Co, 2007 land use cover)

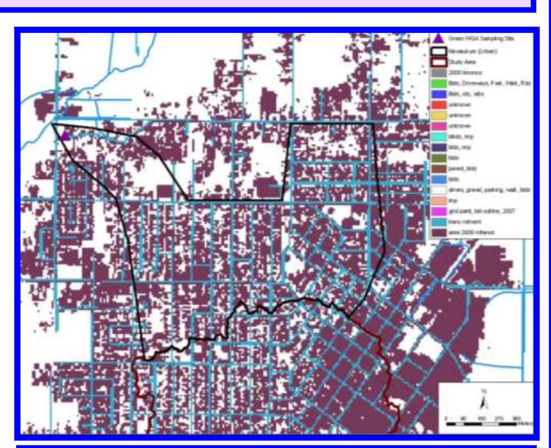

Figure 3. Newaukum Urban Impervious Surfaces (King Co, 2009 Imp Coverage)

3. Data Sources

Hourly streamflow data at the outlet of the Newaukum Urban basin was obtained from King County. Hourly precipitation and air temperature data were obtained from King County's Enumclaw rain gage (http://green.kingcounty.gov/wlr /waterres/hydrology/). Incoming solar radiation data was gathered from Washington State University Puyallup AgWeatherNet location (http://weather.wsu.edu/awn.php).

Field photos of Newaukum Urban neighborhoods (Taken 10/2/2012)

