Stormwater Runoff Reduction on the Worcester Polytechnic Institute Campus

Massachusetts Water Resource Outreach Center
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Abstract

Stormwater from Worcester Polytechnic Institute (WPI) drains directly into nearby Salisbury Pond, contributing to its chronic pollution. For our project, we worked with WPI Facilities to develop a plan to more effectively manage stormwater runoff in one area of campus. We assessed WPI's current stormwater management practices, investigated existing solutions, and detailed which solution was most feasible for WPI. We found that a combined stone swale and rain garden would best serve our campus' needs by reducing or eliminating frequent flooding in the center of campus and simultaneously reducing the quantity of stormwater entering Salisbury Pond through storm sewers. In collaboration with WPI's Office of Sustainability, we submitted our proposal to the US EPA's RainWorks Challenge.

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Supplementary Materials

Appendix A: Compiled Interview Matrix

			Rain Gardens				Bioswales				Rain Barrels				Permeable Pavers/Pervious Pavement				Cistern				
Interviewee	Organization	General Information	General	Pros/Successes	Cons/Failures	Cost	General	Pros/Successes	Cons/Failures	Cost	General	Pros/Successes	Cons/Failures	Cost	General	Pros/Successes	Cons/Failures	Cost	General	Pros/Successes	Cons/Failures	Cost	Social Aspect
Bill Spratt	Office of Sustainability	Pipe Maintenance: Light, cleaning and root cutting Erosion: Signnificant behind Ellsworth apartments Erosion Damange $3000-$5000 yearly Flooding: First Baptist Church, Edges of Quad, Higgins field, Higgins window wells, Founders basement stairs, Harrington roof corners Desired irrigation: East with stormwater	Drainage problem areas, Behind alden, Between AK and fuller Gets very flooded, Corners of Harrington when wells overflow			NA	Bioswale by Higgins House. Signage and fencing. Possible Locations: Areas that head to main road, West st. and alden, Corner of library driveway	Catch water before it enters MS4, stops students from walking on grass		NA				NA	Possible locations: Around Quad, Founders basement steps, Alden loading dock, Rec center loading dock	Quad could use better pavement	Hard to maintain Doesn't work awesome, not a huge fan	NA	2 25,000 gal cisterns under quad, Could use cisterns to water quad, All irrigation currently with city water, Rainwater from Harrington could be collected better, Quad buildings could use existing cisterns, these buildings collect simultaneously, cisterns could overflow. The Black pipes are the diffusers	No added chemicals, Cleaned by using water, refilling with fresh water		NA	
Chris Stone	CT DEEP		Need to just let it grow aesthetically nicer Rain garden is more contained than a swale, easier to put signage around Flashier than swale		Hard to educat Facilities	Minimal	Need to let it grow		Hard to educate facilities	Minimal						Worthwhile		Expensive					Highlight educational benefit to university Signage Tour groups
Dan Sarachick	Office of Sustainability EHS	Project will be in addition to MS4 and City of Worcester permits, so it is technically eligible for the 319 grant																					
Ed Himlan	MA Watershed Coalition	Also look into tree box filters (simple, maintainable, compact, but extensive), ground cover buffers (grass or native, inexpensive, like rain garden, not as aesthetically pleasing), baffle boxes, and infiltration basins - any BMP can be successful if it is designed well. Most common problem is design oversights	Maintenance is big factor, depends on the plants you put in				helps move water from one place to next, can be combined with rain garden																
Martha Morgan	Nashua River Watershed Association	neglected bmps will always fail	sediment needs to be routinly cleaned out																				
Elisabeth Cianciola	Charles River Watershed Association		3 Bio rention systems installed	succesfull is removing phosporous	inconsitent from storm to storm	NA	Green Street in Watertown implemented 4 bioswales			NA	Widespread adoption because public water usage restrictions, inserted into schools to water small gardens	Easy installation		NA	worked better than expected, drained into combined sewer overflow, small and well placed = best	65% reduction on phosphorus loads, continued to perform even when not properly maintained	over time will be like more traditional asphalt only lasts 10 years in ideal conditions	NA	public schools implemented a custern: unused, just educational, Boston College built rainwater storage tanks also unused. both because boston water and sewer commission requires a reduction in phosphorus put into charles river			NA	For green street, Open house discussion, Well-attended, Update meeting was not well-attended, Once plans are set, people care less, Big developers meet minimum requirements, they don't want to do more
David Harris and Jaquelyn Burmeister	City of Worcester DPW	City of Worester has implemented several types of BMPs, most commonly hydrodynamic separators and tree box filters. There are plans for other projects surrounding Salisbury Pond in the near future. Friends of Salisbuy Pond may be interested in a collaboration. For all BMPs, maintenance is key.	Worcester has a rain garden next to a softball field	Little maintenance involved generally - depends on how you want it to look		Most affordable way to go					There are many, many rain barrels implemented in Worcester				Have to be swept every year. Hard to maintain, but vacuum trucks may not be that expensive								
Justin Dufrense	VHB	Architects:rec center-Cannon; Field and Garage- SMMA	Most use an overflow drain and an underflow drain to collect water, top mix is hardwood mulch, then a boretention soil followed by a pea-stone and then a crushed stone where the underflow pipe is located. Bioretention soil is about 2-3 ft deep	Is able to trap sediment well before it gets to the rain garden also tyoically has an underdrain to prevent standing water	Has to be maintained to all for sediment to continue to be trapped	Expensive if you do overflow and underflow piping. these can cost almost $50,000 or more	Most use an overflow drain and an underflow drain to collect water, top mix is hardwood mulch, then a boretention soil followed by a pea-stone and then a crushed stone where the underflow pipe is located. Bioretention soil is about 2-3 ft deep	Is able to trap sediment well before it gets to the bioswale it often has to an underdrain to help remove standing water	Has to be maintained to all for sediment to continue to be trapped	Expensive if you do overflow and underflow piping. these can cost almost $50,000 or more													
Malcolm Harper	MA DEP	Maintenance, will to maintain Get dig safe, have backup sites, check soil types for permeability Major sources of pollutants are streets roofs walkways, our goal is to remove it before it enters a waterway		Removes a lot of sediment, nutrients and bacteria		for 1/4 acre impervious drainage area: insallation - $4,775, design/permitting - $1,000, yearly maintenance - $250				for 1 acre imperivoius drainage area: installation - $19,383, design/permitting - $3,000, yearly maintenance - $500					Worcester would need to get a Vacuum Truck, agree to let WPI borrow it twice a year	Can be cheap if we have a vacum truck	expensive, they are expenisve initially - installation (porous asphalt: $3-5, pervious concrete/porous: $5-10)						
Mike Dietz	CT NEMO (UConn)	Start small retro fitting is hard			If the get filled with mulch then theres no storage	175 sqft was only $400 for plants alone, mulch was provided by the university	If attemoting to retrofit start with rain garden or small bioswale	redirect roof rainfall and gather it in a small rain garden tangible stormwater reduction	directing water from a parking lot will often cause a change in the grade of the lot to get proper flow	NA	Rain barrel can be implemented off of a small building		Large systems cost more money and have to be underground or the will freeze and crack in winter	NA		Feasable in small area like sidewalk	need heavy equipment problems with out big machinerary, can become clogged without proper vacuming	Big money for big projects, $12/sqft					
Stacy Pappano	CT DEEP	"The most important part of an LID project is finding a contractor who knows what they need to do" (Doesn't destroy things). Best to take water and divert it to a place where it can be used as a resource	Plants Restrictions on which could be planted by Historic Council		Poor soil reduces drainage "Looks horrible", Maintainers need to be aware. Water sits for about a day before dissipating		Needed to slow water so it didn't just flush right out, Substrate is important for good drainage			Didn't cost that much					Commonly used, high traffic prevents grass growing	Easy, successfully reduced flooding & icing, Lasts a good amount of time	Needs good subsrate, otherwise sand will fill voids, Need good contractor for substrate	low cost, More reasonable to buy them	There is a pump Works well, No problems with it	Low maintenance, not many problems			
Stefanie Covino	MA Audubon			Low tech, most effective	Often built without consideration of maintenance	$2-12 /SF (Depends on types of plants), Leave budget money for signage	similar to rain gardens, Poor Farm Brook	Great for catching runoff	Often built without consideration of maintenance			small, simple, great for hand watered areas		$100 per barrel 50 gal (possibly cheaper through the city)		Less maintenance than pervious pavement, better stopping factor	Careful plowing	$10-$12 per sqft				Above ground is much cheaper	Use signage to educate community
Al Carlsen	Office of Sustainability	We need to check soil quality the quality of soil would be the most expensive part to remove and add new soil	Would be more expensive harder to implement				A overfill drain is a must for when a heavy storm comes you dont want to over fill and run over the burm.								Possible infront of the campus center but not ideal because of the location of the mail room roof								Signage is important to educate the people on why the system is there and what the system can do
Roger Griffin	Office of Sustainability																		Cisterns are located under the quad near the rec center, two tanks 25000 gallons each		Hard to measure the capacity available in each cistern		
Kelly Freda	MA Department of Water Supply	everything is in an email such as PDF booklets	Great for a small, but beneficial project	If you have good soil, you can minimize costs easily	if no berms, there may be a heavy sand build up																		Around Wachusett Reservoir there are also several detention and retention centers, as well as a gravel wetland

The above matrix summarizes the results of our interviews with experts in BMP implementation. The matrix is organized by expert and opinion on specific BMPs.

