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WATER QUALITY ANALYSIS OF ECOROOF RUNOFF IN PORTLAND

By

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A research project report submitted in partial fulfillment of the
requirement for the degree of

MASTER OF SCIENCE

IN

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Abstract

Portland, Oregon is internationally recognized for its implementation of sustainable stormwater management technologies. Ecoroof is one of the sustainable solutions to reduce stormwater runoff which also provides multiple environmental benefits. However, very little is known about the impact of ecoroofs on water quality of roof runoff. Stormwater runoff carries a significant amount of pollutants, which, if it directly enters a stream or river, degrades water quality and severely harms aquatic life.

This study evaluates the trends in the long-term water quality data from ecoroofs and conventional roofs in the Portland area. Mann Kendall trend test was used to detect the trends in concentrations of parameters. Concentration levels of metals (copper, lead, zinc) and nutrients (nitrogen and phosphorous) in runoff from ecoroofs were compared with the runoff from conventional roofs using Mann Whitney U test. Results indicated elevated levels of copper and phosphorous in ecoroof runoff. Concentrations of lead and zinc were found to be lower in ecoroof runoff than conventional roof runoff. Monitoring of ecoroof for a longer period is recommended for future studies to quantify the effect of roof age, thickness and composition of soil media, and plant types on runoff.

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1. Introduction

Urban stormwater management presents a unique challenge worldwide because of continuously expanding urban impervious areas (Czemiel Berndtsson, 2010). Stormwater runoff picks up a wide variety of contaminants as it flows over the ground, rooftops, streets, and parking lots. Additionally, precipitation itself can contain a significant load of pollutants. Many larger and older cities, including Portland, have a combined sewer system to carry storm water and wastewater to treatment facilities (Figure 1). Excessive runoff can overburden Portland's combined storm sewers and wastewater treatment facilities, leading to combined sewer overflows (CSO) where untreated sewage and storm water is discharged to the Willamette River.

The City of Portland's Bureau of Environmental Services (BES) manages Portland's wastewater and storm water infrastructure and is responsible for watershed planning. BES provides wastewater and storm water collection and treatment services to the city, protecting human health and the quality of water in rivers and streams.

Figure 1: Portland Sewer Systems, (BES, City of Portland)

The City of Portland adopted a citywide Storm Water Management Manual (SWMM) in 1999 that includes water quality and flow control design standards for onsite storm water management facilities. Portland's SWMM gives priority to vegetated storm water management systems, low-impact development practices, and maintenance and operational best management practices (BMPs) designed to improve storm water quality.

BES monitors the performance of storm water management facilities around Portland. Gathering performance data on storm water management facilities and long-term monitoring helps in improving design, function, and lowering in maintenance cost.

1.1 Green Infrastructure for Stormwater Management

Portland's average annual rainfall of 37 inches generates approximately 10 billion gallons of storm water runoff. Green infrastructure comprises interconnected natural areas or engineered systems that use soil and plants to control, filter, and infiltrate runoff. Green infrastructure manages storm water runoff closer to the source by mimicking natural hydrology and provides multiple environmental benefits.

The City of Portland is a recognized leader in green and sustainable storm water management and promoting green infrastructure through various policies and incentive programs. Between 2008 and 2013, BES adopted a Grey to Green initiative to boost the city's green infrastructure. Portland's green infrastructure techniques are designed to address region's small and frequent storms. The City's Grey to green initiative includes award-winning BMP project designs, constructing green streets, ecoroofs, rain gardens, permeable pavements, bio-retention cells (or bio-swales), infiltration trenches, planter boxes, rooftop (downspout) disconnection, and urban tree canopies (BES, 2010).

1.2 Ecoroof Overview and Pollution Concerns

With the increase in impervious area associated with urban development, there is a need of more sustainable urban drainage systems for attenuating runoff. Green roofs are one such a type of sustainable system to control urban runoff (Ferrans, Rey, Pérez, Rodríguez, & Díaz-Granados, 2018).

An ecoroof, or green roof, is the roof of a building, partially or fully covered with vegetated material along with waterproofing and a drainage system (Figure 2). An ecoroof decreases storm water runoff, helps to reduce urban heat island effect (Susca, Gaffin, & Dell’Osso, 2011), improves air quality (Yang, Yu, & Gong, 2008), and biodiversity. An ecoroof also saves energy (Spolek, 2008), absorbs CO₂ and improves the aesthetics of the space.

Figure 2: Ecoroof cross section (BES, City of Portland.)

An ecoroof is a best management practice for urban storm water management, however, more research is required to determine the impact of ecoroofs on the quality of roof runoff.

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Theoretically, vegetation on the ecoroof should absorb pollutants, but an ecoroof can also release pollutants depending upon the roofing material, the age of the roof, use of fertilizers, quality of precipitation, etc. (Li & Babcock, 2014). Precipitation itself is a source of multiple contaminants (Sullivan, 2005).

Figure 3: Ecoroof Facilities: Portland (BES, City of Portland)

Several studies have investigated the water quality of runoff from ecoroofs compared to the runoff from conventional roofs. Most of the studies examined concentration of nutrients (i.e., nitrogen and phosphorus) in the runoff and the findings indicate that ecoroofs are source of nutrients (Carpenter, Todorov, Driscoll, & Montesdeoca, 2016; Mitchell, Matter, Durtsche, & Buffam, 2017; Razzaghmanesh, Beecham, & Myers, 2016; Teemusk, 2011). Primary sources of nutrients in green roof runoff are atmospheric deposition and leaching from the soil medium. A

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few studies investigated metal concentration, however, and some found that runoff metal concentrations were higher than for conventional roof (Buffam, Mitchell, & Durtsche, 2016; Gregoire & Clausen, 2011). Elevated concentrations of heavy metals, such as Cu and Zn, in storm water runoff can be toxic to aquatic life. Cu concentrations as low as 2 µg/L can impact aquatic life (Sandahl et al. 2007). Elevated concentration of nutrients can lead to production of algal blooms in the receiving water body.

