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Green Roof Performance as Reported in the Literature

Contents

Main Conclusions from the Literature

I reviewed about 50 published papers and reports on green roof runoff quality, with about half containing potentially useful information for use in WinSLAMM and summarized in this white paper. The main conclusions from these papers were:

1) Vegetation affects runoff quantity (evapotranspiration is a major water loss mechanism)
2) Vegetation does not consistently affect green roof water quality (pollutant uptake is minor, especially in the absence of harvesting). Vegetation uptake of nitrates and orthophosphates were periodically observed.
3) Green roof phosphorus runoff quality is dependent on the substrate type and fertilization
4) Green roof phosphorus runoff quality is highly seasonal with long-term downward trend, but is not related to rain depth or runoff quantity

The following review includes excerpts from the references supporting these comments, along with suggested WinSLAMM use of these data and information.

Types of Green Roofs

The two main types of green roofs are intensive and extensive, as illustrated in the following photographs. Extensive green roofs are far more common and suitable for retrofit installations, especially considering the weight of intensive green roof systems. Berndtsson, *et al.* (2009) noted the release of phosphorus from the extensive green roof (mostly in form of PO_4), while no release was noted from the intensive green roof. They state that the probable source of phosphorus was from the fertilizer applied during construction and from phosphorus leaching from the soil substrate, as also concluded in many other studies.

Emilsson, *et al.* (2007) described typical extensive green roofs in Sweden as having water-saturated weights of approximately 50–55 kg/m^2. They have a 3 to 5 cm growing substrate layer composed of inorganic low-density material with large water-holding capacities, such as pumice, scoria or lava. They are dry for long periods and can therefore only support drought-tolerant species unless irrigated. The substrate mixes also have high water permeability and low organic content to prevent decomposition and compaction of the growing layer. The fertilizers used are most often encapsulated controlled release fertilizers, which are designed to release nutrients at a pace similar to the nutrient requirements of the vegetation.

Fig. 2 – Study site at the intensive vegetated roof at ACROS Fukuoka, Japan.

Source: Berndtsson, *et al.* 2009.

Fig. 3 – Study site at the extensive vegetated roof at Augustenborg, Malmö, Sweden.

Source: Berndtsson, *et al.* 2009.

Substrates used in Green Roofs

The following table lists the variety of substrates that have been reported in extensive green roofs. Jennett and Zheng (2018) report that substrates may behave as either sources or sinks of P, depending on the components they are formulated from. They also found that few direct links have been established among substrate components and their physicochemical characteristics that would affect P-retention.

Table 1
Total unique and detailed substrates by component class in articles published from January 1st, 2005 to October 31st, 2017. Components listed within each class are the major component (greatest % v/v). Substrate composition information was retrieved from articles using the Web of Science database and search terms "green roof," "substrate," and "runoff." 'Proprietary' substrates are those protected by trade practices that do not provide a comprehensive list of components or the proportions of each component.

Substrate Component	No. of Instances
Proprietary ($n = 89$)	
Clay and Clay-Like Materials ($n = 74$)	
Crushed Brick	32
Decomposed Granite	1
Expanded Clay	17
Expanded Shale/Slate	24
Industrial Waste and Synthetics ($n = 4$)	
Bottom Fly Ash	4
Lightweight Inorganics ($n = 86$)	
Lapillus	6
Lightweight Aggregate	7
Limestone Derivatives	8
Perlite	16
Pumice	27
Scoria	14
Vermiculite	6
Zeolite	2
Organics ($n = 15$)	
Coir/Coco-peat	2
Compost	7
Paper Ash Pellets	3
Peat	3
Conventional Soils and Sands ($n = 35$)	
Conventional Soil	21
Sand	14
Total ($n = 303$)	

Source: Jennett and Zheng (2018)

Green Roof Substrate Selection and Potential Amendments to Control Runoff Quality

The Fertilizer Association of Ireland and Teagasc (2019) describes the P-index and how it relates to phosphorus from soils. The soil index system divides soils into one of four soil index levels based on the soil P test results. They also present the following figure indicating the relationship of soil pH with phosphorus fixation with iron (very low pH less than about 4.5), with aluminum (acidic soils in the pH range of about 4.5 to 6), and with calcium for alkaline soils (soil pH above 7).

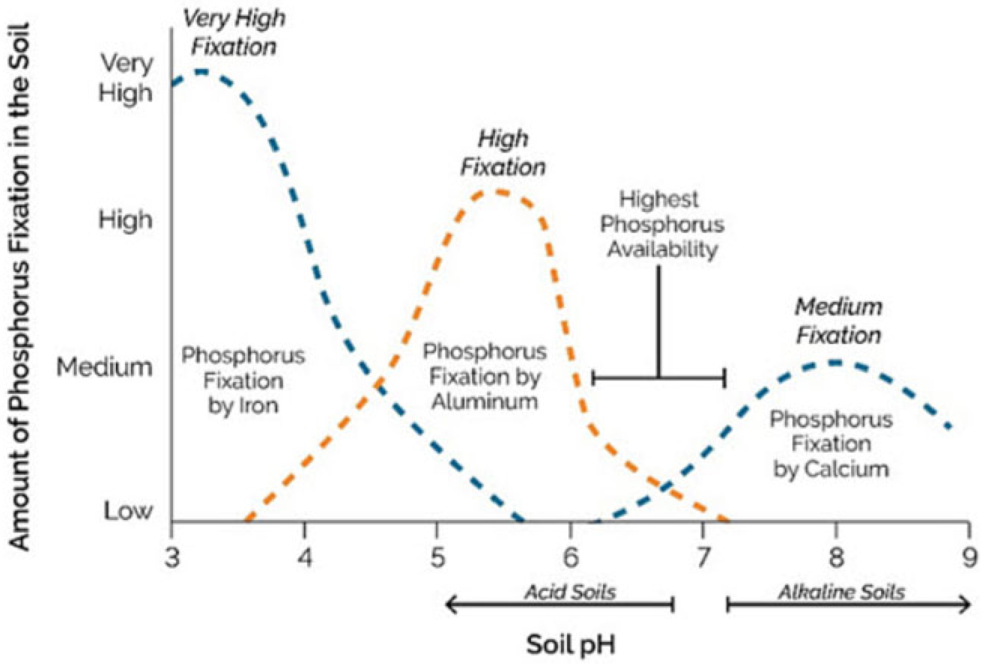

Figure 3. Typical strength and P bond types found in soils across the soil pH range

Source: Fertilizer Association of Ireland and Teagasc (2019)

Cornell University (2019) published the New York Phosphorus Runoff Index for agricultural areas to determine the relative risk of phosphorus runoff. This process also requires an evaluation of the material (soil or substrate) and the site conditions. The user's manual and documentation (Czymmek, *et al.* (undated) describes the features of this index, as summarized in the following tables.