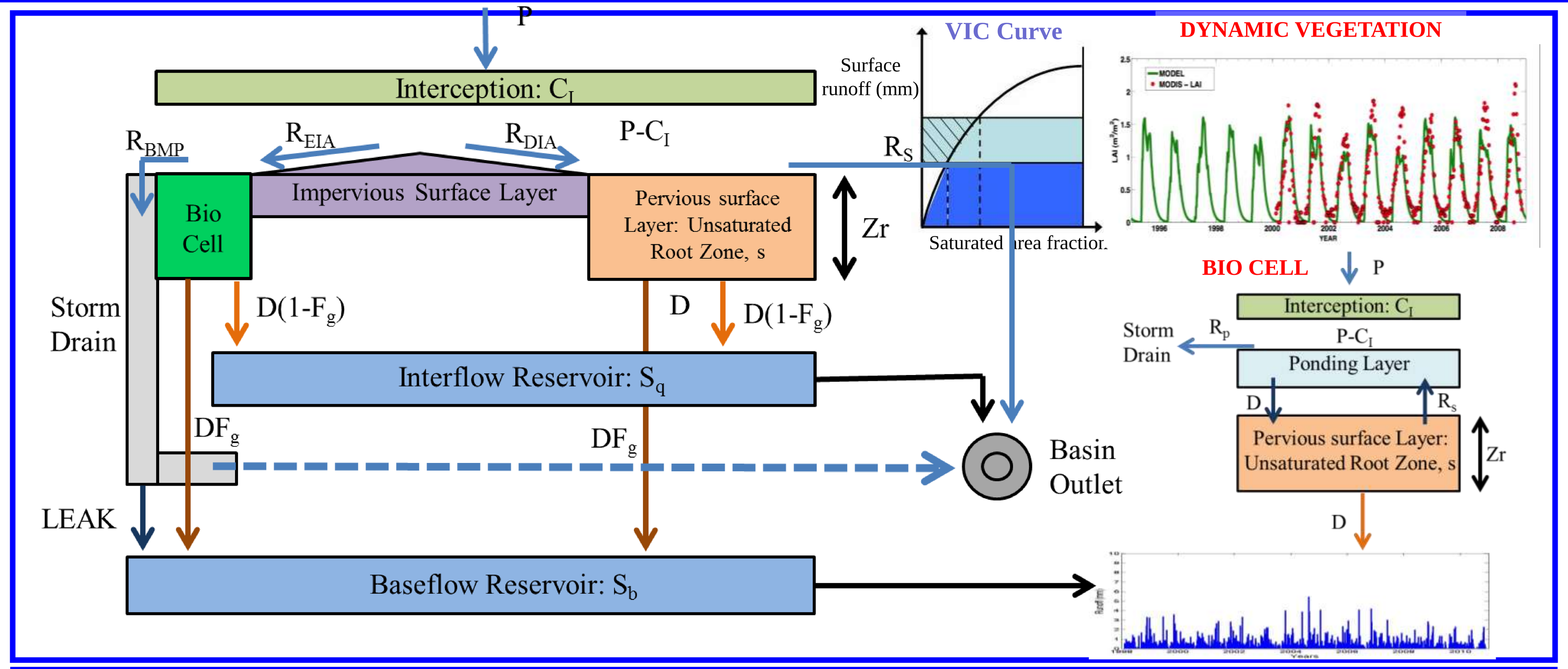

Figure 4 Urban Ecohydrology Model and Bioretention Cell Model Schematic

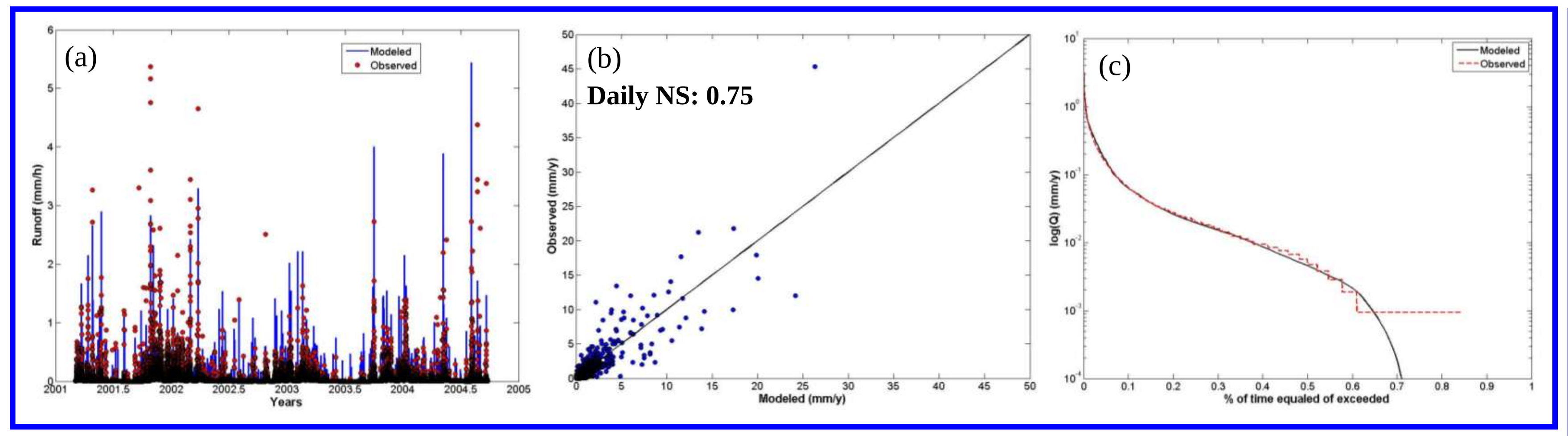

Figure 6. 3-yr model calibration.(a) Observed and modeled runoff, (b) daily 1:1 plot, (c) flow duration curve

4. Urban Ecohydrology Model (UEM)

This study develops the lumped Urban Ecohydrology Model (UEM) (Figure 4) to simulate the urban landscape and examine the impact of bioretention stormwater treatment at the catchment scale. The depth averaged soil moisture in the root zone layer is calculated by the mass balance equation:

$$nZ_r \frac{ds}{dt} = [f(s,p,V) - ET(s,V) - D(s)] \quad (1)$$

The model calculates the water balance components for the catchment pervious surfaces and bioretention cells as follows:

Pervious Surface Input
$$p = (P - C_I) + \frac{(P - C_I) * (IMPfrac - EIAfrac)}{1 - IMPfrac - Biofrac} \quad (2)$$