A study conducted in Lahti, Finland found higher concentrations of nitrate and total phosphorus in runoff from ecoroofs. However, bio char amendments in the growing media did decrease total nitrogen (TN) and total phosphorus (TP) load after one year of the experiment (Jokimaa, 2016). In a Swedish study, runoff from extensive sedum moss roofs and conventional roofs was measured for metals and nutrients (Berndtsson, Emilsson, & Bengtsson, 2006). The results indicated that the ecoroofs studied were a source of pollutants, with the exception of nitrogen. A study carried out in North Carolina found that green roofs with high organic matter (e.g., compost) served as an additional source of TN and TP (Moran, Hunt, & Jennings, 2004).

Approximately 38 acres of ecoroofs (over 560 roofs) have been installed on Portland buildings since the 1990s (Figure 3). Monitoring of ecoroofs in Portland by BES has previously shown that ecoroofs reduce peak flow and total runoff volumes compared to conventional roofs. However, little is known about ecoroof impact on water quality. Limited data collected from the City of Portland for one ecoroof has indicated that runoff from ecoroofs can have elevated concentrations of nutrients, mostly TN and TP (Hutchinson, et al , 2003). Cu concentrations were significantly higher than the concentration in conventional roof runoff (City of Portland BES, 2010). The City of Portland's Central City 2035 plan, which went into effect from July 2018, includes a requirement that all new structures (>20,000 sq. ft) constructed within the central city

boundary should have 60% ecoroof coverage (Portland, 2018). With the expectation of new ecoroof installations, it is increasingly important to develop an improved understanding of the water quality of ecoroof runoff.

1.3 Objective

This study seeks to evaluate the trends in the long-term water quality data from ecoroofs in Portland area and provide recommendation for future monitoring plans. Six ecoroofs and two conventional roofs monitored by BES were studied.

Analysis of the results for each ecoroof facility will help to identify possible sources of contamination and will be used by BES to understand how soil media, age of the roof, and roofing material contribute to runoff water quality.

2. Methods

2.1 Site Descriptions

In 2001 BES began monitoring the water quality of various ecoroof facilities to determine the effect of ecoroofs on runoff water quality. Six different ecoroofs were selected for this analysis based on availability of water quality data. The ecoroofs evaluated in this study are located within the Portland city limits (Figure 4). A description of each ecoroof, including installation year, roof area, and soil media depth is included in Table 1.

Figure 4: Locations of the ecoroofs used in this study

Table 1: Site Characteristics

Site	Installation year	Ecoroof (sq. ft)	Drainage area (sq. ft)	Soil Depth (in)	Soil Media
HA East	1999	2520	3811	3	25% encapsulated polystyrene, 15% digested fiber, 15% coir fiber, 15% perlite, 15% peat moss, 15% compost
HA West	1999	2620	3655	5	28% sandy loam, 22% perlite, 20% digested fiber, 20% coir fiber, 10% compost
PDX	2006	16000	5250	5	Mixture of sandy loam, pumice, compost, and Stockosorb® polymer
MD	2012	288	**	5	Mixture of sandy loam, soil life compost, fiber life compost and pumice
RA	2012	32000	**	3.5	70% Pumice and 30% organic materials
SW	2012	2200	**	5	Mixture of sandy loam, soil life compost, fiber life compost and pumice
WA	2013	54000	12915	5	Mixture of sandy loam, pumice, and compost
			12915	3	

**Exact areas not available for the blank spaces in tables

2.1.1 Hamilton West Apartments (HA): Hamilton West is a nine-story apartment building with 152 homes. The ecoroof on Hamilton apartments was installed in the Fall of 1999 and has been monitored since 2001. To test stormwater capacity of different types of soil, the ecoroof was divided into east and west drainage areas with different soil media and separate roof drains (Figure 5). The east side was installed with three inches of lightweight material while the west side with five inches of heavier material. To prevent soil loss due to wind, red pumice was added to the east side.

Figure 5: Hamilton ecoroof layout (BES, City of Portland)

This ecoroof was planted with 75 species of succulents and grasses. The Hamilton ecoroof receives precipitation and runoff from stone terrace.

2.1.2 Marine Drive pump station (MD): The ecoroof on the Marine Drive pump station was installed in 2012 and was monitored until 2014. A five-inch deep growing medium consisting of a mixture of sandy loam, soil life compost, fiber life compost and pumice ('Pro Gro Semi Intensive Media') was used (Figure 6).

Figure 6: Marine Drive pump station ecoroof

2.1.3 Portland building (PDX): The Portland Building is a 15-story municipal office building in downtown Portland. The roof of the Portland Building was retrofitted in the summer of 2006 with a new ecoroof (approximately 5250 sq. ft) The Portland Building ecoroof was monitored from March 2007 to Jun 2012. Three inches of soil media was used with a proprietary mix of sandy loam, pumice, compost, and Stockosorb® Polymer (Figure 7).

Figure 7: Portland building ecoroof

2.1.4 The Ramona Apartments (RA): The Ramona is a 6-story apartment building with 138 homes. A 32,000 sq. ft ecoroof was installed on The Ramona Apartments in 2011. A 3.5” deep soil mix was used, which consisted of roughly 70% pumice and 30% organic material. 26 species of succulents and grasses were planted (Figure 8).

Figure 8: Ramona Apartment ecoroof

2.1.5 Sellwood Pump Station (SW): An ecoroof on the Sellwood pump station was installed in 2012 and was monitored until 2014. A five-inch growing medium consists of Gro Pro semi intensive mixture was used (Figure 9) and succulents and grasses were planted.

Figure 9: Sellwood pump station ecoroof

2.1.6 Walmart store (WA): An ecoroof on a Walmart store was installed in 2013. The ecoroof was divided into three equal 12915 sq.ft sections of different media depths next to an impermeable 15,800 sq.ft conventional roof (Figure 10). WA 5 denotes ecoroof with a five-inch soil media while WA 3 denotes ecoroof with three-inch soil media. Mixture of pumice, compost, and sandy loam was used on both ecoroof sections. Succulents and grasses were planted on ecoroofs.

