Disclaimer: This paper partially fulfills a writing requirement for first-year (freshmen) engineering students at the University of Pittsburgh Swanson School of Engineering. *This paper is a **student paper, not a professional*** paper. This paper is not intended for publication or public circulation. This paper is based on publicly available information, and while this paper might contain the names of actual companies, products, and people, it cannot and does not contain *all* relevant information/data or analyses related to companies, products, and people named. All conclusions drawn by the authors are the opinions of the authors, first-year (freshmen) students completing this paper to fulfill a university writing requirement. If this paper or the information therein is used for any purpose other than the authors' partial fulfillment of a writing requirement for first-year (freshmen) engineering students at the University of Pittsburgh Swanson School of Engineering, the users are doing so at their own--not at the students', at the Swanson School's, or at the University of Pittsburgh's—risk.

BIOSWALES AND GREEN INFRASTRUCTURE: THE NATURAL PURIFICATION OF POLLUTED WATER

Lauren Wilmoth lnw28@pitt.edu, Katherine Lebrun kbl15@pitt.edu, Matthew Jaros mcj29@pitt.edu

Abstract—*In an industrialized world, it can be nearly impossible to keep water sources clear of pollution. Purifying water can be expensive, but new methods of water filtration remove pollutants from water naturally. Bioswales are shallow ditches filled with vegetation that collect and purify surface water. Water then reenters rivers, lakes, and oceans free of pollutants or contaminants. This method of purification can be very beneficial to urban areas, as bioswales combat flooding. The plants inside bioswales are able to purify water as well as capture carbon dioxide from the air. Our paper will discuss and analyze the process of water purification through a bioswale, as well as the effects this has on the surrounding environment.*

We will also discuss the benefits of bioswales near highways in greater detail. It is essential to find a solution to the growing pollution problem that is caused by todays roads, and roads that may be built in the future. The Ray, a sustainable highway project along I-85 in Georgia, is implementing bioswales as a major component of the system to create a "net zero" highway—free of fatal accidents, waste, pollution, or any negative environmental impact. Not only do the bioswales sit right next to the interstate, a major source of pollution, but they also help prevent flooding and standing water, which can cause hydroplaning and car accidents.

Overall, bioswales are excellent tools to remove water pollutants in urban areas. Bioswales are very sustainable implementations, as they are cost effective, environmentally friendly, and easy to construct. The simple process by which a bioswale is built will be discussed in this paper. We will also compare bioswales to other practical ways of managing highway runoff such as infiltration trenches and vegetated filter strips. The key focuses of these comparisons will be cost, implementation, and effectiveness.

Key Words—Bioswales, Green Infrastructure, Sustainability, Water Filtration, Water Pollution, Water Purification

BENEFITS OF GREEN INFRASTRUCTURE

Green infrastructure, or the use of the natural environment to reintegrate runoff into the water cycle, is one of the most sustainable ways to combat water pollution. Conversely, gray infrastructure uses man-made systems like sewers, pipes, and gutters to manage water—flushing it back into a body of water without treatment, or artificially filtering it in a water treatment center. Gray infrastructure has a very large set of problems associated with it; Margaret Palmer lists some in an article for *Science*: gray infrastructure is often expensive to construct and maintain, can displace people who live near new construction sites, increases flood risk, and interferes with natural ecosystems [1].

Because green infrastructure uses natural environmental processes, the need for artificial structures to purify water is drastically reduced. Bioswales, or shallow trenches lined with highly absorbent sands, soils, and plants, are one type of green infrastructure that can be implemented as a sustainable substitute for traditional methods of water filtration using gray infrastructure. As types of green infrastructure such as bioswales are made entirely of natural materials, they have no negative impact on the environment. The design and types of plants and soils used in bioswales can vary greatly depending on the region and type of environment around the bioswale.

Green infrastructure creates a more sustainable method of water filtration. It's very important to consider sustainability before starting any urban development projects. In the context of water filtration, sustainability is measured by a method's benefit to the community, environmental impact, cost-effectiveness, and ease of construction and maintenance. Sustainable practices, by nature, create longer-lasting infrastructure and amplify the benefit to surrounding communities.

This paper will focus on bioswales being used to purify water runoff in areas where pollution caused by transportation and its carbon emissions is a major concern. Solutions to this problem that implement bioswales and other green infrastructure will be discussed later in the paper, using examples such as The Ray—a sustainable highway project—and new water filtration plans in the city of Pittsburgh. By explaining a variety of applications of green infrastructure, this paper will demonstrate the importance of green infrastructure— specifically bioswales—in improving water quality, decreasing reliance on harmful environmental practices, and creating a more sustainable and environmentally-conscious society.

PROBLEMS AND CONSEQUENCES ASSOCIATED WITH WATER POLLUTION

Carbon emissions from cars and trucks are very harmful to the environment, affecting soil and water quality, surrounding ecosystems, and nearby communities. This can be detrimental, as clean water is an essential part of every society and contributes to the growth of a healthy population. In heavily populated and industrialized areas, it is necessary to combat water pollution and contamination actively. The lack of sustainable methods to purify water causes numerous problems for nearby communities.

One example of this is in China, where overpopulation and industrialization contribute to contaminated water. The country's economic boom of the late twentieth century has led to rapid industrialization, distracting attention from the growing need for environmental protection. As many factories release chemical waste and hydrocarbons—the same pollution caused by fuel-powered transportation—nearby water sources and air are becoming heavily polluted. As water pollution has increased, a study conducted by the Massachusetts Institute of Technology shows that stomach cancer among nearby inhabitants has increased as well [2]. Frequent ingestion of these harmful chemicals has already shown to cause health problems in local population. This is such a recent problem that the effects have not yet been studied extensively, leaving the fate of pollutant-exposed populations uncertain. The health problems caused by ineffective water purification demonstrates the lack of sustainable methods to filter water in China and similar areas.

Threat to water security is another problem created by water pollution. Research conducted in 2016 by Stuart Bunn suggests that up to eighty percent of the world's population is experiencing threats to water security as a result of pollution [3]. Even in regions where access to safe water is not yet jeopardized, Bunn's research shows that water quality is rapidly declining. Unsustainable methods to purify water and combat the effects of rapid urbanization have contributed greatly to this rapid decline in water quality around the world. This decline, coupled with the recent threat of overpopulation, puts a large portion of Earth's population in peril in the coming decades. Human beings are not the only victims of this crisis; plants and animals—especially species that are already endangered—are threatened by contaminated water sources.

