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Impact of Green Stormwater Infrastructure Age and Type on Water Quality

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Abstract: Green stormwater infrastructure (GSI) has become increasingly common to mitigate urban stormwater runoff. However, there is limited research on the impact of age and type of GSI. This study evaluated nutrient and metals concentrations in the soil water of five different GSI systems located at the University of Portland in Portland, Oregon. The GSI systems included a bioretention curb extension (part of Portland's Green Street project), a bioretention basin, a bioretention planter, an infiltration basin, and a bioswale ranging in age from 2 to 11 years. Samples were taken from each system during rain events over a 10-month period and analyzed for copper (Cu), zinc (Zn), phosphate (PO_4^{3-}), and total phosphorus (TP). Copper and zinc concentrations were found to be impacted by GSI age, with lower concentrations in older systems. The same trend was not found with PO_4^{3-} and TP, where almost all GSI systems had soil water concentrations much higher than average stormwater concentrations. Age likely played a role in phosphorus soil water concentrations, but other factors such as sources had a stronger influence. Phosphorus is likely coming from the compost in the soil mix in addition to other sources in runoff. This study shows that GSI systems can be effective for copper and zinc, but changes to the soil mix design are needed to reduce high levels of PO_4^{3-} and TP in soil water.

Keywords: stormwater; water quality; phosphorus; copper; zinc

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1. Introduction

Increased impervious surfaces in urban areas have caused disruption of the natural hydrologic cycle and increased pollutant transport to receiving waters [1]. Peak flows increase and time to peak decreases, which can cause significant erosion and increased solids loading [2]. If the drainage system is combined stormwater and sewer, urban stormwater can overwhelm the wastewater treatment plant and cause overflows of untreated wastewater to receiving waters. This is a common issue in cities that have older infrastructure, such as Portland, Seattle, New York, and Philadelphia, among others. Common pollutants of concern in urban stormwater include copper, zinc, and nutrients. Copper and zinc are toxic to aquatic species at relatively low levels [3]. Excess nitrogen and phosphorus can cause algal blooms. When the algae die, bacteria deplete the oxygen in the water when decomposing the algae. This causes fish kills and dead zones [4].

Green stormwater infrastructure (GSI) is one way to mitigate the impacts of urban stormwater runoff, and it has become increasingly common. Many cities have used GSI to reduce combined sewer overflows (CSOs) as well as reduce pollutants to receiving waters. Systems considered to be GSI include bioretention basins, planters, curb extensions, infiltration basins, bioswales, green roofs, detention ponds, filter strips, and sand filters [5]. These systems essentially use natural processes to slow, store, and treat runoff. For this study, we focused on bioretention systems, infiltration basins, and bioswales. All of these GSI types have a 46–61 cm (18–24 in) soil layer and plants. Runoff from impervious areas drains to the system through an inlet pipe, and the stormwater infiltrates through the soil. The main difference between bioretention systems and an infiltration basin is that bioretention systems typically only store and treat the water quality design storm, whereas infiltration basins are designed to infiltrate all runoff from a 10-year storm event [5]. Bioswales are designed to treat stormwater as it moves laterally, although there is some infiltration. Bioretention basins are typically larger than planters and curb extensions and can therefore store and treat a larger volume of stormwater.

Each of these GSI types has been shown to have water quality benefits. Many studies have shown that bioretention systems reduce copper (Cu), Zinc (Zn), phosphorus, and nitrogen [6–13]. Removal rates of zinc and copper are on the order of 80% [11,12], although a few studies observed 95–99% removal rates [14,15]. Removal of nitrogen and phosphorus is more variable. Valtanen et al. (2017) observed 81–98% phosphate (PO_4^{3-}) removal using lysimeters [8], and Freeborn et al. (2012) observed 25% removal of total phosphorus (TP) and 40% removal of total nitrogen (TN) [6]. However, some studies have shown that nitrogen, phosphorus, and Cu can leach from bioretention systems [8,16–19]. This is likely due to the organic matter, typically in the form of compost [18,20–22]. Hurley et al. (2017) found that leaching from compost increased with saturated conditions over a 10-day period [21]. Infiltration basins and bioswales have similar removal efficiencies compared to bioretention [23,24].

Only a few studies have investigated GSI systems that are past their establishment period [25–27]. Generally, the leaching of nitrogen and phosphorus may decrease with time as nutrients are effectively "flushed out" of the GSI system [10,28]. Johnson and Hunt (2019) found improved removal of TN and TP from a bioretention cell at 17 years compared to 1 year [27], and Kandel et al. (2017) found accumulation of TP in the soil that corresponded with the removal of TP from stormwater in a 7-year-old bioretention system [26]. However, Kohlsmith et al. (2021) observed leaching of nitrate (NO_3^-) and PO_4^{3-} and removal of Cu and Zn in lined bioretention systems ranging from 4 to 8 years of service life, with no significant difference in older facilities compared to newer facilities [25]. This may have been due to varying sources of pollutants, catchment area, and/or facility area, which may have impacted results more than facility age. Costello et al. (2020) observed higher soil concentrations of Cu and Zn in older facilities, indicating accumulation and storage over time [29]. More research is needed on aging GSI systems to determine how soil accumulation, storage, and plant/microbial community maturity impact water quality over time.