Figure 10: Walmart store ecoroof layout

2.2 Data Description

Sampling was conducted by BES Field Operations Staff to analyze for various parameters from ecoroof runoff. Grab samples were collected by placing a decontaminated stainless-steel beaker or the analyte specific sample containers under the flow discharging from the flumes (City of Portland BES, 2010). To compare ecoroof performance with conventional roof, runoff samples from conventional roofs of HA and WA were also collected. Due to technical issues monitoring

equipment from east side of HA was removed in 2008. A detailed description of monitoring periods and the collected number of samples is included in Table 2. In this study, a total of 117 samples were analyzed by descriptive and analytical statistics.

Table 2: Number of samples in monitoring period, 2001-2018

Site	Monitoring Period	No of Samples
HA East	2001-2008	15
HA West	2001-2018	31
HA Conventional	2002-2018	18
MD	2012-2014	6
PDX	2007-2012	14
RA	2012-2014	4
SW	2012-2014	4
WA 5	2014-2018	8
WA 3	2014-2018	8
WA Conventional	2014-2018	9

2.3 Data Analysis

The water quality data from six ecoroof sites in Portland were analyzed. The analyzed water quality parameters included arsenic, copper, chromium, lead, zinc, conductivity, *E.coli*, hardness, ammonia, nitrate, orthophosphate, total phosphorus, solids. In this study water quality parameters of concern in the Portland area, metals (copper, zinc, lead), nutrients (phosphorus and nitrogen) and total suspended solids which can have potentially adverse impact on human health or aquatic organisms were analyzed statistically (Table 3). Orthophosphate (PO_4^{3-}) is a biologically highly available form of soluble phosphorus readily used by plants. Total phosphorus (TP) is a measurement of all phosphorus species, including polyphosphates and organic forms.

Table 3: Water quality parameters analyzed in this study with their abbreviations and units

Parameters	Abbreviations	Units
Copper	Cu	µg/L
Dissolved copper	Dissolved Cu	µg/L
Lead	Pb	µg/L
Dissolved lead	Dissolved Pb	µg/L
Zinc	Zn	µg/L
Dissolved zinc	Dissolved Zn	µg/L
Ammonium nitrate	NH ₄ -N	mg/L
Nitrate nitrogen	NO ₃ -N	mg/L
Orthophosphate	PO ₄ ⁻³	mg/L
Total phosphorus	TP	mg/L
Total suspended solids	TSS	mg/L

Statistical analyses were carried out using R programming software (version 3.4.3).

To present summary statistics (min, mean, median, max) of all parameters, data were first analyzed using descriptive analysis. To detect the existence of trends in the data, the Mann Kendall (MK) trend test was used. This test showed whether concentration values for parameter increased, decreased or were statistically trendless over time.

The data of ecoroof runoff from all sites were graphically analyzed before performing MK trend test. Box plots and scatter plots were used for exploratory data analysis. The null hypothesis (H_0) for the MK trend test was that there is no trend present in the data. That is, data obtained over time were identically distributed and not correlated over time. The alternative hypothesis (H_a) was that there is a trend present in the data.

To compare the data of conventional roof and ecoroof runoff from WA and HA, non-parametric Mann Whitney U test was carried out. The null hypothesis for this test was that the concentration distribution from the two roof types were equal.

3. Results and Discussion

A statistical summary of the concentrations of all parameters from ecoroof runoff are presented in the Appendix (Table 10). Graphical results for the concentrations over time for the studied parameters are included in the appendix (Figure 17- Figure 20). Results from Mann Kendall trend test and Mann Whitney U test are included in Table 8 and Table 9 respectively.

3.1 Metals

A statistical summary of concentrations of metals on all sites is given in the Appendix (Table 10) and mean values for total and dissolved Cu, Pb and Zn are presented in Table 5. As there are no standards for water quality of roof runoff, results were only compared with water quality standards in streams.

Table 4: Water quality standards for aquatic life in Oregon (Oregon DEQ, 2013) and the national drinking water standards (U.S. EPA, 2017).

Parameters (µg/L)	Cu	Pb	Zn
Aquatic Life Chronic Criteria	2-4*	0.5**	36**
Drinking Water Standards	1300	15	n/a

*The freshwater criterion for copper is a function of the concentration of ions, alkalinity, organic carbon, pH and temperature, and is calculated using the Biotic Ligand Model. For purposes of illustration, a limit calculated using default values is included.

** The freshwater criterion for lead and zinc is calculated as a function of hardness. For the purposes of illustration, limits calculated using default values are included.

Table 5: Mean concentration of metals from ecoroof runoff for all sites

Parameters ($\mu\text{g/L}$)	Sites									
	HA East	HA West	HA Conv	MD	PDX	RA	SW	WA 5	WA 3	WA Conv
Cu	8.98	11.80	2.6	18.93	11.4	10.31	7.7	5.93	6.02	1.34
Dissolved Cu	7.28	10.35	1.9	16.16	10.07	9.38	7.6	5.55	5.59	0.45
Pb	2.86	0.45	0.35	0.22	2.09	0.16	0.1	0.19	0.16	0.21
Dissolved Pb	1.28	0.44	0.10	0.17	0.65	0.1	0.1	0.10	0.1	0.1
Zn	55.85	20.7	335.2	62.6	17.99	7.24	191	19.5	19.0	40.9
Dissolved Zn	49.8	17.7	305.9	56.32	15.57	5.21	17.1	16.9	15.8	35.1