Appendix B: Best Management Practices at US Colleges and Universities

The table below shows which BMPs have been proposed or implemented at various colleges and universities across the United States.

Best Management Practice	Implemented or Proposed Location
Artificial Wetland	University of New Mexico, University of Vermont
Bioswale	University of Cincinnati, East Georgia State College, City College of New York, Chabot-Las Positas Community College
Cistern	East Georgia State College, City College of New York, Northeastern, California Polytechnic State University, Chabot-Las Positas Community College, Oregon Health and Sciences University, Texas A&M, University of New Mexico, Southern Illinois University - Carbondale, Kansas State University, Yale University
Detention Cell	Chabot-Las Positas Community College, Northeastern University, Kansas State University
Green Facade	University of Cincinnati, East Georgia State College, University of New Mexico
Green Roof	City College of New York, Worcester Polytechnic Institute, California Polytechnic State University, Oregon Health and Sciences University, Boston University
Habitat Creation	University of New Mexico
Hydrodynamic Separators	Northeastern University
Permeable Pavers	University of Cincinnati, East Georgia State College, Worcester Polytechnic Institute, California Polytechnic State University, Texas A&M, Southern Illinois University, University of Vermont
Pervious Pavement	University of Cincinnati, East Georgia State College, Worcester Polytechnic Institute, California Polytechnic State University, Texas A&M, Southern Illinois University, University of Vermont
Rain Garden	University of Cincinnati, East Georgia State College, Northeastern, California Polytechnic State University, Chabot-Las Positas Community College, Oregon Health and Sciences University, University of New Mexico, Yale University
Riparian Buffer System	Texas A&M
Soil Amendment	East Georgia State College
Tree Box Filter	Northeastern University, Worcester Polytechnic Institute, California Polytechnic State University

(M. Clark, Sustainability Manager, University of New Mexico, personal communication, March 16, 2018; J. Lens, University of Vermont, personal communication, March 16, 2018; Kusnier, 2016; D. Chevalier, East Georgia State College, personal communication, March 18, 2018; Bugala, 2016; Corey, 2011; Nelson, 2017; Paz, 2010; Wittenbrink, 2008a; Prakash, n.d.; E. Zechman Berglund, Texas A&M, personal communication, March 16, 2018; Peterein, n.d.; McDonough, 2016; Yale University, 2017; Houyou, 2014; Wang, 2009; Marsh, 2015; Boston University, 2017)

Appendix C: Analysis of BMPs against Necessary Criteria

Solution	Implementation Affordability Score	Maintenance Affordability Score	Environmental Benefit Score	Financial Return Score	Applicability Score	Ease of Installation Score	Aesthetic Appearance Score	Does WPI have Space Required?	Overall Score
Rain Garden	High	Medium	High	Low	High	Medium	High	Yes	17
Rain Barrels	High	High	Low	Medium	High	Medium	Medium	Yes	16
Bioswale	Medium	High	Medium	Low	High	Medium	Medium	Yes	15
Pervious Pavement	High	Medium	High	Low	High	Medium	Low	Yes	15
Cisterns	Low	High	Medium	High	High	Low	Low	Yes	14
Habitat Creation	High	High	High	Low	Low	Low	Medium	No	14
Riparian Buffer System	High	High	High	Low	Low	Low	Medium	No	14
Artificial Wetland	High	High	High	Low	Low	Low	Low	No	13
Tree box filters	Low	Medium	Medium	Low	High	Medium	Medium	Yes	13
Detention Cell	Medium	Low	High	Low	Medium	Low	Low	No	11
Green Roof	Low	Medium	Medium	Low	Medium	Low	Medium	Yes	11
Soil Amendment	Medium	Medium	Low	Low	Medium	Low	Low	Yes	10
Green Facades	Low	Low	Low	Low	Low	Low	Medium	Yes	8
Hydrodynamic Separators	Low	Low	Medium	Low	Low	Low	Low	Yes	8

This matrix compares all BMPs that have been previously proposed or implemented at universities and colleges in the United States (see Best Management Practices at US Colleges and Universities) against our Necessary Criteria (see Findings and Conclusions). The top-scoring BMPs from this matrix were given further consideration (see Analysis of Leading Solutions). The overall score was calculated by adding 3 points for each "High" score, 2 points for each "Medium" score, and 1 point for each "Low" score

Appendix D: Analysis of Leading Solutions

Top Solutions	For	Against	Implementable Locations on Campus

Cistern	• Can reduce water demand for irrigation/non-potable water uses
	• Return on investment
	• Reduce stormwater runoff volume for small storms
	• Minimal maintenance required
		• No pollutant removal
		• Could be breeding ground for mosquitoes/algae
		• May need to be drained in winter to avoid cracking
		• Requires flat surface or in-ground placement - low ease of installation
			• Quad
			  ○ Repurpose existing or increase holding capacity
			  ○ Irrigate Quad
			• East Hall
			  ○ Irrigate courtyard

Pervious Pavement	• Reduce stormwater runoff volume from paved surfaces
	• Reduce peak discharge rates.
	• Increase recharge through infiltration.
	• Reduce pollutant transport through direct infiltration.
	• Can last for decades in cold climates if properly designed, installed, and maintained
	• Improved site landscaping benefits (grass pavers only).
	• Can be used as a retrofit when parking lots are replaced.
		• Prone to clogging so aggressive maintenance with jet washing and vacuum street sweepers is required.
		• No winter sanding is allowed.
		• Winter road salt and deicer runoff concern near drinking water supplies for both porous pavements and impervious pavements.
		• Soils need to have a permeability of at least 0.17 inches per hour.
		• Special care is needed to avoid compacting underlying parent soils.
			• Founders Basement Steps
			  ○ Reduce flooding
			• Quad boundary
			  ○ Reduce pooling

Rain Garden	• Provide excellent pollutant removal
	  ○ 80-90% of total suspended solids
	• Can be designed to provide groundwater recharge and preserves the natural water balance of the site
	• Can be designed to prevent recharge where appropriate
	• Supplies shade, absorbs noise, and provides windbreaks
	• Can remove other pollutants besides TSS including phosphorus, nitrogen and metals
	• Can be used as a stormwater retrofit by modifying existing landscape or if a parking lot is being resurfaced
	• Can be used on small lots with space constraints
	• Small rain gardens are mosquito death traps
	• Little or no hazard for amphibians or other small animals
		• Requires careful landscaping and maintenance
		• Not suitable for large drainage areas
		• Cannot contain large amounts of snow
			• Between Fuller and AK
			  ○ Reduce flooding
			• Beneath roof wells on Harrington Auditorium
			  ○ Reduce flooding and erosion
			• Behind Alden
			  ○ Reduce erosion
			• Behind Schussler lot
			  ○ Reduce erosion

Bioswale	• Provides pretreatment if used as the first part of a treatment train. • Open drainage system aids maintenance • Accepts sheet or pipe flow • Compatible with LID design measures. • Little or no entrapment hazard for amphibians or other small animals	• Short retention time does not allow for full gravity separation· • Limited biofiltration provided by grass lining.·Cannot alone achieve 80% TSS removal • Must be designed carefully to achieve low flow rates for Water Quality Volume purposes (<1.0 fps) • Mosquito control considerations	• Beside the library/Boynton driveway on ○ Reduce runoff and erosion from foot traffic • Beside West St. at Institute Rd. intersection

This matrix consists of a more in-depth analysis of the five leading BMPs identified above (see Analysis of BMPs against Necessary Criteria). The matrix compares the strengths, weaknesses, and potential locations for implementation for each BMP.

