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Stormwater Runoff Reduction on the Worcester Polytechnic Institute Campus

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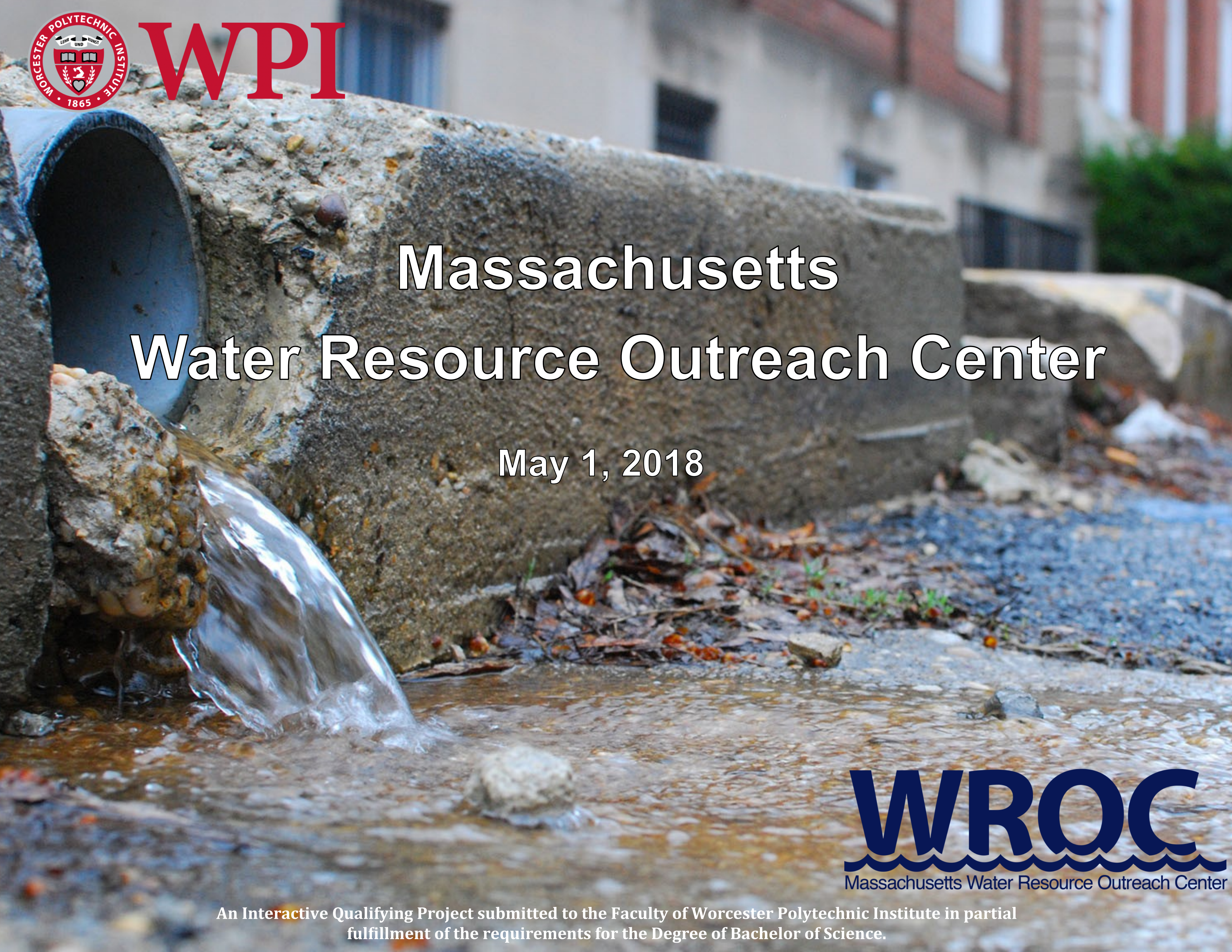

WPI

Massachusetts Water Resource Outreach Center

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WROC
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Massachusetts Water Resource Outreach Center

Stormwater Runoff Reduction on the Worcester Polytechnic Institute Campus

Blayne Merchant investigating a clogged tree box filter in Worcester.

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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Impacts of Stormwater Runoff

Globally, stormwater runoff is routinely identified as a leading cause of water pollution (Lee, 2000). Stormwater is defined as any form of precipitation, such as rain, snow, or hail. Large amounts of stormwater falling in one area lead to runoff, which is created whenever more stormwater lands than can be quickly absorbed into the ground (GCSWCD, n.d.). Stormwater runoff sweeps over impervious and saturated surfaces, collecting pollutants, such as chemical sediments and debris, and carrying them to larger bodies of water (Hwang, 2016).

Urban settings generate more runoff than rural settings because of the increased prevalence of impervious surfaces, such as pavement, rooftops, and other areas that prevent stormwater from filtering through to the underlying soil. In 2013, Erickson et al., researchers from the University of Minnesota determined that 12 percent of rainwater in rural settings reaches surface water as runoff, compared to 90 percent in urban areas (2013). Urban environments also have a higher level of contaminants and pollutants on the ground that get picked up by stormwater runoff. The National Water Quality Inventory (NWQI), put out by the United States Environmental Protection Agency (US EPA), is an informational paper intended to educate the US Congress and the general public about surface water body conditions in the United States (US EPA, 2017). The NWQI reported that urban-related runoff is a leading source of water pollution in the United States because it contains such pollutants as oil, road salt, trace metals, and pathogens (US EPA, 2017; Hwang, 2016).