3.1.1 Copper (Cu): The Cu concentrations in ecoroof runoff were generally higher initially but then decreased over time. The concentration of dissolved Cu was slightly higher on the HA west ecoroof than HA east and ranged from 0.5 $\mu\text{g/L}$ to 26.3 $\mu\text{g/L}$ (Appendix; Table 10). The average dissolved Cu concentration on east and west side ecoroofs was much higher than conventional roof (average of 2.6 $\mu\text{g/L}$ total; 1.9 $\mu\text{g/L}$ dissolved). Similarly, average concentration on conventional roof of site WA (1.34 $\mu\text{g/L}$ total; 0.45 $\mu\text{g/L}$ dissolved) was lower than ecoroofs on WA 5 and WA 3. All other sites had similar concentration of average Cu concentration though slightly higher on MD (18.9 $\mu\text{g/L}$ total; 16.16 $\mu\text{g/L}$ dissolved). Total Cu concentration ranged from 4.08 $\mu\text{g/L}$ to 72.8 $\mu\text{g/L}$ while dissolved Cu from 3.64 $\mu\text{g/L}$ to 59.4 $\mu\text{g/L}$. Boxplots for concentration of Cu are presented in figure 11. For comparison, the mean Cu concentration standard for aquatic life in Oregon is 2-4 $\mu\text{g/L}$ in stream (Table 4).

Results from MK test showed no trend for Cu concentration except for the PDX site, where based on p and tau values, decreasing trend was observed (Table 8). Using Mann Whitney U test,

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significant differences were found in Cu concentrations at conventional roof and ecoroofs sites (p value < 0.05) on both HA and WA site (Table 9).

Figure 11: Boxplots showing total and dissolved Cu concentrations for all the sites.

Graphical representation for HA showed variable concentration of Cu however, all other sites showed downward trend of concentration over time (Appendix; Figure 17).

3.1.2 Lead: The average concentration levels of Pb were much lower on the HA west ecoroof (0.45 µg/L total; 0.44 µg/L dissolved) than HA east side (2.86 µg/L total; 1.89 µg/L dissolved).

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Total Pb concentration on HA east ranged from 0.16 µg/L to 23.5 µg/L and that of HA west from 0.1 µg/L to 5.12 µg/L. Maximum dissolved Pb concentration on HA east was 13.6 µg/L versus 1.02 µg/L in HA west. The east side media contains higher amount of Pb than media on west side which could be the source of higher concentration of Pb on east side. The concentration levels on both HA west and HA east ecoroof were higher than a conventional roof. All other sites including WA showed lower concentration of Pb (ranged from 0.1 µg/L to 0.6 µg/L) except on PDX where average total Pb concentration was slightly higher (2.09 µg/L). Boxplots for the concentration of Pb are presented in figure 12. Thus, mean Pb concentration was higher than Oregon water quality standards for aquatic life in stream for HA east and PDX sites (Table 4). Results from all other sites indicated Pb concentration below that water quality benchmark.

Results from MK test showed a decreasing concentration trend on HA west site but increasing trend on HA east and WA 3 (Table 8). HA east and WA3 both ecoroofs have soil media depth of 3 inches. No trend detected on other remaining sites. Results from Mann Whitney U test showed significant difference in only HA east and HA conventional roof (Table 9).

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Figure 12: Boxplots showing total and dissolved Pb concentrations for all the sites

3.1.3 Zinc: The average concentration levels of Zn were much higher on HA east than on HA west (55.85 $\mu\text{g/L}$ total; 49.8 $\mu\text{g/L}$ dissolved on east versus 20.7 $\mu\text{g/L}$ total; 17.7 $\mu\text{g/L}$ dissolved on west). The maximum concentration of total Zn on east side was 304 $\mu\text{g/L}$ and that of dissolved Zn was 274 $\mu\text{g/L}$. Galvanized metal railing on east side could be a source of higher concentration of Zn levels. The average concentration levels on HA conventional roof were much higher than

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east and west ecoroof (335.2 $\mu\text{g/L}$ total; 305.9 $\mu\text{g/L}$ dissolved). Similarly, WA conventional roof showed higher average Zn concentration than WA 5 and WA 3 ecoroofs (40.96 $\mu\text{g/L}$ total on conventional versus 19.5 $\mu\text{g/L}$ on WA 5 and 19.01 $\mu\text{g/L}$ on WA 3). This would suggest the ecoroof can capture zinc from conventional roof sources like galvanized metals. The average concentration levels of Zn on MD (62.6 $\mu\text{g/L}$) and SW (54.3 $\mu\text{g/L}$) were generally higher comparative to PDX (17.9 $\mu\text{g/L}$) and RA (7.24 $\mu\text{g/L}$) ecoroof. Boxplots for concentration of total and dissolved Zn are presented in figure 13.

MK test result showed decreasing concentrations on only the PDX site for total Zn and increasing concentration trend in dissolved Zn (Table 8). East HA also showed increasing concentration trend for total Zn. Results from Mann Whitney U test showed significant difference in concentration of Zn for ecoroof and conventional roof (Table 9).

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Figure 13: Boxplots showing total and dissolved Zn concentrations for all the sites

However, because of limited number of samples and scatter of data points, statistical trend tests did not provide satisfactory results, and graphical results showed downward trends in concentrations of metals over time (Appendix; Table 10).

3.2 Nutrients and Solids

The concentrations of ammonia on all ecoroofs were relatively constant and much lower in concentration than water quality criteria levels. Boxplots for concentration of ammonia and nitrate are presented in Figure 14.

The average concentration of nitrate on HA west (0.58 mg/L) was higher than HA east (0.34 mg/L) and the conventional roof (0.131 mg/L). The maximum nitrate concentration on HA west was 10 mg/L and that of conventional roof was 0.57 mg/L. All sites showed similar levels of nitrate concentration, ranging from 0.1 mg/L to 0.3 mg/L, except PDX, where the maximum concentration was 3.2 mg/L. However, average nitrate concentrations on all ecoroof as well as conventional roof sites were well below the water quality benchmark for streams.