Appendix E: Analysis of BMPs at Specific Locations against Necessary Criteria

Solution	Expert Opinion on General BMP	Specifications	Social Impact Opportunities	Cost (Average)	Cost (Realized)	Implementation Cost Score (1-10), 1 = Expensive, 10 = Affordable **Exponential Scale	Maintenance over 5 Years	Maintenance over 10 Years	Maintenance over 25 Years	Average Annual Maintenance	Annual Maintenance Cost (Realized)	Maintanance Cost Score (1-10) 1 = Expensive, 10 = Affordable	Runoff Volume Affected Annually (gal)	Added Environmental Benefit (Runoff Reduction)	Added Environmental Benefit (Total Runoff Reduction, runoff reduction times volume affected)	Added Environmental Benefit Runoff Reduction Score (1 = small reduction, 10 = large reduction)	Added Environmental Benefit (Pollutant Load Reduction)	Added Environmental Benefit (Total Pollutant Load Reduction, pollutant reduction times volume affected)	Added Environmental Benefit Pollutant Load Reduction Score (1 = Small reduction, 10 = Large reduction)	Annual Costs of Existing System (including maintanance, repairs from runoff damage, irrigation costs, and other regularly occuring expenses)	Annual Costs of Proposed System (including maintanance, repairs from runoff damage, irrigation costs, and other regularly occuring expenses)	Financial Return	Financial Return Score (1-10) 1 = minimal return, 10 = maximum return	Ease of installation (1-5) 1 = Extensive Construction/Disturbance, 5 = Minimal Construction/Disturbance	Aesthetic appearance of solution (1-5) 1 = Neutral, 5 = Positive Visual Appeal	Sponsor Opinion (1-5)	Total Score
Bioswale (add by Library Driveway)	Catches water before it enters MS4, Prevents pedestrians from walking on eroding areas (Spratt 3/21) Tangable stormwater reduction, Good for retrofiting existing landscaping, but you will need to change the grade of a parking lot to properly direct water into the swale (Dietz 3/21) Great for catching runoff, Similar advantages to Rain Gardens, but often built without consideration of maintanance (Covino 3/22)	Add bioswale by library driveway to reduce erosion and runoff on hill and reduce foot traffic (150 x 15 ft, 2250 SF)	Informative signs, student involvement through installation labor, youthGROW maintanance	$0.5 /SF (*bioswales/vegetated swales*, UF, 2008); $27,383/acre=0.62/SF (Cost Catalog, MWC, 2017) AVG=$.56/SF	$1,260.00	9.54	$0.3-1.05 per sqft	$0.6-2.1 per sqft	$1.5-5.25 per sqft	$0.06-0.21 per sqft (greenvalues,nd); $500/acre (2017 - MWC) AVG= .14/sqft	315	3.08	67,460.25	88.8% (Qingfu 2009)	59,904.70	4.42	95.4% (Qingfu 2009)	64357.0785	9.14	$800.00	$315.00	$485.00	10	3	3		42.18
Rain Garden (add by Schussler lot)	Good for addressing areas where runoff causes erosion (Spratt 3/21) Successful at removing phosphorus, but inconsistant from storm to storm (Cianciola 3/20) Removes a lot of sediment, nutrients, and bacteria (Harper 3/21) Low tech, most effective BMP, but often build without considering maintanance (Covino 3/22) Good for retrofiting existing landscaping, but can get filled with mulch and become ineffective if maintained incorrectly (Dietz 3/21)	New rain garden to address erosion by lot (60 x 10 ft, 600 SF)	Informative signs, student involvement through installation labor, youthGROW maintanance	$6/SF - Cal Poly 2017; $9/SF-OHSU 2007; $75,000/acre=1.72/SF; 33,100/acre=0.75/SF (Cost Catalog, MWC, 2017); $2-12/SF(MA audubon Fact Sheet 3). AVG=4.40/SF	$2,640.00	8.06	$1467/acre	$2933/acre	$7333/acre	$250/quarter acre = 0.02/SF (2017 - MWC); 0.31-0.61/SF (Green Value) AVG=0.24/SF	144	4.02	17,989.40	90% (Mass Audubon Fact Sheet 3)	16,190.46	1.01	65-90% of nutrient, trace metal, and TSS removal (MWC V2C2 Structural BMPs)	13941.785	8.02	$800.00	$144.00	$656.00	10.43952808	4	5		40.55
Rain Garden (add by Alden)	Good for addressing areas where runoff causes erosion (Spratt 3/21) Successful at removing phosphorus, but inconsistant from storm to storm (Cianciola 3/20) Removes a lot of sediment, nutrients, and bacteria (Harper 3/21) Low tech, most effective BMP, but often build without considering maintanance (Covino 3/22) Good for retrofiting existing landscaping, but can get filled with mulch and become ineffective if maintained incorrectly (Dietz 3/21)	New rain garden to reduce erosion behind Alden and reduce runoff (75 x 10 ft, 750 SF)	Informative signs, student involvement through installation labor, youthGROW maintanance	$6/SF - Cal Poly 2017; $9/SF-OHSU 2007; $75,000/acre=1.72/SF; 33,100/acre=0.75/SF (Cost Catalog, MWC, 2017); $2-12/SF(MA audubon Fact Sheet 3). AVG=4.40/SF	$3,300.00	7.62	$1467/acre	$2933/acre	$7333/acre	$250/quarter acre (2017 - MWC); $200/year (Mass Audubon, 2016); 0.31-0.61/SF (Green Value) AVG= .24/SF	180	3.76	22,486.75	90% (Mass Audubon Fact Sheet 3)	20,238.08	1.59	65-90% of nutrient, trace metal, and TSS removal (MWC V2C2 Structural BMPs)	17427.23125	8.18	$800.00	$180.00	$620.00	10.35738714	4	5		40.50
Rain Garden (add by Fuller)	Good for addressing areas where runoff causes erosion (Spratt 3/21) Successful at removing phosphorus, but inconsistant from storm to storm (Cianciola 3/20) Removes a lot of sediment, nutrients, and bacteria (Harper 3/21) Low tech, most effective BMP, but often build without considering maintanance (Covino 3/22) Good for retrofiting existing landscaping, but can get filled with mulch and become ineffective if maintained incorrectly (Dietz 3/21)	New rain garden to reduce runoff and erosion between Fuller and AK (50 x 30 ft, 1500 SF)	Informative signs, student involvement through installation labor, youthGROW maintanance	$6/SF (Cal Poly, 2017); $9/SF (OHSU,2007); $75,000/acre=1.72/SF; 33,100/acre=0.75/SF (Cost Catalog, MWC, 2017); $2-12/SF (Mass Audubon Fact Sheet 3). AVG=4.40/SF	$6,600.00	6.23	$1467/acre	$2933/acre	$7333/acre	$250/quarter acre = 0.02/SF (2017 - MWC); 0.31-0.61/SF (Green Value) AVG=0.24/SF	360	2.92	44,973.50	90% (Mass Audubon Fact Sheet 3)	40,476.15	3.40	65-90% of nutrient, trace metal, and TSS removal (MWC V2C2 Structural BMPs)	34854.4625	8.69	$800.00	$360.00	$440.00	9.858288102	4	5		40.10
Rain Garden (add by Library Driveway)	Good for addressing areas where runoff causes erosion (Spratt 3/21) Successful at removing phosphorus, but inconsistant from storm to storm (Cianciola 3/20) Removes a lot of sediment, nutrients, and bacteria (Harper 3/21) Low tech, most effective BMP, but often build without considering maintanance (Covino 3/22) Good for retrofiting existing landscaping, but can get filled with mulch and become ineffective if maintained incorrectly (Dietz 3/21)	New rain garden to reduce erosion on hill, reduce runoff, and reduce foot traffic (150 x 15 ft, 2250 SF)	Informative signs, student involvement through installation labor, youthGROW maintanance	$6/SF - Cal Poly 2017; $9/SF (OHSU, 2007); $75,000/acre=1.72/SF; 33,100/acre=0.75/SF (Cost Catalog, MWC, 2017); $2-12/SF. AVG=4.40/SF	$9,900.00	5.42	$1467/acre	$2933/acre	$7333/acre	$250/quarter acre = 0.02/SF (2017 - MWC); 0.31-0.61/SF (Green Value) AVG=0.24/SF	540	2.43	67,459.32	90% (Mass Audubon Fact Sheet 3)	60,713.39	4.45	65-90% of nutrient, trace metal, and TSS removal (MWC V2C2 Structural BMPs)	52280.973	8.99	$800.00	$540.00	$260.00	9.092647115	4	5		39.39
Rain Barrel (East Hall/East Hall Parking Garage)	Beautify East Hall gardens through irrigation (Spratt 3/21) Widespread public adoption, Easy installation (Cianciola 3/20) Can be implemented off small and large buildings, But large systems cost more money and need to be buried to avoid freezing in winter (Dietz 3/21)	Unsure of size, but would collect stormwater off East Hall or the East Hall Parking Garage and be used to irrigate the East Hall Courtyard - for calculations sake: collection from East Hall Garage (175 x 100, 17500 SF)	Informative signs	$100 for a 50gal rain barrel(Covino 3/21); $60-100/60gal rain barrel (Boston Water and Sewer Comission, 2013); gravel pit - $500 (estim.)	$1,000.00	10.00	$0	$0	$0	0 (Green Value)	0	10.00	506,975.00	collects 100% of runoff from building	506,975.00	9.99	runoff does not have time to collection pollution so 0%	0	1.00	$0.00	$0.00	$0.00	1	5	1		37.99
Permeable pavers (add by Founders stairs)	Can work well if kept small and placed strategically where most water pools, 65% reduction in phosphorus loads, May continue to work well even if not properly maintained, But will become more like traditional asphalt over time, 10 year life (Cianciola 3/20) Might be able to get vacuum truck in partnership with Worcester, But expensive installation (Harper 3/21) Feasable in small areas, need heavy equipment for instalation and maintanance (Dietz 3/21) Permeable pavers have less maintanance than pervious pavement, Better stopping factor than traditional asphalt, But require careful plowing (Covino 3/22)	Add permeable pavers at base of Founders basement stairs to reduce chance of flooding(13 x 10 ft, 13 x 20 ft, 20 x 20 ft, 790 SF)	Informative signs	$10-13/SF (Covino 3/21); $5-10/SF (Cost Catalog, MWC, 2017). AVG=$9.50/SF	$7,505.00	5.97	$3,750	$7,500	$18,750	$.01-.23sqft (green Values, nd) $500-1000/acre (2017 MWC)AVG=.12/sqft	94.8	4.53	23,686.04	can infiltrate 70-80% of annual rainfall (Mass Audubon Fact Sheet 3)	17,764.53	1.25	up to 80% TSS removal if proper bed and drainage (MWC V2C2 Structural BMPs)	18948.83467	8.24	$0.00	$94.80	-$94.80	1	1	3		24.99
Permeable pavers (add around Quad)	Can work well if kept small and placed strategically where most water pools, 65% reduction in phosphorus loads, May continue to work well even if not properly maintained, But will become more like traditional asphalt over time, 10 year life (Cianciola 3/20) Might be able to get vacuum truck in partnership with Worcester, But expensive installation (Harper 3/21) Feasable in small areas, need heavy equipment for instalation and maintanance (Dietz 3/21) Permeable pavers have less maintanance than pervious pavement, Better stopping factor than traditional asphalt, But require careful plowing (Covino 3/22)	Add permiable pavers around edge of quad in palce of stamped concrete to reduce puddling (3 x 575 ft, 1725 SF)	Informative signs	$10-13/sq ft (Covino); $5-10/SF (Cost Catalog, MWC, 2017) - AVG=$9.50/SF	$16,387.00	4.41	$3,750	$7,500	$18,750	$.01-.23sqft (green Values, nd); $500-1000/acre (2017 MWC) AVG=.12/sqft	207	3.59	51,718.80	70-80% of annual rainfall (MA Audubon)	38,789.10	3.28	up to 80% TSS removal if proper bed and drainage (MWC V2C2 Structural BMPs)	41375.04	8.82	$0.00	$207.00	-$207.00	1	1	2		24.10
Permeable Pavement (add around Quad)	Can work well if kept small and placed strategically where most water pools, 65% reduction in phosphorus loads, May continue to work well even if not properly maintained, But will become more like traditional asphalt over time, 10 year life (Cianciola 3/20) Might be able to get vacuum truck in partnership with Worcester, But expensive installation (Harper 3/21) Feasable in small areas, need heavy equipment for instalation and maintanance (Dietz 3/21) Permeable pavers have less maintanance than pervious pavement, Better stopping factor than traditional asphalt, But require careful plowing (Covino 3/22)	Add pervious pavement around edge of quad in palce of stamped concrete to reduce puddling (15 x 575 ft, 8625 SF)	Informative signs	$9-12/SF (Covino 3/21), AVG=10.50	$90,562.50	0.99	$4000 per 1/2 acre	$10000 per 1/2 acre	$36000 per 1/2 acre	$.09-.23sqft (Green Values, nd), $500-1000/acre (2017 - MWC) AVG= .16/sqft	1780	1.00	258,594.08	can infiltrate 70-80% of annual rainfall (Mass Audubon Fact Sheet 3)	193,945.56	7.48	up to 80% TSS removal if proper bed and drainage (MWC V2C2 Structural BMPs)	206875.264	10.00	$0.00	$1,780.00	-$1,780.00	1	1	1		22.48
Permeable Pavement (add by Founders stairs)	Can work well if kept small and placed strategically where most water pools, 65% reduction in phosphorus loads, May continue to work well even if not properly maintained, But will become more like traditional asphalt over time, 10 year life (Cianciola 3/20) Might be able to get vacuum truck in partnership with Worcester, But expensive installation (Harper 3/21) Feasable in small areas, need heavy equipment for instalation and maintanance (Dietz 3/21) Permeable pavers have less maintanance than pervious pavement, Better stopping factor than traditional asphalt, But require careful plowing (Covino 3/22)	Add pervious pavement at base of Founders basement stairs to reduce chance of flooding (13 x 10 ft, 13 x 20 ft, 20 x 20 ft, 790 SF)	Informative signs	$9-12/SF(covino), AVG=10.50	$8,295.00	5.77	$4000 per 1/2 acre	$10000 per 1/2 acre	$36000 per 1/2 acre	$.09-.23sqft (Green Values, nd), $500-1000/acre (2017 - MWC) AVG= .16/sqft	526.4	2.46	23,686.04	can infiltrate 70-80% of annual rainfall (Mass Audubon Fact Sheet 3)	17,764.53	1.25	up to 80% TSS removal if proper bed and drainage (MWC V2C2 Structural BMPs)	18948.83467	8.24	$0.00	$526.40	-$526.40	1	1	1		20.73