To further understand how water quality is impacted by age and GSI type, we monitored five different GSI systems over a 10-month period. The GSI systems included a bioretention curb extension (part of Portland's Green Street project), a bioretention basin, a bioretention planter, an infiltration basin, and a bioswale, and it ranged from a newly established system (2 years) to an 11-year-old system. Samples were collected from each GSI system every time it rained at the drainage layer using soil lysimeters. Samples were analyzed for PO_4^{3-}, TP, Zn, and Cu concentrations. Results were compared to determine whether there was a significant difference between older, more established systems and GSI type.

2. Materials and Methods

2.1. Sampling Sites

All GSI systems are located at the University of Portland (Figure 1). Each system has vegetation, mulch, an 18-inch soil layer consisting of 60% sandy loam and 40% compost, and a 12-inch gravel drainage layer. Stormwater infiltrates directly to the native soil below. All systems are maintained by the University of Portland facilities department, which includes annual vegetation pruning. The main differences between each site are the amount of stormwater that is treated, GSI size, and the date of installation. A summary of the site characteristics is shown in Table 1 below.

Figure 1. Sampling sites. 1 = Bioswale, 2 = Infiltration Basin, 3 = Bioretention Planter, 4 = Bioretention Basin, 5 = Bioretention Curb Extension (aerial photo source: Google.com).

Table 1. Summary of GSI sampling site characteristics.

GSI Type	Date Established	Age	Surface Area (m^2)	Catchment Area (m^2)	Catchment: Surface Area Ratio
1. Bioswale	2009	11	96.2	776	8.1
2. Infiltration Basin	2011	9	172	8052	46.8
3. Bioretention Planter	2018	2	600	11,533	19.2
4. Bioretention Basin	2015	5	350	6516	18.6
5. Bioretention Curb Extension	2014	6	45	1164	25.8

2.1.1. Bioswale

The bioswale wraps around Shiley Hall on the southeast corner of the University of Portland (Figure 2). Runoff from the roof of Shiley Hall drains into the bioswale and infiltrates through the soil or flows into dry well drains located in the bioswale. The roof consists of a 520 m^2 built-up membrane roof and a 256 m^2 green roof. The bioswale is designed to treat and convey the water quality design storm (6-month, 24 h storm) for the City of Portland. Vegetation includes *Cornus sericea* (red-twig dogwood), *Acer circinatum* (vine maple), *Rosa nutkana* (nootka rose), and *Buddleja davidii* (butterfly bush).

2.1.2. Infiltration Basin

The infiltration basin is adjacent to Shipstad Hall on the northeast corner of the University of Portland (Figure 3). It has a flat bottom with structural walls supporting the basin. Stormwater runoff is collected from the adjacent streets and buildings into a catch basin that drains to the infiltration basin. The infiltration basin is designed to collect and infiltrate the 10-year storm, with an overflow structure for higher flows. Vegetation is primarily *Juncus effuses* (soft rush).

Figure 2. Bioswale adjacent to Shiley Hall. The solid red line indicates the catchment area, and the dashed line indicates the surface area of the bioswale (aerial photo source: Google.com).

Figure 3. Infiltration Basin. The solid red line indicates the catchment area, and the dashed line indicates the surface area of the bioswale (aerial photo source: Google.com).

2.1.3. Bioretention Planter

The bioretention planter is adjacent to the soccer fields on the northwest corner of the University of Portland (Figure 4). Stormwater runoff is collected from the adjacent street and parking lot, and it discharges into the planters. The bioretention planters are designed to treat and convey the water quality design storm (6-month, 24 h storm) for the City of Portland, with an overflow structure for larger storms that conveys runoff to the Willamette River. Vegetation includes *Viburnum plicatum* (doublefile viburnum), *Acer circinatum* (vine maple), and *Juncus effuses* (soft rush).

Figure 4. Bioretention Planter. The solid red line indicates the catchment area, and the dashed line indicates the surface area of the bioswale (aerial photo source: Google.com).

2.1.4. Bioretention Basin

The bioretention basin, adjacent to North Van Houten Place, is located on the northwestern corner of the University of Portland (Figure 5). Stormwater runoff is collected from the adjacent parking lot and discharges into the basin. The bioretention basin is designed to treat and convey the water quality design storm (6-month, 24 h storm) for the City of Portland, with an overflow structure for larger storms that conveys runoff to the Willamette River. Vegetation includes *Mahonia aquifolium* (Oregon grape), *Buddleja davidii* (butterfly bush), *Ribes sanguineum* (red flowering currant), *Populus trichocarpa* (black cottonwood), and *Lupinus bicolor* (bicolor lupine).

Figure 5. Bioretention Basin. The solid red line indicates the catchment area, and the dashed line indicates the surface area of the bioswale (aerial photo source: Google.com).

