

A WATER QUALITY ASSESMENT OF A GREEN ROOF STORMWATER TREATMENT SYSTEMS

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Abstract

The use of green roofs in the United States for stormwater management purposes has become more popular in recent years. As a result there has been several research projects aimed at determining the volume control benefits of green roofs. While it has been speculated that green roofs also offer water quality benefits, little research has been done to quantify this claim. Within this paper, focus is placed on the water quality benefits of a specifically designed green roof stormwater treatment system. This system consists of an irrigated green roof with a cistern to store and reuse stormwater for irrigation. The primary water quality pollutants of concern are nutrients, such as nitrogen and phosphorus species. These pollutants have been suspected of leaching out of the green roof growing media and from rainfall. This work quantifies the water quality benefits of a green roof stormwater treatment system and proposes a design to achieve removal of the nutrients.

Introduction & Background

Many urban areas across the United States face a number of problems associated with stormwater management. These problems range from poor water quality to flooding. Currently there are several ways to address these problems such as stormwater ponds and infiltration systems. These current methods for addressing stormwater problems take up valuable space often not available in urban areas. Green roof stormwater treatment systems utilize roof space to store and treat stormwater. This option is particularly appealing to older areas that have already developed most of the useable land.

The use of green roofs for stormwater management in the United States is starting to be more common. While the volume control elements of a green roof are starting to become better understood, water quality issues are still largely unknown. The water quality research that has been done to date has shown that green roofs tend to leach high concentrations of nutrients, specifically nitrogen and phosphorus. Hunt et al., 2006, showed that, while atmospheric deposition was thought to be the source of the extra nutrients, the organic content of the soil was leaching out during precipitation events. The leaching of nutrients out of the growing media is expected to decrease with time, but water quality analysis has yet to support this theory (Hunt et al., 2006).

Stormwater treatment solutions similar to green roofs, called bioretention units, have been studied in more detail. Bioretention, like green roofs, are a plant and soil based stormwater treatment method (Kim et al., 2003; Davis et al., 2003; & Hunt and Moran 2004). Bioretention has previously been shown to be effective at removing metals

and most nitrogen species, except nitrate (Davis et al., 2003; & Hunt and Moran, 2004). The removal of nitrate in stormwater is desired to protect surface waters and the conventional bioretention unit is frequently noted as a nitrate producer (Kim et al., 2003). Nitrate production is attributed to the process of nitrification, where ammonia is converted to nitrate in an aerobic environment (Kim et al., 2003). Kim et al., 2003 and Hunt and Moran, 2004 have modified the conventional bioretention unit to achieve denitrification. This is done by the addition of an anoxic zone and a sufficient electron donor and carbon source (Kim et al., 2003).

The green roof stormwater treatment system presented in this paper includes the addition of a cistern. This work will report on the fate of nitrogen species as well as phosphorus using the specifically designed green roof stormwater treatment system discussed.

Approach

An irrigated green roof stormwater treatment system at the University of Central Florida was monitored to determine the water quality benefits of using a green roof. A green roof stormwater treatment system is defined as an irrigated green roof with a cistern to store green roof filtrate which is to be used for irrigation. Eighteen experimental chambers were also constructed to determine the affects of growing media type, the use of plants, and the irrigation volume. The types of growing media examined were an expanded clay mix and the Black & Gold™ mix. The irrigation volumes studied were regular irrigation, 1 inch per week, and over irrigation, 2 inches per week. Several

water quality parameters were measured including pH, alkalinity, turbidity, solids, ammonia, nitrate + nitrite, TKN, TN, ortho-phosphorus, and total phosphorus. All water quality samples were taken from the cistern for analysis. The cistern was used because that is the point of discharge to adjacent waters.

The green roof at the University of Central Florida is located on the student union building at the main campus. The green roof used the expanded clay growing media mix and is 1600 square feet. A control roof of the same size was also monitored for a basis of comparison. The green roof was irrigated twice a week using the regular irrigation volume of 1 inch per week. If it rained more than one half inch the previous day, no irrigation was done. A 1500 gallon cistern was used to both create an anoxic zone as well as collect green roof filtrate for irrigation.

The experimental chambers were 16 square feet with two constructed exactly the same as the green roof on the student union building and two control chambers constructed the same as the control roof on the student union building. Each of the eighteen chambers, with the exception of the control chambers, had a 50 gallon cistern for the storage of green roof filtrate which was used as irrigation water. The other chambers were constructed as follows: two the same as the green roof but used over irrigation, four with the expanded clay growing media and no plants, two of which had over irrigation and two regular irrigation, four with the Black & Gold™ growing media and plants, two of which had over irrigation while the other two used regular irrigation, four with the Black & Gold™ growing media and no plants, two of which had over irrigation while the other two had regular irrigation (see figure 1).

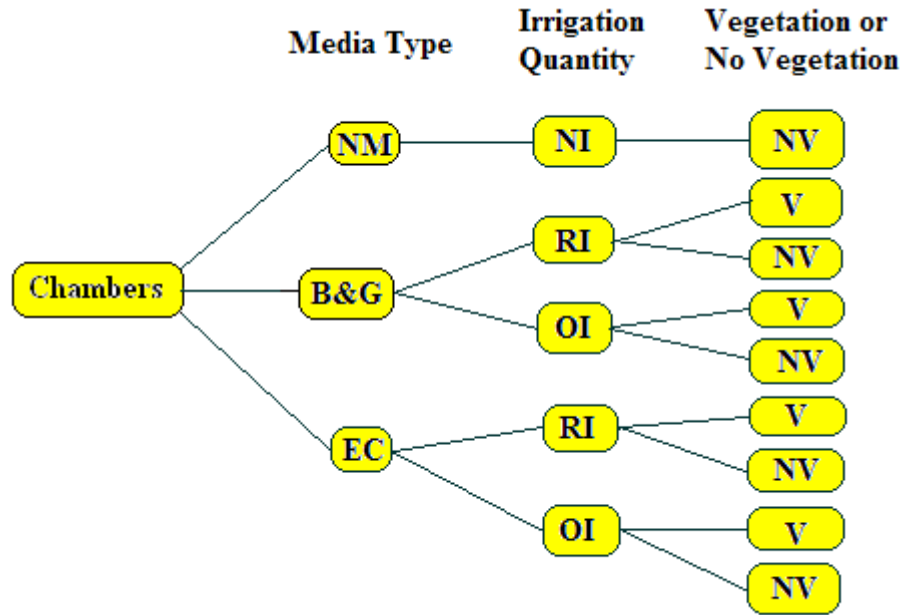


Figure 1: Experiment Design

Where:

NM = No Media

B&G = Black & Gold™ growing media mix

EC = Expanded Clay growing media mix

RI = Regular Irrigation

V = Vegetation

NV = No Vegetation

NI = No Irrigation

OI = Over Irrigation

Results

The green roof stormwater treatment system water quality focused on the removal of nitrogen and phosphorus species. Other water quality parameters were studied but are not presented in this work. For more water quality information see Hardin (2006). The total suspended solids concentration was studied during this project, but detailed analysis will not be presented in this work. The average total suspended solids concentration of the green roof chambers and control chambers were 17.3 mg/L and 23.9 mg/L, respectively and the standard deviation was 15.7 mg/L and 28.7 mg/L respectively.

The results of the ortho-phosphorus analysis show that, while there is no visible difference between the control chambers and the Black & Gold™ growing media chambers, the Black & Gold™ growing media chambers have a lower concentration of ortho-phosphorus than the expanded clay growing media chambers (see Figure 2). The results for total phosphorus are similar to that of ortho-phosphorus so will not be presented.

The results of the nitrate analysis show that, when compared to the control chambers, all the green roof vegetated chambers did not significantly reduce the nitrate concentration (see Figure 3). The results of the ammonia analysis show similar results and will therefore not be presented. The TKN and the total nitrogen results were similar showing no clear visual trend, but it should be noted that the control chamber concentration was lower than all the other chambers. This can be seen in the total nitrogen concentration graph shown in Figure 4.