Figure 1: Picture of Salisbury Pond adjacent to WPI

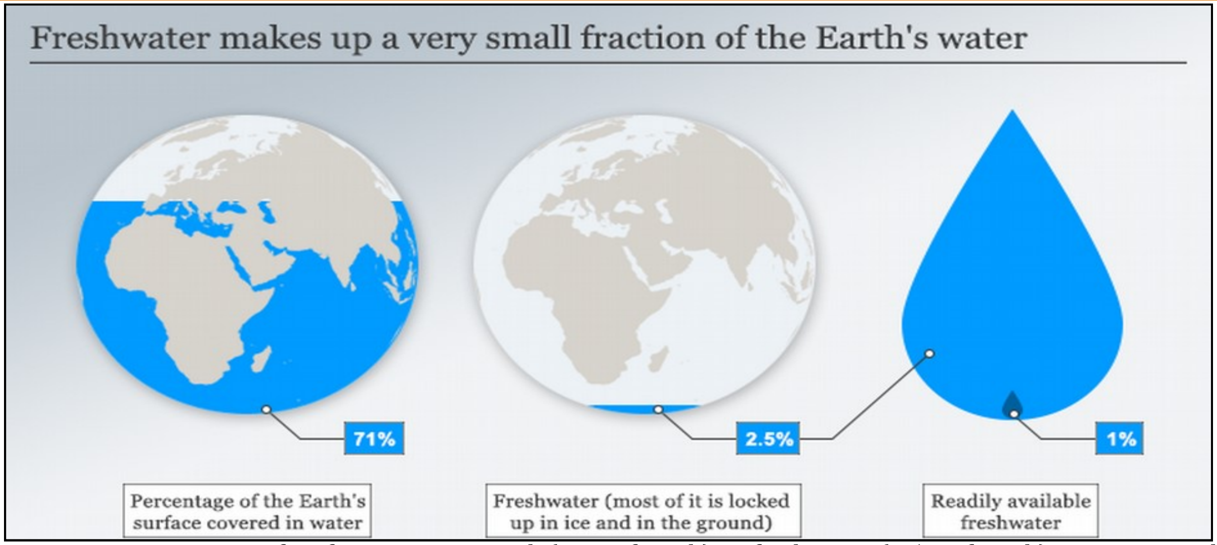


Figure 2: Comparison of surface water on earth (71% of earth) to freshwater (2.5% of earth) to current usable freshwater (<1% of surface water).

The most common approach to managing stormwater in urban settings is to transport runoff from its source to an outflow point without filtration or treatment (US EPA, 2017a). Although these transport systems aim to collect stormwater runoff before it becomes too polluted, they frequently fail to prevent the flow of pollution into freshwater sources. Since the early 2000s, innovations in green infrastructure have allowed college campuses to address stormwater runoff on their own to reduce flooding, erosion, and water pollution.

Following this trend, Worcester Polytechnic Institute (WPI) of Worcester, Massachusetts, is working to reduce its impact on the environment by implementing progressive stormwater management techniques. Due in part to its location on top of a hill and the large percentage of campus that is covered by impervious pavement, WPI generates a large volume of stormwater runoff that is released directly into nearby Salisbury Pond without treatment (Houyou, A., & Medeglio, R., 2014) [See Figure 1]. Because of this, runoff from WPI has been identified as a major cause of the systemic pollution of Salis-

Figure 3: Erosion example on a similar campus. Image credit: http://www.news-apstate.edu/2008/11/24/boone-creek-restoration

bury Pond (MassDEP, Division of Watershed Management, 2002). Several WPI student projects have attempted to find effective solutions to this problem. These proposals, however, have been too expensive, and therefore have never been enacted (Mathisen & Tomaszewski, 2018). In response, the WPI Office of Sustainability and the WPI Massachusetts Water Resource Outreach Center proposed a collaborative project to develop a realistic, high-impact, and cost-effective method for reducing campus runoff and improving the environmental health of the surrounding area.

The Consequences of Freshwater Pollution

In 2016, drinkable freshwater made up only 0.78 percent of the total water on earth, as shown in Figure 2 (USGS, 2016). With more than 7.6 billion people in the world, freshwater is a valuable and limited resource that is used every day for cooking, drinking, and manufacturing (Worldometers, 2018). Despite its inherent value, in the United States, it is estimated that 37% of accessible freshwater is polluted (Wasi, Tabrez, and Ahmad, 2013). The most common chemicals that pollute water include pesticides, lead, arsenic, and petrochemicals (Hwang, Fiala, Park, & Wade, 2016).

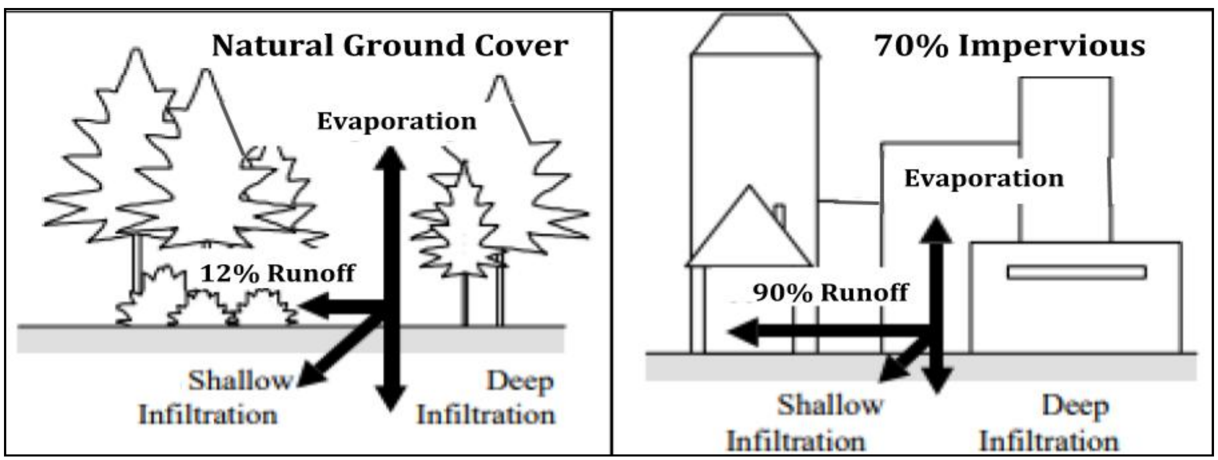


Figure 4: Percentages of stormwater that becomes runoff in rural areas (left,) and in urban areas (right) (Erickson, Weiss, & Gulliver, 2013). Image credit: EPA, https://www.epa.gov/sites/production/files/2015-10/documents/usw_b.pdf

Impact of Stormwater Runoff on the Environment

One of the leading causes of water pollution is stormwater runoff (Byeon, Koo, Jang, & Baeck, 2016). In the most benign of cases, stormwater runoff can cause erosion by carrying soil particles away from their source, as is seen in Figure 3 (Perlman, 2016). Through erosion, soil quality can be quickly depleted, hindering farming efforts (Favis-Mortlock, 2017). By decreasing soil quality and transporting heavy sediments into waterways, erosion can have severe impacts on the economy. Researchers at the University of Sao Paulo have estimated that in the United States, erosion is responsible for 44 billion dollars of lost productivity every year (Telles et al., 2011).

Though erosion represents a persistent hazard, erosion by itself is relatively harmless compared to another common danger brought on by stormwater runoff. When stormwater runoff sweeps over the ground, it can pick up and transport harmful pollutants such as trace metals, organic material, and pesticides (Byeon et al., 2016; Daly, Bach, & Deletic, 2014; Hoekstra & Mekonnen, 2012; Hwang et al., 2016; Pan & Miao, 2015). This polluted water can cause a wide array of health problems for species dependent on clean water. Researchers from Clemson University found that 92 percent of fish populations living in water polluted by stormwater runoff had decreased survival and reproduction rates (McQueen, Johnson, Rodgers, & English, 2010). Similarly, a study from Oregon State University demonstrated that salmon exposed to contaminated stormwater runoff experienced neurological damage (Sandahl, Baldwin, Jenkins, & Scholz, 2007).

Figure 5: Storm drain labeled with its outflow point

Stormwater Runoff in Urban Environments

The vast majority of runoff is generated in urban settings. In highly developed areas, up to 70 percent of surfaces are impervious (Hwang et al., 2016). In contrast, rural areas frequently have less than 15 percent impervious surfaces because of minimal development (Mallin, Johnson, & Ensign, 2008). This difference in ground cover has wide-ranging implications for runoff generation, and causes a 750 percent increase in stormwater runoff [See Figure 4]. Urban settings also produce runoff with higher levels of contaminants (McQueen et al., 2010). This increase is explained by the large amounts of pollutants present on the ground in urban areas (Torno, Marsalek, & Desbordes, 1984). Given this combination of increased quantity and enhanced toxicity, stormwater runoff in urban environments creates a dangerous situation for the surface water bodies it flows into.

Flow of Stormwater Runoff in Urban Settings

The most common stormwater management systems in cities are Municipal Separate Storm Sewer Systems (MS4). An MS4 is a system of storm drains used to collect stormwater from various locations and transport it through underground pipes to a designated outflow point, often a local lake or river, as can be seen in Figure 5 (US EPA, 2017d). More than 80 percent of the U.S. population lives within areas utilizing MS4s (US EPA, 2017d). However, MS4s do not contain any filtration or treatment systems. This means that the pipes simply transport the runoff and dump polluted runoff directly into bodies of water (Northeast Michigan Council of Government, n.d.).

Common Stormwater Management Practices on Urban College Campuses

Because of these significant shortcomings in the MS4, experts have developed Best Management Practices (BMPs) and Low Impact Development (LID) systems to more effectively manage stormwater runoff (Ice, 2004). BMPs

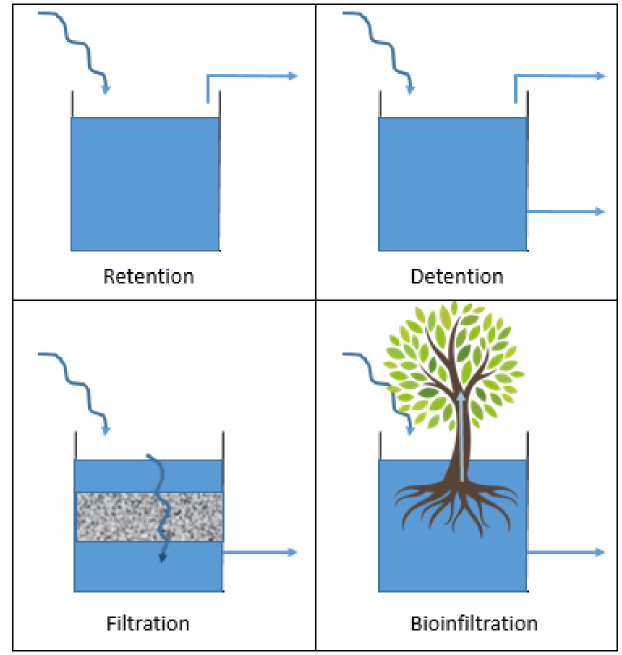


Figure 6: The major stormwater management techniques: retention (storage), detention (slow-release), filtration (pollutant removal), and bioinfiltration (return to water cycle).

are systems that manage water to reduce runoff

Technique	Definition
Bioretention	Stormwater collection tank that uses an organic, or plant-based, layer to optimize bioinfiltration [see Figure 6] (EPA, n.d.).
Detention Basins	Stormwater collection system that slowly releases water to the surrounding environment [see Figure 6] (Sustainable Stormwater Management, 2009).
Media Filters	Stormwater collection tank with natural filter to reduce pollutant load [see Figure 6] (Wojtenko, 2001).
Porous Pavement	Pavement that allows stormwater to infiltrate into the land and return to the underground water sources (EPA ,n.d.)
Retention Pond	Stormwater collection system that stores water and improves quality by allowing settling time for particulates (Sustainable Stormwater Management, 2009).
Artificial Wetlands	Bioretention cell using natural processes involving wetland vegetation, soils, and their associated microbial assemblages to improve water quality (EPA, 2004)

Figure 7: Common stormwater management techniques

volume or pollutant concentration (Rouge River, n.d.). These systems operate by increasing the detention, retention, filtration, or infiltration of stormwater before it is returned to the environment [see Figure 6] (Barrett, 2005). In Figure 7, we display common BMP techniques (Clary, Jones, Leisenring, Hobson, & Strecker, 2017). An LID method is a BMP that aims to reduce costs and increase efficiency by implementing nature-based solutions (Fletcher et al., 2015).

Colleges have used a variety of LID methods to increase the permeable surface area and encourage infiltration of water into the ground [See figure 8] (Peterein, Kandissounon, Ajay, & Sajjad, 2016). For instance, institutions such as the Southern Illinois University at Carbondale (SIUC), the Chabot-Las Positas Community College in California (CLPCC), and the Oregon Health and Science University (OHSU), have utilized rain gardens and bio-infiltration cells to reduce runoff volume (Peterein, Kandissounon, Ajay, & Sajjad, 2016; Paz, 2010; Wittenbrink, Timmins, & Donnelly, 2007). Additionally, both OHSU and SIUC have increased permeable area through the use of ecoroofs and permeable pavement (Wittenbrink, 2007, Peterein, 2016). Colleges have also implemented other methods such as rainwater harvesting, vegetated swales, and storage detention cells (Heasom & Traver, 2006; Wittenbrink et al., 2007, Paz, 2010).

College	Techniques Implemented
Southern Illinois University at Carbondale (SUIC)	Pervious pavement, rain gardens, retention cells. (Peterein, Kandissounon, Ajay, & Sajjad, 2016)
Chabot-Las Positas Community College, California (CLPCC)	Bioretention cells, vegetated swales, control basins, subsurface retention cells. (Paz, 2010)
Oregon Health and Science University	Bioretention cells, green roof, retention cells. (Wittenbrink, Timmins, & Donnelly, 2007)
Northeastern University	Infiltration system, detention cell. (Corey, 2011)
City College of New York	Retention cells, green roof, bioswales, pervious pavement, rain gardens (Bugala, Crescenzi, Fenichell, Greene, & Vulis, 2016)

Figure 8: Stormwater Management Techniques Implemented at Other Colleges

Stormwater Management Practices at Worcester Polytechnic Institute

Worcester, Massachusetts, gets more than 1 trillion gallons of precipitation each year, or 48.1 inches (Current Results, 2018). As a whole, Massachusetts is ranked 14th nationwide in terms of highest annual rainfall, receiving 47.1 inches every year, compared to the national average of 30.2 inches (Average Annual Precipitation by State, n.d.). Most of the runoff from this precipitation is channeled into local rivers, lakes, and ponds. Worcester is home to Worcester Polytechnic Institute (WPI), an urban college campus built on top of a steep hill. Unlike many other colleges, WPI has yet to fully implement a stormwater management plan. Much of the runoff generated on the WPI campus either flows naturally or is piped to nearby Salisbury Pond (Houyou & Medeglio, 2014). Untreated runoff from WPI has contributed to the chronic pollution of Salisbury Pond, which is continually in violation of water quality standards (US EPA, 2010). To address this, WPI's Office of Sustainability is working with student groups to develop effective solutions(Houyou & Medeglio, 2014).

A 2009 student project team proposed constructing a green roof on the Salisbury Laboratories building, which would have cost almost $500,000, but would have reduced runoff by 39% (Wang, Y., Hoang, H., & Milechin, D, 2009). In 2014, another student team suggested repaving the Boynton Parking Lot with permeable pavement, which would have reduced runoff by nearly 18 percent and cost $1.5 million over 15 years (Houyou & Medeglio, 2014). Most recently, in 2015, a team proposed constructing tree box filters that would have reduced pollutant loads by 45-95% at a cost of $60,000 (Marsh, MacMullen, & Grills, 2015). Unfortunately, because of high construction costs, none of these suggestions have ever been implemented (Mathisen & Tomaszewski, 2018).

Project Goal

Although past projects have looked into developing a stormwater management system on the WPI campus, as of yet no comprehensive plan has been implemented, due largely to prohibitive costs. Therefore, the goal of this project was to propose a cost-effective solution to address stormwater runoff on WPI's campus. This report will be submitted to the 2018 United States Environmental Protection Agency Campus RainWorks Challenge, which tasks teams to develop an innovative green infrastructure design to effectively address stormwater runoff and benefit the environment (US EPA, 2017c).

Developing a Stormwater

Objective	Methods
Objective #1: Assess Current System	•Semi-structured Interviews •Participant Mapping •Content Analysis of Campus Documents and Facilities Records
Objective #2: Identify Existing Solutions	•Content Analysis of Previously Implemented WPI BMPs •Content Analysis of Other Colleges' Solutions •Weighted Decision Matrix
Objective #3: Develop Stormwater Management Plan	•Cost-Benefit Analysis •Develop Implementation Details •Present Proposal to the Office of Sustainability

Figure 9: Overview of Objectives and Methods

Runoff Solution

In order to accomplish our project's goals, we took a number of systematic steps to better define the underlying issues and select appropriate countermeasures, as can be seen in Figure 9.

