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Attenuation of copper in runoff from copper roofing materials by two stormwater control measures

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ABSTRACT

Concerns have been raised over diffuse and non-point sources of metals including releases from copper (Cu) roofs during storm events. A picnic shelter with a partitioned Cu roof was constructed with two types of stormwater control measures (SCMs), bioretention planter boxes and biofiltration swales, to evaluate the ability of the SCMs to attenuate Cu in stormwater runoff from the roof. Cu was measured as it entered the SCMs from the roof as influent as well as after it left the SCMs as effluent. Samples from twenty-six storms were collected with flow-weighted composite sampling. Samples from seven storms were collected with discrete sampling. Total Cu in composite samples of the influent waters ranged from 306 to 2863 μg L^{-1} and had a median concentration of 1087 μg L^{-1}. Total Cu in the effluent from the planter boxes ranged from 28 to 141 μg L^{-1}, with a median of 66 μg L^{-1}. Total Cu in effluent from the swales ranged from 7 to 51 μg L^{-1} with a median of 28 μg L^{-1}. Attenuation in the planter boxes ranged from 85 to 99% with a median of 94% by concentration and in the swales ranged from 93 to 99% with a median of 99%. As the roof aged, discrete storm events showed a pronounced first-flush effect of Cu in SCM influent but this was less pronounced in the planter outlets. Stormwater retention time in the media varied with antecedent conditions, stormwater intensity and volume with median values from 6.6 to 73.5 min. Based on local conditions, a previously-published Cu weathering model gave a predicted Cu runoff rate of 2.02 g m^{-2} yr^{-1}. The measured rate based on stormwater sampling was 2.16 g m^{-2} yr^{-1}. Overall, both SCMs were highly successful at retaining and preventing offsite transport of Cu from Cu roof runoff.

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1. Introduction

Copper (Cu) roofs have been used for centuries in various parts of the world. They are considered long lasting and require little maintenance, however the mass loading of Cu in runoff from Cu roofing materials has been variously estimated at 2.12 g Cu m^{-2} yr^{-1} (Arnold, 2005), 1.0–3.9 g m^{-2} yr^{-1} (Athanasiadis et al., 2010) and as high as 8.6 g Cu m^{-2} yr^{-1} (Wallinder et al., 2007) with release rates highly correlated with differences in rainfall quantities. Copper runoff rates from copper roofing materials are orders of magnitude greater than background Cu deposition rates which have been estimated from 0.23 to 71 mg m^{-2} yr^{-1} for dry deposition and 0.02–15 mg m^{-2} yr^{-1} for wet deposition (Pan and Wang, 2015 and references therein).

The biological impacts of Cu depend strongly on site specific water chemistry; neither total Cu nor dissolved Cu concentrations are sufficient to predict the bioavailable fraction of Cu or the impacts on receiving waters (Hedberg et al., 2011). However, because of the potential for adverse effects from Cu in surface waters, states such as Washington and Oregon are seeking ways to mitigate the potentially adverse effects of nonpoint sources of Cu. Research in the Puget Sound Basin estimated that roofing materials ranked among the top seven sources of Cu releases out of the 14 categories evaluated (Ecology and King County, 2011). Because salmonids have been shown to be sensitive to Cu in the low μg L^{-1} range, regulators have paid particular attention to increased levels of Cu in waterways where such sensitive species are of concern.

Runoff from new Cu roofs can contain 1000 to 14,000 μg L^{-1} total Cu (Bertling et al., 2006a,b, and references therein) compared to non-Cu roof runoff concentrations of 7.6 and 12.7 μg L^{-1} for tar

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felt and asbestos cement, respectively (Quek and Forster, 2000). Algae-resistant asphalt roofing shingles containing Cu granules have been shown to result in intermediate Cu releases with modeled Cu concentrations of 160 μg L^{-1} at the shingle surface during rainfall (Velleux et al., 2012).

It has been estimated that 13% of rivers, 18% of lakes, and 32% of estuaries in the US are impaired due to urban stormwater even though urban lands only cover only about 3% of the land surface (National Research Council, 2009). Stormwater control measures (SCMs) [also known as best management practices, (BMPs)] are intended to minimize stormwater pollution and/or reduce volume using flexible practices (Taylor and Fletcher, 2007). Bioretention is a category of SCM that can be implemented with various designs, but generally entails a shallow area for water storage, treatment or conveyance that contains a matrix of soils with mulch and drainage layers as well as plants. Previous studies of Cu removal in bioretention systems have largely focused on loading concentrations commensurate with urban roadway runoff (~80–140 μg L^{-1}). These studies have demonstrated that bioretention SCMs can successfully remove Cu from stormwater, generally achieving mass removal rates >95% and outlet concentrations <10 μg L^{-1} (Davis et al., 2001, 2003). Several studies have also estimated that bioretention media receiving roadway runoff should be able to successfully sequester metals for time spans on the order of decades (Jones and Davis, 2012; Paus et al., 2013). However, Cu attenuation by bioretention media receiving loadings from Cu roofing materials (on the order of 1000 μg L^{-1}) has not previously been evaluated.

The revised Stormwater Management Manual for Western Washington (SWMMWW; (Washington State Department of Ecology, 2014)), released in 2012 and amended in 2014, details design specifications related to various SCMs. Due to the regulatory concerns regarding Cu roofing materials in the Pacific Northwest region of the United States, the SCMs used in this study were based on SWMMWW design specifications.