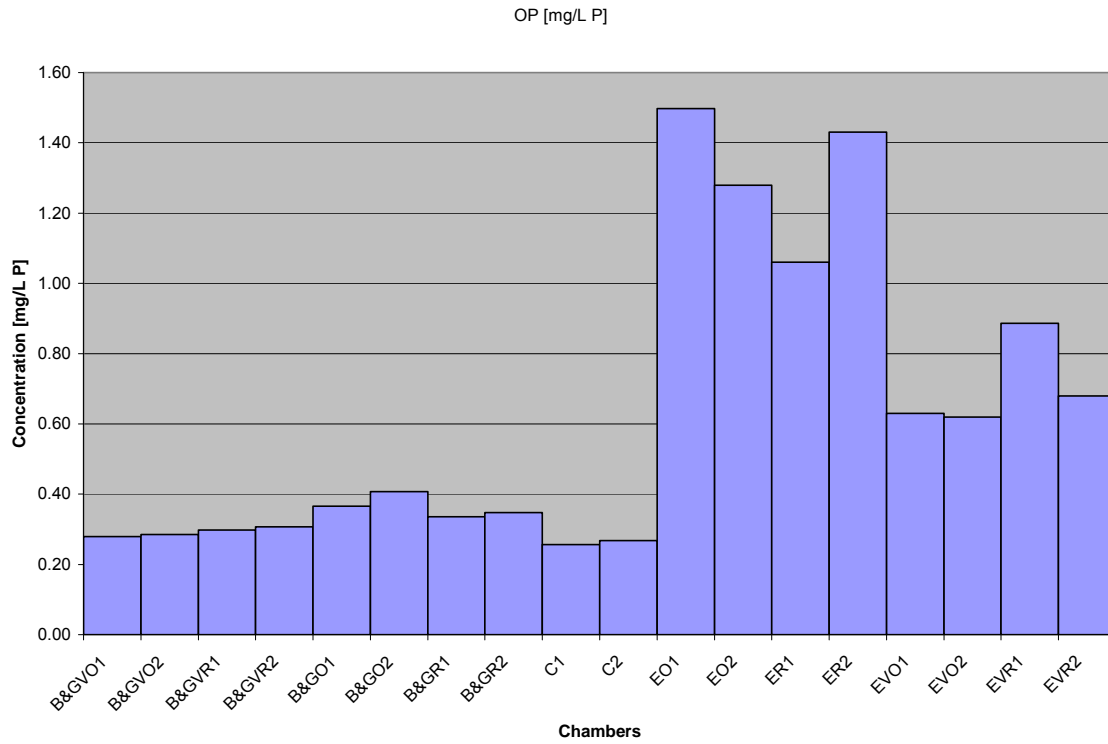


Figure 2: Ortho-Phosphorus Concentration Comparison. Source: Hardin 2006

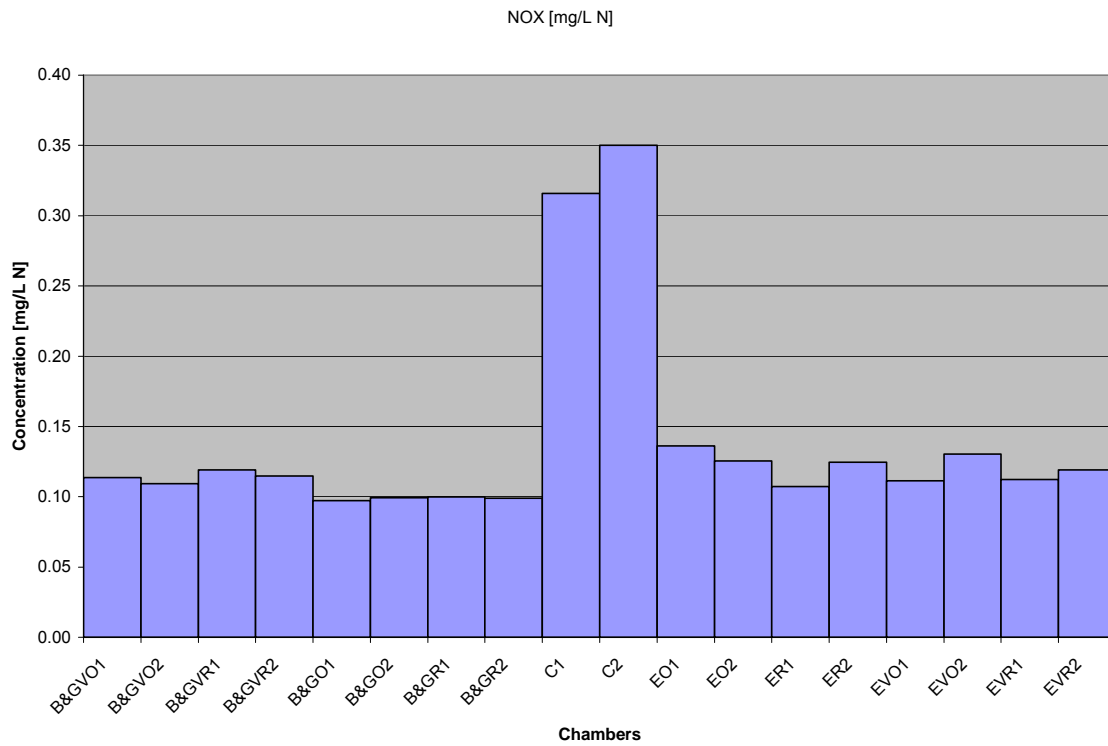


Figure 3: Nitrate Concentration Comparison. Source: Hardin 2006

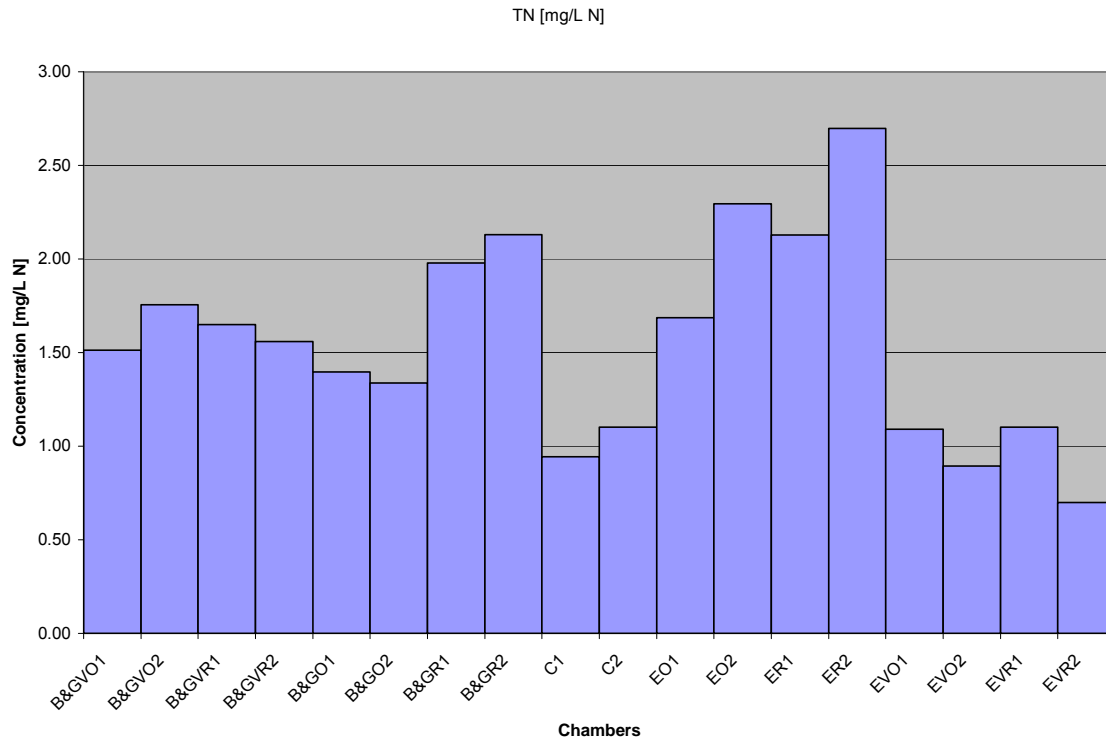


Figure 4: Total Nitrogen Concentration Comparison. Source: Hardin 2006

Hypothesis testing was performed to determine the affect of irrigation volume, growing media selection, and plant use on water quality. The results of the total and ortho-phosphorus hypothesis testing show that irrigation volume has no significant affect on both total and ortho-phosphorus concentrations, $\alpha = 0.05$ (see Table 1). The hypothesis tests show that the use of vegetation and the use of the Black & Gold™ growing media significantly reduces the concentration of both total and ortho-phosphorus, $\alpha = 0.05$ (see Table 1). The total phosphorus concentration, when compared to the control chambers, was significantly higher, $\alpha = 0.05$, for all chambers. The ortho-phosphorus concentration was higher for all chambers when compared to the control chambers, except there was no difference for the Black & Gold™ growing media

chambers, $\alpha = 0.05$ (see Table 1). Due to the similarity of the total and ortho-phosphorus results, only the ortho-phosphorus hypothesis tests are presented (see Table 1).

The results of the nitrate and ammonia hypothesis tests show that the irrigation volume, plant use, and media selection had no significant affect on both nitrate and ammonia concentrations, $\alpha = 0.05$ (see Table 2). The hypothesis test results comparing both the vegetated and non-vegetated chambers to the control chambers showed that the concentration of both nitrate and ammonia were significantly lower for the green roof chambers, $\alpha = 0.05$ (see Table 2). Due to the similarity of the nitrate and ammonia hypothesis test results, only the nitrate hypothesis tests are presented (see Table 2).