Objective #1: Assess the Current System to Identify Areas for Improvement

Before proposing any solutions, we assessed current stormwater management efforts on WPI's campus through expert interviews and content analysis of internal Facilities documents.

We selected semi-structured interviews as our primary research method because they allowed us to explore our topics of interest while allowing interviewees to give unprompted answers (Wilson, 2016). To find out more about WPI's Best Management Practices (BMPs), we interviewed four individuals who either work directly to address the effects of stormwater runoff at WPI or who have worked to design the physical systems for stormwater management [See Figure 10]. We received help in identifying potential interviewees from our project sponsors, Paul Mathisen and Elizabeth Tomaszewski (Mathisen & Tomaszewski, 2018).

In addition to interviews, we studied WPI's stormwater management system by reviewing internal documents, including utility usage records and BMP construction plans. These documents offered further understanding of campus water usage, BMP integration, and revealed opportunities to redesign existing systems.

Objective #2: Identify and Evaluate Applicability of Existing Solutions

Many solutions already address the problem of stormwater runoff in urban areas. Because of this, one of our primary tasks was to compile a list of BMPs applicable to WPI's campus. We identified BMPs by conducting a content analysis of twenty different documents from college campuses, including proposals from past WPI projects, and the comparing the different potential BMPs using a weighted decision matrix. We obtained additional information on BMP implementation, maintenance, successes, and shortcomings that was not recorded in the papers through interviews with officers from the Office of Sustainabil-

Interviewee	Interview Topics
Al Carlsen, Manager of Grounds and Properties	• Current BMPs used by WPI • Successes of WPI's BMPs • Shortcomings of WPI's BMPs • Participant mapping of critical campus areas • WPI's irrigation practices
Roger Griffin, Associate Director of Mechanical Services	• Existing integration of BMPs into campus buildings and structures • Participant mapping of critical campus areas
William Spratt, Director of Facilities Operations	• Current BMPs used by WPI • Maintenance of implemented BMPs • Successes of WPI's BMPs • Shortcomings of WPI's BMPs • Participant mapping of critical campus areas • WPI's irrigation practices
Daniel Sarachick, Director of Environmental Health and Safety	• Federal regulations and WPI-specific permits that may place restrictions on our design

Figure 10: Objective #1 Interviewees and Interview Topics

ity and Facilities Department employees from twenty-two different college campuses, and with representatives of seven local watershed associations, four green infrastructure consulting firms, three not-for-profit organizations, and three municipalities. Our decision matrix included cost of implementation, environmental benefit, financial return, applicability to WPI, ease of installation, aesthetic appearance, and sponsor opinion. We then used this matrix to compare the solutions

Figure 11: Research in Progress

and determine which BMP was best suited to the WPI campus' needs. This list and comparative matrix helped us present our recommendations to the WPI Office of Sustainability and Facilities Department for which BMPs are best for the WPI campus.

Objective #3: Develop Detailed Stormwater Management Implementation Plan

After consulting with the WPI Office of Sustainability, Facilities Office, and Department of Environmental Health and Safety and choosing a specific stormwater management approach, we developed a detailed plan for its implementation. We identified and defined Necessary Implementation Components, performed a cost-benefit analysis for the solution, and presented our proposal to the Office of Sustainability. For Necessary Implementation Components, we included: 1) the selection of an implementation site; 2) design plans for any associated construction; and 3) any changes in operating procedures for WPI's Facilities Office. For our cost estimate of the solution, we considered installation, operation, and maintenance costs, and compared it to the existing system to determine the cost savings within five years. This timeframe was defined by the Office of Sustainability as a desired metric of success. We also considered any potential environmental and societal benefits from the solution. After deciding on the solution and demonstrating its benefits, we proposed the solution to the Office of Sustainability.

Findings and Conclusions

Throughout our project, we worked with experts to assess stormwater management across the WPI campus, and to mitigate the effects of stormwater runoff in one high-impact area. We found that stormwater runoff at WPI would be best managed by the construction of a combined stone swale and rain garden by the side of the Gordon Library's access road. Throughout this section, we present our findings in the order they were investigated, as outlined in the Methodology section of this report. First, we discuss existing stormwater management techniques at WPI. We then present an analysis of BMPs that have been implemented or proposed at other college campuses, using criteria developed from interviews with stormwater management experts. Finally, we propose the BMP system that best suits the WPI campus.

Existing BMPs on the WPI Campus

From consultations with WPI Facilities staff, we identified three BMPs that already exist to combat stormwater runoff on the WPI campus. First, the Sports and Recreation Center (Rec Center) is outfitted with two 25,000 gallon cisterns that capture stormwater from the roof. These cisterns are buried underneath the Quadrangle, and are used to fill portable tanks that irrigate gardens around campus (W. Spratt, personal communication, March 21, 2018). Second, East Hall is home to Worcester's first green roof, which filters water and aids evapotranspiration (Spratt, p.c., 2018; "WPI Installs," 2008).

Finally, stormwater from the Rec Center and the Park Ave Parking Garage funnels into a bioswale by the Higgins House parking lot (J. Dufresne, p.c., March 26, 2018; Spratt, p.c., 2018). This bioswale helps infiltrate runoff before it reaches Salisbury Pond. However, due to improper grading, the bioswale does not capture runoff from the adjacent parking lot. Mr. Carlsen, Manager of Grounds and Properties at WPI, has also noticed that the bioswale is always dry, even after heavy rain, indicating improper design (p.c., April 2, 2018). Additionally, the bioswale's maintenance is more labor-intensive than originally planned, requiring regular mulching and weeding (A. Carlsen, p.c., 2018).