Table 1: Overall interpretation and management implication of the NY-PI 2.0.

Overall interpretation (transport factor score × BMP score × 10)					
		Management implication			
P-loss risk	PI score	Soil test P (Cornell Morgan extraction in lbs/acre)[1]			
		< 40	40-100	101-160	> 160
Low	< 50	N-based	N-based	P-based	Zero P
Medium	50-74	N-based	P-based	Zero P	Zero P
High	75-99	P-based	P-based	Zero P	Zero P
Very high	≥ 100	Zero P	Zero P	Zero P	Zero P

[1]When Cornell crop guidelines call for P above the STP or rate limits in this table, P can be added to not exceed land grant guidelines as long as the NY-PI 2.0 score is 99 or lower.

Source: Czymmek, *et al.* (undated)

Table 2: Transport factors and coefficients included in the NY-PI 2.0. Coefficients are added and both the DP and PP sums are multiplied by 10 to obtain a field's raw PI score (without BMP reduction). The management implication is determined by the greater of the two scores and both scores must be below 100 for manure or fertilizer P to be applied.

Raw Score = Transport Factor Score × 10 (DP score = FD + FF + CF + HSG_{DP} + VB_{DP}; PP score = FD + FF + CF + HSG_{PP} + E + VB_{PP})					
Factor	Option	Coefficient	Factor	Option	Coefficient
Flow distance (FD) to stream or ditch in ft	> 500	0	Hydrologic soil group (HSG)	A	DP: 0 PP: 0
	300-500	4		B	DP: 4 PP: 1
	100-300	6		C	DP: 6 PP: 3
	≤ 100	8		D	DP: 8 PP: 5
Flooding frequency (FF)	Never	0	Erosion (E)[1] in ton/acre	≤ 1.0	0
	Occasionally	2		1.1-3.0	1
	Frequent	5		3.1-5.0	3
Concentrated flow (CF)	Absent/Treated	0		> 5	5
	Present	4	Vegetated buffer (VB)	Absent	0
				Present	DP: -2 PP: -4

[1] Determined by the RUSLE2 A-factor.

Source: Czymmek, *et al.* (undated)

As an example, a potential application to a green roof may include the following factors:

- Flow distance (FD): <100 ft
- Flooding frequency (FF): frequent (whenever it rains)
- Concentrated flow present (discharge from green roof)
- Soil types depending on texture class of substrate mixture
- Erosion rate: < 1 ton/acre
- Buffer absent

Beecham and Razzaghmanesh (2014) studied green roofs having different substrates in the dry and hot climate of Adelaide, South Australia. They found that the organic substrate mix produced higher orthophosphate concentrations. The scoria mix had intermediate concentrations, while the crushed brick mix had the lowest concentrations. This indicates that leaching of organics in the growing media resulted in higher orthophosphate concentrations in the runoff. However, in the vegetated green roofs, the phosphorous concentration was reduced by 60% to 80%, while there were no differences between the different types of vegetated green roofs. Plant uptake of the orthophosphate was therefore observed during these studies. The following table summarizes these findings.

Table 3 – Water quality of outflows from green roofs and impervious surfaces compared to Australian and international water quality standards.

Water quality parameter	Experimental data				Experimental data from authors' previous studies [6]			Range recommended by standards			Ranges reported in the literature [7]			
	Stormwater	Green roofs (N-f)		Non-vegetated roofs	Asphalt roof	Aluminium roof	Green roofs (F)	Potable reuse	Non-potable reuse	Urban irrigation	Rainwater	Roofs	Trafficable areas with low density	Trafficable areas with high density
		Brick or scoria mixes	Organic mix				Brick or scoria mixes							
pH	7.45–7.55	4.2–8.01	5.65–8.22	4.5–7.55	7.13	7.58	6.72–8.45	6.5–8.5 [1&2]	4.5–9.0 [4]	4.5–8.4 [1&4]	3.9–7.5	4.7–6.8	6.4–7.9	6.4–7.9
Turbidity (NTU)*	1.3–1.35	1.51–67.5	1.54–104	1.8–100	2.98	1.26	4.0–300	<5 [3]	<2 [4] to 2–5 [1]	n.a.	n.a.	n.a.	n.a.	n.a.
EC (µS/cm)	<0.5	1.82–59	1.27–86	0.85–75	75.00	23.00	<100-	<200 [4]	–	0–8100 [4]	28–223	25–269	n.a.	108–2436
Total dissolved solids (mg/l)	2.4–5.9	6.50–150	8.1–220	5.4–380	37.00	31.00	385.77	<600.00 [5]	–	–	n.a.	n.a.	n.a.	n.a.
Nitrate (mg/l)*	<1	1–40	1.01–100	20–350	2.62	1.90	2.20–39.20	<10 [4]	<10 [4]	<30 [4]	0.0–7.4	0.1–4.7	n.a.	0.0–16
Nitrite (mg/l)	0.07–0.10	0.02–3.5	0.04–4	2.2–16.5	n.a.	n.a.	n.a.	<3 [2&3]	<10 [3]	<10 [3]	n.a.	n.a.	n.a.	n.a.
Ammonia (mg/l)	1.01–1.10	1–16.5	1–20	1–55	n.a.	n.a.	n.a.	0.50 [3]	20–30 [2]		n.a.	n.a.	n.a.	n.a.
Orthophosphate (mg/l)*	<0.01	0.03–2.37	0.04–4.39	0.46–7.5	0.14	0.16	0.20–2.20	0.1 [5]	–	0.50 [4]	<0.20	<0.50	n.a.	0.34
Potassium (mg/l)	0–0.46	0.03–3.0	0.52–6.45	0.05–7.03	9.60	3.00	38.37	10–20 [1]	–	–	0.46–0.65	n.a.	n.a.	1.7–3.8
Sodium (mg/l)	0–1.84	0.10–10.4	1.26–15	0.16–19.46	n.a.	n.a.	n.a.		<180 [3]		0.22–20	n.a.	n.a.	5–474
Calcium (mg/l)	0	1–104	4–140	2–151	n.a.	n.a.	n.a.	60–200 [3]	200–500 [3]	<400 [3]	1.1–67.13	1–1900	n.a.	13.7–57
SAR	0	0.15–0.21	0.18–0.22	0.2–0.42	n.a.	n.a.	n.a.	n.a.	n.a.	<3 [1]	n.a.	n.a.	n.a.	n.a.

N-f: Non-fertilized, F: Fertilized, n.a.: data not available, * Pollutant levels exceed potable standards [1] (USEPA, 2012); [2] (EPA South Australia, 1999); [3] (EPA South Australia, 2003); [4] (Higgins et al., 2007); [5] (NRMMC, 2011); [6] (Razzaghmanesh et al., 2014a); [7] (Göbel et al., 2007).

Source: Beecham and Razzaghmanesh (2014)

Wang, *et al.* (2017) examined dual-substrate layered green roofs in Beijing. All of the dual-substrate-layered green roofs appeared to be sinks for organics, heavy metals and all forms of nitrogen in all cases, while they acted as sources of phosphorus contaminants during heavy rains. They recommend a mixture of activated charcoal and/or pumice with perlite and vermiculite as the adsorption substrate for long service life and pollutant reduction.

Biochar as a Component of Green Roof Substrates

Qianqian, *et al.* (2019) examined the use of biochar as a substrate on green roofs located in China. They did not identify any significance difference in the runoff retention for green roofs having commercial substrates and with biochar substrates (both about 72%). They found that both substrates had gradually decreasing concentrations of total nitrogen, total phosphorus, COD, and iron with time. The biochar substrate resulted in TN (9.8 mg/L) and COD (97 mg/L) concentrations, which were about half of the commercial substrate (TN at 16 mg/L and COD at 172 mg/L).

Kuoppamäki and Lehvävirta (2016) also investigated two birch biochars (prepared at different pyrolysis temperatures and times) on green roofs in Finland. The green roofs were thin-layered (2 to 12 cm of substrate) Sedum/moss roofs, while two were meadow roofs (with substrate depths of 21 and 23 cm). At the beginning of the measurement period they found negligible effects due to the biochar, but after one year, the biochar retained nutrients. The total annual loads (product of both quantity and concentration reductions) of nutrients were significantly reduced by the biochar amendments in both green roof types. The following tables describe the biochar characteristics.

Table 2
The percentage of different sized particles in terms of weight for crushed brick mixture and biochar, used in the green roof platform experiment.

Particle size mm:	<0.25	0.25–0.50	0.5–1.0	1–2	2–4	>4
crushed brick mixture	13.9	12.8	17.2	18.8	20.9	16.5
biochar	5.7	12.0	28.0	27.4	23.0	3.9

Source: Kuoppamäki and Lehvävirta (2016)

Table 6
Water holding capacity, pH and electric conductivity of crushed brick and biochar as well as average (±SE) organic matter content (%) of the substrate samples taken from the planted and pre-grown treatments with and without biochar at the beginning of the green roof platform experiment in August 2013.

Substrate property	crushed brick	biochar
Water holding capacity (%)	60	230
pH	7.8	8.4
Electric conductivity (μS/cm)	149	130
	planted	pre-grown
Organic matter content (%)		
–biochar absent	1.8 (±0.2)	7.0 (±0.2)
–biochar present	4.6 (±0.5)	6.9 (±0.6)

Source: Kuoppamäki and Lehvävirta (2016)

Kuoppamäki, *et al.* (2016) in another publication stated that the biochar reduced the cumulative leaching of nutrients, even though biochar did not significantly reduce nutrient concentrations. In the laboratory experiments, one type of biochar reduced nutrient concentrations and loads in the runoff, while another type had an opposite effect. The properties and effects of biochar can vary considerably, requiring specific testing to measure their benefits for green roof use. Pyrolysis conditions and the raw material have strong effects on the characteristics of a biochar, with varying runoff results due to the quality of the biochar.

Although grasses have been shown to be more effective in reducing runoff than Sedum, Kuoppamäki, *et al*. (2016) did not find any effects of vegetation type (Sedum vs. meadow) in terms of water retention. This was probably due to the poor survival of grasses and herbs in the green roofs monitored. They found that substrate depth, rather than vegetation type, can determine retention capacity. They concluded that avoiding fertilization and careful selection of substrate material, including use of studied amendments, are appropriate means to control nutrient leaching from green roofs.

Table 1
Characteristics of biochar A (used both in the field and the laboratory) and biochar B (used in the laboratory).

	A	B
Dry matter (%)	96	84
Organic matter (% dw)	97	94
pH	7.6	9.2
BET surface area ($m^2\ g^{-1}$)	7	140
Water holding capacity (%)	77	163
Bulk density ($g\ l^{-1}$)	389	245

Source: Kuoppamäki, *et al.* (2016)

Green Roof Water Quantity

The following figure, from Peczkowski, *et al.* (2018), shows a typical cross-section of an extensive green roof and the water loss mechanisms.

