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Evaluating Capital and Maintenance Costs for Four Low Impact Development Treatment Systems, and their Efficiency in Removing Total Suspended Solids from Storm Water Runoff

Jimmy A. Dileo
jimmydileo@gmail.com

This Master's Project

Evaluating capital and maintenance costs for four Low Impact Development treatment systems, and their efficiency in removing Total Suspended Solids from storm water runoff

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Jimmy A. Dileo

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ABSTRACT

Storm water runoff is the leading source of surface water pollution. To reduce the amount of contaminants in storm water runoff, municipalities and city governments require developers to construct storm water treatment measures, or low impact development (LID) systems, as part of the development project. LID storm water treatment systems utilize a mix of sedimentation, filtration, adsorption, and phytoremediation as mechanisms that remove pollutants from storm water prior to discharging to waterbodies. Existing studies have shown that LID storm water measures are effective in reducing runoff and improving water quality, but studies that can assist decision makers in selecting the most effective practices for their water quality needs and budgets are limited. This master's project study compared the percentage of total suspended solids (TSS) removed, and capital and maintenance costs required for each treatment measure. Data were collected from primary literature from previous studies and an analysis of variance (ANOVA) test was performed to determine any differences in TSS removal efficiencies between the four treatment types. Physical, biological, and chemical properties involved with each treatment LID were assessed to determine potential causes for differences observed in removal efficiencies. Data from primary literature were also collected for capital and maintenance costs for each treatment measure, and bar graphs were generated to visually determine the least costly LID over a 20-year time period. Maintenance requirements for each treatment measure were evaluated to provide insight into potential differences observed in treatment costs. By comparing the costs and TSS removal for each LID structure, owners and operators can now better understand and select the most cost effective and efficient solution for treating storm water runoff at their development site. Sand Filters, Porous Pavement, and Vegetated Swales were not significantly different, and achieved high removal of TSS in storm water runoff. Detention Basins were the least costly per volume of storm water runoff the LID is capable of treating due to its open-pit structural design, and minimal maintenance involved. Vegetative Swales were the most cost effective due to its high TSS removal efficiency and affordable costs relative to Sand Filter and Porous Pavement systems.

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1. INTRODUCTION

Storm water runoff is one of the leading sources of surface water pollution (Morton, 2017). Storm water runoff contains a multitude of pollutants that range from hydrocarbons from roads and highways, to heavy metals from industrial sources, or pesticides from agricultural practices. Rain falls to the ground, picks up these contaminants, and discharges directly into local waterways (USEPA, 2012). Many studies have linked environmental and human health issues with storm water pollution. Storm water contamination can lead to the death of aquatic organisms, as well as cause human health concerns as severe as developing cancer (Wood and Armitage, 1997; King and Blanton, 2011; Dadi et al., 2017). These issues are a result of urbanization.

As urban communities develop, and industrial and commercial properties grow, the amount of contaminants in storm water runoff may also increase. Developing urban, industrial, or commercial areas increase the amount of impermeable surfaces available. The additional impervious surfaces prevent storm water from soaking into naturally existing soil or ground cover. A larger impermeable surface area will collect a higher volume of storm water runoff that can lead to erosion in streambanks and channels, and further accumulate contaminants in surface water (Morton, 2017). The varying chemical and biological characteristics caused by metal and organic pollutants in storm water runoff in urban, industrial, and commercial areas demonstrate the need for treatment measures that can reduce runoff pollution and improve water quality (Sandoval, 2017).

In order to manage rainfall volume and provide treatment to storm water runoff, many municipalities require commercial property owners to implement strategies that catch or delay the flow of rainwater (Morton, 2017). Delaying the flow of storm water can prevent overloading municipal storm water conveyance systems during high volume rain events. One type of control method commonly used for development projects are low impact development (LID) structures. LIDs attempt to restore natural or pre-development hydrological characteristics of a developmental site by capturing total suspended solids (TSS) through mechanisms including infiltration, filtration, evaporation, and detention runoff (Joksimovic and Alam, 2014).

TSS is a measure of organic and inorganic material in water, which may include silt, decaying plant and animal matter, industrial wastes, and sewage. TSS disturbed or created by anthropogenic sources may travel with storm water runoff and negatively affect the water quality of the receiving waterbody (Bilottaa and Braziera, 2008). TSS is a surrogate for assessing the level of contamination in storm water runoff because of its organic content and its ability to react with other harmful pollutants (Takamatsu et al., 2010). However, Scholes et al. (2008) notes that it is difficult for storm water managers to make water quality decisions due to the limited availability and reliability in data for different pollutants. Thus, it is important to characterize the various treatment methods available, and how they factor into the efficiency of removing sediment and contaminants from storm water runoff. There are numerous studies in the available literature that promote hydrological benefits, as well as the treatment performance for removing TSS. Opposed to the hydrological benefits, this master's project study will focus on the treatment performance aspect of LID technology by evaluating the properties that affect treatment performance for various LID storm water treatment devices. Depending on the LID treatment type, treatment mechanisms may include sedimentation, filtration, adsorption, and/or phytoremediation. This master's project attempts to evaluate these treatment mechanisms and explore whether a single, or a combination of treatment mechanisms fair more appropriately for removing contaminants from storm water runoff.

Existing studies have shown that LID storm water measures are effective in reducing runoff and improving water quality, but studies that can assist decision makers in selecting the most effective practices for their needs and budgets are limited (Wright et al., 2016). Owners and operators of future LID treatment systems need to be able to select the most cost effective and efficient pollutant removal option for their development plan. At the industrial level, these results are meaningful because it is important to understand how the LID potentially installed can influence the results of storm water discharge permit requirements. At the commercial or urban development level, a similar concern should be considered as these development projects must adhere to specific municipal and regional water quality requirements.

There are studies in the available literature that compare various costs involved with LID technology, but the majority of these studies confined their analyses to measuring installation costs (MacMullan and Reich, 2007). