EFFECT OF GREEN ROOF AGE ON RUNOFF WATER QUALITY IN PORTLAND, OREGON

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ABSTRACT

Green roofs have become a common method to increase water retention on-site in urban areas. However, the long-term water quality of runoff from green roofs is poorly understood. This study evaluated the water quality of stormwater runoff from a regular (non-vegetated) roof, a green roof installed 6 months previously, and a green roof installed 6 years ago in Portland, Oregon. Samples of runoff were taken during every rain event for 10 months, and analyzed for total phosphorus (TP), phosphate (PO_4^{3-}), total nitrogen (TN), nitrate (NO_3^-), ammonia (NH_3), copper (Cu), and zinc (Zn). Runoff from the green roofs had higher concentrations of TP and PO_4^{3-} and lower concentrations of Zn compared to the regular roof. Average TP concentrations from the 6-year old roof and 6-month old roof were 6.3 and 14.6 times higher, respectively, than concentrations from the regular roof, and average PO_4^{3-} concentrations from the 6-year old roof and 6-month old roof were 13.5 and 26.6 times higher, respectively, compared to the regular roof. Runoff from the 6-month old green roof had higher concentrations of TP and PO_4^{3-} than the 6-year old green roof during the wet season, but lower concentrations during the dry season. The 6-month old green roof installations where receiving waters are sensitive or impaired may need additional treatment methods to reduce phosphorus levels. As green roofs age, water retention decreases and phosphorus leaching increases during the dry season.

KEYWORDS

aging and green roofs, long term impact of green roofs, concentrations of zinc, copper, phosphorous and phosphate in green roof stormwater runoff, soil moisture, water quality

INTRODUCTION

Urban settings have large areas of impervious surfaces, which increase the volume of stormwater runoff that must be managed. As stormwater flows over streets, rooftops, and parking lots, accumulated particulate matter and other pollutants from these impervious surfaces contribute to stormwater pollution (US EPA 2010). Portland, Oregon, like many other U.S. cities, has a combined sewer system, all of which is conveyed to the wastewater treatment plant (WWTP).

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During large rain events, runoff volumes exceed WWTP capacity leading to combined sewer overflow (CSO) events where raw sewage and stormwater is discharged into nearby water bodies. Some cities have implemented mitigation strategies, including the use of green roofs (Stutz 2010; City of Portland 2016).

Green roofs are installed on building rooftops and have become one method for decreasing stormwater volumes (Dvorak and Volder 2010). Green roofs provide a number of additional environmental benefits, including reducing summertime air temperatures in urban areas (Castleton et al. 2010), absorbing carbon dioxide and other air pollutants (Yang et al. 2008), and increasing roof longevity (Clark et al. 2008). Green roofs are typically comprised of a waterproof barrier, a layer of soil media, and plants (City of Portland 2016). Extensive roofs have a soil layer approximately 8–15 cm (3–6 inches) thick, with drought-tolerant plants such as sedum, and require minimal maintenance. Intensive roofs have a soil media layer that is 15 cm (6 inches) or greater, with a variety of plants that can include trees and shrubs, and require significant maintenance and irrigation. For both types of roofs, the soil stores rainfall that can evaporate or be taken up by plants. Any excess runoff drains from the roof to the sewer system or separated stormwater system. In many U.S. cities, including Portland, green roofs have decreased the volume of stormwater contributing to CSO systems, thus decreasing the amount of pollution that ends up in rivers and streams (Dvorak and Volder 2010).

Although green roofs provide a variety of beneficial measures to mitigate issues related to stormwater runoff, they may also increase nutrient loading to receiving waters. Excess nutrients can lead to algal blooms, which, when the algae degrades, can lead to oxygen levels below the threshold for fish survival (National Research Council 2000). Limited data collected from the City of Portland has indicated that runoff from green roofs can have elevated levels of nutrients, particularly nitrogen and phosphorus (BES 2010; Hutchinson et al. 2003). Nitrogen and phosphorus levels in runoff were found to be higher than those in rainfall, indicating nutrients are likely leaching from the green roof system (BES 2010). Liptan and Strecker (2003) conducted a study of green roofs in Portland, Oregon, and found that green roofs can help with stormwater runoff retention, but nutrient concentrations can differ based on soil media. Moran et al. (2004) observed two extensive green roofs in the Neuse River Basin of North Carolina over nine months and found green roofs were able to retain significant volumes of stormwater, but generated higher concentrations of total nitrogen and phosphorus. Similar results were found in other studies conducted in the eastern United States and Europe (Mitchell et al., 2017; Berndtsson et al., 2006; Gregoire and Clausen 2011; Carpenter et al., 2016; Harper et al., 2015; Buffam et al., 2016). These studies have shown green roofs contribute nutrients to receiving waters, but it is unclear how this contribution changes over time, particularly in the northwestern United States where the climate (wet winters, dry summers) is different from the eastern United States (cold winters, rainfall throughout the year). Maintenance, compaction, and other factors may impact green roof performance over time.