The United States' pollution problem has not yet reached this extreme, but it is a possibility if adequate measures are not taken to combat the issue. One major source of pollution is the interstate, where most vehicles are powered by combustion reactions that release harmful carbon dioxide into the air. Later in this paper, we will discuss the use of bioswales near highways to combat this issue.

DESIGN, CONSTRUCTION, AND IMPLEMENTATION OF BIOSWALES

Design, Construction, and Costs

Bioswales function by collecting and retaining water, then purifying it naturally, using plants to metabolize dissolved substances. A team from the Civil Engineering Department at Southern Illinois University wrote a report detailing the designs of bioswales and similar systems of water purification [4]. Most highway systems are built with a very basic water drainage system that consists of a short slope down from the raised highway to level ground, followed by a slope back up to highway-level, creating a ditch to retain storm water. The double-sided slope creates a buildup of water in the ditch during heavy periods of rainfall; however, this provides no system to release the water or prevent flooding. This method of water control is a minimal effort to reduce standing water on roads and does nothing to combat water pollution.

Bioswales look to improve this system by absorbing runoff water and cleaning it, reducing pollutants in the water supply and surrounding ecosystems. Bioswales are structured much like traditional drainage systems, as both contain concave surfaces for collecting stormwater. Because of this, bioswales can be implemented easily along highways. Bioswales are also more effective than traditional highway drainage, due to the types of plants and soil used. The top layer of a typical bioswale system is vegetation grown in rich soil with a layer of sand underneath. Sand is highly absorbent, causing colloids in turbid water to gather into larger masses and ease removal from the water [5]. Plants native to the region that absorb and cycle water quickly are good candidates for use in bioswales. Figure 1 presents the design of a bioswale that would be implemented near a road system.

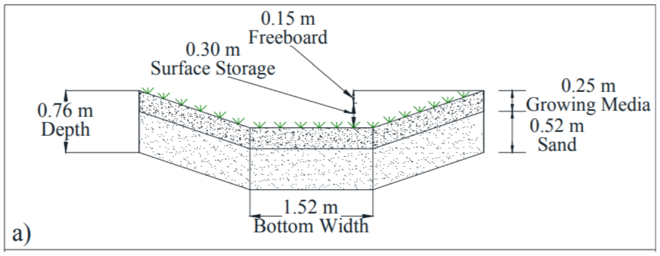

Figure 1 [4]
Cross section of a bioswale

The cost of constructing a 4.3-meter-wide bioswale like the one pictured in Figure 1 is about $16,000 per 30 meters of highway [4]. Bioswales must be maintained to function at peak efficiency; regular mowing promotes plant growth and trash removal prevents clogging of the drainage ditch. The annual cost of maintenance for a 30-meter-long, 4.3-meter-wide bioswale used for collecting highway runoff is approximately $431 according to civil engineers from Southern Illinois University [4]. The dimensions of a bioswale such as this one have shown to be impactful in reducing water contamination. Efficiency and magnitude of water purification and price per length increase proportionally with the width of the bioswale. For areas of heavy rainfall, a more expansive and expensive bioswale will produce better results, while a highway that experiences less rain may use a cheaper and smaller system. This is not a significant cost, creating an economically sustainable solution for water purification near highways.

Bioswales can be installed in existing highway systems without making significant changes to the highway because they can be easily fitted into a highway's existing right-of-way [6]. The right-of-way is an approximately 33-foot-wide space on either side of a highway that has been designated for traffic signs, sidewalks, and drainage systems. There is enough room in these areas for construction on the highways to inconvenience the general public and the environment as little as possible. The bioswales can be implemented without significantly modifying the surroundings of the highway, therefore minimizing the ecological effects of construction. Road blockages would not be a major concern, as construction can be done in the confines of the right-of-way, without causing traffic delays. This demonstrates the economic and social sustainability of bioswales, as the minimal construction and maintenance would not give rise to large labor costs or transportation problems.

Bioswales in Urban Areas

Bioswales can also be implemented in cities to assist the sewage system by retaining drainage from streets and sidewalks. If a sewer system is overloaded with storm water, it will flood and dump untreated water into nearby rivers and other bodies of water. Bioswales can reduce the likelihood of sewer overload by absorbing and purifying any water not treated by the main system. As part of the 2010 NYC Green Infrastructure Plan, New York City constructed bioswales to combat sewer overload and protect rivers. The bioswales sit slightly lower than the surrounding street and sidewalk to cause water to flow into them easily. The top layer is vegetation and soil, but underneath is a "subsurface layer of engineered soil, gravel, glass or storage chambers" [5]. This mixture yields high absorption of water that eases the load the city's sewage system must bear during storms. Hardy plants that can survive in wildly varying conditions must be chosen for these bioswales, as the soil will undergo periods of extreme moisture content and extreme dryness.

Water Purification in Bioswales

In addition to relieving drainage systems, bioswales clean the water that they absorb. A study done by a team at the Department of Environmental Toxicology at the University of California examined water purification in bioswales adjacent to parking lots in urban areas [7]. They found that bioswales cleaned the water by reducing suspended solids by 81%, metals by 81%, hydrocarbons by 82%, and pyrethroid pesticides by 74% through the metabolism of plants. High levels of suspended solids in bodies of waters can be harmful to aquatic plants, as they cloud the water, slowing photosynthesis and therefore lowering the water's oxygen content. They also have been found to clog the gills of fish, suffocating them [8]. Metals in drinking water can be harmful to a city's population, exemplified by Pittsburgh's current lead issue, which will be explained below. Hydrocarbons, like those found in all petroleum products, are harmful to the health of wildlife and humans, especially to children and pregnant women [9]. Pyrethroid pesticides are a common pest control that have been found to be highly toxic to honey bees and aquatic creatures when introduced to a standing body of water [10]. Removing these toxins from the environment is very beneficial—not only to the wildlife in our ecosystems, but to the health of human beings.

Variations of Bioswale Design

Planting trees in a bioswale can improve the efficiency of the bioswale and have positive effects on the surrounding environment. Due to their size, trees cycle a much greater amount of water through transpiration than smaller plants can, while trees' long root systems increase infiltration rates. The tree species, *Q. macrocarpa*, or Burr Oak, performed the best as a natural filtration system in the Morton Arboretum's bioswales [11].

The Morton Arboretum included trees in their comprehensive system of bioswales as part of their eco-friendly parking lot. The parking lot works effectively to filter rainwater before it enters neighboring bodies of water. The bioswales are 3 meters wide and slope down to a level 30 cm below the elevation of the parking lot. Multiple types of trees, shrubs, and herbaceous plants are planted throughout the system. The soil used is a mixture of 60% sand, 10% clay, and 5% course organic material to increase absorption. Catch basins underneath the bioswales allow for more water to be held and filtered. When water levels are high, these basins can be opened, rapidly discharging water and preventing flooding in the parking lot. This system is a great example for future green parking lots and other urban systems [11].