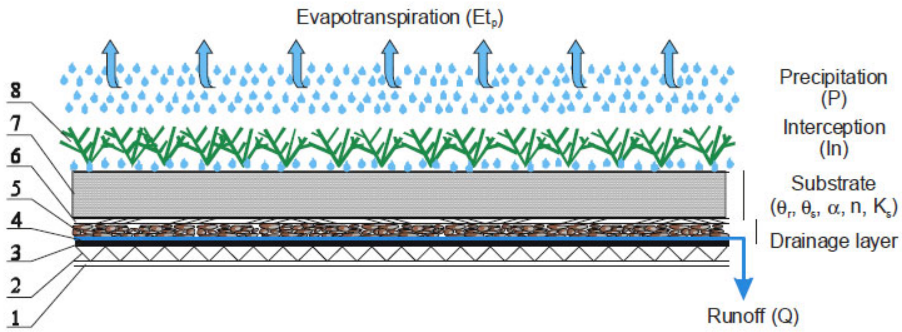

Figure 1. Construction details of extensive type green roof, substrate with pumice or zeolite, physically based model. 1—model support structure, 2—thermal insulation—extruded polystyrene (XPS), 3—water proofing membrane, 4—geotextile type RMS 300 (absorptive-protective), 5—gravel layer, granulation from 1 to 2 cm, 6—filtration geotextile, 7—substrate with pumice or zeolite, 8—vegetation on the substrate layer—Sedum sexangulare, Sedum telephium, Sedum spurium, Sedum floriferum, Sedum album.

Source: Peczkowski, *et al.* (2018)

Carter and Rasmussen (2006) monitored a paired test of a green roof and a control roof in Georgia over a one-year period. The rains ranged from 0.28 to 8.43 cm for the 31 events monitored. As shown on the following graph, the green roof rainfall capture decreased with increasing rainfall depth, ranging from just under 90 percent for the smaller storms (< 2.54 cm) to slightly less than 50 percent for the larger storms (> 7.62 cm). Runoff from the green roof was also delayed with an average increase of about 18 minutes for the green roof compared to the control roof.

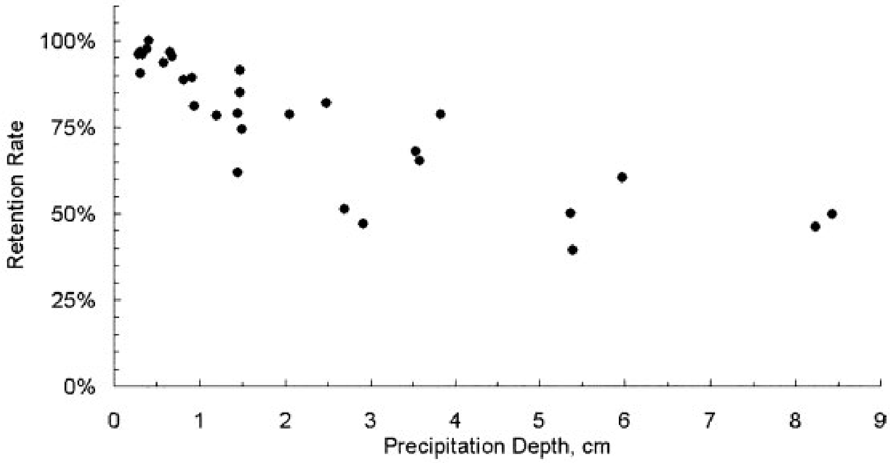

Figure 7. Precipitation Retention Rates as a Function of Total Precipitation Depth.

Source: Carter and Rasmussen (2006)

Fassman-Beck, *et al*. (2013) monitored green roofs in Auckland, New Zeeland. The roof was irrigated on each day having no rainfall. They found this was too much as the irrigation caused increased runoff due to lengthy periods of higher saturated substrate. The following table compares the retention rate and peak flow reductions for the green roof compared to control roof conditions.

Table 5. Summary statistics per rainfall event comparing living roof runoff and modelled control roof runoff

	Storms With P≥ 2 mm		**All Storms**	
	Retention %	Peak Flow Reduction %	Retention %	Peak Flow Reduction %
Mean*	71 ± 3.6	87 ± 2.0	85 ± 2.3	93 ± 1.2
Median	76	90	98	100
Maximum	100	100	100	100
Minimum	7	8	7	8
* ± 95% confidence interval				

Source: Fassman-Beck, *et al*. (2013)

They also found seasonal variations in the hydrologic response of the green roof, as shown in the following table.

Table 6. Median %-reduction when compared with modelled control roof runoff, for rainfall events >2 mm depth

	Spring	Summer	Autumn	Winter
Retention	83	92	75	66
Peak Reduction	95	98	91	87
Event Count	63	38	32	65

Source: Fassman-Beck, *et al*. (2013)

During their tests, they also compared green roof runoff conditions for the two large installations with a series of small green roofs on small sheds. The shed green roofs responded quite differently (faster runoff responses) due to the shorted path to the roof outlet, and different permeability of the substrate material.

Fassman-Beck, *et al*. (2013) also compared evapotranspiration for stressed (overly dry conditions) to unstressed conditions for several different plants and growing environments, as shown in the table below.

Table 19. Summary of hourly ET results from the bench-scale trials, all values in mm h^{-1}

		Unstressed		Stressed	
		Peak	Overnight	Peak	Overnight
Unplanted	Greenhouse	0.10–0.30	0.02–0.05	0.01–0.08	0.00–0.02
	Field	0.26	0.01	0.06	0.02
S. mexicanum	Greenhouse	0.25–0.46	0.02–0.04	0.01–0.02	0.00–0.01
	Field	0.40	0.02	0.05	0.01
D. australe	Greenhouse	0.22–0.50	0.03–0.04	0.02–0.07	0.01–0.02
	Field	0.46	0.02	0.05	0.01

Note: "Greenhouse" data is the range of values for Trials 1 to 4, "Field" data is for Trial 5.
Reprinted with permission Voyde (2011).

Source: Fassman-Beck, *et al*. (2013)

Fassman-Beck and Simcock (2013) also reported that Individual rains had 56%-72% runoff retention by the green roofs which had 100 to 150 mm substrate depths which were designed to maximize water storage.

Green Roof Water Quality

Green Roofs as Sources or Sinks of Pollutants

Fassman-Beck, *et al*, (2013) found little agreement in the literature as to green roofs being sinks or sources of nutrients. However, there is much agreement that the composition of the substrate and the application of fertilizer affects green roof runoff quality.