Copper and zinc have been shown to be toxic to aquatic species at concentrations typically observed in stormwater (EPA, 2011). Retention of copper and zinc in green roofs has been mixed, likely due to the soil media. If the soil media contains high levels of copper and zinc, the green roof will act as a source of these metals and concentrations will be higher in the runoff. Alternatively, if atmospheric deposition of copper and zinc is high due to industrial activity, green roofs can act as a sink of copper and zinc and decrease concentrations in the runoff. Berndtsson et al. (2006) observed green roofs acting as a source of copper and zinc, whereas the green roof served as a sink for both copper and zinc in studies conducted by Gnecco et al.

(2013) and Speak et al. (2014). Other studies have observed some green roofs acting as a sink for zinc, but not copper (Gregoire and Clausen 2011; Vijayaraghavan et al. 2012).

Leach tests have shown compost, a common constituent of green roof soil media, is often the source of metals and nutrients, but the impact of this source decreases over time (Mullane et al. 2015). Although the leaching of nutrients and metals from green roofs may decrease over time (Moran et al. 2004; Kohler and Schmidt 2003; Mullane et al. 2015), studies are commonly conducted during the first few years after installation, leaving questions regarding the long-term impact and the role of ongoing maintenance in performance. Only a few researchers in the U.S. have collected runoff water quality data from green roofs and these data sets are not comprehensive enough to evaluate long-term water quality impacts (Johnson 2008; Buffam et al. 2016). Most of the studies evaluating nutrient and metal concentrations from green roof runoff were conducted in the eastern United States and Europe, with a few in Asia. In addition to differences in soil media, regional differences in atmospheric deposition due to climate and industrial activity will impact runoff water quality. More studies in different geographic regions on established green roofs are needed to evaluate runoff water quality over time.

To further understand the long-term impact of green roofs on the water quality of receiving waters, data collection from older green roofs over an extended period of time is needed. This study compares the runoff water quality from two extensive green roofs in Portland, Oregon. Samples from a newly installed green roof, a green roof installed in 2009, and a regular (non-vegetated) roof were collected during every rain event large enough for runoff to occur over a ten-month period, and analyzed for total phosphorus (TP), phosphate (PO_4^{3-}), total nitrogen (TN), nitrate (NO_3^-), ammonia (NH_3), copper (Cu), and zinc (Zn).

METHODS

The green roofs used in this study were monitored at two separate locations, Shiley Hall at the University of Portland (UP), and Templeton Hall at Lewis and Clark College (LC). Photos of the green roofs used in this study are shown in Figure 1 and a summary of the characteristics of each green roof is provided in Table 1. A built-up flat membrane roof covered in gravel, used as the control for this study and referred to as "regular roof," was also located on Shiley Hall at the University of Portland. Built-up roof membranes are commonly used on low slope roofs, and consist of alternating layers of bitumen and membrane fabric, with a gravel cover to protect the

FIGURE 1. Green Roof on (a) Shiley Hall (6 years old) and (b) Templeton Hall (6 months old).

TABLE 1. Summary of characteristics of each green roof installation.

Location	Installation Year	Number of Months Since Installation	Size [m^2]	Average Soil Thickness [cm]	Soil Type	Plant Type
Shiley Hall, University of Portland	2009	78	255.5	8.0	Loamy Sand	*Sedum Album*, *Sedum Reflexum*
Templeton Hall, Lewis and Clark College	2015	6	70.61	12.0	Loamy Sand	*Sedum Rupestre*, *Sedum Reflexum*, *Sedum Spirium*, *Sedum Divergens*, *Sedum Sexangulare*, *Sedum Album*, *Phedimus Takesimensis*

roof. The regular roof was installed in 2009 and is approximately 520 m^2 (5600 ft^2). Stormwater runoff from the regular roof is collected in a drain on the west side of the roof and discharges to a bioretention cell adjacent to Shiley Hall. The sampling period for this project was January 2016 through October 2016.

6-Year Old Green Roof

The extensive green roof on Shiley Hall at UP was installed in 2009 and is 256 m^2 (2750 ft^2), and will be referred to as the "6-year old" roof. The green roof is exposed to full sun. The green roof consists of a drainage layer made up of multiple 116.8-cm square modular drainage trays, covered by a membrane and mulch, then topped with a soil mix and sedum. The soil mix was a standard extensive green roof soil produced in Portland by Pro-Gro. Soil thickness was designed to be approximately 10 cm (4 inches), but has varied in some areas due to drainage and sloping of the roof. Thickness measurements were taken at 35 different locations on the roof. The average thickness was 8.0 cm (3.2 in), with a minimum thickness of 5.5 cm (2.2 in) and maximum thickness of 11.3 cm (4.4 in). A sieve test was conducted to characterize the soil mix, indicating it is a loamy sand (82% sand, 10% gravel, and 8% silt and clay). The 6-year old green roof was originally planted with several types of sedum, but many of the sedums have died and several invasive weed species have become established. The current sedum types are *Sedum Album* (White Stonecrop) and *Sedum Reflexum* (Blue Stonecrop). Stormwater runoff from the green roof drains to a drain in the center of the green roof and discharges to a bioretention cell adjacent to Shiley Hall.