2.1.5. Bioretention Curb Extension

The bioretention curb extension, adjacent to North Willamette Boulevard, is located on the northern corner of the University of Portland (Figure 6). Stormwater runoff is collected from the adjacent street and sidewalk, which discharges into the cell. The bioretention basin is designed to treat and convey the water quality design storm (6-month, 24 h storm) for the City of Portland, with an overflow structure for larger storms that conveys runoff to the storm sewer. Vegetation is *Juncus effuses* (soft rush).

Figure 6. Bioretention Curb Extension. The solid red line indicates the catchment area, and the dashed line indicates the surface area of the bioswale (aerial photo source: Google.com).

2.2. Data Collection and Analysis

Samples were collected from each site using lysimeters at the bottom of the soil layer. A 1.2 m (4 ft) long agricultural soil auger (AMS) with a 10.2 cm (4 in) diameter mud type core was used to remove soil to install the lysimeter. The lysimeter was placed at approximately 0.6 m (2 ft) or until the AMS reached the gravel layer. The cored soil was used to backfill the voids created and was necessary to ensure the structural stability of the lysimeter. The lysimeter was composed of a 2-inch plastic tube with a porous cup on the end, a suction tube that ran the length of the 2-inch plastic tube, and a rubber stopper on top. Figure 7 shows the general installation of the lysimeter at each site. These samples represent soil water after water has infiltrated through the soil medium. Although not technically effluent, it provides an indication of the runoff water quality that will infiltrate to the native soil.

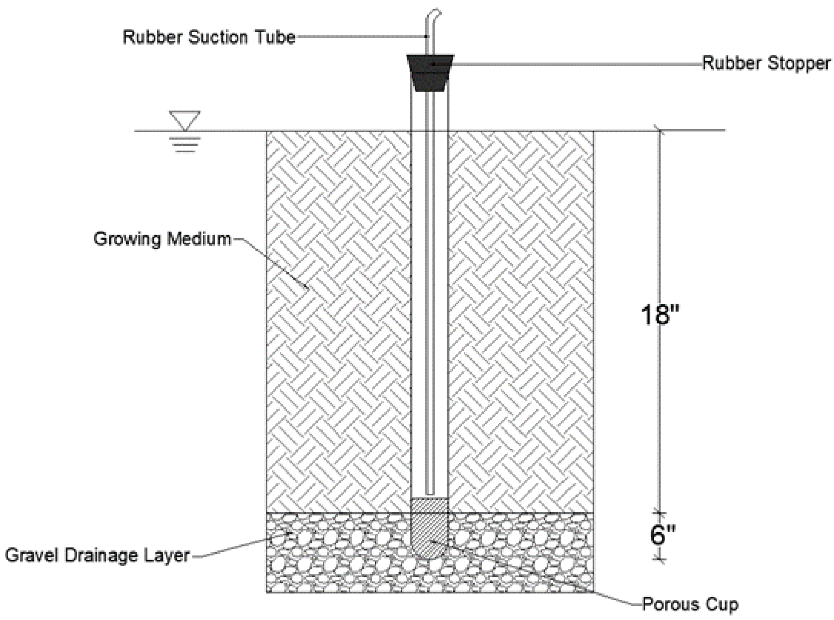

Figure 7. Soil lysimeter setup.

A total of 23 samples were collected at each site from January–March 2020 and September 2020–March 2021. Sampling was temporarily suspended March–September 2020 due to the COVID-19 pandemic. To collect samples, a vacuum pressure was created using a hand pump; then, the stormwater was pumped through the suction tube and collected in a 250 mL HDPE sample bottle. Samples were collected each time there was a large enough rain event to cause drainage through each GSI system. The volume of sample collection ranged from 10 to 50 mL. All sample bottles were acid washed, and samples were stored in accordance with *Standard Methods* [30]. Samples were collected within 2–12 h after the start of the rain event.

All samples were analyzed for Cu, Zn, PO_4^{3-}, and TP. Nutrients were analyzed in accordance with *Standard Methods* Section 4000: Inorganic Nonmetallic Constituent, and metals were analyzed using a Shimadzu Atomic Absorption Spectrophotometer (AAS) in accordance with *Standard Methods* Section 3000: Metals [30]. A one-way analysis of variance (ANOVA) was conducted to determine statistical significance between each GSI type [31]. The data were considered statistically different if the significance level (p-value) was less than 0.05.

Precipitation data from the United States Geological Survey rain gage station 193 located at Astor Elementary School were used to evaluate the size of the storm during each collection event. This rain gage is 0.6 miles from the University of Portland.

3. Results and Discussion

The summary of average concentrations for all GSI systems is shown in Table 2. Stormwater data from the National Stormwater Quality Database (NSQD) are also shown. We were not able to collect inflow samples due to the dispersive nature of runoff to each GSI system. Therefore, we are comparing the average stormwater quality data for Portland, which provides a very approximate indication of inflow water quality to these GSI systems, to the soil water collected at each GSI site. Copper and Zn concentrations in the soil water were slightly lower than the average stormwater concentrations, and PO_4^{3-} and TP concentrations in the soil water were higher compared to the average stormwater concentrations.

Table 2. Summary of average concentrations at GSI sites and NSQD stormwater data (https://bmpdatabase.org/national-stormwater-quality-database, accessed 1 April 2021).