For all existing BMPs, the lack of educational signage has negatively impacted maintenance and public awareness (Spratt, p.c., 2018; Carlsen, p.c., 2018). Because the bioswale is unmarked, maintenance is sometimes neglected by groundworkers who are unaware of the swale's importance. WPI students are also largely unaware of the existence of any BMPs (Carlsen, p.c., 2018). Mr. Carlsen has suggested that education signage be implemented around existing BMPs to address these issues (Carlsen, p.c., 2018).

Selecting the Right BMP

Our first step in selecting a BMP was to identify potential options. From our 12 interviews with experts in BMP implementation and our review of literature on stormwater management, we identified 15 types of BMPs that were implemented or proposed at colleges across the country: Artificial Wetlands, Bioswales, Cisterns, Detention Cells, Green Facades, Green Roofs, Habitat Creation, Hydrodynamic Separators, Permeable Pavers, Pervious Pavement, Rain Barrels, Rain Gardens, Riparian Buffer Systems, Soil Amendment, and Tree Box Filters.

After our initial research on BMPs, we developed a list of eight *Necessary Considerations* based on criteria that frequently appeared in papers and interview responses. *These Necessary Considerations* for BMP design are: 1) Opportunities for Social Impact, 2) Affordability of Implementation, 3) Financial Return, 4) Affordability of Maintenance, 5) Stormwater Runoff Volume Reduction, 6) Stormwater Runoff Pollutant Load Reduction, 7) Ease of Installation, and 8) Design Aesthetics.

One factor of BMP design was Opportunities for Social Impact. According to environmental advocates Stefanie Covino from the Massachusetts Audubon and Chris Humphrey from the Worcester Regional Environmental Council, an effective way to promote stormwater awareness is through community engagement sessions, educating individuals on issues posed by runoff and explaining ways to protect the environment (S. Covino, p.c., March 22, 2018; C. Humphrey, p.c., April 4, 2018). One way to do this is to invite school children to participate in the construction of BMPs. After reaching out to 15 nearby primary schools, we discovered that six were immediately interested in collaborating with WPI on implementation of a new BMP.

Affordability of Implementation is critical when developing a BMP design. According to Ms. Tomaszewski, Assistant Director of Sustainability at WPI, and Dr. Mathisen, Director of Sustainability at WPI, high implementation costs are a major reason why three BMP projects proposed at WPI over the past nine years were not implemented (E. Tomaszewski and P. Mathisen, p.c., February 9, 2018). Another *Necessary Consideration* that takes into account the economics of a project is the Financial Return of a system. If a BMP could eliminate current costs, such as irrigation or erosion treatment, then it becomes desirable as a long-term investment (Tomaszewski, p.c., 2018; Spratt, p.c., 2018; Carlsen, p.c., 2018).

Another *Necessary Consideration* was Affordability of Maintenance. Five of our interviewees identified maintenance as a key factor that "can lead to a BMP's success" (E. Himlan, p.c., March 26, 2018)(M. Dietz, p.c., March 23, 2018; Covino, p.c., 2018; J. Burmeister, p.c., March 29, 2018; E. Ciancioli, p.c., March 23, 2018). Because the proposed system will be maintained by WPI's Grounds Crew, it is important that the system be low-maintenance and that the crew be informed of the system's needs. Our interviews with the Connecticut DEEP and the Regional Environmental Commission confirmed that if a grounds crew is not informed of proper maintenance procedures, they may over-prune an area or remove beneficial plants (S. Pappano, p.c., March 28, 2018; Humphrey, p.c., 2018; C. Stone, p.c., March 28, 2018).

We discovered that different BMPs treat runoff in different ways. Some BMPs, such as cisterns and rain barrels, decrease runoff volume, while others, like hydrodynamic separators and tree box filters, simply remove pollutants (*Massachusetts Stormwater Handbook,* 644[2]). We therefore took both Stormwater Runoff Volume Reduction and Stormwater Runoff Pollutant Load Reduction into consideration when evaluating environmental benefits.

The final *Necessary Consideration* was Ease of Installation, also described as ease of retrofitting. According to Michael Dietz, Nonpoint Education for Municipal Officials Program Director for the University of Connecticut, we found that retrofitting existing construction is often costly, difficult, and less effective than proper original construction (Dietz, p.c., 2018).

We used these *Necessary Considerations* to evaluate the 59 BMPs listed above. After an initial evaluation, we identified five BMPs that, as measured by the *Necessary Considerations,* could make the biggest impact on stormwater management at WPI. These BMPs are shown in Figure 12, where they are graded against the *Necessary Considerations.*

Of the BMPs in Figure 12, Permeable Pavers and Pavement were quickly recognized as least desirable due mainly to high implementation and maintenance costs, and were removed from further consideration. Our attention turned to Rain Gardens, Bioswales, and Rain Barrels. We analyzed these BMPs using a SWOT or Strength-Weakness-Opportunity-Threat analysis, illustrated in Figures 13 and 14. After identifying Rain Barrels, Bioswales, and Rain Gardens as the most desirable BMPs, we considered implementable locations to evaluate the specific benefits of each solution and make an informed selection.