6-month Old Green Roof

The extensive green roof on Templeton Hall at LC was installed in August 2015 and is 70.6 m^2 (760 ft^2), and will be referred to as the "6-month old" roof. The green roof is partially shaded by surrounding trees. Leaves fall on the green roof from the surrounding trees, but are routinely removed by the campus maintenance crew. Similar to the 6-year old green roof, the 6-month old green roof consists of a drainage layer, membrane, mulch, soil mix, and sedum. The soil mix was a standard extensive green roof soil produced in Portland by Pro-Gro. Soil thickness was designed to be approximately 10 cm (4 inches), but has varied in some locations due to drainage and sloping of the roof. Thickness measurements were taken at 21 different locations on the roof. The average thickness was 12.0 cm (4.7 in), with a minimum thickness of 7.0 cm (2.8 in) and maximum thickness of 15.2 cm (6.0 in). A sieve test was conducted to characterize the soil mix, indicating it is a loamy sand (81% sand, 11% gravel, and 8% silt and clay). The 6-month old green roof is planted with various types of sedum. Sedum types include: *Sedum Rupestre* (Angelina Stonecrop), *Sedum Reflexum* (Blue Stonecrip), *Sedum Spirium* (Two Row Stonecrop), *Sedum Divergens* (Pacific Stonecrop), *Sedum Sexangulare* (Tasteless Stonecrop), *Sedum Album* (White Stonecrop), and *Phedimus Takesimensis* (Golden Carpet). Stormwater runoff from the 6-month old green roof is conveyed to two drains, located on either end of the green roof, that discharge to a stormwater catch basin.

Data Collection and Analysis

Runoff from the regular roof and 6-year old green roof were collected in polyethylene containers placed beneath the drainage downspouts. Following each rain event, 500-mL HDPE bottles were used to collect a grab sample from the containers if runoff occurred. After collecting the samples, the containers were emptied and placed under the downspout. Runoff samples from the 6-month old green roof were taken directly from one of the two drains during rain events. The drain was partially blocked to create pooling and collected with a pipet. Runoff volumes and/or flow rates could not be measured due to the drainage piping for the 6-month old roof. The drainage piping travels through the building directly to the catch basin, and there is not a way to collect volume or flow rate without significantly altering the drainage pipe. Sample bottles were acid washed and samples were stored in accordance with Standard Methods (Rice et al. 2012). A total of 106 samples were collected from the regular and green roofs on Shiley Hall and 59 samples were collected from the 6-month old green roof.

All water samples were tested for TP, PO_4^{3-}, TN, NO_3^-, NH_3, Cu, and Zn. The metals were analyzed using a Shimadzu atomic absorption spectrophotometer (AAS), in accordance with *Standard Methods* Section 3000: Metals (Rice et al. 2012). Nutrients were analyzed using Hach kits, in accordance with *Standard Methods* Section 4000: Inorganic Nonmetallic Constituent (Rice et al. 2012). Ammonia, TN, and NO_3^- analyses were discontinued after the first 2 months of sampling due to negligible concentrations of TN, NO_3^-, and NH_3 in the samples from both green roofs and the regular roof. Total phosphorus, PO_4^{3-}, Cu, and Zn were analyzed for the full sampling period. To determine whether water quality differences between the three roof surfaces were statistically significant, a one-way analysis of variance (ANOVA) was conducted for each constituent (Helsel and Hirsch, 2002).

Climatological data was collected from four different weather stations. An existing weather station on Christie Hall was used to collect precipitation data at UP. Christie Hall is located approximately 400 meters from Shiley Hall. At LC, an existing weather station on Olin Hall was used to collect precipitation data. Olin Hall is approximately 300 meters from Templeton Hall. A weather station was installed on the 6-month old green roof May 12, 2016 to measure additional climate data, including relative humidity, temperature, wind direction, wind speed, and soil moisture. Temperature was measured 0.5 m, 1 m, and 2 m above each green roof. Prior to installation, this additional climate data was collected from the weather station on Olin Hall. An existing weather station on the 6-year old green roof was used to measure the same additional climate data during the sampling period. Using this climate data, the potential evapotranspiration (PET) was calculated for both green roofs. The simplified Penman method was used for PET estimates (Thompson, 1999).

Soil moisture was measured with an Onset S-SMC-M005 Soil Moisture Smart Sensor. Measurements were taken at five-minute intervals at both green roof sites. Prior to the installation of the weather station on the 6-month old green roof on May 12, 2016, soil moisture observations were obtained using a Vernier soil moisture sensor at five-minute intervals. Readily available water (RAW), or the water that a plant can easily extract from soil, was calculated using soil type, plant type, and root depth (Lacey 2016). Using the RAW and volumetric pore space, the minimum moisture content needed for runoff to occur was estimated using methods similar to Fassman and Simcock (2012). This minimum moisture content was used as a runoff baseline to predict when runoff occurred from the green roofs. Runoff was predicted to occur if observed soil moisture rose above the runoff baseline during a storm event. Predictions were verified during sample collection by visually determining whether or not runoff occurred.