Gnecco, *et al.* (2013) compared the pollutant loads from atmospheric deposition with green roof runoff. Infiltration through the green roof substrate resulted in increasing concentrations for solids, K, Ca and Fe, while Zn and Cu were reduced. They concluded that the substrate can be a source of some metals, while reducing other pollutant concentrations.

Vijayaraghavan and Joshi (2014) also investigated green roofs as sinks for various pollutants. They found that Ca, Mg, Al, Fe, Cr, Cu, Ni, Zn, Pb, and Cd were reduced by the green roofs, along with neutralizing acid rain. They stated that low-cost and locally available materials such as perlite, vermiculite, sand, crushed brick, and coco-peat produced better runoff in comparison with that of local garden soil. They also note that runoff from unplanted green roofs appeared earlier and had higher dissolved pollutant concentrations than the planted (P. grandiflora) green roofs. They concluded that the selection of plant species for green roofs should not be entirely dictated by aesthetics and drought-tolerant potential, but also on their phytoremediation potential (which is not well known for plants being used on green roofs).

Fassman-Beck and Simcock (2013) during their green (living) roof monitoring in Auckland found that neither the green roof nor the conventional roof surfaces produced elevated suspended solids (TSS) or nitrate+nitrite concentrations. Copper may be from the green roof substrates, while both copper and zinc are from roofing materials. Soluble Reactive Phosphorus (SRP) and Total Kjeldhal Nitrogen (TKN) are the predominant nutrients discharged at elevated concentrations from the green roofs, as shown on the following table. Runoff from all the green roofs were a source of nitrogen, primarily in the form of TKN as opposed to NOx. NOx is readily taken up by plants, while TKN is less plant-available and is comprised of ammonia, ammonium, and organic nitrogen.

Table 2: Median Water Quality EMCs + 95% Confidence Interval from Eight Sampled Events at Each Site

Parameter	Tamaki		WCC	
	Living Roof	Control Roof	Living Roof	Control Roof
TSS (mg/L)	4.8 + 2.7	3.0 + 2.1	1.4 + 1.6	1.8 + 0.5
NO_x (mg/L)	0.143 + 0.17	0.056 + 0.02	0.482 + 0.24	0.04 + 0.05
TN (mg/L)	1.601 + 0.73	0.374 + 0.19	2.022 + 2.97	0.235 + 0.28
SRP (mg/L)	0.596 + 0.20	0.045 + 0.01	0.40 + 0.15	0.005 + 0.0
TP (mg/L)	0.669 + 0.25	0.07 + 0.13	0.41 + 0.16	0.011 + 0.0
Sol Cu (µg/L)	3.63 + 0.7	0.32 + 0.2	14.0 + 2.2	8.2 + 9.3
Cu (µg/L)	3.98 + 1.0	0.54 + 0.2	16.0 + 2.0	9.0 + 9.7
Sol Zn (µg/L)	30.83 + 11.3	35.5 + 10.2	12.0 + 1.5	7.55 + 10.0
Zn (µg/L)	42.0 + 50.3	43.5 + 75.6*	13.0 + 2.4	8.65 + 10.7

* One storm event generated 350 µg/L. Excluding this event results in median 39.0 + 16.4 µg/L.

Source: Fassman-Beck and Simcock (2013) (Tamaki are the small shed test green roofs while the WWC are full-sized green roofs.

Culligan, *et al.* (2014) monitored green roofs and control roofs in New York City. The roofs were located on a variety of buildings and represented a wide range of extensive green roof installation types, including vegetated mat, built up, and modular tray systems, as well as different plant types. A number of constituents had greater concentrations in the runoff from the green roof runoffs compared to the runoff from the control roofs (as shown in the following table). However, there is an overall reduction in the volume of runoff from green roofs, and therefore less mass of pollutants discharged from the green roofs. They also state that improved management by reduced fertilization of green roofs would also result in reduced nutrient discharges.

Table 5-2 Summary of Mean Water Quality Results with Standard of Deviation

Water Quality Measurement	Green Roof		Control Roof		Precipitation	
	Mean	Standard of deviation	Mean	Standard of deviation	Mean	Standard of deviation
pH	7.28	± 0.51	6.27	± 0.69	4.82	± 0.39
Conductivity (uS/cm)	127.67	± 48.89	57.11	± 57.63	32	± 20.71
Turbidity (NTU)	2.47	± 2.74	1.47	± 1.48	0.62	± 0.39
Color (PtCo)	162.53	± 90.24	28.45	± 32.42	5.32	± 9.79
Nitrate (mg/L)	0.27	± 0.59	0.87	± 1.31	0.6	± 0.53
Ammonium (mg/L)	0.86	± 1.86	1.47	± 2.55	1.19	± 1.85
Total phosphorous (mg/L)	0.47	± 0.47	0.25	± 0.38	0.21	± 0.41
Calcium (mg/L)	13.59	± 6.8	3.93	± 5.23	0.74	± 0.50
Potassium (mg/L)	2.22	± 2.86	0.78	± 1.98	0.1	± 0.2
Sodium (mg/L)	3.58	± 3.47	1.8	± 3.01	0.98	± 0.88
Magnesium (mg/L)	2.92	± 1.03	1.31	± 2.30	0.2	± 0.24
Boron (mg/L)	0.58	± 1.19	0.03	± 0.1	0.0	± 0.0

Source: Culligan, *et al.* (2014)

Ferrans, *et al.* (2018) studied green roofs in Bogota. Rainfall and green roof runoff from 12 rain events were monitored for total Kjeldahl nitrogen, nitrates, nitrites, ammonia, total phosphorus, phosphates, pH, total dissolved solids, total suspended solids, color, turbidity, biological oxygen demand, chemical oxygen demand, total coliforms, metals (i.e., zinc, copper, nickel, lead, selenium, aluminum, barium, boron, calcium, strontium, iron, lithium, magnesium, manganese, potassium, sodium), and polyaromatic hydrocarbons, as shown on the following table. The results showed that green roofs can neutralize pH, but they were also a source of the rest of the above listed constituents, excluding PAHs, ammonia, TSS, selenium and lithium. Substrate type, event size, and rainfall characteristics were all found to be significant variables for explaining runoff water quality. The retention efficiencies were not significantly different for both the vegetated (86%) and non-vegetated (85%) systems.