Table 6: Oregon water quality criteria for nutrients

Parameters (mg/L)	NH ₄ -N	NO ₃ -N	PO ₄ ⁻³	TP
Water Quality Criteria	3.5	10*	N/A	0.13-0.16**

*Based on drinking water standards (Oregon Administrative Rule (OAR) 340-041 Table 33A), Criterion for NH₄-N is a function of the pH and temperature.

**The Fanno Creek TMDL is 0.13 mg/L and the industrial NPDES permit benchmark is 0.16 mg/L;

Table 7: Mean concentration of nutrients and TSS of ecoroof runoff for all sites

	Sites									
Parameters	HA East	HA West	HA Conv	MD	PDX	RA	SW	WA 5	WA 3	WA Conv
(mg/L)										
NH₄-N	0.03	0.04	0.06	0.06	0.04	0.034	0.023	0.07	0.04	0.05
NO₃-N	0.34	0.58	0.13	0.12	0.41	0.11	0.19	0.13	0.1	0.1
PO₄⁻³	0.22	0.25	0.02	0.64	0.56	0.39	10.33	0.4	0.2	0.02
TP	0.28	0.33	0.03	0.81	0.64	0.53	10.63	0.5	0.24	0.029
TSS	50.36	60.41	30.11	6.2	4.42	3.25	2	3.25	2.75	3.33

Results from MK test showed decreasing trend in nitrate on runoff from PDX site however, no trends were detected for ammonia on any site (Table 8). A significant difference was observed for nitrate concentrations and no difference for ammonia concentrations for ecoroof and conventional roof (Table 9).

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Figure 14: Boxplots showing ammonia and nitrate concentrations for all the sites

The average concentration of TP was higher in HA east (0.28 mg/L) and HA west (0.33 mg/L) than for the conventional roof (0.038 mg/L) and was higher than water quality criteria (0.13-0.16 mg/L) in streams. Similarly, all other ecoroof sites had TP concentrations higher than water quality benchmark in stream (ranging from 0.05 mg/L to 3.16 mg/L) and PO₄³ ranged from a minimum of 0.02 to a maximum 2.44 mg/L. Conventional roof runoff from both HA and WA showed very little

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or no presence of nutrients. This suggests that soil media and plant life cycles are important drivers of the nutrient runoff from ecoroofs. Boxplots for concentration of o-phosphate and TP are presented in Figure 15.

MK trend test result showed a decreasing trend in TP on HA east, HA west, PDX, WA5, WA3 and on both conventional roofs. Results for PO_4 showed decreasing trends on PDX, HA east, and HA west. No trends were observed for other sites (Table 8).

Figure 15: Boxplots showing o-phosphate and total phosphorous concentrations for all the sites

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Though descriptive statistical results showed elevated levels of phosphorus in ecoroof runoff, graphical results showed downward trends over time (Appendix; Figure 20).

TSS levels were higher for the HA west (6.41 mg/L) than HA east (5.36 mg/L) and conventional roof (3.11 mg/L). Runoff from all other ecoroof sites showed lower TSS level, averaging about 5 mg/L. Boxplots for TSS concentration are presented in Figure 16.

Figure 16: Boxplots showing total suspended solids concentrations for all the sites

Results from MK trend test showed increasing trend of TSS for HA east and conventional WA, however, no trend was detected on any other site. Mann Whitney U test showed no statistically significant difference in TSS concentration for ecoroof and conventional roof runoff.

Table 8 summarizes the results from MK trend tests for each site. Values in the ‘n’ row indicates number of samples used for the analysis. Colored boxes denote statistically significant result (p value < 0.05) showing that there is a trend in the concentrations of the parameter. Red

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boxes with upward arrow indicate positive correlation (positive tau value) and shows increasing trend while blue boxes with downward arrows denote negative correlation indicating decreasing trend. All p and tau values associated with each parameter for all sites are include in appendix (Table 11). Results indicated that, data from HA east runoff showed increasing trend in the concentration of total and dissolved Pb, total Zn, and TSS and decreasing trends of o-phosphate and TP. Concentration of Pb, orthophosphate, and TP showed decreasing trend in HA west. Results from PDX site indicated decreasing trends in the concentration of total and dissolved Cu, total Zn, nitrate, and phosphorus and increasing trend in dissolved Zn. A decreasing trend in TP concentration was also found in WA and HA sites. MK test failed to provide any results for MD, RA, and SW sites due to very limited number of samples.

Table 8: Results from MK trend test based on p and tau value

Parameter	Unit	HA									
		East	West	Conv	MD	PDX	RA	SW	WA 5	WA 3	WA Conv
n		13	31	18	5	12	4	4	8	8	8
Cu	(ug/l)					↘					
Cu dissolved	(ug/l)					↘					
Pb	(ug/l)	↗	↘								
Pb dissolved	(ug/l)	↗								↗	
Zn	(ug/l)	↗				↘					
Zn dissolved	(ug/l)					↗					
NH ₄ -N	(mg/L)										
NO ₃ -N	(mg/L)					↘					
PO ₄ ⁻³	(mg/L)	↘	↘			↘					
TP	(mg/L)	↘	↘	↘		↘			↘	↘	↘
TSS	(mg/L)	↗									↗

Results from Mann-Whitney U test are included in Table 9. Colored boxes show the concentration distribution of conventional roof and ecoroof is significantly ($p < 0.05$) different. All p values associated with each parameter for all sites are include in the Appendix (Table 12). Red boxes indicate higher concentrations of parameters in ecoroof runoff than conventional roof runoff. Blue

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boxes indicate lower concentrations of parameters in ecoroof runoff than conventional roof runoff. Results indicated that almost all parameters showed significant difference in concentrations on HA East ecoroof and HA conventional roof except for dissolved Pb and TSS. Concentrations of total and dissolved Pb, nitrate, and TSS did not show significant difference on HA west and HA conventional. Results for WA sites showed significance difference in concentrations of all parameters on ecoroof and conventional roof except for Pb, nitrogen, and TSS.