RESULTS AND DISCUSSION

Soil Moisture

Soil moisture was highest for both green roofs during the wet season, January to May (Figures 2 and 3). Soil moisture levels were above the runoff baseline every day until April 9, 2016, for the 6-year old green roof and nearly every day until June 6, 2016, for 6-month old green roof. Soil moisture levels above the runoff baseline were rare during the dry season (June–August), but increased at the beginning of the following wet season in October. The 6-year old green roof started drying out about 2 months prior to the 6-month old green roof. This may be partly explained by the differences in soil depth and sun exposure; soil depth on the 6-month old green roof was 4.1 cm (1.6 inches) higher than the soil depth on the 6-year old green roof and the 6-year old green roof is exposed to full sun throughout the day. Temperature above the 6-month old green roof was consistently cooler in the early morning due to the shading from nearby trees.

FIGURE 2. Soil moisture measurements from the 6-year old green roof with precipitation data. The runoff baseline was 7.89%; moisture levels above 7.89% likely resulted in runoff.

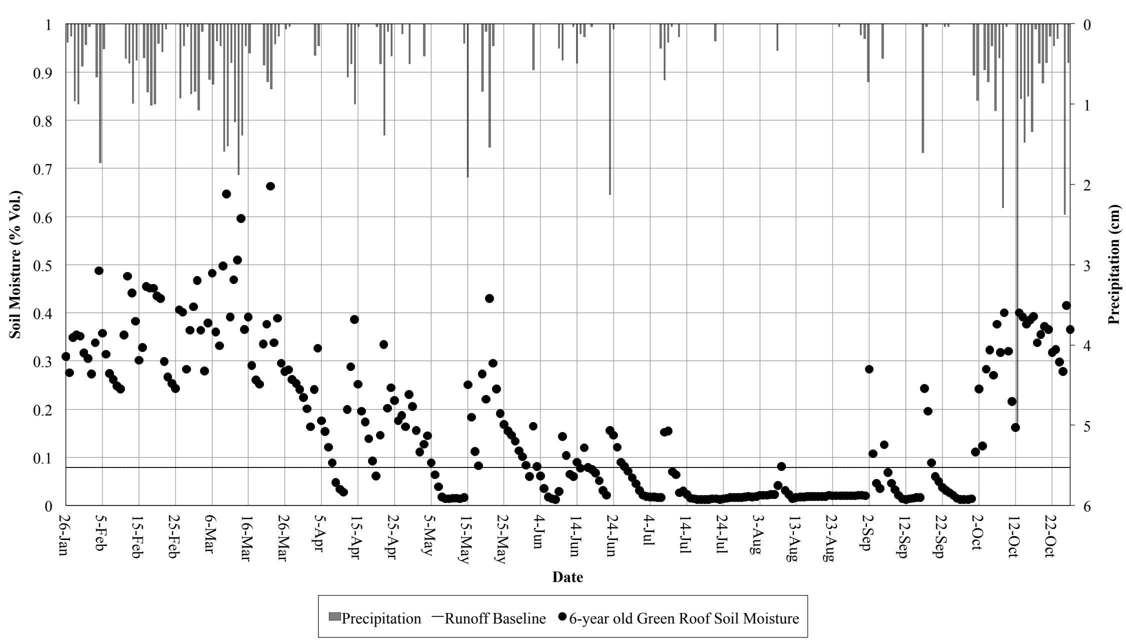
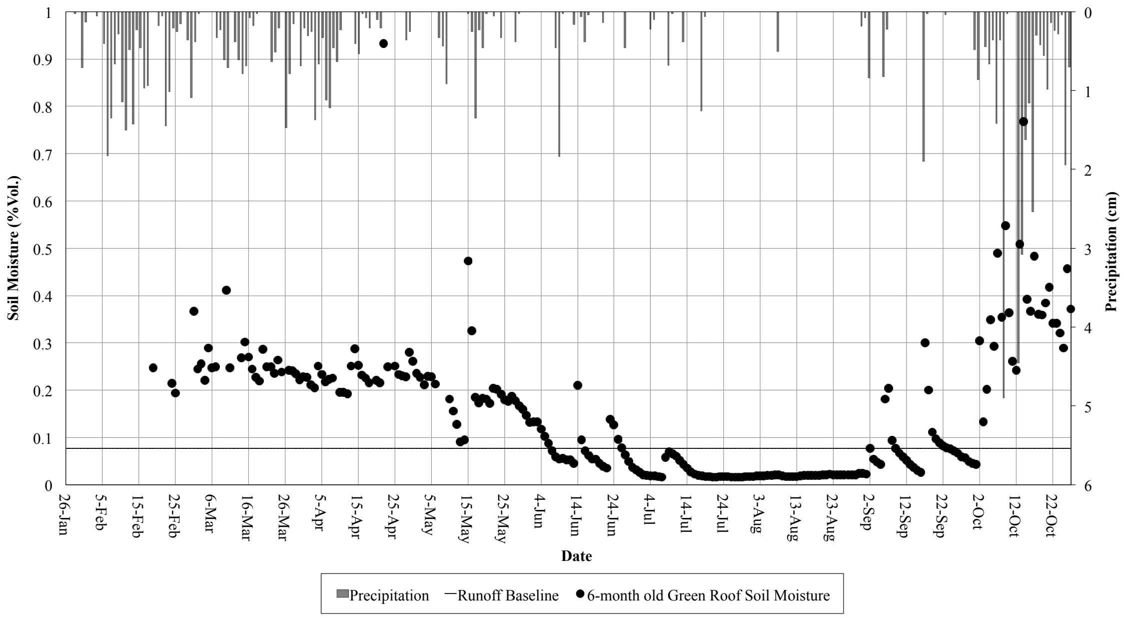


FIGURE 3. Soil moisture measurements observed from the 6-month old green roof with precipitation data. The runoff baseline was 7.64%; moisture levels above 7.64% likely resulted in runoff.