Table 3. Descriptive statistics and *t*-test results for the effect of green roofs on water quality parameters.

Parameter	Group	Mean (Min–Max)	Deviation	Observations	*p*-Value
pH (Units)	Control	6.51	1.25	29	0.000
	Green Roofs	8.22	0.57	20	
Conductivity (us/cm)	Control	29.47	36.50	30	0.000
	Green Roofs	1080.80	762.88	30	
Organic matter parameters					
BOD (mg/L)	Control	2.77 (0.46, 6.6)	1.65	24	0.000
	Green Roofs	9.15 (1.61, 36.5)	7.49	43	
COD (mg/L)	Control	12.85 (2.70, 31.50)	10.10	19	0.000
	Green Roofs	416.19 (144.08, 1054)	194.26	46	
Phosphorus parameters					
Total phosphorus (mg/L-P)	Control	0.08 (0.02, 0.26)	0.07	23	0.000
	Green Roofs	4.06 (0.02, 17.2)	3.97	46	
Phosphates (mg/L-P)	Control	0.36 (0.02, 1.97)	0.48	24	0.000
	Green Roofs	5.39 (0.2, 20.38)	5.03	38	
Coliform					
Total coliforms (MPN)	Control	7.5×10^2 (3.0×10^3, 4.6×10^3)	1.3×10^3	24	0.000
	Green Roofs	1.5×10^5 (3.0×10^6, 1.1×10^6)	2.5×10^5	45	
Nitrogen Parameters					
TKN (mg/L-N)	Control	1.08 (0.24, 2.10)	0.56	23	0.000
	Green Roofs	11.91 (2, 29.10)	6.03	46	
Nitrates (mg/L-N)	Control	1.83 (0, 6.03)	1.73	20	0.000
	Green Roofs	9.24 (0.80, 24.97)	6.80	32	
Nitrites (mg/L-N)	Control	0.02 (0.004, 0.04)	0.01	24	0.005
	Green Roofs	0.10 (0.007, 1.21)	0.18	46	
Ammonia (mg/L-N)	Control	0.62 (0.10, 1.13)	0.34	23	0.247
	Green Roofs	0.50	0.40	46	
Physical Parameters					
Color (Platinum-Cobalt Scale)	Control	4.33 (2.00, 6.00)	1.46	24	0.000
	Green Roofs	34.46 (10.00, 70.00)	17.55	46	
Turbidity (Nefelometric Turbidity Unit)	Control	6.81 (0.62, 43.5)	9.60	24	0.015
	Green Roofs	18.74 (1.96, 177.00)	29.41	46	
TSS (mg/L)	Control	23.42 (0.10, 181.51)	41.91	24	0.545
	Green Roofs	31.19 (3.00, 322.00)	54.77	46	

Metals					
Zinc (mg/L-Zn)	Control	0.04 (0.01, 0.08)	0.02	23	0.000
	Green Roofs	2.34 (0.52, 9.11)	2.05	44	
Copper (mg/L-Cu)	Control	0.03 (0.03, 0.03)	0.00	23	0.002
	Green Roofs	0.03 (0.03, 0.08)	0.01	44	
Nickel (mg/L-Ni)	Control	0.00 (0.00, 0.00)	0.00	23	0.000
	Green Roofs	0.01 (0.00, 0.02)	0.00	44	
Lead (mg/L-Pb)	Control	0.01 (0.00, 0.01)	0.00	23	0.000
	Green Roofs	0.05 (0.01, 0.18)	0.04	44	
Selenium (mg/L-Se)	Control	0.03 (0.01, 0.03)	0.01	23	0.305
	Green Roofs	0.03 (0.01, 0.32)	0.05	44	
Aluminium (mg/L-Al)	Control	0.29 (0.15, 0.77)	0.15	23	0.012
	Green Roofs	0.67 (0.10, 4.96)	0.95	44	
Barium (mg/L-Ba)	Control	0.01 (0.00, 0.02)	0.01	23	0.000
	Green Roofs	0.04 (0.00, 0.18)	0.04	44	
Boron (mg/L-B)	Control	0.06 (0.03, 0.10)	0.02	23	0.000
	Green Roofs	0.10 (0.06, 0.17)	0.03	44	
Calcium (mg/L-Ca)	Control	2.34 (0.81, 5.42)	1.31	23	0.001
	Green Roofs	138.82 (17.90, 797.00)	182.00	44	
Strontium (mg/L-Sr)	Control	0.06 (0.00, 0.07)	0.01	23	0.000
	Green Roofs	0.52 (0.07, 2.88)	0.66	44	
Iron (mg/L-Fe)	Control	0.13 (0.03, 0.54)	0.14	23	0.000
	Green Roofs	0.44 (0.08, 2.29)	0.42	44	
Lithium (mg/L-Li)	Control	0.00 (0.00, 0.00)	0.00	23	0.473
	Green Roofs	1.45 (0.00, 63.60)	9.59	44	
Magnesium (mg/L-Mg)	Control	0.18 (0.10, 0.63)	0.14	23	0.000
	Green Roofs	14.82 (1.94, 79.90)	18.63	44	
Manganese (mg/L-Mn)	Control	0.01 (0.00, 0.02)	0.00	23	0.000
	Green Roofs	0.02 (0.00, 0.10)	0.02	44	
Potassium (mg/L-K)	Control	0.44 (0.10, 2.97)	0.62	23	0.000
	Green Roofs	189.67 (20.20, 1017)	224.54	44	
Sodium (mg/L-Na)	Control	2.80 (0.26, 3.56)	1.32	23	0.000
	Green Roofs	97.87 (4.08, 583.00)	133.89	42	

Source: Ferrans, *et al.* (2018)

Comparisons of Green Roof Runoff Quality to Other Source Areas

Barr, *et al.* (2017) compared fertilized green roof runoff water quality with other vegetated locations and stormwater control measure effluents, near Villanova University, PA. The vegetated sites included a grassed site, a wooded site, and a mixed-use site with pavement and grass on or adjacent to the Villanova University campus. The stormwater control measures included a constructed stormwater wetland and a bioinfiltration rain garden. They found that the green roof discharges much greater phosphorus concentrations than the other locations, except for the fertilized grass area. They also did not identify any significant correlations between green roof runoff concentrations and rainfall volume.