The results of the TKN and total nitrogen hypothesis tests show that the irrigation volume and media selection had no significant affect on both TKN and total nitrogen concentration, $\alpha = 0.05$ (see Table 3). The hypothesis test comparing vegetation verses non-vegetation show that when using the expanded clay mix vegetation significantly reduces the concentration of both TKN and total nitrogen, but when using the Black & GoldTM growing media vegetation makes no significant difference in the TKN and total nitrogen concentrations, $\alpha = 0.05$ (see Table 3). The hypothesis tests comparing the vegetated chambers to the control chambers shows that there is no significant difference in both TKN and total nitrogen concentrations, $\alpha = 0.05$ (see Table 3). The hypothesis tests comparing the non-vegetated chambers to the control chambers show that the chambers without vegetation significantly increase the concentrations of both TKN and total nitrogen, $\alpha = 0.05$ (see Table 3). Due to the similarity of the results for both the TKN hypothesis tests and the total nitrogen tests only the total nitrogen results are presented in this work (see Table 3).

Water quality analysis was also performed on a mass basis. Hardin and Wanielista, 2007 showed that an irrigated green roof in Central Florida will reduce the peak flow by a factor of 0.5 for a one inch, ten minute duration storm event. They further showed that irrigated green roofs will reduce the runoff by about 43% and if a cistern is used a reduction of 87% can be expected for the year. The mass reduction analysis is based on the aforementioned work.

The results of the mass comparison show that a green roof stormwater treatment system is effective at reducing the mass of both total and ortho-phosphorus by as much as 83% and 84% respectively (see Figure 5). Due to the similarity of the results for total and ortho-phosphorus mass comparison, only the ortho-phosphorus mass comparison graph is presented in this work. The mass removal efficiencies for ammonia and nitrate are as much as 98% (see Figure 6). Again, only the nitrate mass comparison graph is presented due to the similarity of the results. The results of the mass comparison for TKN and total nitrogen show that green roof stormwater treatment systems remove as much as 93% and 95% respectively (see Figure 7). Only the total nitrogen mass comparison graph is presented in this work due to the similarity of the results.