The accuracy of the runoff baseline to predict runoff from the green roofs was evaluated by daily observations of runoff and whether or not a sample was collected. The dates of predicted runoff events were compared to actual observed runoff events. The 6-year old green roof runoff baseline correctly predicted runoff events 65% of the time, while the 6-month old green roof runoff baseline correctly predicted runoff events 53% of the time. Although not highly accurate, the runoff baseline still provided an indication of events that may produce runoff. With additional refinements, the runoff baseline tool could potentially help municipalities predict when runoff that may impact water quality will occur from green roofs.

The older and 6-month old green roofs had similar trends in moisture content above the runoff baseline, despite the difference in age. Figures 2 and 3 suggest that seasonal change is the largest contributing factor for water retention of a green roof. However, the age of a green roof may also be a contributing factor. A noteworthy difference between the green roofs is the magnitude of the response in soil moisture caused by rain events during the dry season. Larger increases in soil moisture in response to rain events were observed on the 6-year old green roof (~14% increase on average compared to ~2% increase on the 6-month old green roof), resulting in moisture content rising above the runoff baseline. Conversely, the 6-month old green roof also displayed increases in soil moisture during rain events, but not large enough to rise above the runoff baseline. This indicates runoff occurred more often from the 6-year old green roof than the 6-month old green roof during the dry season due to the greater increase in soil moisture per rain event, and is supported by observations of runoff occurring from the 6-year old green roof while no runoff occurred from the 6-month old green roof during the same rain events. A newer green roof may be more efficient retaining water during dry seasons, which may be due to the plants and/or soil structure. The 6-month old green roof also had more shade during the day, which may have impacted moisture content. A large portion of the 6-year old green roof contains invasive weed species that are mostly senesced during the dry season, whereas the 6-month old green roof has several varieties of sedums that are still growing in the dry season. These growing plants may take up more water than the two varieties of sedums and weeds on the 6-year old green roof (Table 1). Average root depth of the sedums on the 6-month old green roof was 2.5 cm (0.98 inches), whereas average root depth of the plants on the 6-year old green roof was 1.6 cm (0.64 inches). In addition, the soil is likely to weather and compact over time due to exposure to wind, rain, and other elements, which leaves less pore spaces for water to fill. Dry bulk density of the soil on the 6-month old green roof was 0.65 g/cm^3 compared to 0.72 g/cm^3 on the 6-year old green roof, which indicates the 6-year old green roof is more compacted.

Total Phosphorus and Phosphate

Total phosphorus and PO_4^{3-} concentrations in runoff from each roof were statistically different ($p < 0.001$), and concentrations were higher from both green roofs compared to the regular roof (Figures 4 and 5). In general, TP and PO_4^{3-} levels were higher in runoff from the 6-month old green roof compared to runoff from the 6-year old green roof and regular roof (Table 2). Differences in TP and PO_4^{3-} concentrations is likely due to the difference in age between the two green roofs; newer soil mixes will initially leach more nutrients than an older soil mix, and leaching may decrease over time (Buffam and Mitchell, 2015).

Runoff from the two green roofs had higher levels of TP and PO_4^{3-} compared to typical concentrations in stormwater (Pitt and Maestre 2015). Average concentrations reported in the National Stormwater Quality Database (NSQD) were 0.54 mg/L for TP and 0.13 mg/L for PO_4^{3-} (Table 2). In general, runoff from the regular roof had lower TP, but similar PO_4^{3-} concentrations

FIGURE 4. Total phosphorus concentrations measured in the runoff from the regular roof, 6-year old green roof, and 6-month old green roof. Precipitation is from the weather station near the 6-year old green roof.