Table 2. Median Nutrient Concentrations

Site	Median concentration (mg/L)					
	Tot-N	NO_2-N	NO_3-N	TKN-N	Tot-P	PO_4-P
Precipitation	0.85	0.01	0.25	0.53	0.05	0.05
Green roof	2.70	0.01	0.56	1.70	1.36	1.28
Woods	2.31	0.16	0.19	1.79	0.43	0.28
Grass	1.19	0.04	0.13	0.72	1.02	0.43
Mixed use	1.47	0.04	0.30	0.87	0.18	0.13
Rain garden	0.77	0.02	0.15	0.38	0.14	0.08
Wetland	1.26	0.03	0.58	0.76	0.13	0.05

Source: Barr, *et al.* (2017)

Seasonal Patterns of Phosphorus Concentrations in Green Roof Runoff

Mitchell, *et al.* (2017) measured phosphate in green roof runoff over a 4-year period at an extensive green roof in Cincinnati, OH. They found that the phosphate concentrations were similar to runoff from heavily fertilized agricultural fields. The pattern of the phosphate concentrations displayed a strong seasonal pattern, along with a rapid decline over the 4-year study (as shown in the following figure and table).

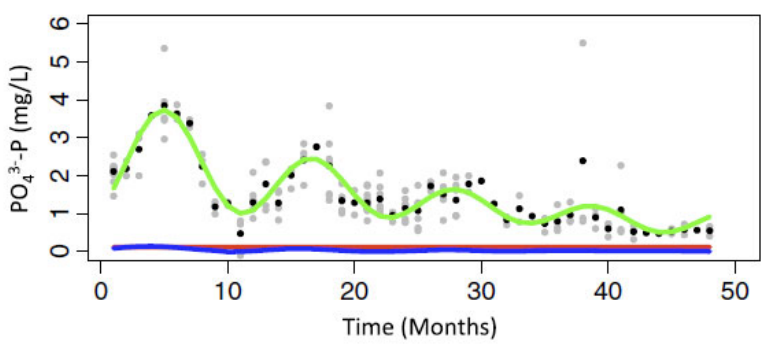

Fig. 1 Phosphate (PO_4^{3-}-P) concentrations from the Civic Garden Center green roof (*grey* and *black points* and *green line*), traditional roof (*red line*), and atmospheric deposition (*blue line*) from April 2011 (Month 1) to March 2015 (Month 48). All sampled concentrations collected from the green roof are shown with *grey points*, with the mean concentration for that sampling month shown with *black points*. The *green line* is the best-fit model for the green roof runoff data, the *red line* for the traditional roof runoff data, and the *blue line* for atmospheric deposition data

Source: Mitchell, *et al.* (2017)

Table 1 Sampling year (April to March of the following year) summaries for precipitation and Civic Garden Center green roof runoff water quality for the 4-year time-series

Sampling Year	N	Total Precip. (mm)	PO_4^{3-}-P (mg/L)	pH	Conductivity (uS/cm)
1 (2011–2012)	44	1285	2.2 (1.1)	7.20 (0.32)	182 (136)
2 (2012–2013)	62	673	1.5 (0.6)	6.99 (0.50)	206 (166)
3 (2013–2014)	38[a]	1000	1.2 (0.5)	6.96 (0.34)	167 (91)
4 (2014–2015)	29	943	0.9 (1.0)	7.00 (0.22)	204 (100)

Values shown are means for that sampling year (except for precipitation, which is the total precipitation for the sampling year), with standard deviations in parentheses. Climate Data are from NOAA's Lunken Airfield Weather Station

[a] 36 samples were included for conductivity and pH in the 3rd year

Source: Mitchell, *et al.* (2017)

They found that even after 5 years following green roof installation, the phosphate concentrations were still high relative to natural systems and even regularly fertilized agricultural areas, often by an order of magnitude, or more. They also found that common green roof plants (such as Sedum), that are selected for stress and drought resistance have reduced nutrient requirements and growth rates, therefore, they do not require the high phosphorus levels found in green roof substrates, let alone additional fertilization.

Buffam, *et al*. (2016) also discussed the Civic Garden Center green roof in Cincinnati. As noted above, they observed strong seasonal patterns in bioactive elements, with carbon, nitrogen, phosphorus, and base cation concentrations highest in the summer, and positively correlated with temperature. They concluded that the dominant mechanism responsible for seasonality in runoff water quality from this green roof are most closely linked to variations in temperature, rather than hydrology (rain size/type) or growing season (plant activity). The following table presents green roof runoff concentrations, by season.

Table 2
Summary (median, 10–90th percentiles) of green roof runoff chemistry, organized by season.