COMPARISON TO OTHER METHODS OF WATER FILTRATION

Biomimicry is a science that uses the design of biological systems as inspiration for technology and engineering. Many artificial water filtration systems are based heavily on natural ones, using similar materials or designs to optimize water purification. Some natural water filters are largely made from soil and sand, such as wetlands.

Wetlands are areas that hold water, whether permanently or temporarily. While providing the base for a valuable ecosystem and habitats for many animals, wetlands serve primarily to regulate water flow in an area. In flood seasons, a wetland absorbs excess water; in times of drought, they slowly release held water into the ecosystem to mitigate the effects of desiccation on plants and dehydration on animals. It is estimated that wetlands account for approximately 6% of the world's land, though this figure has decreased between 64-71% since the beginning of the twentieth century according to the American Association for the Advancement of Science in their published "Atlas of Population and Environment" [12,13]. The loss of such a crucial habitat drives the humanity not only to help save wetlands, but also to use them as inspiration for our own innovation.

A Comparison of Green and Gray Infrastructure

Green infrastructure is much more sustainable than gray infrastructure. This is made obvious by comparing the longevity, monetary cost, and ability to benefit both the man-made and natural environments. Gray infrastructure, while typically made with materials meant to last such as concrete or metal, doesn't tend to last under severe and changing conditions. For example, the sewer systems in many major cities were constructed when the cities were home to a smaller population. As cities and populations grow, the systems are unable to cope with the extreme influx of water.

Green infrastructure uses the natural environment and naturally occurring materials as they are meant to be used, resulting in a greater ability to grow and adapt with changing conditions. Due to the inflexibility of gray infrastructure and materials, there is a greater financial strain. To control waste water in New York City, the city analyzed two plans: one using gray infrastructure and the other using green infrastructure. The green plan, which used green roofs and bioswales, had a projected savings of one and a half billion dollars.

Sustainable urban planning is very important to the development of green infrastructure; rehabilitating upstream wetlands rather than implementing green infrastructure in a city could end up being more cost effective and beneficial to surrounding environments in the long run [14]. Green infrastructure's sustainability is demonstrated by its many benefits to the environment: it improves stormwater quality, increases urban biodiversity, cools the urban landscape, provides passive irrigation, and improves air quality [15]. The advantages of green infrastructure over gray infrastructure are clear and demonstrate that when used correctly and efficiently, green infrastructure can be used to develop more sustainable practices in urban planning and building.

Vegetated Filter Strips

Artificial water filtration systems, such as vegetated filter strips and infiltration trenches, function similarly to bioswales to filter waste water. A vegetated filter strip is an area of either planted or indigenous vegetation put in between a potential source of pollution and a surface body of water. A guide published by the USDA in New Jersey breaks down the purpose and the materials used in effective vegetative filter strips. They serve two primary purposes: to remove dissolved and suspended sediment or pollution from waste water and to protect against land erosion [16]. Vegetated filter strips are often used near farms to protect bodies of water from dissolved pesticides but can also be used alongside roadways—particularly in urban areas with bodies of water close to the roads. They can be constructed using a variety of vegetation, such as grass or trees [16]. Figure 2 demonstrates the use of a vegetative filter strip in an agricultural context.

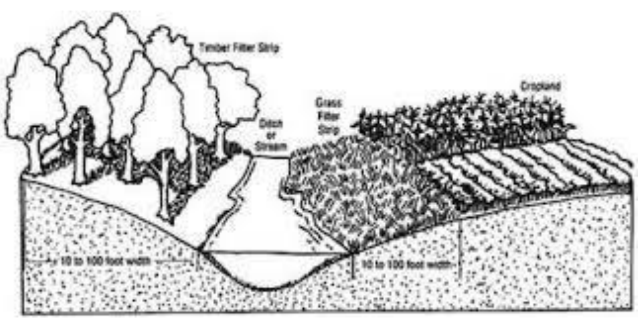

Figure 2 [16]
Vegetative filter strips prevent pesticides from leaking into water sources.

The design and construction of a vegetated filter strip is fairly simple; it consists of laying vegetation on a small slope near a source of pollution. However, cost was found to be an issue be an issue in the "Pennsylvania Stormwater

Management Manual" where they analyzed cost breakdown of different green infrastructure, due to the significant portion of land needed, as the vegetated filter strip must run along the length of the pollutant source and be wide enough to be able to absorb all the pollutants [17]. In places where land is readily available, vegetated filter strips are a good approach to stormwater management; otherwise, it can be hard to find cost-effective land.

One significant advantage to a vegetated filter strip is the ability to remove dissolved substances from water by using plants, which pick up particles and process them, eliminating need for further treatment. When implemented near agriculture, vegetated filter strips are able to remove excess phosphorous and nitrogen caused by fertilizers and pesticides from the water, eliminating the need for further water treatment. According to an analysis done by the University of California Davis when implemented near agriculture, vegetated filter strips can remove great amounts of excess phosphorous and nitrogen caused by fertilizers and pesticides from the water, eliminating the need for further water treatment [18]. This protects surface bodies of water in a big way, reducing the potential for algal blooms and the number of dead zones in the water caused by increased oxygen consumption of algae.

Infiltration Trenches

While vegetated filter strips and bioswales use primarily naturally existing materials, infiltration trenches tend to be laid down in concrete or pipes under a vegetated or gravel surface. The Minnesota Pollution Control Agency says they are most effectively constructed using a perforated pipe at a slope through a stone filled trench and are usually a component of a larger system to manage high water flow during large storm events [19]. Infiltration trenches are usually part of the end of pipe facilities, which are the last barrier before the stormwater is released into the ground or water source according to the Ryerson University Department of Civil Engineering [20]. This means that infiltration can't purify wastewater enough on their own to be useful in urban areas. Infiltration trenches are a type of gray infrastructure, constructed from processed materials, as shown by Figure 3.