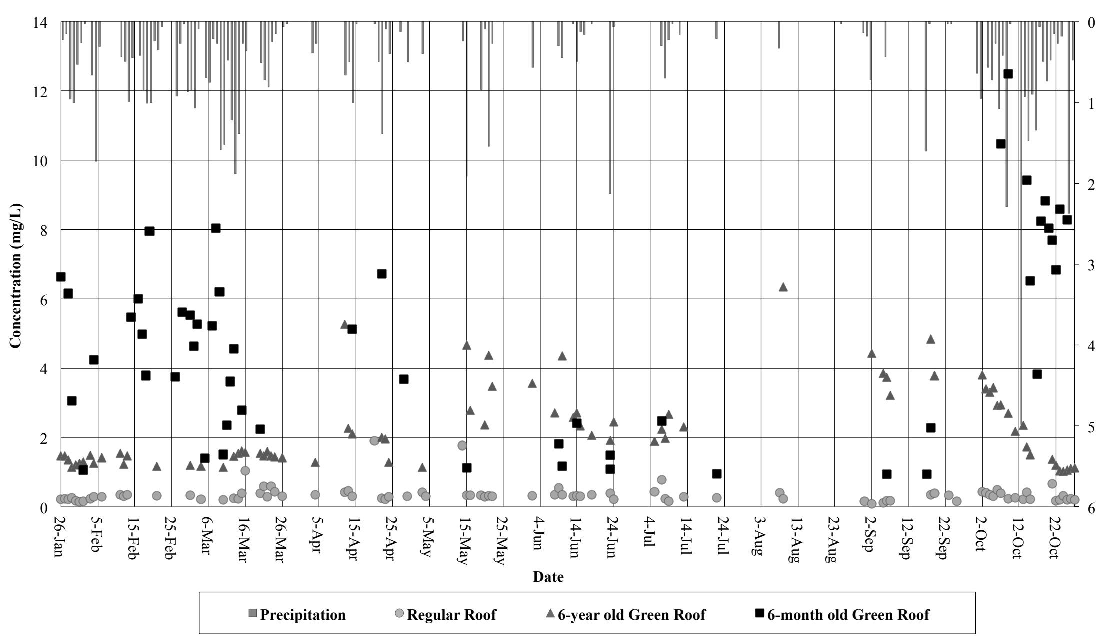
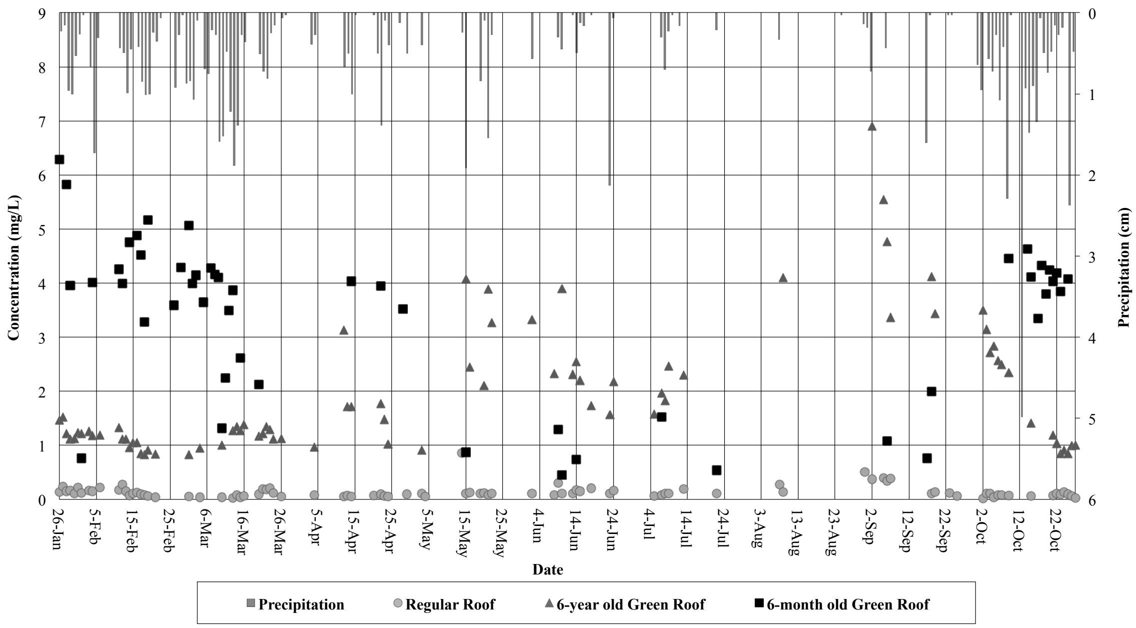


FIGURE 5. Phosphate concentrations measured in the water runoff samples from the regular roof, 6-year old green roof, and 6-month old green roof. Precipitation is from the weather station near the 6-year old green roof.



compared to NSQD averages. Both the older and 6-month old green roofs had higher TP and PO_4^{3-} compared to the NSQD averages.

A fluctuation in TP and PO_4^{3-} concentrations in green roof runoff was observed with season (Figures 4 and 5). Higher TP and PO_4^{3-} concentrations were observed in the 6-month old green roof compared to the 6-year old green roof runoff during the wet season, from January to April. However, concentrations in the runoff from the 6-month old green roof decreased below concentrations in the runoff from 6-year old green roof during the dry season, from

TABLE 2. Summary of average concentrations for the three roof types compared to data from the NSQD (http://www.bmpdatabase.org/nsqd.html), and the results of the ANOVA analysis used to determine whether concentrations from the three roofs were statistically different. Copper concentrations were statistically the same for all roofs, and zinc concentrations were statistically the same for both green roofs.