xx

The above matrix shows the specific solutions that we investigated as potential proposals, with logarithmic quantified values for the identified Necessary Considerations of BMPs.

Appendix F: Detailed SWOT Analyses

All SWOT anslyses (Strengths Weaknesses Opportunities Threats) in this section look closely at the leading solutions identified above (see Analysis of Leading Solutions).

Rain Gardens		
Internal	**Strengths** Environmental ● Excellent pollutant removal (80-90%), esp. Phosphorous [5]. [1,2,3, 6,10] ● Designed to provide groundwater recharge (or not depending on what is preferred). [1,2] Cost ● Can be easily (cheaply) as a retrofit. [1] ● Cost depends on the types of plants. [8] Other ● Can be as small or large as necessary. [1,10] ● Low tech is usually the most effective. [8] ● Reduces urban heat island event [10]	**Weaknesses** Environmental ● Not suitable for large drainage areas/low peak flow reduction. [1,10] ● Cannot contain large amounts of snow. [1] ● If mulch fills up, it won't allow infiltration. [7] Cost ● Requires careful landscaping and maintenance. [1] ● Requires soil with good permeability and adequate depth. [2] Other ● NA
External	**Opportunities** Environmental ● Little or no hazard for amphibians or small animals. [1] ● Improved biodiversity. [8,10] Cost ● Can be maintained by volunteers. [3] Other ● Supplies shade, absorbs noise, and provides windbreaks. [1] ● Can be used for community/education events. [3]	**Threats** Environmental ● Breeding ground for mosquitoes. [1] Cost ● NA Other ● NA

	Bioswales	
Internal	**Strengths** Environmental ● Provides pretreatment - can be included with other treatment cells. [1] ● Excellent pollutant removal (80-90%), esp. Phosphorous [5]. [1,2,3, 6,10] ● Designed to provide groundwater recharge (or not depending on what is preferred). [1,2] Cost ● Open drainage system requires less maintenance. [1] Other ● Accepts sheet or pipe flow. [1] ● Reduces urban heat island event [10]	**Weaknesses** Environmental ● Short retention time does not allow for full gravity separation. [1] ● Limited bioinfiltration by grass lining. [1] ● Works best if there are lower flow rates. [1] ● Low peak flow reduction. [10] Cost ● Requires soil with good permeability and adequate depth. [2] Other ● Requires an area that is not too steep or too flat. [2]
External	**Opportunities** Environmental ● Little or no hazard for amphibians or small animals. [1] ● Improved biodiversity. [8,10] Cost ● Can be maintained by volunteers. [3] Other ● Can be used for community/education events. [3]	**Threats** Environmental ● Breeding ground for mosquitoes. [1] Cost ● NA Other ● NA

Rain Barrels		
Internal	**Strengths** Environmental ● eliminates stormwater runoff from an entire building. [1,3] ● runoff does not have time to pick up pollutants. [1] Cost ● Relatively inexpensive, especially if there is already a drainage system (easy installation). [3,5,7] Other ● Great for watered areas. [8] ● Small footprint. [10]	**Weaknesses** Environmental ● Cost ● Larger systems cost more money and have to be stored underground. [7,8] ● If used for irrigation, may require a pump. [8] Other ● If used for irrigation, must be located close to that area. [4]
External	**Opportunities** Environmental ● Cost ● reduces need for potable irrigation water (return on investment). [1,3,10] Other ●	**Threats** Environmental ● Breeding ground for mosquitoes or algae. [1] Cost ● may need to be drained in winter to avoid cracking. [1,7,10] Other ● Requires reliable and constant demand. [10]

Porous Pavement		
Internal	**Strengths** Environmental ● Reduces stormwater runoff volume from paved surfaces. [1,10] ● Reduces peak discharge rates. [1,10] ● Increases recharge through infiltration. [1,10] ● Reduces pollutant (up to 80%) transport through infiltration. [1,2] Cost ● Other ● Can last for decades if properly designed, installed, and maintained. [1]	**Weaknesses** Environmental ● Prone to clogging - limits effectiveness. [1,10] ● Limited pollutant removal when underdrains are used. [10] Cost ● requires heavy maintenance, including vacuuming. [1,4,6] ● requires soil with specified permeability. [1] ● More expensive (capital) and shorter lifetime than normal pavement. [3,5,6] Other ●
External	**Opportunities** Environmental ● Cost ● Reduces need for salting. [3] Other ●	**Threats** Environmental ● Cost ● Other ● sand cannot be used in the winter. [1] ● area needs to be plowed carefully. [8]