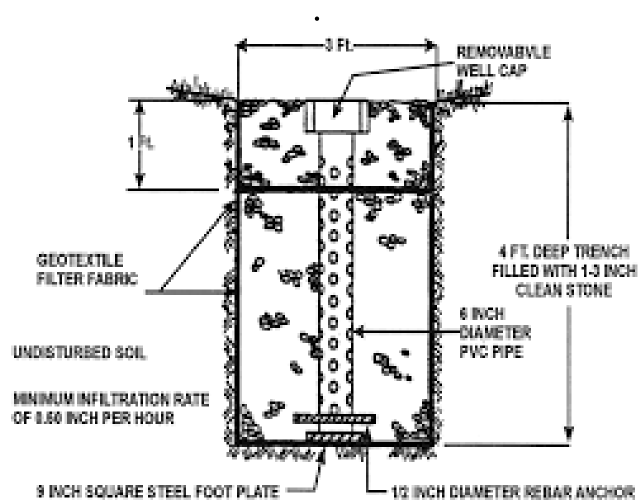

Figure 3 [21]
Design of an infiltration trench

The narrow water passage puts the system at risk for clogging by large amounts of organic debris and sediment. Usually, gravel is used in the trench itself, allowing clean water to flow through. An infiltration trench is lined with permeable filter fabric, which acts as a final barrier between the stone in the trench and the ground soil. Infiltration trenches are unable to remove a large percentage of pollutants, meaning water must be pre-treated before it arrives at the trench to be percolated back into ground soil [20]. Their inability to remove dissolved pollutants limits applications. The Spokane Conservation District states that in locations close to drinking wells or with sensitive bedrock, infiltration trenches are hazardous, potentially contaminating groundwater [21].

Infiltration trenches are also susceptible to clogging from sediment and are incompatible with terrain featuring steep slopes, which would cause water and debris to flow in too quickly [19]. The EPA, in a report on developing cost estimates analyzed cost breakdown for green infrastructure projects including infiltration trenches. Since infiltration trenches require grey infrastructure below ground, they can be costly to construct and maintain, averaging around $12.50 per cubic foot [22]. This cost does not include the necessary systems needed to treat water before arriving at the trench to prevent groundwater contamination.

Analysis of Comparable Methods

Both infiltration trenches and vegetated filter strips are good systems to use alongside roadways but are more effective in small areas due to the inability to handle uptake of large quantities of water. This makes them largely ineffective in areas with high amounts of pollution or runoff water. Slope limitations on both infiltration trenches and vegetated filter strips limit application in mountainous terrain.

THE IMPLEMENTATION OF BIOSWALES NEAR HIGHWAYS

Most roadways are paved with impermeable hot mix asphalt (HMA) and topped with a thin layer of permeable asphalt [23]. Permeable asphalt can prevent standing water but has a very low capacity. Flooding can cause the permeable asphalt to reach this water-absorption capacity, causing excess water to stand on roadways. This method of pavement does nothing to combat water pollution and instead leaves the water to sit under the asphalt as cars drive over and emit pollutants, leaving highway runoff extremely susceptible to high levels of contamination. Paving with permeable asphalt is a very unsustainable and harmful practice to prevent standing water on highways and must be replaced with more environmentally-friendly methods, as the water sources of nearby ecosystems are threatened by the high levels of pollution.

The Ray, a sustainable highway project created along eighteen miles of I-85 in Georgia, is implementing bioswales as a method to minimize the environmental impact of roadways on the natural habitats.

Figure 4 [24]
A map of The Ray, an eighteen-mile section of Georgia's I-85

These bioswales serve a multitude of purposes and work in harmony with other fixtures along the highway. Their main purpose is to collect runoff water and filter particulate pollution. This has many benefits for The Ray, as draining water from the roadway reduces hydroplaning and accidents. Main contributors to the project also cite aesthetic as a major benefit of bioswales, saying the introduction of native plants beautifies the highway and surrounding areas creates a more pleasant drive for travelers. In a press release, Harriet Langford, president of The Ray, said that "creating the highway of the future is going to require going back to nature" [25]. The planet functioned healthily without human intervention for millions of years. Essentially, the cheapest, most effective way to combat pollution is to do so with the resources our planet already provides. Man-made water collection and filtration systems can be very costly, difficult to maintain, and harmful to the surrounding environment. Conversely, bioswales are cheaply and easily constructed and require very little maintenance, all while enhancing the environment and reintroducing native plant species. This is a very sustainable way to both purify water and strengthen the presence of vital plant species in their native environments.

Bioswales were one of the first steps taken to create a sustainable highway for The Ray in 2016. They have been installed through collaboration with the University of Georgia and the Georgia Department of Transportation. The Ray's press release regarding bioswales reports that installation is being monitored and analyzed by both entities, and as data is collected, it will be used in further improvement of The Ray's bioswales [25]. According to this press release, the Georgia Department of Transportation is planning on implementing bioswales in various locations across the state and will use this data to design and install the best bioswale possible for the needs of the area [25]. This project is a leader in bioswale development and has the potential to educate and inspire bioswale installation around the world.

In the same press release, Water Resource Management and Policy Specialist at the University of Georgia, Dr. Gary Hawkins discusses trends seen since bioswales have been installed. Riparian buffer grasses that are native to Georgia are being planted inside the bioswales because their deep roots aid in the infiltration of water into the soil. This reduces flooding by allowing more water to be collected by the bioswale, while trapping more pollutants and purifying the water before it returns to the water cycle. A study by Chengfu Zhang et al. describes riparian buffers and analyzes their benefits [26]. According to Zhang, riparian buffers have been accepted as a "best management practice" [26]. While the vegetated strip design of a riparian buffer has not been used in The Ray, the concept is the same. Plants that are widely used in riparian buffers are planted in bioswales and function similarly to reduce pollution. Water samples taken by Zhang's research team after they flowed through the riparian buffer region consistently demonstrate a reduction in sediment, nitrogen, and phosphorous contamination.

Bioswales in The Ray are usually placed in the median of the highway or on the outer sides of the road. The gradual slope uses basic principles of gravity to prevent flooding and standing water on the roadway. Figure 5 shows the placement and grade of a model bioswale along The Ray.

Figure 5 [27]
A bioswale collects water next to The Ray

The figure demonstrates the water entering the bioswale, where riparian plants can filter it and ease infiltration. After the bioswale soaks up the water, it can purify the water and return it to the water cycle as it flows down into the ground. Dr. Hawkins explains in The Ray's press release that water absorption and decontamination by bioswales along The Ray will increase water quality in nearby water sources, such as Lone Cane Creek and the Chattahoochee River. For the citizens of Georgia, this is a major step toward safer drinking water. The Chattahoochee River is the source of drinking water and wastewater dilution for several cities, including Atlanta. This region, and therefore much of Georgia's population, has battled water contamination for some time. As of 2005, long before The Ray was working toward water filtration, a report by the US Geological Survey showed that multiple water samples taken from the Chattahoochee River were tested and thirty-three common organic compounds were detected in the water. Of these compounds, a majority were harmful pesticides, hydrocarbons produced by fuel combustion (emissions from vehicles), and manufacturing byproducts [28].

Now that The Ray is combatting these water contaminants, especially hydrocarbons, through the implementation of bioswales, residents of Atlanta and the rest of Georgia can be hopeful for improvements in their water quality. The load placed on the city's system of gray infrastructure will be reduced, lowering costs and easing maintenance. This is a much more sustainable and simpler way to purify water. Water pollution is a major problem for many other urban areas. This paper will continue to discuss other manners of using bioswales to fight urban water contamination.

THE APPLICATION OF BIOSWALES AND SIMILAR GREEN INFRASTRUCTURE IN THE CITY OF PITTSBURGH

Water quality is a crucial issue in Pittsburgh. The Allegheny River, which supplies drinking water to the city, is full of untreated water due to poor terrain and stormwater management, according to the Pittsburgh Water and Sewer Authority (PWSA) [29]. Current waste water systems rely primarily on storm drains, but Pittsburgh's rainy climate often overloads the water system, causing overflow, backwash of water, and flooding. This further contaminates already polluted water. An analysis of Pittsburgh's current stormwater management plan, pictured in Figure 6, shows that all the stormwater flows through storm drains and into the river, where it is then chemically treated. The outdated sewer system allows sewage to flow backwards, overwhelming the system and releasing harmful waste into rivers or buildings. Not only could this potentially cause flooding in people's homes, but it also returns contaminated water to the river.

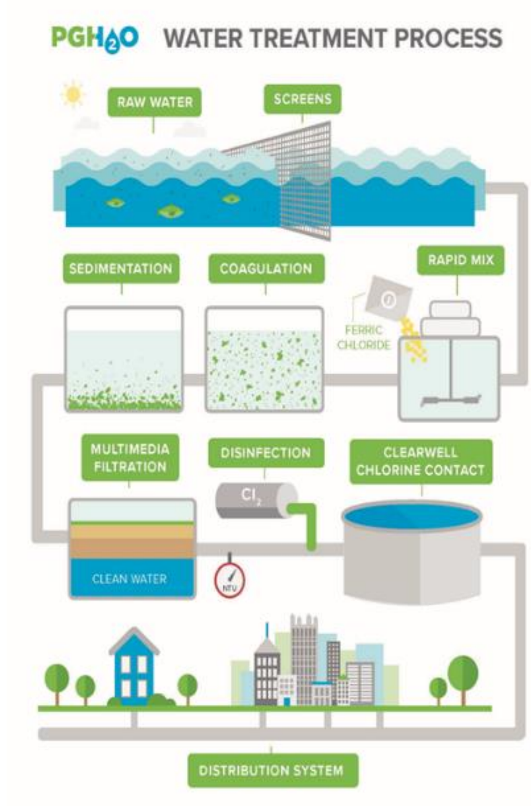

Figure 6 [29]
Current water treatment in the city of Pittsburgh

In August 2017, The Pittsburgh Post-Gazette published an article titled "Tortured Water: PWSA is the city's biggest problem to fix." The article criticizes the Pittsburgh Water and Sewer Authority's protection of drinking water in the city, stating that PWSA had to release a boiled water advisory to residents of "North Side, Millvale and Reserve…after bird and animal droppings were feared to have penetrated torn reservoir covers and contaminated the water" [30]. The city of Pittsburgh does need to examine current practices of storm water management. A possible solution is for the city to integrate green infrastructure into the current system, which could reduce overflow by slowing down water flow and pre-treating water naturally before it reaches treatment plants.

One project, called "The Four Mile Run," is working to "mitigate chronic flooding in the Run, a low-lying part of Greenfield" [31]. This project plans to install green infrastructure that will drive water to the Monongahela River by planting trees for erosion control and constructing rain gardens. This project also plans to install infiltration trenches next to the running path and expand the capacity of the Panther Hollow Lake in Schenley Park to prevent flooding during heavy rains [32]. There are also plans to disconnect Panther Hollow Watershed from the sewer system and connect it into a new stream valley to redirect water and allow for rehabilitation of the lake and surrounding green space [33]. This does not solve water contamination problems for the rest of the city, but PWSA and other independent groups are drafting plans for installing green infrastructure throughout the city. In some locations, empty lots will be turned into biofiltration rain gardens [34]. Due to the diversity in the design of the city, multiple forms of green infrastructure must be installed to have an overall positive effect on water quality.

A shift toward green infrastructure in the city of Pittsburgh requires a careful examination of available green space and population density to determine areas at greatest risk of high water flow. Figure 7 shows a breakdown of the green space in the city of Pittsburgh, and Figure 8 shows the population density by census block.

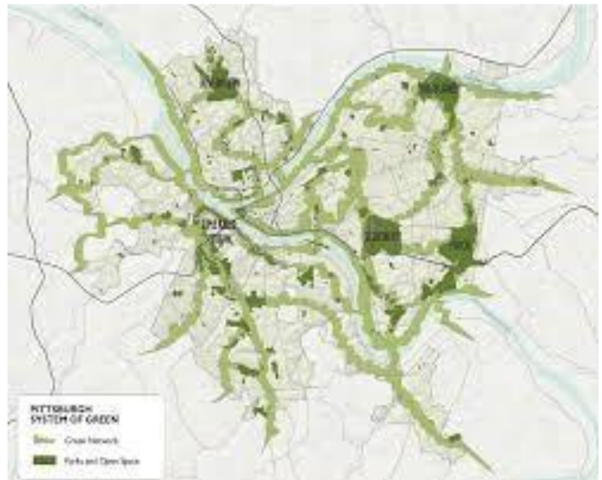

Figure 7 [34]
Green space in the city of Pittsburgh

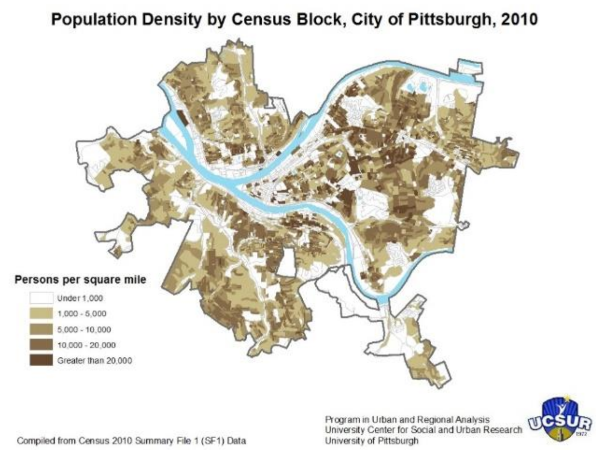

Figure 8 [35]
Population density in Pittsburgh (2010)

Because green infrastructure is less expensive and requires less construction and maintenance than gray infrastructure, it is possible for individuals and communities to contribute to the improvement of water quality. Some green infrastructure, like rain gardens, rain barrels, green roofs, community gardens, or trees can be implemented by individuals and communities. These kinds of green infrastructure can be very effective in areas that are not densely-populated. In downtown Pittsburgh, however, water issues are more severe and require the organized work of groups like PWSA.

As previously explained, bioswales effectively purify water and slow its flow by percolating it gradually back into ground soil. Their small size and ability, as demonstrated in New York City, make it reasonable to assume that they could be a solution in Pittsburgh. By installing bioswales near the sidewalks, streets, and in medians of Downtown and other urban areas of Pittsburgh, the water flow into the sewers would be greatly reduced, decreasing the backflow and flooding that occurs with significant rainfall.

On the Southside slopes, Mount Washington, and other elevated areas, landslides are another hazard. The steep slopes funnel all the rain down and into the rivers, preventing flooding, but also causing erosion. This can result in decreased stability of buildings in these areas. Some green infrastructure, such as vegetated filter strips and bioswales with trees, can work to combat the erosion, providing support from roots to strengthen the ground structure and prevent sliding. Vegetated filter strips and bioswales would slow the water flow downhill during rainstorms, preventing flooding and the overflow of Pittsburgh's water system. An important aspect of sustainable planning is using the existing environment. Pittsburgh's topography makes water flow and flooding serious issues because of steep slopes down to the river. When designing green infrastructure for the city, the steep slopes and heavy water events must be considered to ensure that whatever is constructed will best fit the city and its needs. Green infrastructure cannot solve every city's water problems in the same way; it needs to be uniquely formed to sustainably fit the city's topographical needs, population size, climate, and existing natural environments.

It is clear that Pittsburgh needs to invest in green infrastructure to ease the load on the city's dated and problematic sewer system. This will aid in water purification and allow PWSA to practice smarter and safer stormwater management and treatment. The addition of bioswales and other types of green infrastructure in the city will reduce the load on PWSA's water system and create a better balance between green and gray infrastructure to best benefit the residents of Pittsburgh. Bioswales will increase the overall efficiency and sustainability of the water treatment in the city by incorporating natural materials and processes to aid the existing system. A short-term benefit to the use of bioswales is the increased safety of drinking water to residents of the city and its surrounding areas by filtering the water and ensuring that the Allegheny River stays clean and safe.

Implementing green infrastructure in a city requires a lot of communication and cooperation between residents and government, fostering a sense of pride in the city and the community. While green infrastructure is merely one component of a solution to the serious problems in our communities, it supplies a good starting point for the city to work to develop new systems. Green infrastructure also benefits the planet as a whole, increasing habitats and biodiversity, decreasing carbon emissions and air pollutants, slowing climate change, and protecting the fragile ecosystems of our planet.

HOW BIOSWALES CONTRIBUTE TO A MORE SUSTAINABLE FUTURE

There is no solution that can single-handedly replace gray infrastructure, but our research shows that when paired with other sustainable methods, bioswales have the potential to replace and improve upon man-made methods of water purification. Gray infrastructure cannot sustain the planet's rapidly growing population indefinitely. Eventually, resources will be depleted, costs will be too high, and construction space will be too scarce for man-made solutions to water filtration to be effective. Luckily, bioswales and green infrastructure are low-cost, require a small number of resources, and can be constructed in nature without disturbing delicate ecosystems or displacing local population. The only maintenance required is regular mowing (if grasses are planted in the bioswale) and litter removal. Animal and plant life, as well as human society, can benefit from the implementation of bioswales, as all life needs access to clean water to survive.

The key to constructing effective and beneficial green infrastructure is understanding the environment in which it will be constructed. Types of green infrastructure that use plants to purify water should only be implemented in areas where the plants are native to avoid invasive species and ensure effectiveness. These plants then act as food sources for the local wildlife, reinforce biodiversity in the ecosystem, and work efficiently to rid water sources of pollution and other contamination.

The sustainability of bioswales takes many different forms. Environmentally, bioswales combat water pollution, strengthen the presence of plant species in their native environments, and contribute toward a healthier ecosystem for all life. Economically, bioswales are inexpensive to construct and maintain and reduce strain on nearby gray infrastructure, decreasing costs associated with its maintenance as well. Socially, bioswales create a more beautiful and healthier environment for surrounding communities. Quality of life increases with water quality, and access to green space improves mood.

At present, bioswales are not completely replacing gray infrastructure, but can improve systems of water filtration that are already being used in urban areas. Previous examples of water contamination in Pittsburgh, Georgia, and China show that gray infrastructure alone does not function with the efficiency needed to combat pollution in an industrial society. Bioswales make gray infrastructure more efficient and work to mitigate its harmful effect on the environment. When man-made systems flood or reach capacity, bioswales protect our water sources from unfiltered and hazardous wastewater by collecting and purifying it. As more bioswales are implemented, they can ease the load of gray infrastructure. It is possible that eventually, bioswales and other forms of green infrastructure can be implemented widely enough that gray infrastructure is gradually replaced. This is the ultimate goal to create a more sustainable and secure future for generations to come.

SOURCES

[1] M. Palmer, J. Liu, J. Matthews, M. Mumba, P. D'Odorico. "Water Security: Gray or Green?" Science. 08.07.2015. Accessed 02.07.2019. http://science.sciencemag.org/content/349/6248/584.1

[2] A. Ebenstein. "The Consequences of Industrialization: Evidence from Water Pollution and Digestive Cancers in China." Review of Economics and Statistics. 01.30.2012. Accessed 02.007.2019. https://www.mitpressjournals.org/doi/abs/10.1162/rest_a_00150

[3] S. Bunn. "Grand Challenge for the Future of Freshwater Ecosystems." Frontiers in Environmental Science. 03.21.2016. Accessed 03.05.2019. https://doi.org/10.3389/fenvs.2016.00021.

[4] A. Osouli, A. Bloorchian, M. Grinter, A. Alborzi, S. Marlow, L. Ahiablame, J. Zhou. "Performance and Cost Perspective in Selecting BMPs for Linear Projects." Water. 04.25.2017. Accessed 01.28.2019. https://res.mdpi.com/water/water-09-00302/article_deploy/water-09-00302.pdf?filename=&attachment=1.