Effective Impervious Area Runoff / Inflow into Bio Cell
$$R_{EIA} = (P - C_I) * EIAfrac * (1 - LEAK) \quad (3)$$

Pervious Surface Runoff
$$R_s = \begin{cases} (p - f) \cdot (1 - IMPfrac - Biofrac) & p > f \\ 0 & p \le f \end{cases} \quad (4)$$

Baseflow
$$R_b = \left(\frac{1}{T_g} S_g\right) \cdot (1 - IMPfrac - Biofrac) \quad (5)$$

Overflow from bio cell connected to storm drain
$$R_{BIO} = \begin{cases} 0 & Pond_{Store} \le Pond_{Max} \\ Inflow - PondMax & Pond_{Store} > Pond_{Max} \end{cases} \quad (6)$$

Drainage
$$D = \begin{cases} K_s \cdot (1 - IMPfrac - BIOfrac) + D_{bio} \cdot (BIOfrac) & s = 1 \\ K_s s^{2b+3} \cdot (1 - IMPfrac - BIOfrac) + D_{bio} \cdot (BIOfrac) & s_{fc} < s \le 1 \end{cases} \quad (7)$$

Total Streamflow
$$R = R_b + R_s + R_{BIO} \quad (8)$$

The model also includes a dynamic vegetation component that updates the amount of biomass and LAI below and above ground (Istanbulluoglu et al. 2012, Figure 5).

The UEM with no bioretention cells is calibrated to 3 years of hourly observed streamflow data. The calibration parameters of the model are *Fg* (0.87), *Variable Infiltration Capacity (VIC) b-shape parameter* (0.3), and *T* (18 hrs). *Fg* controls the fraction of drainage water directly contributing to groundwater and *T* controls the reservoir drainage timescale. Model calibration was performed using flow duration curves and the Nash-Sutcliffe (NS) model efficiency coefficient to match the modeled runoff to observed (Figure 6, a-c). Our model calibration assumes groundwater storage bypasses the Newaukum Urban outlet and joins the channel network farther downstream in the basin. Table 1 presents the water balance components of the model. We used the model to simulate the catchment hydrologic response for 12 years of hourly observed precipitation data. The rainfall-runoff depth analysis (Boyd et al. 1993) estimates the EIA to be 20% of the basin.

Table 1. Water Balance Model Output

	Obs 3-year	Urban (3 yr calibration)	Urban (12 yrs)	Forested
BFI	0.4907	0.3098	0.3063	0.8895
Q/P	0.2319	0.2356	0.2315	0.0668
ETa/P		0.3012	0.294	0.5354
Drainage*Fg/P		0.4895	0.4733	0.3971

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5. Biological and Terrestrial Health

The Benthic index of Biological Integrity (B-IBI) in streams is correlated with the following hydrologic indices in Puget Sound Low Lands: (DeGasperi et al., 2009; Horner, 2012; see Table 2):

- **High Pulse Count (HPC):** number of days each water year that discrete high pulses occur above 2 X long-term mean
- **High Pulse Range (HPR):** range of days between first and last high pulse flow in water year.

Simulations: ***Urban no treatment***; ***forested***; ***Urban with bioretention treatment.*** The treatment conditions apply a single bioretention cell to intercept runoff from 1,000 ft^2 of impervious area. Terrestrial health was evaluated by comparing the long term mean total leaf area index (LAI) for the various scenarios.

Table 4. HPC for bioretention scenarios

Treated Area	HPC 20%	HPC 40%	HPC 60%
5x5	13.58	18.58	21.83
10x5	9.67	9.00	9.17
10x10	9.50	7.67	7.08
15x10	10.08	7.83	7.33
15x15	10.17	7.92	7.25
20x15	10.75	8.58	7.25
20x20	11.25	9.67	7.67

Table 5. HPR for bioretention scenarios

Treated Area	HPR 20%	HPR 40%	HPR 60%
5x5	296.67	315.17	326.33
10x5	261.67	254.75	262.08
10x10	241.33	212.00	199.08
15x10	251.58	213.33	199.50
15x15	248.50	213.42	199.42
20x15	253.00	225.17	199.33
20x20	268.17	240.167	213.250