Table 9: Results from Mann Whitney U Test

Parameter	Unit	Conventional ~ HA East	Conventional ~ HA West	Conventional ~ WA 5	Conventional ~ WA 3
n		13	18	8	8
Cu	(ug/l)				
Cu dissolved	(ug/l)				
Pb	(ug/l)				
Pb dissolved	(ug/l)				
Zn	(ug/l)				
Zn dissolved	(ug/l)				
NH ₄ -N	(mg/L)				
NO ₃ -N	(mg/L)				
PO ₄ ⁻³	(mg/L)				
TP	(mg/L)				
TSS	(mg/L)				

4. Conclusions and Recommendations

In this study, the trends in the long-term water quality data of runoff from six ecoroof sites were evaluated. Due to limited seasonal data, storm patterns, and lack of information about precipitation quality statistical trend tests did not provide conclusive results for some of the sites.

Copper: Results for Cu indicated higher levels of concentrations in runoff from ecoroof as compared to conventional roofs. Higher levels of Cu concentrations in the ecoroof runoff may be the result of Cu export from the soil media. Elevated Cu in runoff is a concern since slightest increase in levels of Cu can be harmful to aquatic life.

Lead: HA east and PDX showed higher level of Pb concentrations in ecoroof runoff than all other sites evaluated in this study. Higher Pb in the soil media on both sites might be the reason for elevated Pb in ecoroof runoff.

Zinc: This study found that Zn concentration in conventional roof runoff was higher than ecoroof runoff. Similar experimental studies conducted by Mendez et al. (2011) and Long et al. (n.d.). also found higher concentrations of Zn in runoff from conventional metal roof. This contamination of runoff is likely due to roofing material in conventional roofs.

Nitrogen and Phosphorus: Ammonia and nitrate levels were significantly lower in ecoroof runoff for all sites. Phosphorus concentrations do appear to be significantly higher for ecoroofs. However, graphical results for sites (HA and WA) with long dataset exhibited downward trend over time. Decreasing trend in net export of phosphorus might be due to stabilization of soil media over time. A study by Long et. al (n.d.) at the Pennsylvania State University campus found similar results for the concentration of ammonia, nitrate, and TP.

Recommendations:

- Higher P concentration in the runoff may be reduced by adding biochar amendment to the soil media. Study conducted by Gerould (2016) at Oregon State University also showed ability of different types of biochar to remove Cu in stormwater.
- To provide additional treatment, ecoroof runoff can be directed to other stormwater management facilities such as rain gardens (Barr, 2015). Runoff from ecoroof may also be reused for urban landscape irrigation or toilet flushing (Razzaghmanesh et al., 2016).
- To further evaluate concentrations of pollutants in ecoroof runoff and to study the effect of roof age on runoff, these roofs must be investigated for a longer period. For future water quality studies, it would be also beneficial to conduct more sampling in wet months.
- Also, it is recommended to evaluate first flush pollutant loading in ecoroof runoff as rainfall after dry period can produce greater pollutant loads than that of succeeding rainfall.
- It would be valuable to expand this water quality study to include precipitation quality. Having data for rainwater constituent levels would enable better understanding of the sources of pollutants in roof runoff.

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Appendix

Table 10: Summary Statistics for all water quality parameters in runoff

Parameters	Summary Statistics	HA east	HA west	HA Conv	MD	PDX	RA	SW	WA 5	WA 3	WA Conv
As (µg/l)	Min	0.44	0.1	0.1	1.42	0.10	0.20	2.31	0.46	0.25	0.10
	Median	0.67	0.63	0.1	2.97	0.37	0.38	2.54	1.02	0.47	0.10
	Mean	0.88	0.81	0.17	3.10	0.47	0.42	3.29	1.59	0.74	0.11
	Max	1.5	2.29	0.82	5.54	1.36	0.75	5.48	3.53	1.86	0.20
As dissolved (µg/l)	Min	0.23	0.1	0.1	1.36	0.1	0.19	2.24	0.46	0.25	0.10
	Median	0.65	0.57	0.10	2.68	0.37	0.29	2.43	0.97	0.45	0.10
	Mean	0.79	0.67	0.17	2.90	0.49	0.34	3.32	1.54	0.72	0.10
	Max	139	1.63	0.74	5.08	1.48	0.66	6.17	3.33	1.81	0.11
Ca (mg/L)	Min	-	0.22	0.27	27.20	13.80	20.50	17.90	26.10	16.50	0.20
	Median	-	4.52	0.89	36.45	17.25	28.10	23.50	29.30	20.75	0.87
	Mean	-	5.20	1.00	59.23	17.95	30.29	23.57	32.11	22.20	1.05
	Max	-	17.50	2.41	160.00	23.50	40.00	29.40	45.20	34.30	2.25
Mg (mg/L)	Min	-	0.05	0.05	2.10	0.39	0.62	5.65	1.04	0.48	0.05
	Median	-	1.77	0.10	4.10	0.50	1.38	8.02	3.17	1.40	0.05
	Mean	-	2.06	0.11	7.59	0.52	1.73	8.52	3.74	2.00	0.06
	Max	-	7.74	2.41	20.70	0.69	3.95	12.40	7.43	4.74	0.11
Conductivity	Min	14	4	3	159	8	102	158	131	80	2
	Median	59	61	10	206	170	150	177	198	140	9
	Mean	65.5	70.95	11.17	237.6	152.7	154.8	212.2	206.1	141.38	12.11
	Max	1226	213	57	372	329	207	337	319	213	43
Cr	Min	0.4	0.279	0.2	0.4	0.4	0.4	0.4	0.2	0.2	0.2
	Median	0.90	0.82	0.40	0.58	0.40	0.40	0.54	0.30	0.30	0.29
	Mean	0.90	1.00	0.4	0.95	0.47	0.41	0.56	0.32	0.30	0.32
	Max	1.37	3.89	1.01	2.72	0.79	0.47	0.74	0.59	0.4	0.582