<table>
<tr><th colspan="3">Permeable Pavers</th></tr>
<tr><td>Internal</td><td>Strengths
<u>Environmental</u>
● Reduces stormwater runoff volume from paved surfaces. [1,10]
● Reduces peak discharge rates. [1,10]
● Increases recharge through infiltration. [1,10]
● Reduces pollutant (up to 80%) transport through infiltration. [1,2]
<u>Cost</u>
● Less expensive than pervious pavement. [8]
<u>Other</u>
● Can last for decades if properly designed, installed, and maintained. [1]
● Feasible in a small area like a sidewalk. [7]
● Improved aesthetic appeal. [1]</td><td>Weaknesses
<u>Environmental</u>
● Prone to clogging - limits effectiveness. [1,10]
<u>Cost</u>
● requires heavy maintenance, plants often grow between pavers. [1]
● requires soil with specified permeability. [1]
<u>Other</u>
●</td></tr>
<tr><td>External</td><td>Opportunities
<u>Environmental</u>
●
<u>Cost</u>
●
<u>Other</u>
●</td><td>Threats
<u>Environmental</u>
●
<u>Cost</u>
●
<u>Other</u>
● sand cannot be used in the winter. [1]
● area needs to be plowed carefully. [8]</td></tr>
</table>

SWOT Table References

[1] (Massachusetts Watershed Coalition, 2008)
[2] (Massachusetts Watershed Coalition, 2017)
[3] (Massachusetts Audubon, 2016)
[4] (Spratt, 2018)
[5] (Cianciola, 2018)
[6] (Harper, 2018)
[7] (Dietz, 2018)
[8] (Covino, 2018)
[9] (Griffin, 2018)
[10] (Boston Water and Sewer Commission, 2013)

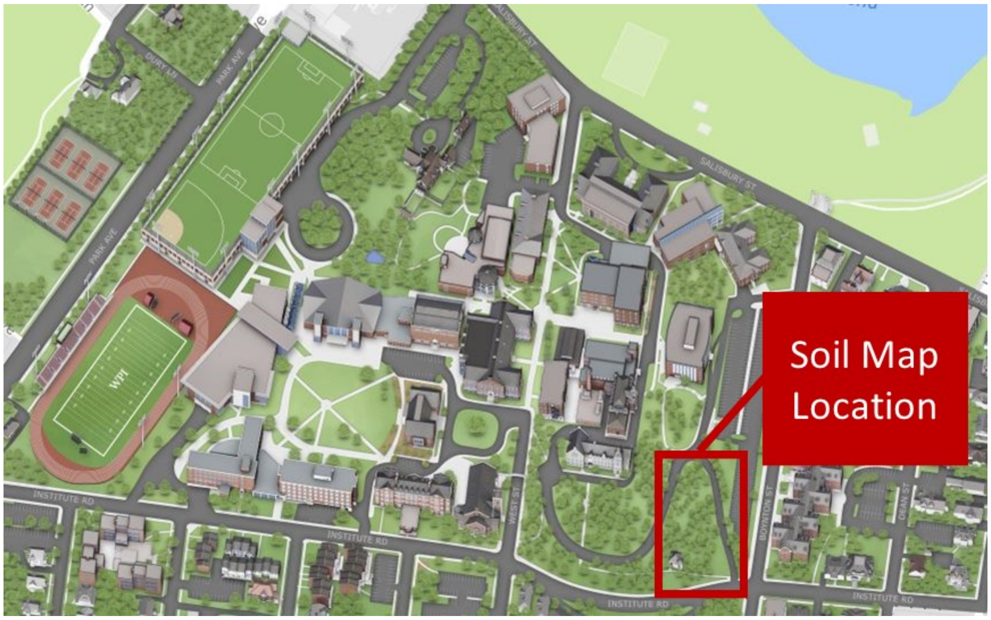
Appendix G: Soil Chart

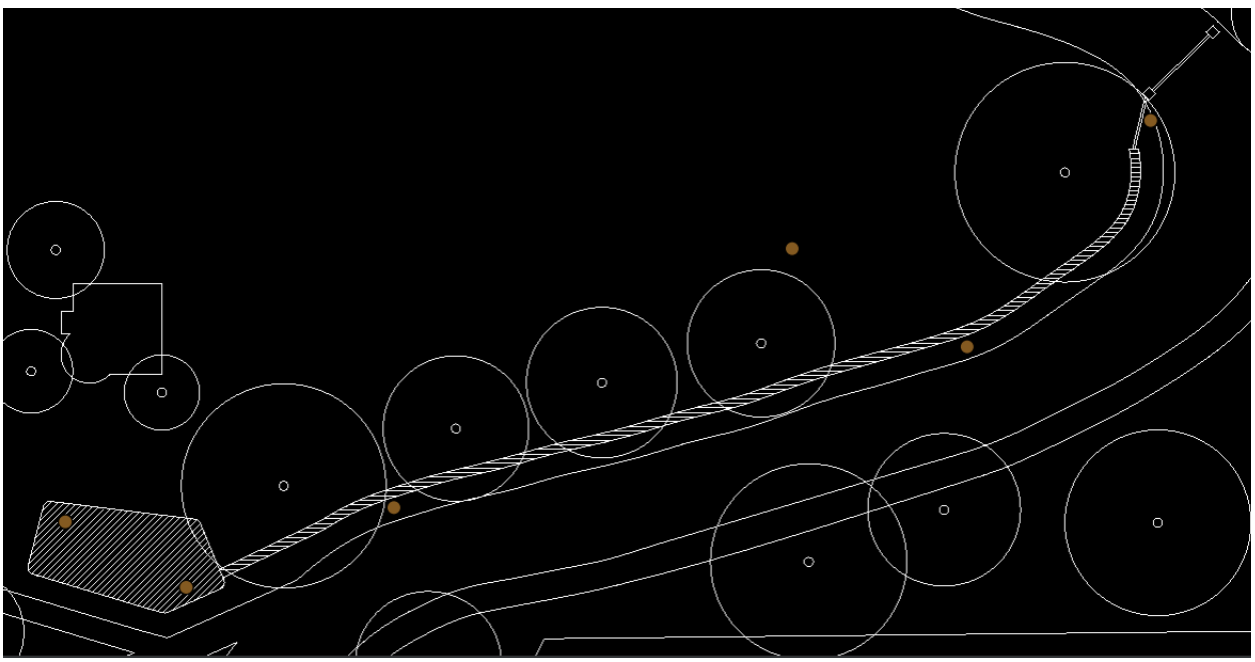
This chart shows the soil types at various locations on the hill by the Access Road. The locations are illustrated in the Soil Map (see Soil Map, Appendix H)

Location	**Depth (inches)**	**Soil Type**	**Infiltration rates (Inches/hour)**
Stop sign	4-6	Silt Loam	0.4
Between first two trees	4-6	Sandy Loam	0.6
Above second tree	4-6	Silt Loam	0.4
Last Light pole	4-6	Silt Loam	0.5
Rain garden front right	4-6	Sandy Loam	0.75
Rain garden back left	4-6	Silt Loam	0.5

Data compiled from soil percolation testing.

Appendix H: Soil Map





This map shows the locations where soil samples were taken. These locations are indicated by brown dots. (Area Shown: Lower portion of the access road downhill from Boynton Hall near the Skull Tomb)

Appendix I: Design Board

This is an image showing the conceptual design of the proposed system.

Appendix J: Cost Analysis

The following charts are a break down of the cost per section of the project. The first is the initial stone swale, followed by the rain garden, then the materials such as the catch basin, then the list of plants used in the rain garden, and finally the labor cost.