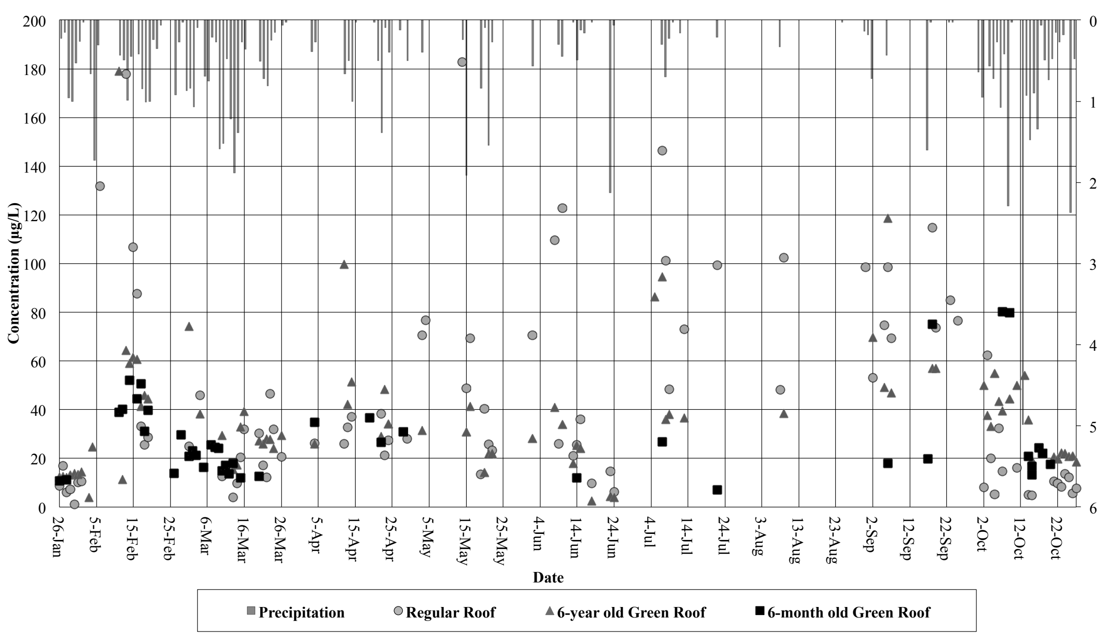
Roof	TP (mg/L)	PO_4^{3-} (mg/L)	Cu (μg/L)	Zn (μg/L)
NSQD	0.54	0.13	35.32	344.91
Regular	0.34	0.14	39.89	101.46
6-year old Green Roof	2.15	1.89	34.11	32.85
6-month old Green Roof	4.98	3.72	26.03	27.26
Statistically different?	yes ($p < 0.001$)	yes ($p < 0.001$)	no	Regular v. Green ($p < 0.001$)

May to September, then increased to levels above those observed from the 6-year old green roof during the following wet season in October. The reverse trend was observed with runoff from the 6-year old green roof, where TP and PO_4^{3-} concentrations increased during the dry season to levels above observed concentrations in the 6-month old green roof runoff, then decreased during the following wet season. The greatest difference in TP occurred on October 9, 2016 when the TP concentration in the runoff from the 6-month old green roof was 9.8 mg/L higher than the TP concentration in runoff from 6-year old green roof. The fluctuation in TP and PO_4^{3-} concentrations in green roof runoff may be due to the observed increase in water retention on the 6-month old green roof during the dry season. In addition, potential evapotranspiration (PET) was consistently higher for the 6-month old green roof compared to the 6-year old green roof during the dry period (average of 21.0 and 15.4 mm/day for new and 6-year old green roofs, respectively). Less runoff occurred from the 6-month old green roof compared to the 6-year old green roof, thus decreasing the amount of TP and PO_4^{3-} discharged in the runoff. Other studies have seen similar fluctuations in phosphorus levels due to changes in season and moisture content (Buffam et al. 2016; Speak et al. 2014; Carpenter et al. 2016).

Copper and Zinc

Copper concentrations in runoff were not statistically different from the regular roof and green roofs, but there was a high fluctuation during most of the sampling period, particularly during the dry season (Figure 6). Average copper concentrations in runoff from the regular roof, 6-year old green roof, and 6-month old green roof were 39.89, 34.11, and 26.03 μg/L, respectively. During the months of February through September, copper concentrations in runoff from the regular roof fluctuated more than runoff from both green roofs. This indicates that although

FIGURE 6. Copper concentrations measured in the water runoff samples from the regular roof, 6-year old green roof, and 6-month old green roof. Precipitation is from the weather station near the 6-year old green roof.