Legend: Fair; Fair/Poor; Poor; Poor/VeryPoor; Very Poor

6. Bioretention Cell Performance

The forested and Urban no treatment condition HPC and HPR values are presented in Table 3. The HPC and HPR values of the observation and UEM simulations estimate the current watershed health to be 'Very Poor'. The indicators for the forested conditions did not fall within the range of indicator values from the Puget Sound lowland study (DeGasperi et al. 2009, Horner 2012) , but resulted in values lower than 'Good' and 'Fair' stream conditions.

While keeping the ratio of one bio cell for every 1,000 ft^2 of impervious area, we varied the size of the bio cells and the fraction of the impervious area treated to evaluate the most effective bioretention treatment scenario for improved biological and terrestrial health. Figure 7 (a-f) shows the HPC, HPR and mean LAI values for the various bioretention scenarios. Table 4 and 5 present the associated stream condition, designated by color, for each scenario's indicator results.

For all three treatment area scenarios, the HPC and HPR values initially decrease as you increase the size of the bioretention cells until they reach a threshold of effectiveness and increase again. The most effective size in all treatment area scenarios is a 10x10ft bio cell for every 1,000 ft^2 of impervious area, reducing HPC and HPR to it's lowest value given the area treated. The best level of performance from the scenarios improved the current stream health from 'Very Poor' to 'Fair'. Figure 8 (a-d) compares hourly modeled runoff for the Urban with no treatment, Forested, optimal treatment (10x10, 40% of basin treated) and maximum treatment (20x20, 60% of basin treated).

The mean unit LAI for the bioretention cells decrease with increasing cell size as expected given that less water is received by each unit as the footprint of the cell gets larger. The mean unit LAI for the pervious area increases as the bio cell gets larger, but decreases as the fraction of the basin treated increases. The mean LAI scaled to the basin (includes bio cell and pervious area) also increases with increasing cell size, but the difference between the fraction of the basin treated decreases as the cell size gets larger.

Table 2. Hydrologic indicator ranges

B-IBI Goal	Stream Condition	HPC	HPR
> 35	Good	3.0 – 7.0	90 – 110
30 – 35	Fair	2.0 – 8.7	34 – 168
24 – 29	Poor	7.3 – 10.7	115 – 178
< 16	Very Poor	10.0 – 22.0	160 – 306

Table 3. HPC and HPR for Urban and Forested conditions

	Obs 3-year	Urban (3 yr calibration)	Urban (12 yrs)	Forested
HPC	22.67	27.33	27.50	1.17
HPR	285.67	332.67	340.50	21.17