Bioretention Areas (Bioswales and Rain Gardens)

Internal	**Strengths** Environmental ● Excellent pollutant removal (80-90%), ● Designed to provide groundwater recharge Cost ● Can be easily (cheaply) as a retrofit. Other ● Low tech is usually the most effective.	**Weaknesses** Environmental ● Not suitable for large drainage areas/low peak flow reduction. ● If mulch fills up, it won't allow infiltration. Cost ● Requires soil with good permeability and adequate depth. Other ● NA
External	**Opportunities** Environmental ● Improved biodiversity. Cost ● Can be maintained by volunteers. Other ● Can be used for community/education events.	**Threats** Environmental ● Breeding ground for mosquitoes. Cost ● N/A Other ● N/A

Figure 13: Abridged SWOT analysis of Bioretention Areas

	Number of Possible Locations	Opportunities for Social Impact	Affordability (Implementation)	Affordability (Maintenance)	Runoff Reduction	Pollutant Reduction	Financial Return	Ease of Installation	Aesthetics
Rain Garden	4	H	M	M	M	H	M	M	H
Bioswale	1	H	H	M	M	H	M	M	H
Rain Barrel	1	M	H	H	H	L	M	H	M
Permeable Pavers	2	L	L	L	M	H	L	L	L
Permeable Pavement	2	L	L	L	M	H	L	L	L

Key:	
	High Desirability
	Medium Desirability
	Low Desirability

Figure 12: Comparative Matrix of Potential Best Management Practices

Evaluating Locations to Select the Correct BMP

According to Jacquelyn Burmeister, Senior Environmental Analyst for the City of Worcester Department of Public Works and Parks, selecting a suitable location is critical for a BMP's success (Burmeister, p.c., 2018; Humphrey, p.c., 2018; Stone, p.c., 2018; Himlin, p.c., 2018; Cianciola, p.c., 2018). For instance, not all buildings lend themselves to

Rain Barrels

Internal	**Strengths** Environmental ● Eliminates stormwater runoff from an entire building. Cost ● Relatively inexpensive (easy installation). Other ● Great for watered areas.	**Weaknesses** Environmental ● N/A Cost ● If used for irrigation, may require a pump. Other ● If used for irrigation, must be located close to that area.
External	**Opportunities** Environmental ● N/A Cost ● Reduces need for potable irrigation water. Other ● N/A	**Threats** Environmental ● Breeding ground for mosquitoes or algae. Cost ● Needs to be drained in winter to avoid cracking. Other ● Requires reliable and constant demand.

Figure 14: Abridged SWOT analysis of Rain Barrels.

Figure 15: Areas with erosion, flooding, current irrigation or desired irrigation (Spratt, 2018)

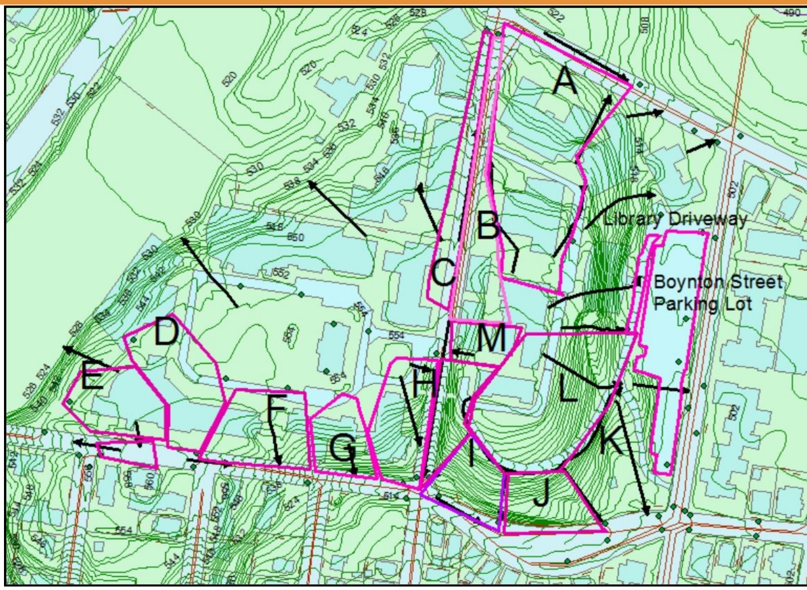
rainwater harvesting. If a building has no external downspouts, adding a rain barrel will require extensive retrofitting. We carefully examined East Hall, Founders Hall, and the Dean St. Parking Garage, both in person and through archived blueprints, and found that none of these locations have an easily accessible gutter systems. Additionally, the volume of water required for irrigating the East Hall Courtyard, 600 gallons per week, was much more than what could be stored in a rain barrel (Carlsen, p.c., 2018). Because of this, we determined that a bioretention area would be the best BMP for WPI.

Bioretention areas are most effective in spaces with documented erosion, high runoff, and low grade. We interviewed Bill Spratt, Director of Facilities Operations at WPI, to identify areas on campus with high runoff and erosion, as shown in Figure 15 (p.c., 2018). One area of significance was along the Gordon Library Access Road, which was eroded by runoff and foot traffic.

Using GIS mapping, we determined that the highest volumes of runoff originate from around Boynton Hall and Gordon Library, including the previously mentioned section of the Access Road (Marsh, McMullin, & Grills, 2015). We also confirmed that most of the runoff from WPI's campus is channeled into Salisbury Pond. We analyzed these maps to identify areas with high pollutant loads. We found the highest pollutant areas to be the Gordon Library driveway (labelled in Figure 16) and the hill behind Boyton Hall (sections L and K in Figure 16), which generate 3705.8 lbs and 835.1 lbs of total suspended solids (TSS) annually, respectively (Marsh, McMullin, & Grills, 2015).

We identified sections L and K as potential sites for a bioretention area because of high runoff, high pollutant loads, and documented erosion. We determined that section K would be more desirable because of its lower grade and because much of the runoff from section L flows through section K toward storm drains along Boynton Street.