	GSI Type	Cu (µg/L)	Zn (µg/L)	PO_4^{3-} (mg/L)	TP (mg/L)
1.	Bioswale	5.5	10.5	2.4	3.9
2.	Infiltration Basin	2.6	9.4	1.5	2.2
3.	Bioretention Planter	19.7	18.7	2.9	4.3
4.	Bioretention Basin	8.0	25.6	2.5	3.5
5.	Bioretention Curb Extension	15.1	12.0	3.9	5.8
	NSQD	10.6	28.8	0.06	0.22

Average concentrations for Cu, Zn, PO_4^{3-}, and TP were also compared to multiple studies reported in the International BMP database [32]. The average Cu concentration in the effluent of bioretention systems for 27 studies was 7.13 µg/L, with a 25th percentile of 4.1 µg/L and 75th percentile of 14 µg/L [32]. For this study, average concentrations ranged from 2.6 to 19.7 µg/L, which is very close to the range reported in the International BMP database. Similar to copper, average Zn concentrations were close to the range reported in the International BMP database. For 26 studies evaluating Zn, the average concentration in bioretention effluent was 12.8 µg/L, ranging from 6.3 µg/L at the 25th percentile to 23 µg/L at the 75th percentile [32]. In the current study, average Zn concentrations ranged from 9.4 to 25.6 µg/L. However, phosphorus concentrations were higher in the current study. The average PO_4^{3-} concentrations in bioretention effluent for 24 studies was 0.81 mg/L, ranging from 0.60 mg/L at the 25th percentile to 0.89 mg/L at the 75th percentile [32]. Similarly, average TP concentrations in bioretention effluent for 44 studies was 0.72 mg/L, ranging from 0.27 mg/L at the 25th percentile to 1.66 mg/L at the 75th percentile [32]. Phosphate concentrations were ≈2–5x higher, and TP concentrations were ≈3–8x higher in the current study. The higher phosphorus concentrations in the current study may be due to differences in the system and sampling method; this study sampled soil water, whereas the other studies sampled effluent from an underdrain in the bioretention system. Phosphorus in the soil water may be retained and not necessarily migrate through the drainage layer of the bioretention system.

The results of the ANOVA analysis are shown in Table 3. Numbers correspond to the GSI locations in Figure 1 and are identified in Tables 1 and 2. Significant differences in water quality were observed between the GSI sites.

Table 3. Statistically significant difference between each GSI site.

Significant Difference?	Cu	Zn	PO_4^{3-}	TP
1 vs. 2	No	No	No	Yes ($p < 0.05$)
1 vs. 3	Yes ($p < 0.01$)	Yes ($p < 0.05$)	No	No
1 vs. 4	No	Yes ($p < 0.01$)	No	No
1 vs. 5	Yes ($p < 0.01$)	No	No	No
2 vs. 3	Yes ($p < 0.01$)	Yes ($p < 0.05$)	No	Yes ($p < 0.05$)
2 vs. 4	Yes ($p < 0.01$)	Yes ($p < 0.01$)	No	No
2 vs. 5	Yes ($p < 0.01$)	No	Yes ($p < 0.05$)	Yes ($p < 0.01$)
3 vs. 4	Yes ($p < 0.01$)	No	No	No
3 vs. 5	No	No	No	No
4 vs. 5	Yes ($p < 0.05$)	Yes ($p < 0.01$)	No	Yes ($p < 0.05$)

Average rainfall amount during sampling events was 1.0 cm, and it ranged from 0.025 to 4.7 cm. This corresponds to an average rainfall intensity of 0.042 cm/h, and a range of 0.001–0.20 cm/h. The average duration between storms was 2 days, and it ranged from 0 to 7 days.

3.1. Copper

Figure 8 shows Cu concentrations at each GSI site during the sampling period. Copper concentrations in the soil water were significantly higher ($p < 0.01$) in the bioretention planter and bioretention curb extension compared to the other GSI types, and they were significantly higher in the bioretention basin compared to the infiltration basin. Higher Cu concentrations in the soil water may be due to age; the bioretention planter, bioretention curb extension, and bioretention basin were installed 2, 5, and 6 years ago, respectively. In general, Cu concentrations in older systems were lower than the average stormwater concentrations from the NSQD. The highest Cu concentration was observed in the bioretention planter, which is the newest GSI system. However, results do not consistently indicate higher concentrations in newly established GSI systems. Other impacts, such as sources and catchment area/surface area ratios may impact Cu concentrations. The bioretention curb extension receives runoff from a very busy roadway near a traffic light. This may increase the Cu deposition from brake pads. All other systems receive runoff from roofs, parking lots, and roadways with significantly less traffic. In addition, the bioretention curb extension is ≈5x smaller than the bioretention basin and bioretention planter and the catchment area/surface area ratio is higher, which may reduce removal efficacy.

Copper concentrations in the soil water appear to decrease over the sampling period, particularly for the newly established GSI systems (bioretention planter, bioretention basin, and bioretention curb extension). Copper concentrations in soil water from the bioswale and infiltration basin are relatively consistent, except for a brief increase in February 2020. This may be due to additional sources or flushing of Cu, although more investigation would be needed to verify this.