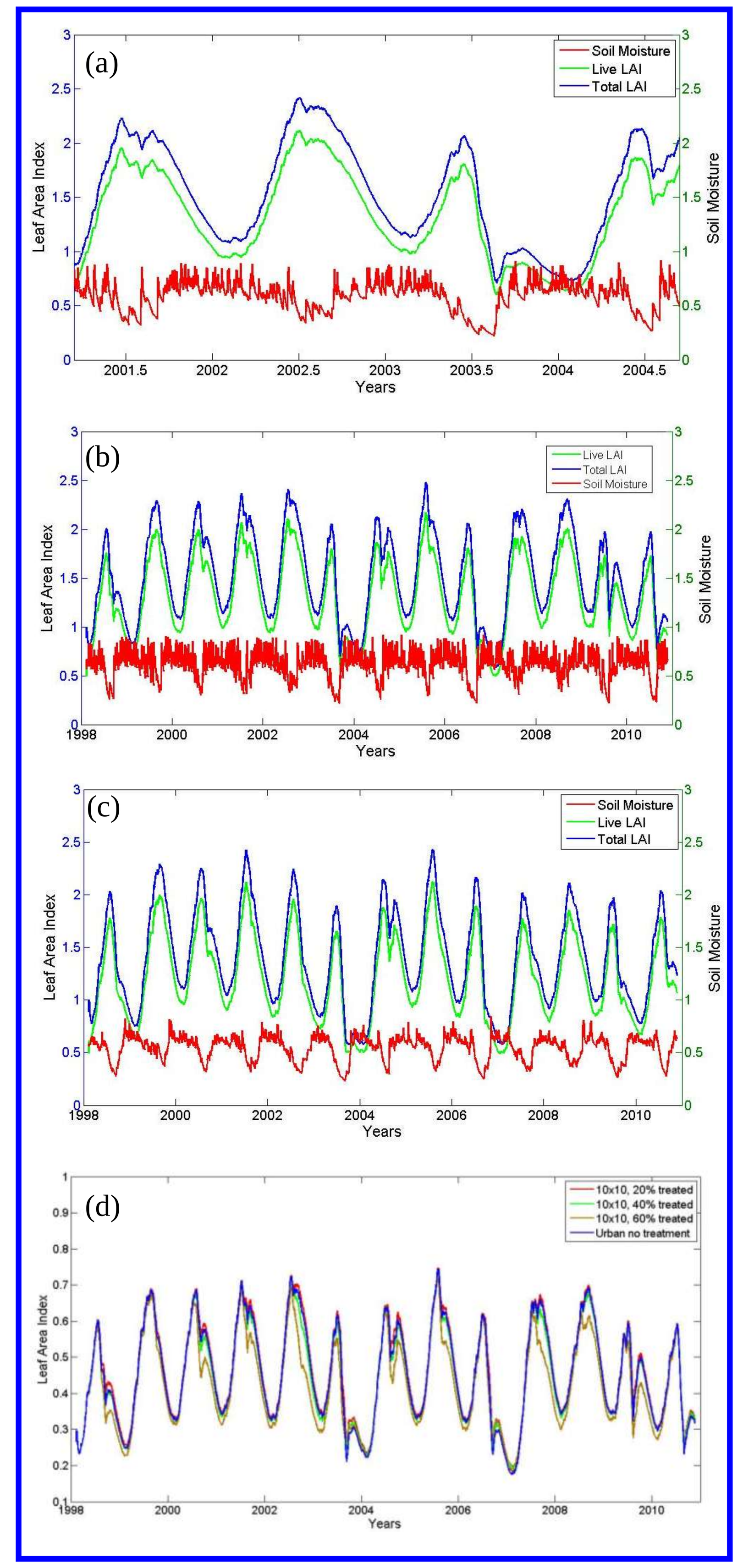

Figure 5. Unit Leaf Area Index for (a) 3-yr calibration, (b) 12-year Urban no treatment simulation,(c) 12-year forested, (d) Basin LAI for Urban no treatment and 10x10ft bio cell treatment scenarios