Initial Swale (entry point)

230ft in length and 2 ft wide so 460ft^2 and 1ft total depth

Material	Cost	Source of Price	Area Covered	Depth of material	Amount needed (yds)	Delivery Cost	Material Cost
Crushed Gravel (pea Stone 3/8in)	$60/yd	New England Nurseries (MA)	460ft^2	6in	8.5	**$50	$540
Stone (cut washed gravel 1.5in)	$60/yd	New England Nurseries (MA)	460ft^2	6in	8.5	**$50	$540
Plant (along side of swale)	Source	Area Covered	Amount needed	Price per plant			Total cost
Cinnamon Fern	Greenwood Nursery (TN)	36in tall 36in spread	100	$10			$1000
						Total Cost	$2180

**$50 delivery Charge for New England Nurseries per 14 yds

Rain garden (material needed for proper drainage)
935ft^2 with 2 ft depth

Material	Cost	Source of price	Area	Depth of material	Amount needed (yds)	Delivery Cost	Material Cost
Crushed Gravel (peastone)	$60/yd	New England Nurseries (MA)	935ft^2	1ft	35	**$150	$2100
Soil Mixture	None (re-used)	WPI	935ft^2	1ft	0	0	0
*Hardwood Mulch	$40/yd	New England Nurseries (MA)	935ft^2	3in depth	9	**$50	$360
						Total Cost	$2660

*must be hardwood so the mulch will not float away
**$50 delivery Charge for New England Nurseries per 14 yds

Rain Garden Plants

Plant	Source	Type	Area Covered	Amount needed	Cost Per Plant	Total Cost
Plant (wet)	New England Nurseries(MA)	Blue Flag Iris	3ft tall 18-24in spread	5	$12	$60
Plant (dry)	High Country Gardens (VT)	Prairie Phlox	2ft tall 12-15in spread	10	$9	$90
Plant (moist)	North Creek Nurseries (PA)	Canada Anemone	2ft tall 6 in spread	14		$65
Plant (moist)	New England Nurseries (MA)	Giant Hyssop (butterfly bush)	3-5ft tall 7 feet spread	5	$38	$190
Plant (dry)	Growers Exchange (VA)	Joe Pye Weed	3-ft tall 4ft spread	5	$8	$40
					Total Cost	$445

External Parts and piping

35 ft of piping under road to swale

Material	Cost	Source of Product	Qty	Use	Material Cost
Catch Basin	$742.58	All cost data info	2	Collect water from road	$1500
Piping for catch basin	$35 per 10’ (6in sewer piping)	Lowes	35ft	Move water to start of swale	$123
Over Flow drainage Grate	$10.99 (6in 36 GPM Atrium Grate)	Drip Depot Inc.	1	Collect water when rain garden fills	$11
Piping for overflow	$35 per 10’ (6in sewer piping)	Lowes	100ft	Move water overflow	$350
				Total Material Cost with Catch basin	$1984

Total Materials Cost including delivery before labor:

With Catch basins on each side of road the cost would be **$7300**

Labor Cost

Item Install	Time	Cost	Total Cost
Catch Basin Dirt Removal Overflow Piping Rock install Dirt install Mulching/Planting	5 day work time to install the full system		
Mini Excavator Operator	5 days 10 hour days	$80/hour	$4000
2 Laborers	5 days 10 hour days	$50/hour	$5000
		Total Cost	$9000

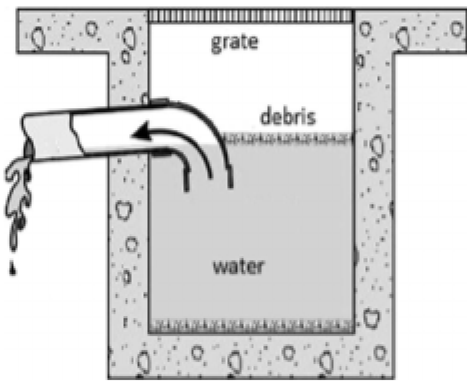
Total cost of labor would be about **$9000**

The total cost of the system to be installed including labor and materials would be **$16,300**

Appendix K: Implementation Plan

The installation of the system will be outsourced to a contractor chosen by the WPI Facilities Department. The Contractor would install the catch basin piping, remove the dirt from the side of the access road and rain garden site, install berms, spread rock, and plant and mulch the garden. The project is expected to take a week and cost around $17,000. The details of implementation are shown below in a 15 step process.

Step 1: Install two catch basins by the stop sign midway down the access road.



Cross-sectional view of a catch basin

Illustration of catch basins by the Access Road stop sign

Step 2: Dig a 230-foot long, 2-foot wide,1-foot deep trench, starting at the stop sign and ending near the skull tomb (see below).

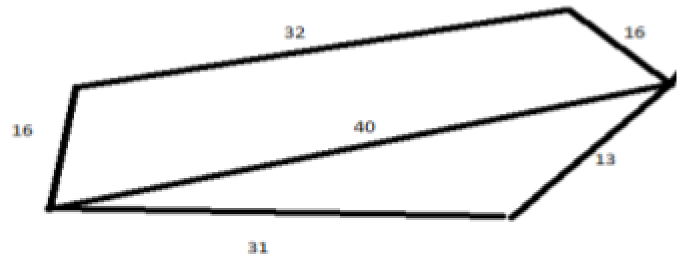
Illustration of a Stone Swale along the Access Road

Implementation Plan Cont'd

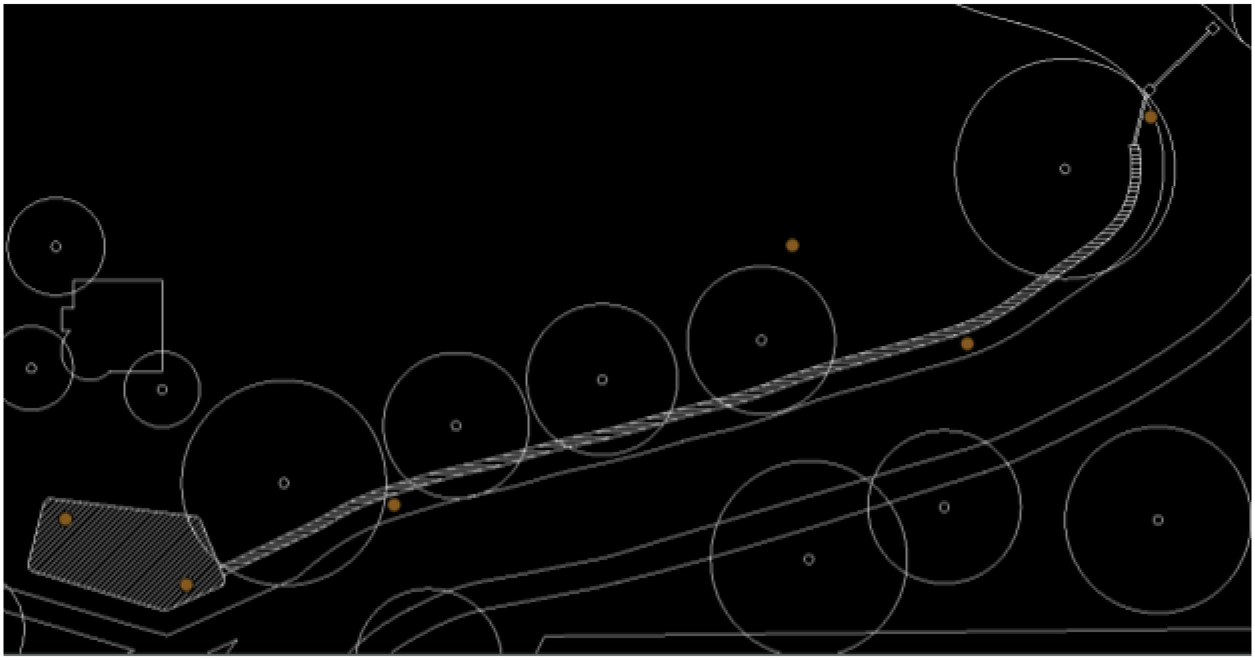
Step 3: Fill the trench with six inches of crushed gravel with an angle to channel water to the center. (shown below)

Cross-sectional view of stone swale

Step 4: Fill the rest of the swale with six inches of river rock at an angle to direct flow to the center of the swale (shown in figure in Step 3).
Step 5: Using the removed dirt to create small berms on either side of the swale to contain flowing water (shown in figure in Step 3).
Step 6: On the small berms, plant Cinnamon Ferns along the swale to absorb some of the water that penetrates the rock swale (shown in figure in Step 3).
Step 7: At the end of the stone swale, dig a two-foot deep rain garden with an area of 935 square feet in the specified shape (see the figures below). The Proposed Rain Garden Dimensions fit into the below Architectural View as the shaded region in the bottom left corner.

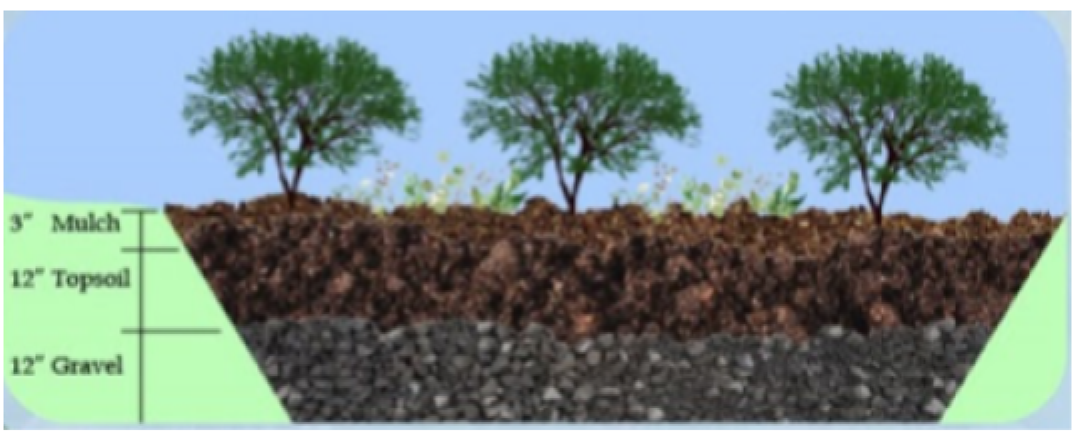


Proposed Rain Garden Dimensions



Architectural view of proposed system, including shape of rain garden and swale.