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Parameters	Summary Statistics	HA east	HA west	HA Conv	MD	PDX	RA	SW	WA 5	WA 3	WA Conv
Cu (µg/l)	Min	4.85	0.78	0.54	4.08	2.95	3.55	4.02	2.13	2.41	0.28
	Median	8.53	10.10	1.96	3.69	7.05	8.86	6.15	4.16	4.53	0.83
	Mean	8.99	11.81	2.63	18.93	11.49	10.31	7.70	5.94	6.03	1.35
	Max	14.40	27.10	13.00	72.80	38.60	18.80	14.50	18.30	19.50	3.17
Cu Dissolved(µg/l)	Min	3.39	0.50	0.27	3.64	1.70	3.01	3.65	2.04	2.36	0.20
	Median	5.34	8.90	1.09	7.87	6.87	8.16	5.89	3.74	4.15	0.39
	Mean	7.28	10.36	1.90	16.16	10.07	9.38	7.61	5.55	5.59	0.46
	Max	7.83	26.30	10.20	59.40	34.70	18.10	15.00	18.30	19.10	0.83
Ecoli(MPN/100)	Min	1	1	1	1	1	10	1	10	10	10
	Median	10	10	10	10	10	10	10.5	10	10	10
	Mean	435.3	151.5	229.7	7.4	249.5	97.5	33	15.25	217.62	47.56
	Max	2400	2200	3400	10	3300	560	110	52	1400	230
Hardness (mg CaCo3)	Min	25.2	0.552	0.683	82.7	34	54.1	68	69.5	43.3	0.71
	Median	37.8	20.8	2.38	107.5	81.3	75.85	91.7	69.75	62.5	2.27
	Mean	36.72	28.74	2.42	179.07	82.26	82.76	94.1	95.56	63.69	2.76
	Max	49.6	75.6	7.1	485	206	110	125	126	91.6	5.86
Ammonia (mg/L)	Min	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Median	0.02	0.02	0.03	0.04	0.02	0.03	0.02	0.05	0.02	0.02
	Mean	0.04	0.05	0.07	0.06	0.04	0.03	0.02	0.08	0.04	0.06
	Max	0.17	0.48	0.39	0.16	0.16	0.07	0.03	0.25	0.11	0.18
Nitrate(mg/L)	Min	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	Median	0.12	0.10	0.10	0.10	0.10	0.10	0.17	0.10	0.10	0.10
	Mean	0.34	0.58	0.13	0.12	0.41	0.12	0.19	0.13	0.11	0.10
	Max	2.7	10	0.57	0.22	3.2	0.24	0.34	0.28	0.16	0.14
o-Phosphate (mg/L)	Min	0.04	0.02	0.02	0.33	0.10	0.08	0.86	0.02	0.02	0.02
	Median	0.18	0.20	0.02	0.64	0.36	0.37	1.02	0.22	0.07	0.02
	Mean	0.22	0.26	0.02	0.64	0.56	0.40	1.34	0.41	0.20	0.02
	Max	0.62	0.34	0.02	0.85	1.46	0.77	2.44	1.26	0.83	0.02
TP (mg/L)	Min	0.11	0.03	0.02	0.28	0.15	0.15	0.94	0.05	0.03	0.03
	Median	0.24	0.32	0.03	0.87	0.41	0.47	1.22	0.28	0.07	0.03
	Mean	0.29	0.34	0.04	0.82	0.64	0.54	1.64	0.51	0.25	0.03
	Max	0.70	1.11	0.19	1.23	1.50	1.11	3.16	1.44	0.93	0.04

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Parameters	Summary Statistics	HA east	HA west	HA Conv	MD	PDX	RA	SW	WA 5	WA 3	WA Conv
Pb (µg/L)	Min	0.16	0.10	0.10	0.10	0.29	0.10	0.10	0.10	0.10	0.10
	Median	0.47	0.16	0.20	0.11	0.96	0.10	0.10	0.17	0.18	0.19
	Mean	2.86	0.46	0.35	0.22	2.10	0.17	0.10	0.19	0.17	0.22
	Max	23.50	5.12	1.02	0.67	11.80	0.48	0.10	0.42	0.23	0.50
Pb dissolved (µg/L)	Min	0.10	0.13	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	Median	0.27	0.21	0.10	0.10	0.36	0.10	0.10	0.10	0.10	0.10
	Mean	1.29	0.45	0.10	0.18	0.66	0.10	0.10	0.10	0.10	0.10
	Max	13.60	1.02	0.14	0.55	3.32	0.10	0.10	0.12	0.11	0.11
pH	Min	4.8	5.1	5.1	7.5	6.3	7.3	7.9	-	-	-
	Median	6	6.3	6.8	7.9	7	7.75	8.1	-	-	-
	Mean	6.05	6.27	6.81	7.88	7.09	7.91	8.45	-	-	-
	Max	6.8	7.3	9.8	8.2	7.9	9.3	9.7	-	-	-
TS (mg/L)	Min	49	2	2	116	53	68	114	104	71	2
	Median	91	106	6.5	289	145.5	134	143	143	100	8
	Mean	92.47	111.4	9	398.5	151.3	138.1	187	164.2	100.6	7.556
	Max	160	274	35	985	425	222	348	301	166	19
TDS (mg/L)	Min	17	5	5	113	49	74	118	94	45	5
	Median	91	82	5	256.5	132	123	132	146.5	96.5	6
	Mean	85.9	100.6	6.611	352.8	139.3	126	161.5	161.1	100.1	8.44
	Max	141	266	11	883	372	196	264	280	157	20
TSS (mg/L)	Min	1	2	2	2	2	2	2	2	2	2
	Median	2	2	2	3	3.5	2	2	2.5	3	3
	Mean	5.367	6.41	3.11	6.2	4.429	3.25	2	3.25	2.75	3.33
	Max	27	43.2	13	20	16	12	2	9	4	7
Zn(µg/L)	Min	20.3	8.87	67.8	10	7.52	2.25	6.98	12.6	12.8	15.1
	Median	33.3	16.7	302	29.45	13.35	6.35	9.615	17.6	17	41.2
	Mean	55.85	20.7	335.2	62.6	17.99	7.24	54.30	19.57	19.01	40.96
	Max	304	69.1	952	231	44.3	13.7	191	33.9	34.9	66.5
Zn dissolved(µg/L)	Min	9.08	7.56	55.2	8.73	4.23	1.7	6.65	10.9	10.2	14
	Median	29.1	13.6	295	26.5	12.75	4	9.435	14.3	14.6	35.6
	Mean	49.8	17.7	305.9	56.32	15.576	5.216	10.655	16.91	15.84	35.14
	Max	274	68	841	211	39.7	10.7	17.1	24.8	23.6	60.9