The purpose of this project was to quantitatively evaluate the amount of Cu released into runoff from Cu roofing materials and then to evaluate the efficacy of two SCM designs for their ability to attenuate that Cu. During the study period, storm events were sampled approximately monthly to quantify Cu in roof runoff and SCM effluent, and consequently to determine the ability of bioretention structures to sequester Cu under the high concentration conditions expected of Cu roof runoff. If SCMs can successfully retain Cu, their use with Cu roofing installations may be able to minimize offsite impacts of runoff originating from such installations, especially when considered in conjunction with other removal mechanisms such as sorption to concrete or soils (Bahar et al., 2008; Bertling et al., 2006b; Boulanger and Nikolaidis, 2003; Ma et al., 2006).

2. Materials and methods

2.1. Site design and equipment

To conduct this study, a 3 m × 6 m picnic shelter with a new Cu roof was constructed in the summer of 2012 at Towson University, in Towson, Maryland. The shelter's roof was constructed of 16 oz. Cu (0.55 mm nominal thickness) with a standing seam design and a roof pitch of 4:12 (18.4° from the horizontal). PVC gutters and downspouts were used to collect stormwater from the roof. The roof was divided into four sections of equal area (4.64 m^2 each) and runoff for each section was segregated by installing partitions in the PVC gutter.

Two reference structures (0.9 m × 1.8 m, 4:12 pitch) were built to compare Cu mass loading from roofs constructed of other materials. Asphalt shingle was chosen to represent Cu loading from a common roofing material and acrylic plastic sheeting was used as a reference for background Cu inputs from wet and dry atmospheric deposition.

Two grass bioretention swales were built according to the SWMMWW BMP T7.30, and parallel to the length of the picnic structure along either side (Fig. 1). They were ~6.1 m long and ~0.9 m wide and were designed on a 1.5% longitudinal slope in a concave form with a ~15 cm bowl depth so that water would not to be able to sheet-flow either into or out of the swales. The top ~15 cm of compost-amended native soil (Glenville silt loam) sat above a ~25 cm limestone pea-gravel drainage layer which sat above a ~5 cm limestone drainage layer. In the center of the bottom drainage layer, a 10 cm diameter perforated PVC subdrain was designed to collect water and convey it to the end of the swale. The swales were constructed with an impermeable PVC liner to prevent exfiltration. While the liner is not part of a conventional design it was included to facilitate sample collection and help to close the water balance in the system. To capture surface sheet flow, surface drains were installed at the lowest points of the swale and connected to the subdrain. This allowed for sampling of combined surface and subsurface flow from the swales so that all potential outflows could be captured. In practice, little to no surface drainage was ever noted at the site, so the majority of sampled water originated from the subdrain. After construction, the swales were seeded with a Red Top and Tall Fescue blend (*Agrostis gigantea* and *Festuca arundinacea* respectively).

Two bioretention planter boxes were constructed (0.9 m × 0.9 m × 1 m; length × width × height) with a top layer of mulch over jute netting, overlying ~46 cm of bioretention soil media (BSM). The BSM used in this project was mostly sand mixed with topsoil and composted leaf and yard litter as per specifications outlined in the SWMMWW. Below the BSM was a ~10 cm layer of limestone over ~15 cm of limestone pea-gravel. Each box had an impermeable liner and a 5 cm perforated PVC subdrain. To maintain complete vegetative cover, 3 containerized plants were planted – *Cornus sericea* 'Kelsey' (Kelseys' Dwarf Red Dogwood), *Polystichum acrostichoides* (Christmas fern), and *Pennisetum aloepecuroides* 'Little Bunny' (Dwarf Fountain Grass).

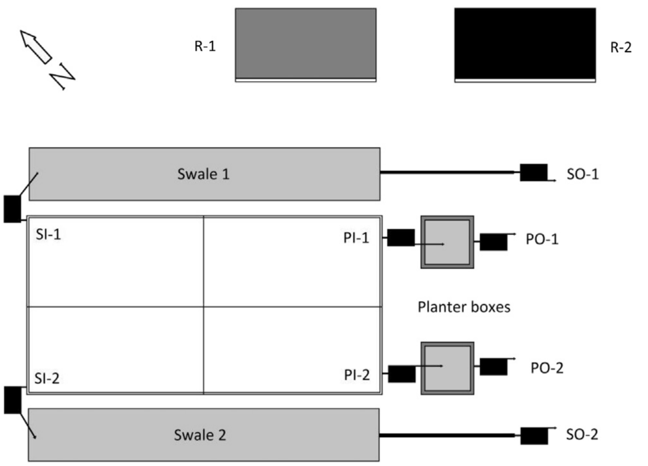

Fig. 1. Plan view of the study site. The Cu roof is partitioned into 4 quarters, each draining to a SCM. The small black boxes represent the sampling boxes. The grey squares are the planter boxes where PI-2 and PI-2 influent enters the planter boxes. PO-2 and PO-2 are the outlet sampling boxes. SI-1 and SI-2 influent flows into the high side of the swales (left side of drawing) and drain to the effluent sampling boxes (SO-1 and SO-2).

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