Step 8: Remove the dirt from the specified location.
Step 9: Insert crushed gravel to a one-foot depth throughout the whole rain garden (shown below).



Cross-sectional view of rain garden with proposed depths

Step 10: Insert piping for overflow drain (shown below).

Example of overflow drain and piping

Step 11: Insert 1 ft depth of removed soil around overflow and throughout rain garden. (shown in figure in Step 9)
Step 12: Use remaining soil to create natural burms to help funnel the water to the center of the rain garden.
Step 13: Plant flowers, shrubs, and other native botanicals (see below).

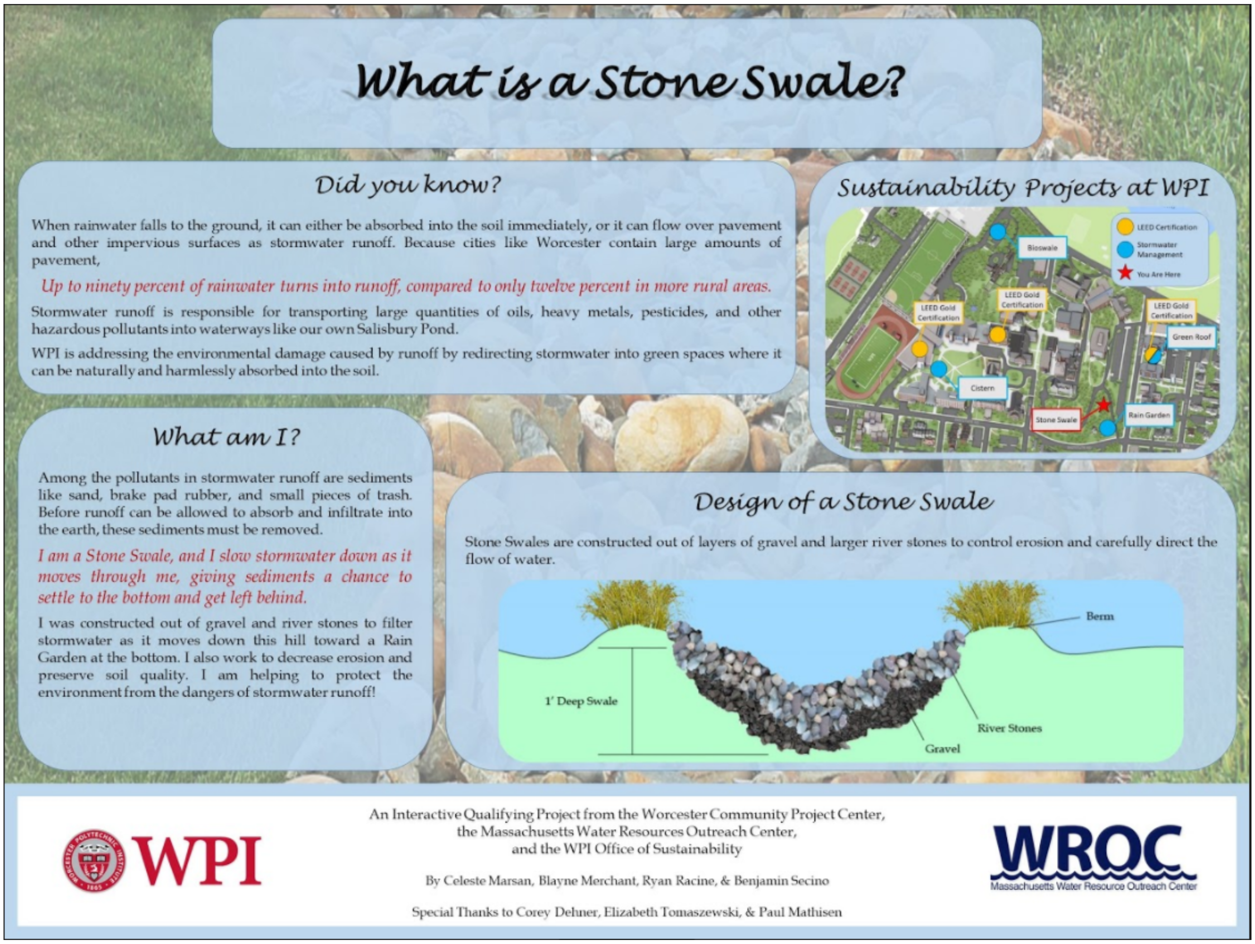
Illustration of planted rain garden

Step 14: Mulch to three-inch depth throughout rain garden
Step 15: Install overflow piping into storm drain system

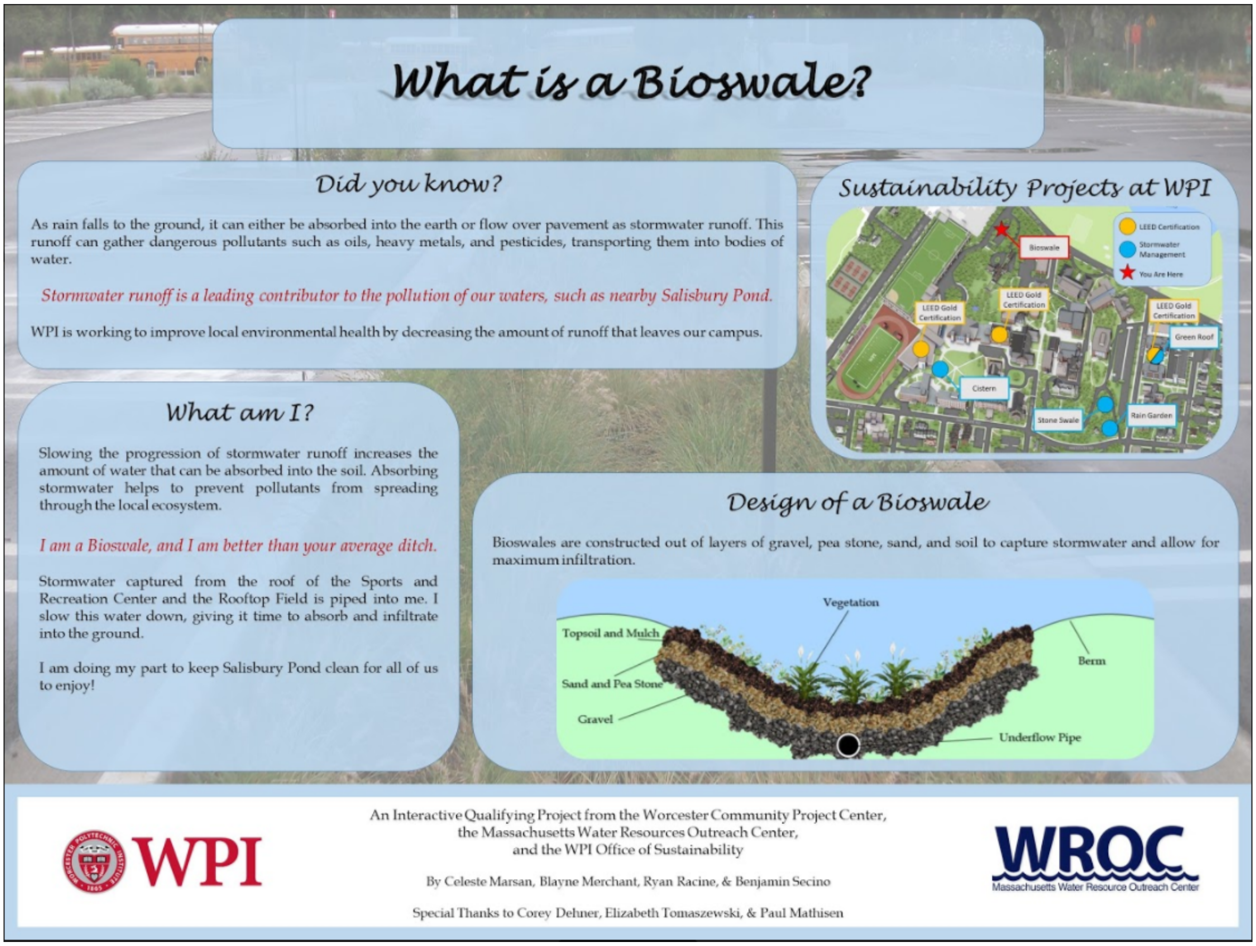
Appendix L: Educational Signs

The following images depict the proposed educational signs for BMPs around the WPI campus.