Table 1: Ortho-Phosphorus Hypothesis Test Results. Source: Hardin 2006

OP Hypothesis Tests

- H₀₁ Media and vegetation are held constant, OP Concentration for Over irrigation = OP Concentration for Regular irrigation
- H_{a1} Media and vegetation are held constant, OP Concentration for Over irrigation < OP Concentration for Regular irrigation
- H₀₂ Media and irrigation rates are held constant, OP Concentration for Vegetated boxes = OP Concentration for Non Vegetated boxes
- H_{a2} Media and irrigation rates are held constant, OP Concentration for Vegetated boxes < OP Concentration for Non Vegetated boxes
- H₀₃ Irrigation rates and vegetation are held constant, OP Concentration for Black & Gold = OP Concentration for Expanded Clay
- H_{a3} Irrigation rates and vegetation are held constant, OP Concentration for Black & Gold < OP Concentration for Expanded Clay
- H₀₄ OP for a vegetated box = OP for a control box
- H_{a4} OP for a vegetated box > OP for a control box
- H₀₅ OP for a non-vegetated box = OP for a control box
- H_{a5} OP for a non-vegetated box > OP for a control box

$\alpha = 0.05$ $z_\alpha = 1.645$ $-z_\alpha = -1.645$

Note: R = Reject H₀ & A = Accept H₀

	TVO1	TVO2	TVR1	TVR2	TO1	TO2	C1	C2	TR1	TR2	EO1	EO2	ER1	ER2	EVO1	EVO2	EVR1	EVR2
Average	0.28	0.28	0.30	0.31	0.37	0.41	0.26	0.27	0.34	0.35	1.50	1.28	1.06	1.43	0.63	0.62	0.89	0.68
Stand. Dev.	0.21	0.23	0.14	0.19	0.16	0.15	0.18	0.35	0.11	0.12	0.77	0.80	0.64	1.02	0.58	0.58	0.66	0.54
Var	0.04	0.05	0.02	0.03	0.03	0.02	0.03	0.13	0.01	0.01	0.59	0.65	0.41	1.04	0.34	0.33	0.43	0.29
n	32	32	32	32	30	30	21	22	30	30	32	32	28	28	38	38	37	37
z ₁	-0.417	-0.419			0.862	1.748					2.415	-0.635			-1.783	-0.460		
H ₀₁	A	A			A	R					R	A			R	A		
z ₂	-1.863	-2.493	-1.207	-1.023											-5.250	-3.870	-1.073	-3.554
H ₀₂	R	R	A	A											R	R	A	R
z ₃	-3.462	-3.277	-5.323	-3.962	-8.162	-6.015			-5.925	-5.601								
H ₀₃	R	R	R	R	R	R			R	R								
z ₄	0.422	0.196	0.888	0.471											3.648	2.922	5.475	3.542
H ₀₄	A	A	A	A											R	R	R	R
z ₅					2.241	1.737			1.774	1.004	8.790	6.278	6.336	5.626				
H ₀₅					R	R			R	A	R	R	R	R				

Table 2: Nitrate Hypothesis Test Results. Source: Hardin 2006

NOx Hypothesis Tests

- H₀₁ Media and vegetation are held constant, NOx Concentration for Over irrigation = NOx Concentration for Regular irrigation
- H_{a1} Media and vegetation are held constant, NOx Concentration for Over irrigation < NOx Concentration for Regular irrigation
- H₀₂ Media and irrigation rates are held constant, NOx Concentration for Vegetated boxes = NOx Concentration for Non Vegetated boxes
- H_{a2} Media and irrigation rates are held constant, NOx Concentration for Vegetated boxes < NOx Concentration for Non Vegetated boxes
- H₀₃ Irrigation rates and vegetation are held constant, NOx Concentration for Black & Gold = NOx Concentration for Expanded Clay
- H_{a3} Irrigation rates and vegetation are held constant, NOx Concentration for Black & Gold < NOx Concentration for Expanded Clay
- H₀₄ NOx for a vegetated box = NOx for a control box
- H_{a4} NOx for a vegetated box < NOx for a control box
- H₀₅ NOx for a non-vegetated box = NOx for a control box
- H_{a5} NOx for a non-vegetated box < NOx for a control box

$\alpha = 0.05$ $z_{\alpha} = 1.645$ $-z_{\alpha} = -1.645$

Note: R = Reject H₀ & A = Accept H₀

	TVO1	TVO2	TVR1	TVR2	TO1	TO2	C1	C2	TR1	TR2	EO1	EO2	ER1	ER2	EVO1	EVO2	EVR1	EVR2
Average	0.11	0.11	0.12	0.11	0.10	0.10	0.32	0.35	0.10	0.10	0.14	0.13	0.11	0.12	0.11	0.13	0.11	0.12
Stand. Dev.	0.06	0.05	0.05	0.05	0.04	0.04	0.24	0.29	0.04	0.03	0.10	0.09	0.04	0.08	0.05	0.09	0.03	0.03
Var	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.09	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.00	0.00
n	37	37	35	36	34	36	28	28	37	36	37	38	33	35	42	42	36	35
z ₁	-0.414	-0.473			-0.288	0.035					1.580	0.049			-0.111	0.772		
H ₀₁	A	A			A	A					A	A			A	A		
z ₂	1.437	0.951	1.807	1.586											-1.351	0.239	0.558	-0.386
H ₀₂	A	A	R	A											A	A	A	A
z ₃	0.204	-1.317	0.674	-0.441	-2.172	-1.683			-0.799	-1.796								
H ₀₃	A	A	A	A	R	R			A	R								
z ₄	-4.362	-4.294	-4.266	-4.194											-4.457	-3.852	-4.463	-4.149
H ₀₄	R	R	R	R											R	R	R	R
z ₅					-4.785	-4.497			-4.725	-4.509	-3.715	-3.921	-4.551	-3.957				
H ₀₅					R	R			R	R	R	R	R	R				