[5] W. Langer. "Water Purification Processes Using Sand Demonstrate Another Green Aggregate Application." Aggregates Manager. 09.26.2017. Accessed 03.05.2019. https://www.aggman.com/green-aggregates-and-water-purification/

[6] M. Garder. "Effects of Sediments on BMPs for Highway Runoff Control." University of Nebraska-Lincoln, Civil Engineering. 12.2015. Accessed 03.27.2019. http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1088&context=civilengdiss.

[7] J. Coffman. "Create a Rain Garden or Bioswale." American Society of Landscape Architects Career Discovery Program. 2008. Accessed 01.27.2019. https://www.asla.org/uploadedFiles/CMS/Chapters/CD_Bioswale.pdf.

[8] B. Anderson, B. Phillips, J. Voorhees, K. Siegler, R. Tjeerdema. "Bioswales reduce contaminants associated with toxicity in urban storm water." Environmental Toxicology and Chemistry. 05.04.2016. Accessed 01.24.2019. https://setac.onlinelibrary.wiley.com/doi/full/10.1002/etc.3472.

[9] S. Murphy. "General Information on Solids." City of Boulder/USGS Water Quality Monitoring. Accessed 03.06.2019. http://bcn.boulder.co.us/basin/data/NEW/info/TSS.html.

[10] S. Abha, C. Swaranjit Singh. "Hydrocarbon Pollution: Effects on Living Organisms, Remediation of Contaminated Environments, and Effects of Heavy Metals Co-Contamination on Bioremediation." Introduction to Enhanced Oil Recovery (EOR) Processes and Bioremediation of Oil-Contaminated Sites. 05.31.2011. Accessed 03.06.2019. https://www.intechopen.com/books/introduction-to-enhanced-oil-recovery-eor-processes-and-bioremediation-of-oil-contaminated-sites/heavy-metals-interference-in-microbial-degradation-of-crude-oil-petroleum-hydrocarbons-the-challenge.

[11] C. Bond, K. Buhl. "Pyrethrins General Fact Sheet." National Pesticide Information Center, Oregon State University Extension Services. 2014. Accessed 03.06.2019. http://npic.orst.edu/factsheets/pyrethrins.html.

[12] "Freshwater Wetlands." AAAS Atlas of Population and Environment. Accessed 03.05.2019. http://atlas.aaas.org/index.php?part=2&sec=eco&sub=wetlands.

[13] R. Gardner, S. Barchiesi, C. Beltrame, C. Finlayson, T. Galewski, I. Harrison, M. Paganini, C. Perennou, D. Pritchard, A. Rosenqvist, M. Walpole. "State of the World's Wetlands and Their Services to People: A Compilation of Recent Analyses." Ramsar Convention Secretariat. 04.05.2015. Accessed 03.05.2019. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2589447.

[14] J. Talberth, C. Hanson. "Green vs. Gray Infrastructure: When Nature is Better than Concrete." World Resources Institute. 07.19.2012. Accessed 03.27.2019. https://www.wri.org/blog/2012/06/green-vs-gray-infrastructure-when-nature-better-concrete

[15] "Benefits of Green Infrastructure." Global Designing Cities Initiative. 06.06.2016. Accessed 03.27.2019. https://globaldesigningcities.org/publication/global-street-design-guide/utilities-and-infrastructure/green-infrastructure-stormwater-management/benefits-green-infrastructure/

[16] "Vegetative Filter Strips." Natural Resources Conservation Service, New Jersey. Accessed 03.06.2019. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/nj/technical/?cid=nrcs141p2_018851.

[17] "Structural BMP Criteria: Vegetated Filter Strip." Pennsylvania Stormwater Management Manual. Accessed 03.05.2019. http://www.bfenvironmental.com/pdfs/VegFilterStrips.pdf.

[18] M. Grismer, A. Toby O'Geen, D. Lewis. "Vegetiative Filter Strips for Nonpoint Source Pollution Control in Agriculture." 2006. Accessed 03.27.2019. https://anrcatalog.ucanr.edu/pdf/8195.pdf.

[19] "Infiltration Trench Conbined." Minnesota Stormwater Manual. 05.15.2017. Accessed 03.06.2019. https://stormwater.pca.state.mn.us/index.php?title=Infiltration_trench_combined.

[20] J. Li. "A Holistic Approach to Stormwater Management." Ryerson University, Department of Civil Engineering. Accessed 03.06.2019. http://www.civil.ryerson.ca/stormwater/menu_1/index.htm.

[21] "Infiltration Trenches." Minnesota Urban Small Sites BMP Manual. Accessed 03.05.2019.

http://www.sccd.org/wp-content/uploads/2015/07/Infiltration-Trenches.pdf.
[22] K. Mateleska. "Methodology for Developing Cost Estimates for Opti-Tool." United States Environmental Protection Agency. 02.20.2016. Accessed 03.06.2019. https://www3.epa.gov/region1/npdes/stormwater/ma/green-infrastructure-stormwater-bmp-cost-estimation.pdf.
[23] R. Winston, W. Hunt, S. Kennedy, J. Wright. "Field Evaluation of Storm-Water Control Measures for Highway Runoff Treatment." Journal of Environmental Engineering. 01.2012. Accessed 03.27.2019. https://ascelibrary.org/doi/full/10.1061/%28ASCE%29EE.1943-7870.0000454.
[24] A. Henebery-Phelan. "Creating the World's First Sustainable Highway." Eno Transportation Weekly. 01.16.2017. Accessed 03.05.2019. https://www.enotrans.org/article/creating-worlds-first-sustainable-highway/#.WIDlJ7tvBWo.twitter.
[25] A. Cullen. "Combatting Pollution with Bioswales." The Ray. 03.27.2017. Accessed 03.04.2019. https://theray.org/2017/03/27/combating-pollution-with-bioswales/.
[26] C. Zhang, S. Li, R. Jamieson, F. Meng. "Segment-based Assessment of Riparian Buffers on Stream Water Quality Improvement by Applying and Integrated Model." Ecological Modelling. 02.10.2017. Accessed 03.06.2019. https://www.sciencedirect.com/science/article/pii/S030438001630758X.
[27] "Bioswales". The Ray. Accessed 03.04.2019. https://theray.org/tech/bioswales/.
[28] B. Hughes, C. Younker. "Organic Compounds Assessed in Chattahoochee River Water Used for Public Supply near Atlanta, Georgia, 2004-05." National Water-Quality Assessment Program, Source Water-Quality Assessment. Accessed 03.06.2019. https://pubs.usgs.gov/fs/2011/3062/pdf/fs2011-3062.pdf.
[29] "PWSA Annual Drinking Water Quality Report 2017." Pittsburgh Water and Sewer Authority. Accessed 03.06.2019. http://www.pgh2o.com/files/2017CCR.pdf.
[30] "Tortured Water: PWSA is the City's Number One Problem to Fix." Pittsburgh Post-Gazette. 08.30.2017. Accessed 03.06.2019. https://www.post-gazette.com/opinion/editorials/2017/08/30/Tortured-water-PWSA-is-the-city-s-No-1-problem-to-fix/stories/201708310053.
[31] M. Krauss. "Pittsburgh Has A Stormwater Problem; But PWSA Has A Plan For Schenley Park." WESA. 09.18.2018. Accessed 03.06.2019. https://www.wesa.fm/post/pittsburgh-has-stormwater-problem-pwsa-has-plan-schenley-park.
[32] "Four Mile Run and Panther Hollow Watersheds." Pittsburgh Parks Conservancy. Accessed 03.06.2019. https://www.pittsburghparks.org/projects/four-mile-run.
[33] "PWSA and Parks Conservancy Engage Phronesis to Explore Stormwater Engineering." 4 Mile Run Watershed and Mobility Plan. Accessed 03.27.2019. http://pittsburghpa.gov/fourmilerunproject/explore-stormwater-engineering.html
[34] "OpenSpace PGH." Pittsburgh City Planning. 07.09.2013. Accessed 03.06.2019. http://apps.pittsburghpa.gov/dcp/OpenSpacePGH%20lo%20res.pdf.
[35] "Parcel Scale Green Infrastructure Siting and Cost Effectiveness Analysis." University of Pittsburgh Center for Social and Urban Research. Accessed 02.07.2019. https://wetweather.pitt.edu/green/.