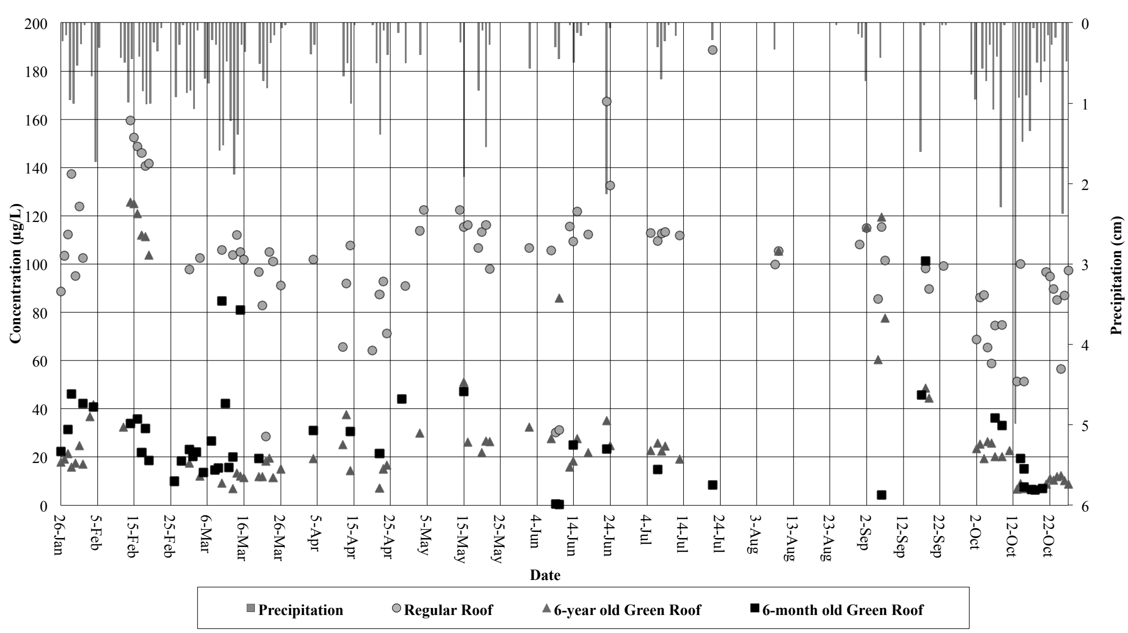
significant removal of copper did not occur with the green roofs, large fluctuations may be dampened by flow through the soil.

Zinc concentrations in the runoff from the regular roof were significantly higher than both green roofs ($p < 0.001$), and zinc concentrations in runoff from both green roofs were similar throughout the sampling period (Figure 7). Zinc concentrations from the older and 6-month old green roofs were not statistically different. Average zinc concentrations in runoff from the regular roof, 6-year old green roof, and 6-month old green roof were 101.46, 32.85, and 27.26 μg/L, respectively. The concentrations in runoff from all three roofs were relatively consistent throughout the wet and dry seasons.

Average concentrations from the NSQD were 35.32 μg/L for copper, and 344.91 μg/L for zinc (Table 2). The regular roof and 6-year old green roof runoff had lower zinc levels, but similar copper concentrations compared to the NSQD averages. The 6-month old green roof runoff had lower copper and zinc concentrations than the NSQD averages. Compared to typical stormwater levels, the runoff from green roofs has significantly lower zinc concentrations, but only slightly lower copper concentrations. It is important to note copper and zinc concentrations measured in this study are total, not dissolved. These results are similar to those found in other studies (Gregoire and Clausen 2011; Vijayaraghavan et al. 2012).

Copper may be present in higher concentrations due to the copper in the drainage flashing and fittings on both green roofs. The copper in the flashing and fittings may increase the amount of copper in the runoff. In contrast, zinc concentrations in runoff from both green roofs were significantly lower than the regular roof and typical stormwater concentrations. Although zinc and copper levels were slightly lower in runoff from the 6-month old green roof than the 6-year old green roof, this study suggests that age does not significantly impact retention of metals in green roofs.

FIGURE 7. Zinc concentrations measured in the water runoff samples from the regular roof, 6-year old green roof, and 6-month old green roof. Precipitation is from the weather station near the 6-year old green roof.



CONCLUSION

In this study, we evaluated the effects of age on runoff water quality by monitoring a 6-month old and 6-year old green roof. Total phosphorus and phosphate concentrations were significantly higher ($p < 0.001$) in green roof stormwater runoff than the regular roof. Average TP concentrations from the 6-year old roof and 6-month old roof were 6.3 and 14.6 times higher, respectively, than concentrations from the regular roof, and average PO_4^{3-} concentrations from the 6-year old roof and 6-month old roof were 13.5 and 26.6 times higher, respectively, than concentrations from the regular roof. A cyclic behavior dependent on seasonal change and the frequency of rain events was observed for TP and PO_4^{3-}. Higher concentrations in the runoff from the 6-month old green roof occurred during the wet season, likely due to nutrient leaching from the green roof soil during large rain events. Despite higher phosphorus concentrations during the wet season, the 6-month old green roof was more efficient at retaining stormwater runoff during the dry season than the 6-year old green roof. The soil moisture in the 6-month old green roof was less responsive to rain events than the 6-year old green roof. While both green roofs were not very effective in reducing copper concentrations, they were effective in reducing zinc concentrations. Additional phosphorus reducing measures may need to be implemented for new and old green roofs, particularly where runoff drains to sensitive or impaired receiving waters. Furthermore, additional steps may need to be implemented to improve the water retention efficiency of older green roofs during dry seasons. Green roofs are beneficial in significantly reducing zinc concentrations and maintaining greater water retention compared to regular rooftops. As green roofs age, water retention decreases and phosphorus leaching increases during the dry season which needs to be addressed in green roof design and maintenance.

ACKNOWLEDGEMENTS

This project was funded by the Oregon Alliance of Independent Colleges and Universities and the Shiley Fellows Fund. We thank Georgia Reid, Perry Pond, William DeLee, Jocelle Tade, and Sean Gestson for their help with sample collection and analysis, and Dan Manning and Amy Dvorak for technical assistance.

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