Table 3: Total Nitrogen Hypothesis Test Results. Source: Hardin 2006

TN Hypothesis Tests

- H_{O1} Media and vegetation are held constant, TN Concentration for Over irrigation = TN Concentration for Regular irrigation
- H_{a1} Media and vegetation are held constant, TN Concentration for Over irrigation < TN Concentration for Regular irrigation
- H_{O2} Media and irrigation rates are held constant, TN Concentration for Vegetated boxes = TN Concentration for Non Vegetated boxes
- H_{a2} Media and irrigation rates are held constant, TN Concentration for Vegetated boxes < TN Concentration for Non Vegetated boxes
- H_{O3} Irrigation rates and vegetation are held constant, TN Concentration for Black & Gold = TN Concentration for Expanded Clay
- H_{a3} Irrigation rates and vegetation are held constant, TN Concentration for Black & Gold < TN Concentration for Expanded Clay
- H_{O4} TN for a vegetated box = TN for a control box
- H_{a4} TN for a vegetated box > TN for a control box
- H_{O5} TN for a non-vegetated box = TN for a control box
- H_{a5} TN for a non-vegetated box > TN for a control box

$\alpha = 0.05 \quad z_{\alpha} = 1.645 \quad -z_{\alpha} = -1.645$

Note: R = Reject H₀ & A = Accept H₀

	TVO1	TVO2	TVR1	TVR2	TO1	TO2	C1	C2	TR1	TR2	EO1	EO2	ER1	ER2	EVO1	EVO2	EVR1	EVR2
Average	1.51	1.75	1.65	1.56	1.40	1.34	0.94	1.10	1.98	2.13	1.69	2.29	2.13	2.70	1.09	0.89	1.10	0.70
Stand. Dev.	0.73	1.17	0.88	0.84	0.46	0.47	0.21	0.50	0.52	0.73	0.73	1.47	1.11	1.39	0.68	0.46	0.69	0.34
Var	0.54	1.36	0.77	0.70	0.21	0.22	0.05	0.25	0.27	0.54	0.53	2.15	1.24	1.95	0.46	0.22	0.48	0.11
n	6.00	6.00	4.00	4.00	5.00	6.00	9.00	9.00	5.00	5.00	6.00	7.00	5.00	3.00	13.00	13.00	11.00	11.00
z ₁	-0.257	0.308			-1.874	-2.082					-0.761	-0.412			-0.044	1.189		
H _{O1}	A	A			R	R					A	A			A	A		
z ₂	0.321	0.813	-0.664	-1.073											-1.698	-2.462	-1.897	-2.462
H _{O2}	A	A	A	A											R	R	R	R
z ₃	1.195	1.745	1.127	2.000	-0.807	-1.632			-0.271	-0.653								
H _{O3}	A	R	A	R	A	A			A	A								
z ₄	1.849	1.296	1.589	1.018											0.724	-0.985	0.720	-2.065
H _{O4}	R	A	A	A											A	A	A	R
z ₅					2.089	0.927			4.227	2.796	2.437	2.063	2.349	1.941				
H _{O5}					R	A			R	R	R	R	R	R				