Analyte	Units	Spring (N = 24)	Summer (N = 17)	Fall (N = 22)	Winter (N = 25)
pH	pH units	7.2 (6.5–7.5)	7.0 (6.2–7.4)	*6.7 (6.3–7.3)*	7.1 (6.7–7.5)
Conductivity	µS/cm	134 (64–234)	**356 (200–549)**	229 (123–451)	*107 (81–173)*
DOC	mg C L^{-1}	21.0 (12.7–28.4)	**33.4 (25.9–69.8)**	28.4 (18.1–49.7)	12.1 (7.6–23.7)
DON	mg N L^{-1}	1.6 (1.1–7.2)	**10.3 (2.6–35.8)**	1.6 (0.1–19.3)	*1.2 (0.7–2.0)*
NO_3^-	mg N L^{-1}	0.1 (0.0–1.9)	**3.1 (0.7–13.2)**	2.5 (0.0–8.5)	*0.1 (−0.1–0.5)*
NH_4^+	mg N L^{-1}	*0.0 (0.0–0.1)*	**0.6 (0.1–1.7)**	0.1 (0.0–0.5)	0.1 (0.0–0.7)
PO_4^{3-}	mg P L^{-1}	1.6 (0.9–2.4)	**2.8 (1.7–4.2)**	2.3 (1.0–3.5)	*1.2 (0.8–1.6)*
Ca	mg L^{-1}	18.3 (13.9–25.5)	**42.2 (23.0–70.3)**	28.7 (13.7–51.1)	*11.8 (9.6–18.8)*
K	mg L^{-1}	1.1 (0.5–9.5)	**23.4 (9.0–44.4)**	9.3 (5.0–22.6)	*4.5 (1.3–7.3)*
Mg	mg L^{-1}	3.3 (2.3–5.3)	**7.8 (3.9–14.1)**	4.8 (2.3–9.0)	*2.2 (1.5–3.5)*
Na	mg L^{-1}	2.0 (0.9–4.3)	4.8 (2.7–10.7)	2.6 (1.1–4.8)	1.9 (0.6–3.6)
Al	mg L^{-1}	0.05 (0.02–0.10)	0.04 (0.03–0.06)	0.05 (0.00–0.08)	0.03 (−0.01–0.06)
Fe	mg L^{-1}	0.08 (0.03–0.11)	0.06 (0.04–0.10)	0.07 (0.03–0.10)	0.07 (0.02–0.12)
Zn	mg L^{-1}	0.36 (0.06–1.28)	1.04 (0.31–1.81)	0.82 (0.21–2.06)	0.50 (0.15–1.64)

Boldface text indicate seasons with exceptionally high values (10th percentile > another season's 90th percentile), while italicized text indicate seasons with exceptionally low values (90th percentile < another season's 10th percentile).

Source: Buffam, *et al.* (2016)

Carpenter, *et al*. (2016) studied green roofs in Syracuse, NY. They monitored wet deposition and roof runoff. Water quality was measured during 87 storms during about a 12-month period in 2011 and 2012. Water and nutrient (total phosphorus, total nitrogen, and dissolved organic carbon) mass balances were conducted on an event basis to evaluate retention annually and during the growing and nongrowing seasons. Green roof runoff had high concentrations of nutrients, especially total nitrogen and dissolved organic carbon, during the warm temperature growing season. Overall, nutrient mass discharges were low because of the large retention of water. However, there were large variations in the retention of the nutrients by season due to variations in concentrations in the roof runoff.

Vijayaraghavan, *et al.* (2012) conducted green roof field tests in Singapore. Concentrations of most of the chemicals in the runoff were highest at the beginning of rain events and decreased during subsequent rain events. The concentration of the chemical components in the roof runoff strongly depends on the nature of the substrates used in the green roof and the volume of rain.

Effects of Green Roof Age on Runoff Quality

Okita, *et al.* (2018) 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, phosphate, total nitrogen, nitrate, ammonia, copper, and zinc. Runoff from the green roofs had higher concentrations of TP and PO4 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 PO4 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. The 6-month old green roof phosphorus and phosphate concentrations were about twice the concentrations as from the 6-year old green roof, while the copper and zinc concentrations were about 30% greater from the 6-year old green roof compared to the newer green roof. The following table shows these concentrations.

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 ($p < 0.001$)

Source: Okita, *et al.* (2018)

Suggested WinSLAMM Green Roof Components

1) If a green roof is intensive (rare), then use standard landscaping runoff quality factors.
2) If a green roof is extensive and fertilized, and/or has organic substrate material (such as compost or soils) having high P-index (≥2) or P-loss risk scores, then use the following seasonal and long-term phosphate trends, depending on the roof age:

Approximate phosphate and nitrates seasonal trends:

	Spring Concentration (range)	Summer Concentration (range)	Fall Concentration (range)	Winter Concentration (range)
Dissolved organic nitrogen (mg/L)	1.6 (1.1 – 7.2)	10.3 (2.6 – 35.8)	1.6 (0.1 – 19.3)	1.2 (0.7 – 2.0)
Nitrate, NO3 (mg/L)	0.1 (0.0 – 1.9)	3.1 (0.7 – 13.2)	2.5 (0.0 – 8.5)	0.1 (0.0 – 0.5)
Phosphate, PO4 (mg/L)	1.6 (0.9 – 2.4)	2.8 (1.7 – 4.2)	2.3 (1.0 – 3.5)	1.2 (0.8 – 1.6)

Source: summarized from Buffam, *et al.* (2016)

Approximate phosphate trends with age of green roof (to adjust the above seasonal values):

	Phosphate (mg/L)	Ratio with year 1
Year 1	2.2	1.0
Year 2	1.5	0.68
Year 3	1.2	0.55
Year 4 and later	0.9	0.41

Source: calculated from Mitchell, *et al*. (2017)

Concentrations of non-nutrient contaminants do not undergo the seasonal or time changes, or respond to fertilizers or organic substrates, so TSS, copper, and zinc concentration values can be selected from the table in the following section.

3) If a green roof is extensive with inert substrate materials (such as sand, clay and clay-like material, lightweight inorganics, and some inert organics such as coir and peat) having low P-index (1) or P-loss risk scores, and not fertilized, use the following constant phosphate values:

Approx. concentrations for unfertilized green roofs:

	Median Concentration (COV)
TSS (mg/L)	1.4 (1.1)
NOx (mg/L)	0.48 (0.50)
TN (mg/L)	2.0 (1.5)
Soluble reactive phosphorus (mg/L)	0.40 (0.40)
Total phosphorus (mg/L)	0.41 (0.39)
Phosphorus particulate strength (mg/kg)	7.1
Filtered copper (ug/L)	14 (0.16)
Total copper (ug/L)	16 (0.13)
Copper particulate strength (mg/kg)	1.4
Filtered zinc (ug/L)	12 (0.13)
Total zinc (ug/L)	13 (0.18)
Zinc particulate strength (mg/kg)	0.7

Sources:
calculate from Fassman-Beck and Simcock (2013) full scale roofs

Amendment (such as biochar) benefits for green roofs are not included due to their highly varying runoff quality benefits reported in the literature. Plant uptake of nutrients is also not considered also due to varying benefits in the literature (no benefit to uptake of NOx and phosphates, if healthy and unstressed).

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