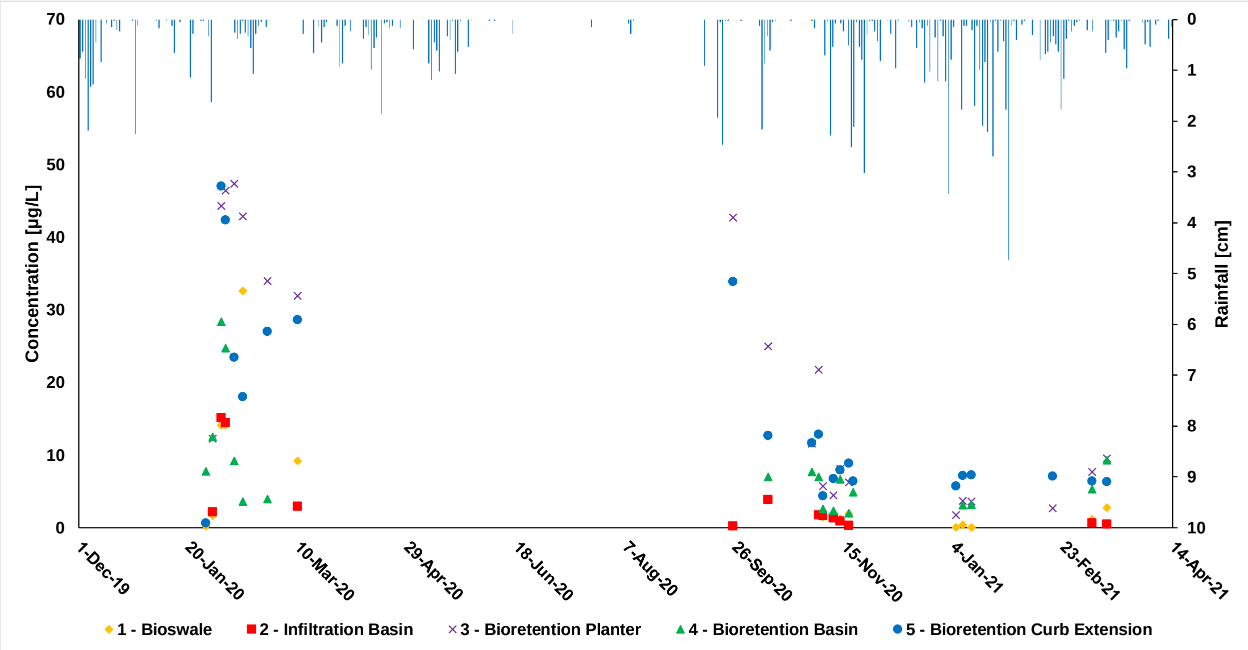

Figure 8. Copper concentrations at each GSI site during the sampling period. Rainfall data are from the weather station located at Astor Elementary School (https://or.water.usgs.gov/precip/astor.rain, accessed on 1 April 2021).

3.2. Zinc

Figure 9 shows Zn concentrations at each GSI site during the sampling period. Zinc concentrations in the soil water were significantly higher ($p < 0.05$) in the bioretention basin and bioretention planter compared to the bioswale and infiltration basin. Zinc concentrations were also significantly higher in the bioretention basin compared to the bioretention curb extension. The bioretention basin and bioretention planters are the newest GSI systems, indicating that age may play a role in zinc removal. Zinc concentrations were statistically the same in the newest GSI sites (bioretention planter and bioretention basin). The bioretention planter was installed 2 years ago, and the bioretention basin was installed 5 years ago. Other impacts such as sources may impact Zn concentrations. High Zn concentrations in the bioretention basin may be due to the steel railroad tracks adjacent to the bioretention basin, which is part of the drainage area. The catchment/surface area ratio does not appear to impact Zn concentrations; the bioswale has the lowest catchment/surface area ratio (8.1) and the infiltration basin has the highest catchment/surface area ratio (46.8). It is likely that the lower concentrations in these GSI types are due to age and sources. The bioswale receives runoff from a green roof and regular roof, and the infiltration basin receives runoff from roofs and campus streets. Zinc concentrations were lower in all GSI types compared to the average stormwater concentrations from the NSQD.

Zinc concentrations in the soil water of all GSI types were relatively consistent over the sampling period. There are a few brief increases in Zn concentrations, but no general trend. These brief increases may be due to additional sources or flushing of Zn, although more investigation would be needed to verify this.