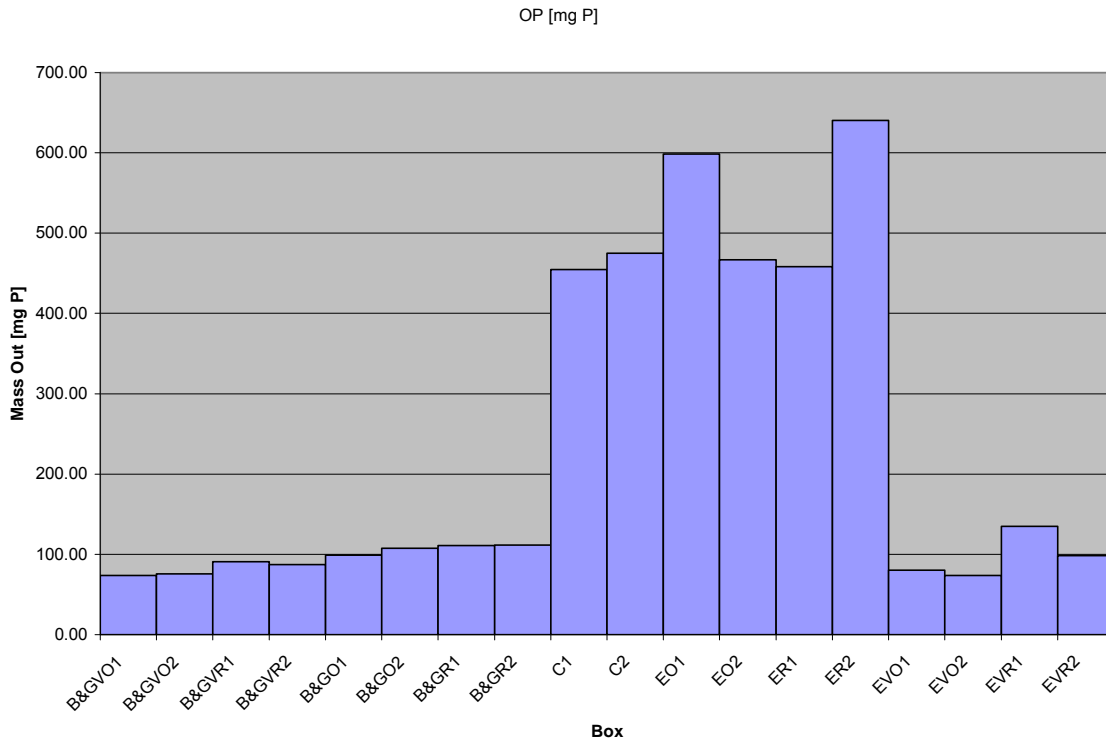


Figure 5: Ortho-Phosphorus Mass Comparison. Source: Hardin 2006

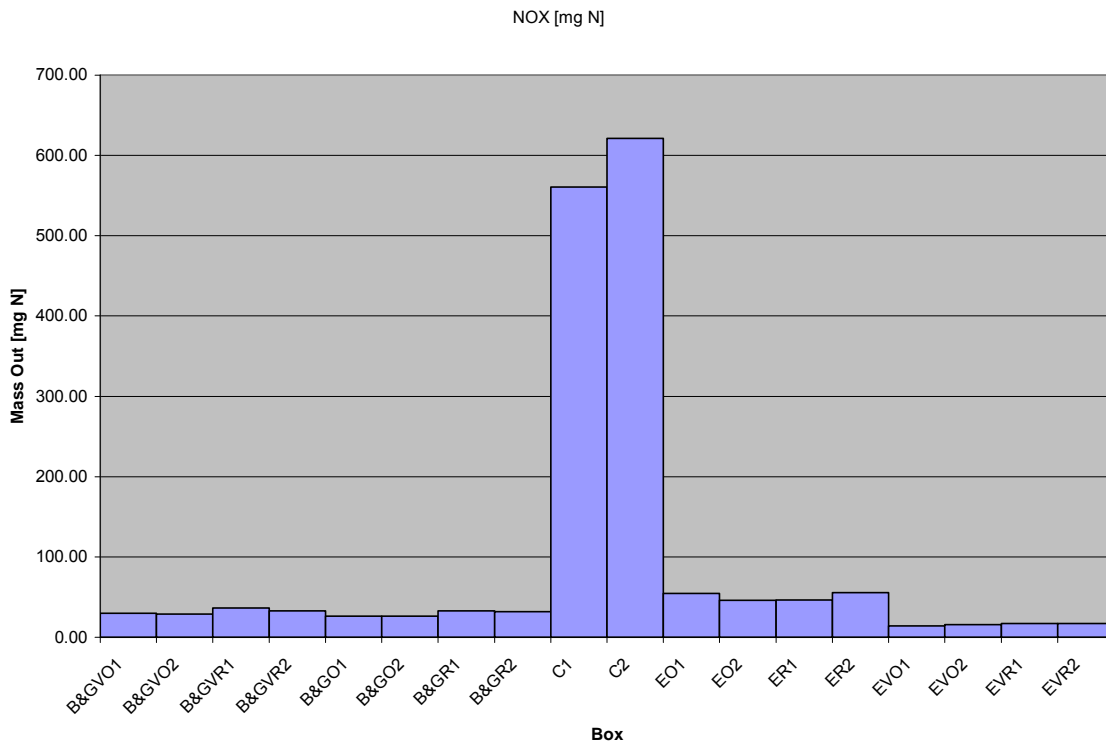


Figure 6: Nitrate Mass Comparison. Source: Hardin 2006

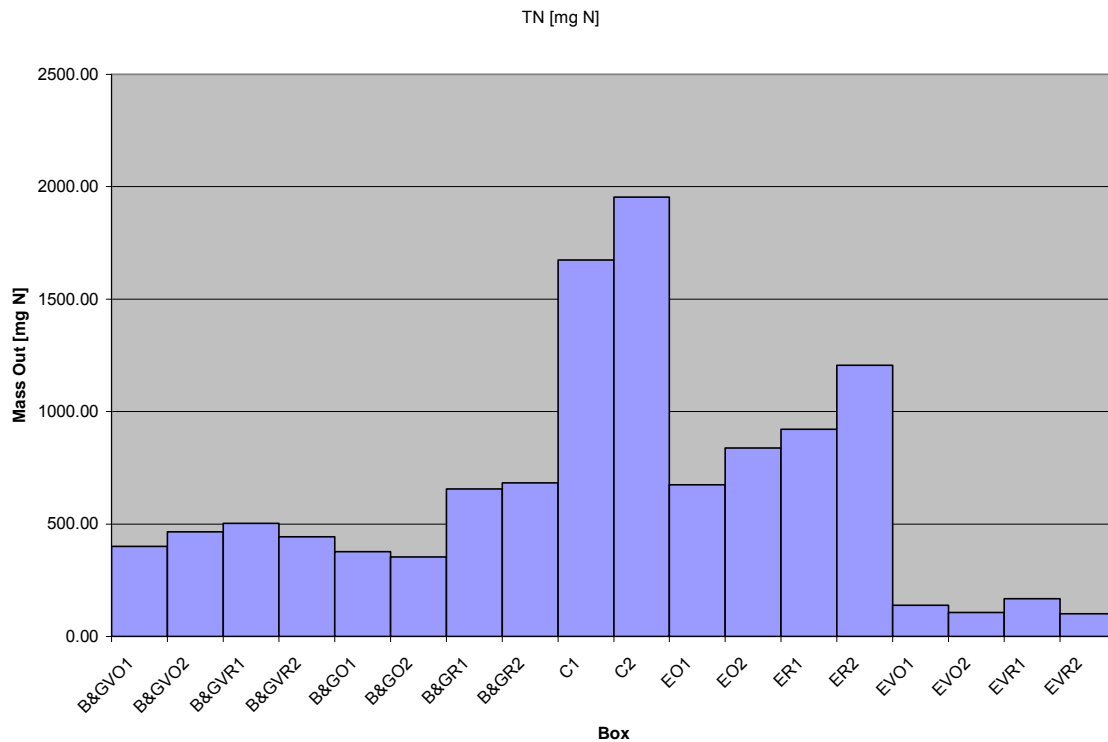


Figure 7: Total Nitrogen Mass Comparison. Source: Hardin 2006

Conclusions

The results of this work show that the use of green roof stormwater treatment systems for the improvement of stormwater quality is a promising treatment option. The total suspended solids results presented show that green roofs had a lower concentration and smaller standard deviation than the control chambers.

The data show that, for the design used in this experiment, green roofs without a pollution control media do not reduce the concentrations of total and ortho-phosphorus. The total and ortho-phosphorus concentrations were actually higher for the green roof chambers when compared to the control chambers.

For ortho-phosphorus concentrations in the Black & Gold™ growing media , there were no significant differences from the control chambers concentrations. It should be noted that the use of vegetation and the Black & Gold™ growing media did significantly reduce the concentrations of both total and ortho-phosphorus when compared to the non-vegetated chambers and the expanded clay chambers.

On a mass basis there was a significant reduction in both total and ortho-phosphorus when compared to the control chambers, as much as 83% and 84% respectively. This shows that green roof stormwater treatment systems can be used for the removal of both total and ortho-phosphorus mass to help meet local total maximum daily load (TMDL) standards.

The results of the nitrate and ammonia analysis show that the irrigation volume, growing media selection, and use of plants had no significant effect on the concentration of either parameter. The green roof stormwater treatment system is effective at significantly reducing the concentrations of both nitrate and ammonia when compared to the control chambers. The mass reduction achieved by this system for both nitrate and ammonia is as much as 98% showing great potential to help meet TMDL standards.

The TKN and total nitrogen analysis show that irrigation volume and media selection have no significant affect on the concentrations of these parameters. The use of vegetation, when compared to non-vegetation, did significantly lower the concentrations of both TKN and total nitrogen when using the expanded clay growing media. This is presumed to be due to the fact that the expanded clay growing media supported more vibrant plant growth. It is for this reason that the authors suggest using the Black & Gold™ media as a pollution control layer under the expanded clay growing media. The