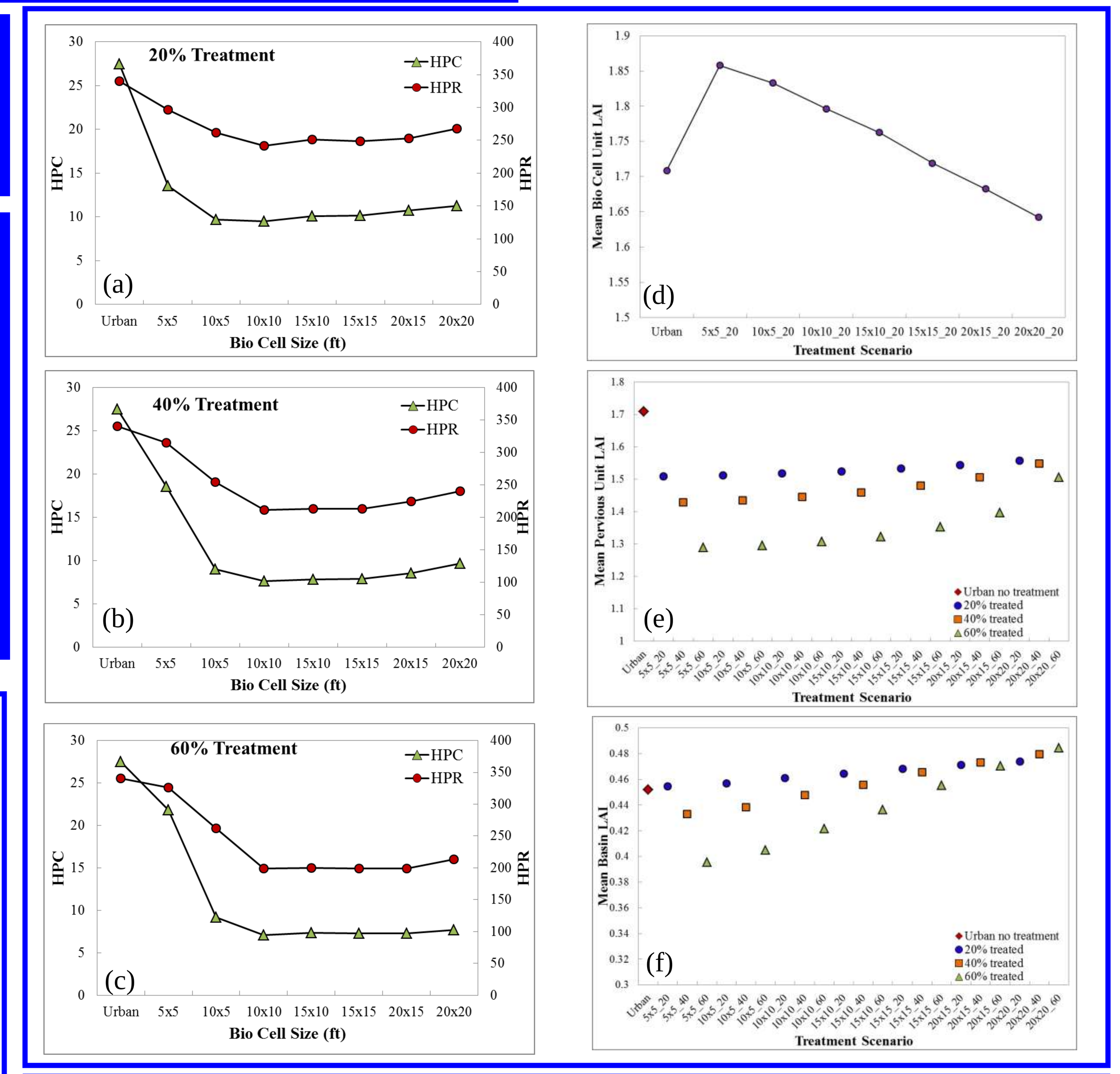

Figure 7. Indicator and LAI results for treatment scenarios (a-c) HPC and, (d-f) mean LAI for bio cell, pervious area and full basin, respectively.