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Figure 17: Graphical representation of concentrations of Cu and Cu dissolved in ecoroof runoff

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Figure 18: Graphical representation of Concentration of Pb and Pb dissolved in ecoroof runoff

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Figure 19: Graphical representation of Concentration of Zn and Zn dissolved in ecoroof runoff

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Figure 20: Graphical representation of Concentration of Ammonia and Nitrate in ecoroof runoff

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Figure 21: Graphical representation of Concentration of o-Phosphate and TP in ecoroof runoff

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Table 11: Results from Mann Kendall Trend Test

Parameters	MK Trend	HA east	HA west	HA Conv	MD	Pdx	RA	SW	WA 5	WA 3	WA Conv
Cu (µg/l)	tau value	0.219	-0.178	-0.262	-0.733	-0.736	-0.286	-0.667	-0.214	-0.143	0.278
	p- value	0.0857	-0.099	-0.105	0.0603	0.0003	0.3865	0.3082	0.53619	0.7105	0.348
Cu dissolved(µg/l)	tau value	0.0857	-0.099	-0.105	-0.733	-0.648	-0.286	-0.667	-0.286	-0.214	0.222
	p- value	0.69218	0.4443	0.5697	0.0603	0.0015	0.3865	0.3082	0.348	0.5362	0.466
Pb (µg/l)	tau value	0.448	-0.232	-0.124	-0.276	0.033	-0.178	Error	-0.265	0.109	0.278
	p- value	0.0228	0.0749	0.4954	0.5661	0.9128	0.6672	Error	0.4448	0.8031	0.348
Pb dissolved (µg/l)	tau value	0.644	0.029	0.397	-0.577	-0.099	Error	Error	0.178	0.681	0.645
	p- value	0.00106	0.86224	0.0521	0.2416	0.6614	Error	Error	0.66717	0.0485	0.043
Zn (µg/l)	tau value	0.352	0.0539	0.281	-0.467	-0.604	-0.109	-0.333	0.0364	0.143	0.44
	p- value	0.0748	0.6832	0.1116	0.2597	0.0031	0.8031	0.7341	1	0.7105	0.118
Zn dissolved (µg/l)	tau value	0.314	0.162	0.262	-0.467	-0.538	0.0714	-0.667	0	0.265	0.5
	p- value	0.113	0.208	0.1393	0.2597	0.0086	0.9015	0.3082	1	0.4448	0.076
Ammonia (mg/l)	tau value	0.411	-0.223	-0.047	-0.105	-0.438	0.189	-0.913	0.5	-0.535	-0.182
	p- value	0.05592	0.0994	0.8189	1	0.0536	0.6105	0.148	0.10776	0.114	0.616
Nitrate (mg/l)	tau value	0.103	-0.0237	0.32	0.316	-0.495	-0.262	0	-0.475	-0.214	0.354
	p- value	0.6443	0.879	0.1104	0.7237	0.0318	0.5108	1	0.18845	0.6625	0.333
o-Phosphate(mg/l)	tau value	-0.606	-0.599	Error	-0.6	-0.56	-0.571	-0.667	-0.286	-0.214	Error
	p- value	0.0021	3.02E-06	Error	0.2207	0.0062	0.0635	0.3081	0.38648	0.5362	Error
TP (mg/l)	tau value	-0.51	-0.682	-0.474	-0.6	-0.486	-0.571	-0.667	-0.643	-0.786	-0.609
	p- value	0.00989	8.50E-08	0.0109	0.2207	0.0184	0.0635	0.3082	0.03545	0.0094	0.044
TSS (mg/l)	tau value	0.358	-0.14	0.305	-0.12	-0.061	-0.5	Error	0.217	-0.13	0.738
	p- value	0.08393	0.3216	0.1325	1	0.8179	0.1904	Error	0.5827	0.7835	0.014

Table 12: Results from Mann Whitney U test

Parameters	Mann Whitney U test	HA east	HA west	WA 5	WA 3
Cu (µg/l)	<i>p</i> -value	1.32E-05	5.48E-07	0.001563	0.000987
Cu dissolved(µg/l)	<i>p</i> -value	9.45E-06	4.92E-07	0.007813	8.23E-05
Pb (µg/l)	<i>p</i> -value	0.01699	4.04E-06	0.5941	0.4729
Pb dissolved (µg/l)	p value	0.1867	0.7822	1	0.9483
Zn (µg/l)	<i>p</i> -value	5.25E-07	-	0.02076	0.01522
Zn dissolved (µg/l)	<i>p</i> -value	1.1E-08	-	0.003702	0.01058
Ammonia (mg/l)	<i>p</i> -value	0.08938	0.06996	0.1783	0.8659
Nitrate (mg/l)	<i>p</i> -value	0.04032	0.1568	0.4262	0.9315
o-Phosphate(mg/l)	<i>p</i> -value	3.29E-08	9.82E-08	0.000839	0.000839
TP (mg/l)	<i>p</i> -value	6.32E-07	1.36E-08	0.00057	0.001502
TSS (mg/l)	<i>p</i> -value	0.7665	0.197	0.835	0.9587