TKN and total nitrogen results further show that when compared to the control chambers the vegetated green roof chambers are not significantly different while the non-vegetated chambers significantly increase the concentrations of both parameters. When comparing the green roof chambers to the control chambers on a mass basis it can be seen that the mass leaving the green roof chambers is significantly lower than the control chambers. As was shown for the previously mentioned water quality parameters, this mass reduction will help designers meet TMDL standards.

Based on the results of this work the optimal design of a green roof stormwater treatment system to achieve the best water quality is to use vegetation, use a cistern to store and reuse water for irrigation, and use a layer of the Black & Gold™ media under the expanded clay growing media. The use of vegetation will help reduce total phosphorus, ortho-phosphorus, TKN, and total nitrogen concentrations. The use of the Black & Gold™ media will help reduce both total and ortho-phosphorus concentrations while the layer of expanded clay growing media on top will promote vigorous plant growth. The use of the cistern will promote denitrification and greatly reduce the volume of runoff leaving the system, thus reducing the mass of all pollutants leaving the system. The use of this design will promote healthy plant growth while maintaining better water quality of the stormwater runoff.

Recommendations for Future Work

Throughout the course of this work several areas of further research were identified. First, more research is needed to quantify the cistern environment.

Parameters such as dissolved oxygen levels, biological oxygen demand, and the bacterial communities present will give designers a better idea of how the cistern should be maintained for water quality purposes. Also, the Black & Gold™ media should be examined further for its potential to adsorb phosphorus. Isotherm analysis should also be performed to determine the effective life of this pollution control layer as well as whether or not the vegetation will help maintain the pollution control layer.

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