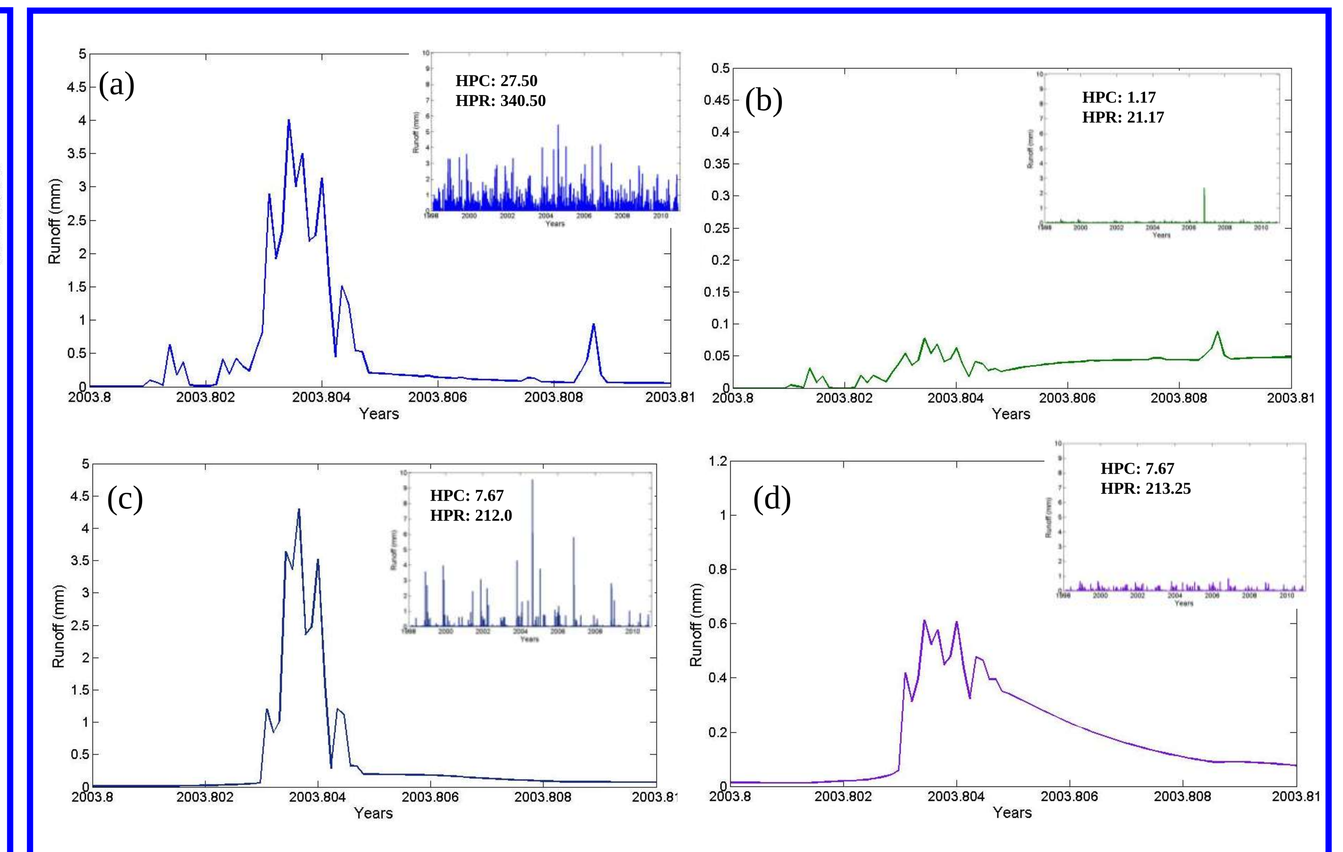

Figure 8. Hourly modeled Runoff (a) Urban no treatment, (b) forested, (c) optimal solution: 10x10, 40%treatment, (d) maximum treatment: 20x20, 60% treatment

7. Summary

This study develops a lumped Urban Ecohydrology Model (UEM) to simulate the hydrology of urbanized catchments and examine the effectiveness of bioretention treatment on improving stream conditions and watershed health. We simulated catchment conditions as Urban with no treatment, Urban with bioretention treatment and forested/pre-development conditions. By implementing various bioretention treatment scenarios, we have made the following observations:

1. Increasing the size of bioretention cells for the same treatment area reaches a threshold of effectiveness for stream health improvement.
2. Mean basin LAI does not have the same threshold effect, but differences in LAI for fraction of basin treated diminishes as bio cell size increases.
3. Although there is some improvement with reduced HPC values, it is not possible with bioretention cells alone to improve the stream conditions of such a highly urbanized catchment from 'Very Poor' to 'Good'.
4. Further assessment of implementation feasibility and cost effectiveness of scenarios is necessary to determine the best treatment scenario for the catchment.
5. Implementing additional best management practices or low impact development where appropriate may be able to reduce the HPC and HPR to further improve watershed health.

8. References

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DeGasperi et al. (2009). Linking hydrologic alteration to biological impairment in urbanization streams of the Puget Lowland, Washington, USA. *Journal of American Water Resource Association*, 45(2), 512-533.
Horner, R. (2012). Development of Flow and Water Quality Indicators. Unpublished Status Report.
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