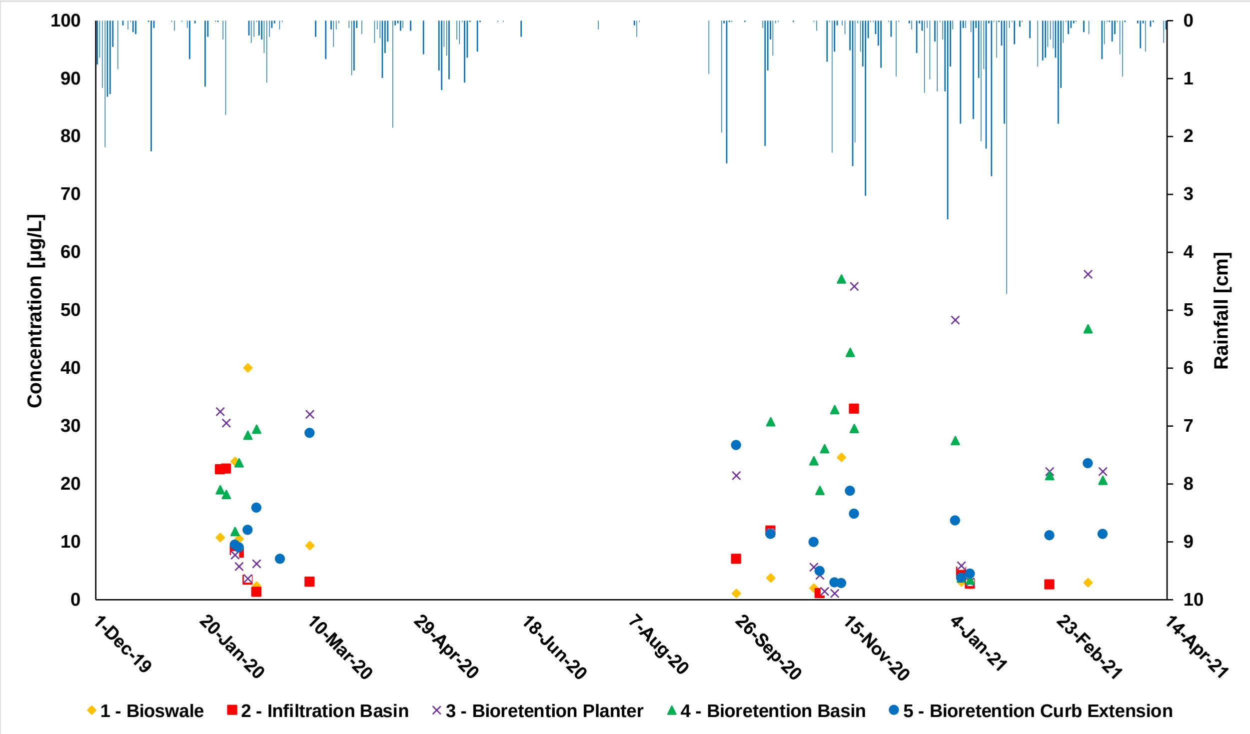

Figure 9. Zinc concentrations at each GSI site during the sampling period. Rainfall data are from the weather station located at Astor Elementary School (https://or.water.usgs.gov/precip/astor.rain, accessed on 1 April 2021).

3.3. Phosphate

Figure 10 shows PO_4^{3-} concentrations at each GSI site during the sampling period. Phosphate concentrations in the soil water were significantly lower ($p < 0.05$) in the infiltration basin compared to the bioretention curb extension. Phosphate concentrations were statistically the same for all other GSI sites. The trends observed with copper and zinc, where older systems tended to have lower copper and zinc concentrations, were not observed with PO_4^{3-}. Catchment area/surface area ratios also did not appear to impact PO_4^{3-} concentrations. Thus, high PO_4^{3-} concentrations were likely due to sources. The higher PO_4^{3-} concentrations in the bioretention curb extension could be due to domestic animal and bird feces. The bioretention curb extension is located adjacent to a busy pedestrian sidewalk, where many people walk their dogs. Poorly managed pet waste has been found to be a major source of phosphorus pollution in urban waterways [33]. It is also directly under the Lund Hall roof overhang, which may be polluted with bird feces that run off into the bioretention curb extension. All other GSI sites are on campus. The infiltration basin, bioretention basin, and bioretention planter are also separated from busy areas. The bioswale is adjacent to Shiley Hall, so there is some foot traffic. Phosphate concentrations at GSI sites were much higher than stormwater concentrations from the NSQD (on the order of 25–65x higher), indicating there is an export of PO_4^{3-} from these systems. High phosphorus concentrations from GSI systems have been observed in many other studies in the northwest as a result of leaching of phosphorus from the compost in the soil mix [8,18–20,34,35]. Due to the relatively high PO_4^{3-} concentrations in all of the GSI systems, it is likely that the GSI systems on the University of Portland campus are exporting PO_4^{3-} due to the compost in the soil mix.