To ensure site viability, we took six



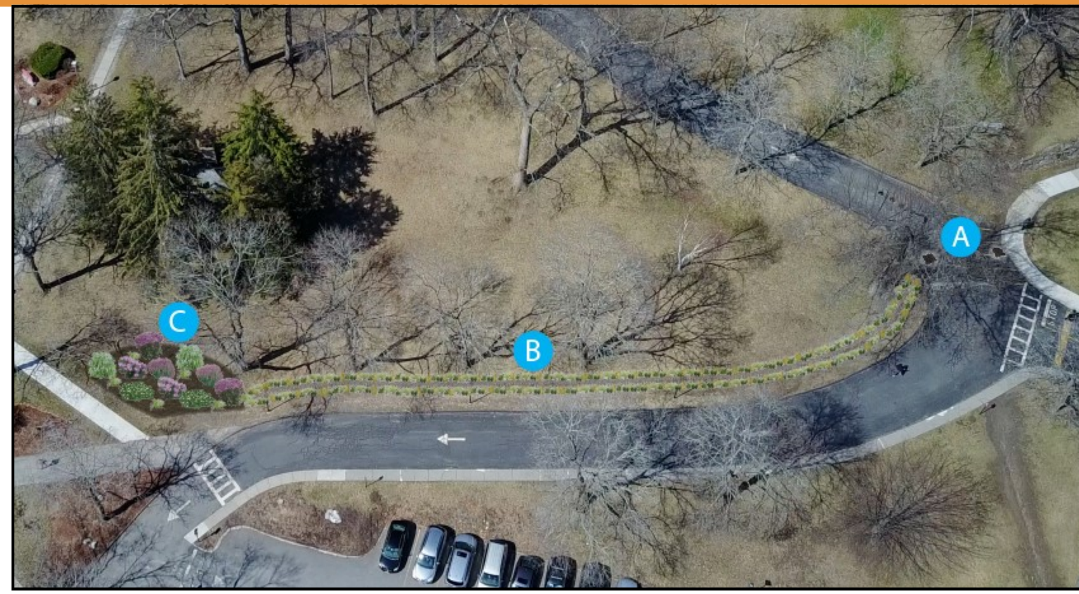


Figure 16 (left): GIS Map of the WPI campus, with arrows depicting stormwater flow patterns and lettered areas marking different drainage areas (Marsh, McMullin, & Grills, 2015) Figure 17 (right): Presentation of final design of combined stone swale and rain garden

soil samples from the area. According to Malcolm Harper, Environmental Analyst for the MassDEP, a BMP can fail if soil conditions are incorrect (M. Harper, p.c., March 21, 2018). If soil has low infiltration rates, a bioretention area will be less effective. Our soil analysis showed a mix of sandy loam and silt loam. With this composition, the percolation rates are high enough for a bioretention area to be effective without soil replacements.

Recommendations

We propose the implementation of a combined stone swale and rain garden near the access road in section K, as shown in Figure 17. In the proposed system, two catch basins will be installed at point A, capturing stormwater from the access road and piping it into a two hundred thirty-foot long stone swale, point B. This swale will be one foot deep, covered in layers of gravel and river stones, and have berms planted with Cinnamon Ferns on either side. The swale will transport runoff to the bottom of the hill, point C, while removing sediment and beginning the infiltration process. Point C will be a trapezoidal, one thousand-square foot rain garden. This garden will be two feet deep, with one foot of gravel under another foot of soil. Displaced soil will be used in construction of berms around the edge of the garden. The garden itself will be planted with native species, including Blueflag Iris, Prairie Phlox, Canada Anemone, Giant Hyssop, and Joe Pye Weed. There will also be an overflow pipe to prevent washouts in extreme rain events.

If installed, this system will remove 80-90% of pollutants from captured runoff (Massachusetts Watershed Coalition, 2008). Even if only half of runoff leaving sections L and K enters the catch basins at point A, the proposed system will still remove nearly 2,250 lbs of TSS each year. Additionally, the proposed system will promote infiltration, reducing the volume of runoff entering Salisbury Pond. Overall, we estimate that this system will cost around $16,300, as shown in Figure 18.

Educational signage should be placed alongside the stone swale and rain garden. If implemented these signs would increase

Cost Group	Material	Material Cost
Stone Swale	Crushed Gravel, River Rock	$1,180
Rain Garden	Crushed Gravel, Hardwood Mulch	$2,660
External Parts	Catch Basin, Piping, Overflow Drainage	$1,984
Plants	Blueflag Iris, Prairie Phlox, Canada Anemone, Giant Hyssop, Joe Pye Weed, Cinnamon Fern	$1,445
Labor (5 days, 10 hour days)	$80/hr (excavator), $50/hr (x2 laborers)	$9,000
	Total Materials Cost	**$16,300**

Figure 18: Simplified cost analysis of the proposed system. See Supplementary Materials for a more extensive cost analysis

community awareness of stormwater management and promote environmental health. A proposed design is shown in Figure 19.

Beyond the implementation of the stone swale and rain garden, we have also identified many retrofitting projects that we recommend WPI undertake in the future. Future projects should investigate these concepts further, suggesting concrete implementation plans. Additionally, we recommend that educational signage be integrated into WPI's existing BMPs to increase awareness of proper stormwater management. Finally, we recommend that future construction projects implement green infrastructure during the initial design process, reducing retrofitting costs and increasing the performance of BMPs.

Increasing Stormwater Management at WPI

Stormwater runoff is a leading contributor to water pollution in the United States (Lee, 2000). Because of the many adverse effects of water pollution, including weakened ecosystems and decreased biodiversity, the problem of stormwater runoff must be resolved (Enviropol, n.d.). Our plan to implement a combined stone swale and rain garden is an affordable way to minimize polluted runoff entering Salisbury pond, while also educating the WPI and greater Worcester community on stormwater management. This project directly aligns with WPI's Strategic Plan to elevate positive impact, not only on campus, but in our local community and environment. Through projects like ours, WPI is working to reduce its environmental impact and show itself to be a leader in sustainable infrastructure.

Figure 19: Example of Educational Signage for the Rain Garden

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