ADDITIONAL SOURCES

A. Bloorchian. "Effect of Major Factors on Bioswale Performance and Hydrologic Processes for the Control of Stormwater Runoff from Highways." Southern Illinois University at Carbondale, ProQuest Dissertations Publishing. 2018. Accessed 02.06.2019. https://search.proquest.com/docview/2080189859?pq-origsite=summon
A. Bloorchian, L. Ahiablame, A. Osouli, J. Zhou. "Modeling BMP and Vegetative Cover Performance for Highway Stormwater Runoff Reduction. https://www.researchgate.net/publication/303398303_Modeling_BMP_and_Vegetative_Cover_Performance_for_Highway_Stormwater_Runoff_Reduction
T. Eniolu Morakinyo, Y. Fat Lam, S. Hao. "Evaluating the Role of Green Infrastructures on Near-Road Pollutant Dispersion and Removal: Modelling and Measurement." Journal of Environmental Management. 07.24.2016. Accessed 02.06.2019. http://www.academia.edu/27934587/Evaluating_the_role_of_green_infrastructures_on_near-road_pollutant_dispersion_and_removal_Modellingand_measurement
"EPA Science Matters Newsletter: Helping Pittsburgh and Other Cities Expand Green Infrastructure." United States Environmental Protection Agency. Accessed 02.07.2019. https://www.epa.gov/water-research/epa-science-matters-newsletter-helping-pittsburgh-and-other-cities-expand-green.
N. Fahui, L. Zhanmeng, M. Lujan, L. Jie. "Role of Media: Implication for Application of Urban Storm Water Runoff Bioretention Systems." 2013 Third International Conference on Intelligent System Design and Engineering Applications. 02.07.2013. Accessed 02.07.2019. https://ieeexplore.ieee.org/document/6455623
J. Kelley. "Performance of Bioswales for Containment and Treatment of Highway Stormwater Runoff." Temple University, ProQuest Dissertations Publishing. 2018. Accessed 02.06.2019. https://search.proquest.com/docview/2046417831?pq-origsite=summon
H. Li. "Green Infrastructure for Highway Stormwater Management: Field Investigation for Future Design, Maintenance, and Management Needs." Journal of

Infrastructure Systems. 2015. Accessed 02.07.2019. https://www.researchgate.net/publication/276846659_Green_Infrastructure_for_Highway_Stormwater_Management_Field_Investigation_for_Future_Design_Maintenance_and_Management_Needs

J. Lee, T. Edil, C. Benson, J. Tinjum. "Building Environmentally and Economically Sustainable Transportation Infrastructure: Green Highway Rating System." Journal of Construction Engineering and Management. 05.23.2013. Accessed 01.24.2019. https://ascelibrary.org/doi/pdf/10.1061/%28ASCE%29CO.1943-7862.0000742.

D. Marcucci, L. Jordan. "Benefits and Challenges of Linking Green Infrastructure and Highway Planning in the United States." Environmental Management. 11.08.2012. Accessed 02.06.2019. https://link.springer.com/article/10.1007%2Fs00267-012-9966-7

J. McLaughlin. "NYC Bioswales Pilot Project Improves Stormwater Management." Clear Waters. 2012. Accessed 01.27.2019. http://m.nywea.org/clearwaters/12-2-summer/7.pdf.

M. Paz Avilez, M. Yoon, N. Boydston. "Is It Worth the Green? Assessing the Value of Green Stormwater Infrastructure Using Triple Bottom Line Analysis." Nine Mile Run Watershed Association. Accessed 02.07.2049. https://ninemilerun.org/wp-content/uploads/2016/08/NMRWA_TBL_GSI_Presentation.pdf

Z. Qin, R. Tang, G. Qian, J. He. "Research Progress of Pavement Runoff." 2011 International Conference of Remote Sensing, Environment and Transportation Engineering. 07.29.2011. Accessed 02.06.2019. https://ieeexplore.ieee.org/document/5965050

B. Scharenbroch, J. Morgenroth, B. Maule. "Tree Species Suitability to Bioswales and Impact on the Urban Water Budget." Journal of Environmental Quality. 06.12.2015. Accessed 03.06.2019. https://www.ncbi.nlm.nih.gov/pubmed/26828175.

M. Shannon, P. Bohn, M. Elimelech, J. Georgiadis, B. Mariñas, A. Mayes. "Science and technology for water purification in the coming decades." Nanoscience and Technology. 2010. Accessed 01.27.2019. https://www.worldscientific.com/doi/abs/10.1142/9789814287005_0035.

ACKNOWLEDGEMENTS

We would like to thank our writing instructor, Janet Zellmann, for her excellent insight and assistance as we began our research and selected a topic for this paper.

We'd also like to thank Nicholas Raible, our undergraduate mentor, for sharing his experience with this assignment and offering advice throughout the writing process.

Lastly, we'd like to acknowledge all those that do their part to save the planet by recycling, conserving energy, reducing their carbon footprint, and researching and implementing systems like bioswales that are able to mitigate the disastrous effects of climate change. Our planet and our future depend on your efforts.