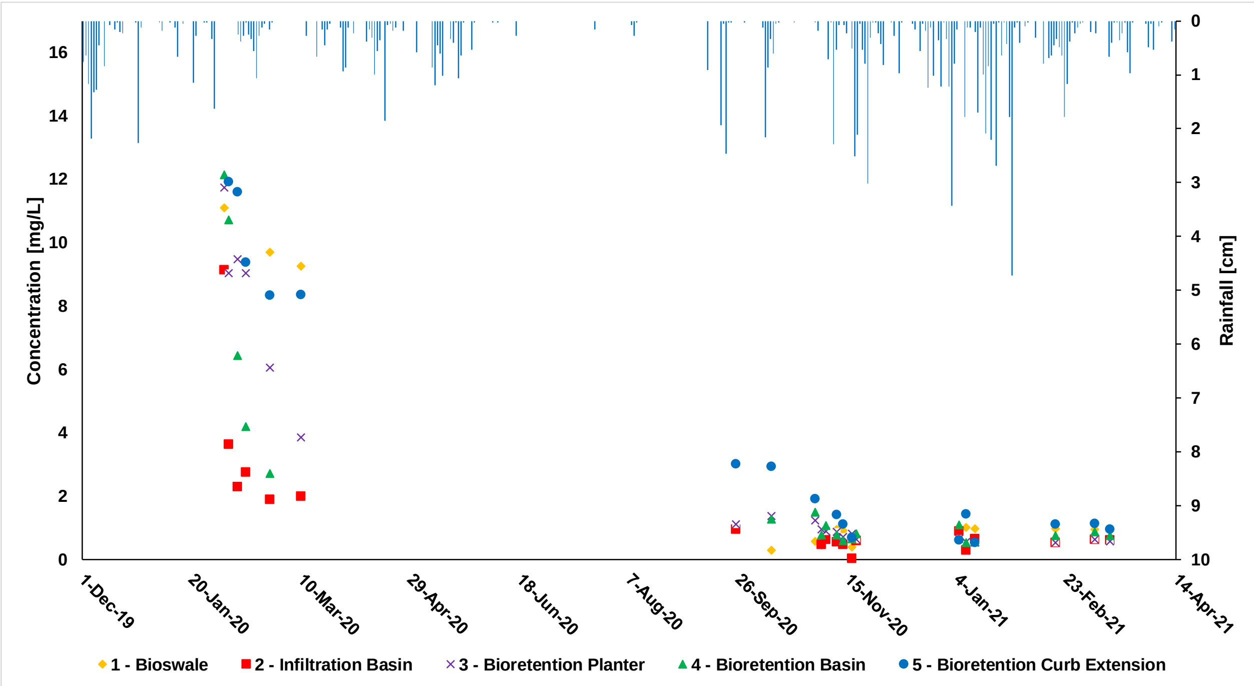

Figure 10. Phosphate concentrations at each GSI site during the sampling period. Rainfall data are from the weather station located at Astor Elementary School (https://or.water.usgs.gov/precip/astor.rain, accessed on 1 April 2021).

There were no significant trends observed during the sampling period, although it appears that PO_4^{3-} concentrations are decreasing throughout the sampling period. Phosphate concentrations were generally higher January–March 2020 compared to September–March 2021. There was 14.2 cm and 12.8 cm of precipitation during the January–March 2020 and January–March 2021 sampling periods, respectively. Although there was less total precipitation during January–March 2021, Figure 10 shows that there were less frequent, larger rain storms. These large rain storms may have "flushed" phosphorus out of the GSI systems, resulting in a lower soil water concentration. The higher levels of PO_4^{3-} may also be due to additional sources in January–March 2020. Additional investigation would be needed to determine the causes of the fluctuation in PO_4^{3-} concentrations.

3.4. Total Phosphorus

Figure 11 shows TP concentrations at each GSI site during the sampling period. Total phosphorus concentrations in the soil water were significantly lower ($p < 0.05$) in the infiltration basin compared to the bioswale, bioretention planter, and bioretention curb extension. Soil water TP concentrations were also significantly lower ($p < 0.05$) in the bioretention basin compared to the bioretention curb extension. There does not appear to be an impact of bioretention age on TP concentrations. Although the infiltration basin (installed 9 years ago) had lower TP concentrations than the bioretention planter (installed 2 years ago), bioretention basin (installed 5 years ago), and bioretention curb extension (installed 6 years ago), the bioswale (installed 11 years ago) had higher TP concentrations than the infiltration basin. Catchment/surface area ratios also did not appear to impact TP concentrations. The difference in TP concentrations may be due to sources. The bioswale treats runoff from a green roof, which has been shown to have higher TP and PO_4^{3-} concentrations compared to the built-up membrane portion of the roof [36]. The green roof is likely leaching phosphorus from the soil media, which drains to the bioswale. This may be why TP concentrations are higher in the bioswale, despite the age of this GSI site. Similar to PO_4^{3-}, TP concentrations at GSI sites were much higher than stormwater concentrations from the NSQD (on the order of 10–26x higher), indicating there is an export of TP from these systems. These high TP concentrations could be due to the compost in the soil mix, in addition to sources.