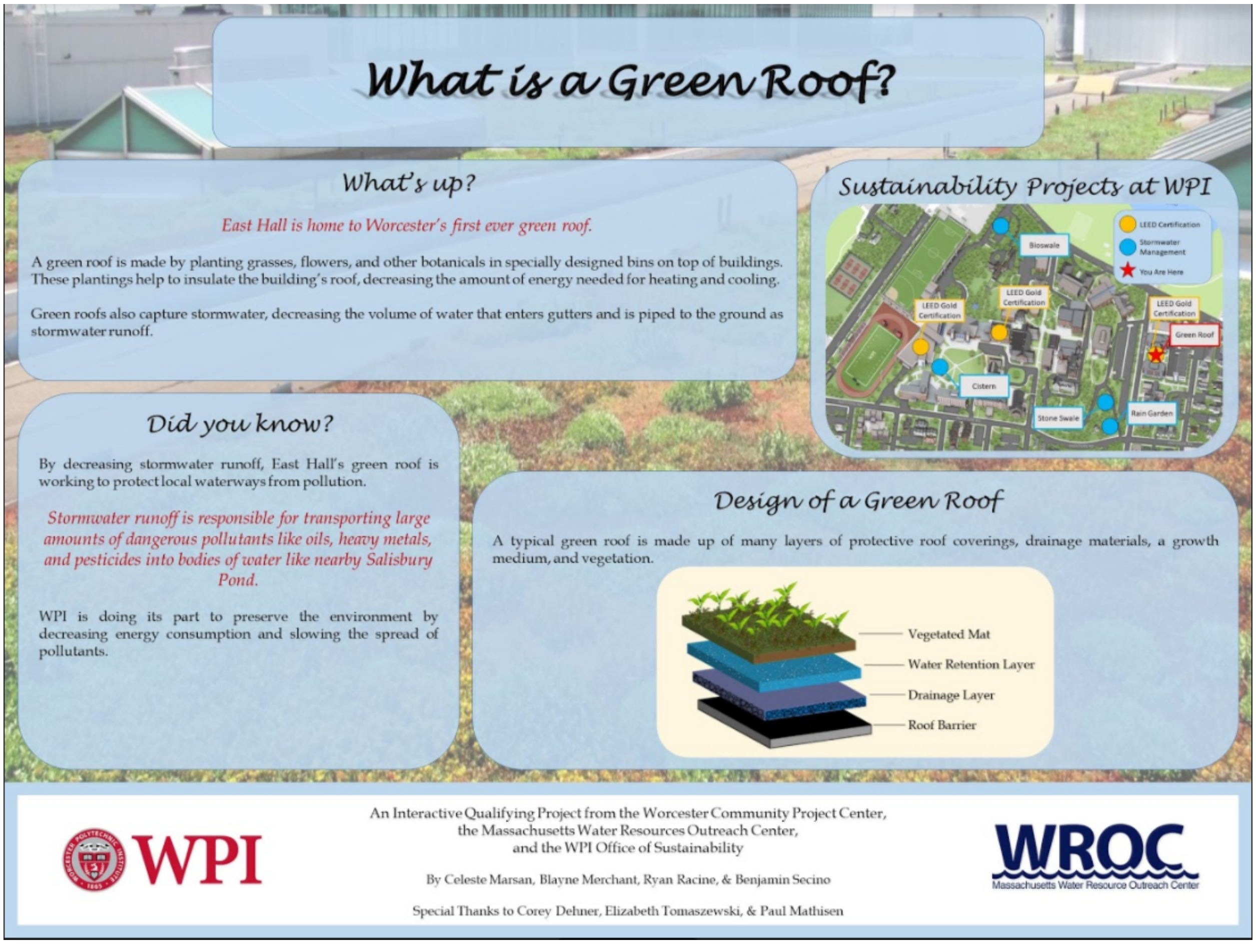
Rain Garden Sign. This sign would appear next to the proposed rain garden by Skull Tomb, at the bottom of the hill on the southeast side of campus.



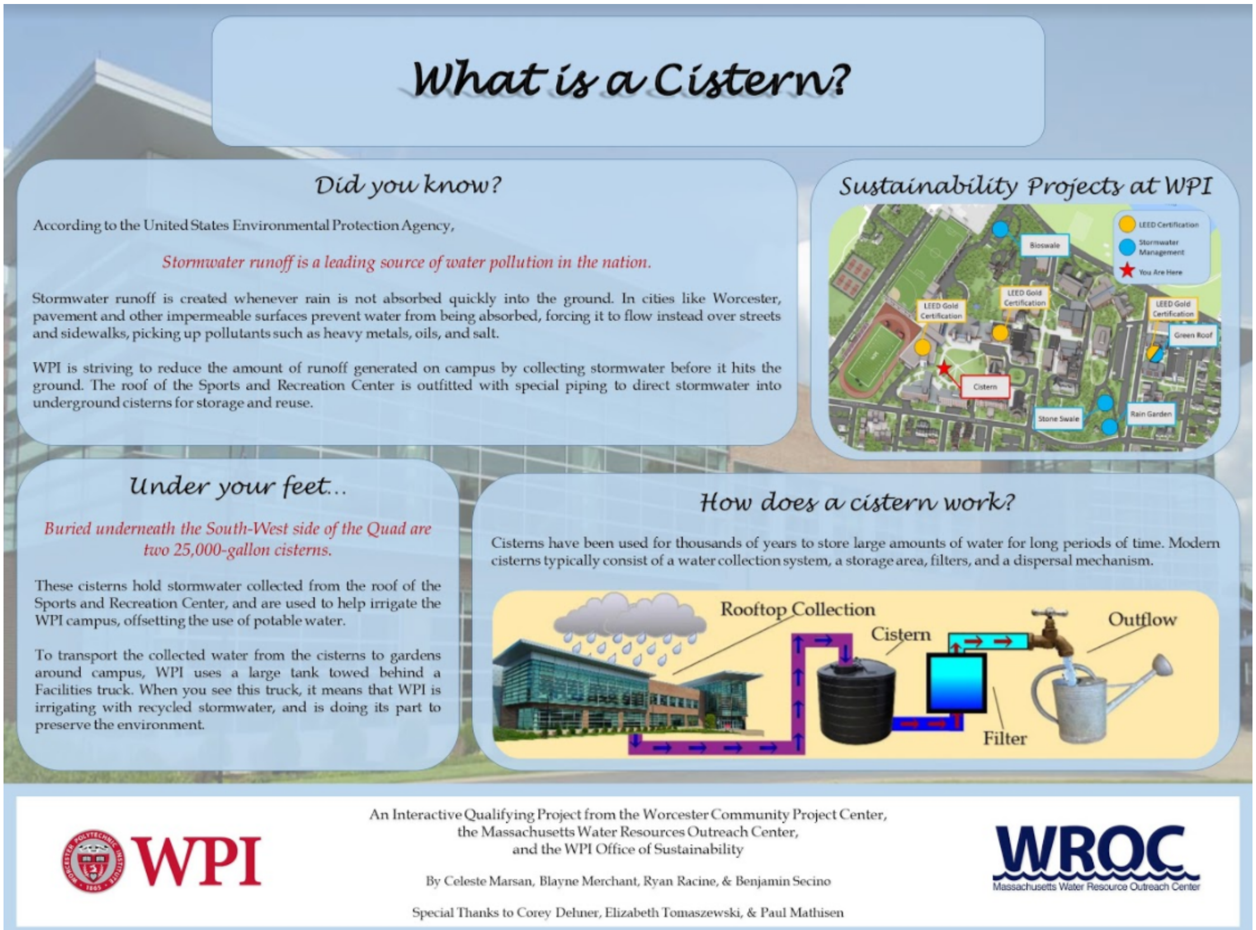
Stone Swale Sign. This sign would appear by the proposed stone swale running along the access road on the hill on the southeast side of campus.



Bioswale Sign. This sign would appear next to the bioswale build on the northwest side of campus by the Higgins House parking lot.



Green Roof Sign. This sign would appear in front of East Hall on the east side of campus.



Cistern Sign. This sign would appear in front of the Sports and Recreation Center on the southwest side of campus.

Appendix M: Future Project Information

We recommend that a number of stormwater management project be implemented on WPI's campus in the future. These recommendations should be reviewed by future student project teams and closely analyzed for applicability and impact. The following table outlines BMP type, proposed location, and potential impact.

BMP	**Location**	**Effect**
Rain Garden	Alden Hall (Institute Rd. side)	Reduce erosion caused by runoff from the roof
	Washburn Shops parking area	Infiltrate runoff from parking area
	Between Atwater Kent and Fuller Laboratories	Capture runoff exiting campus towards Salisbury St.
	Olin Hall (adjacent to Goddard Hall parking area)	Capture runoff that currently runs down the driveway
Rain Barrel	East Hall/Dean St. Parking Garage	Irrigate the East Hall Courtyard
	Faraday Hall	Irrigate of the Faraday Courtyard
	Higgins Laboratories (West St. side)	Collect water from the roof to be used in irrigation of the West St. area
Cistern	Morgan or Daniels Hall, or Harrington Auditorium	Provide sustainable irrigation for the Quadrangle
Porous Concrete/Permeable Pavers/Tree Box Filters	Freeman Plaza	Reduce runoff in a highly impermeable part of campus