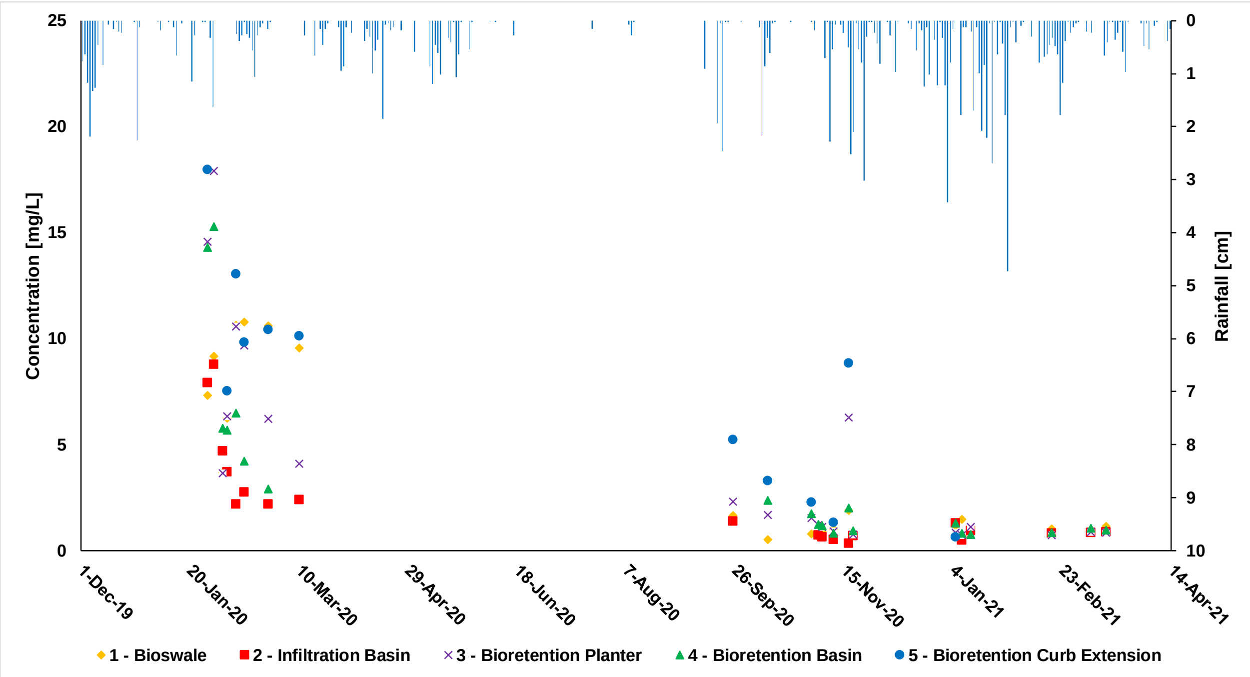

Figure 11. Total phosphorus concentrations at each GSI site during the sampling period. Rainfall data are from the weather station located at Astor Elementary School (https://or.water.usgs.gov/precip/astor.rain, accessed on 1 April 2021).

Similar to PO_4^{3-}, there were no significant trends observed during the sampling period, although it appears that TP concentrations are decreasing throughout the sampling period. Total phosphorus concentrations were generally higher during January–March 2020 compared to September–March 2021. The higher levels of TP may be due to different rainfall patterns or additional sources in January–March 2020. Additional investigation would be needed to determine the causes of fluctuation in TP concentrations.

Changes to the soil mix may help reduce PO_4^{3-} and TP soil water concentrations. These may include reducing or replacing the compost with another carbon source such as shredded bark or wood fiber mulch as has been done in many municipalities [37–39], or adding amendments to sequester phosphorus such as WTRs, iron filings, or fly ash [26,34,40]. This is particularly important for systems that have an underdrain discharging to sensitive receiving waters. All GSI systems on the University of Portland campus infiltrate to the native soil, and thus are less likely to cause algal blooms and other water quality degradation in surface water.

4. Conclusions

Green stormwater infrastructure is becoming an increasingly common tool to manage stormwater, and thus, it is important to understand how removal efficiencies and water quality change with time and GSI type. This study evaluated soil water quality in five different GSI systems on the University of Portland campus. Since there were no underdrains in the GSI systems, soil water at the drainage layer was sampled and compared to average stormwater concentrations in Portland. Influent samples were not collected during storm events due to the dispersive nature of inflow. Thus, we were not able to compare the removal efficiencies or influent and effluent water quality. Despite these limitations, we were still able to compare soil water quality in each GSI system during storm events.

No clear trend was observed between GSI type and water quality. All GSI systems had low Cu and Zn concentrations compared to average stormwater concentrations in

Portland. Copper and Zn concentrations were found to be impacted by GSI age, with lower concentrations in older systems. This indicates that Cu and Zn removal may improve with age. The same trend was not found with PO_4^{3-} and TP, where almost all GSI systems had soil water concentrations much higher than average stormwater concentrations. Age likely played a role in soil water concentrations, but other factors such as sources had a stronger influence. Phosphorus is likely coming from the compost in the soil mix, in addition to other sources in runoff. The water quality in GSI systems is highly variable due to the microbial population, vegetation, and wetting/drying cycles. Pollutant sources will also impact water quality in GSI systems and can vary by location. This study showed that GSI systems can be effective for copper and zinc in this particular setting, but they may cause high levels of PO_4^{3-} and TP in soil water. High phosphorus concentrations are likely due to phosphorus in the soil mix. Future GSI designs should include measures for reducing phosphorus in the soil mix design to minimize export to receiving waters.

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Data Availability Statement: Publicly available rainfall was used in this study and can be found here: https://or.water.usgs.gov/precip/astor.rain. Water quality data are available on request from the corresponding author.

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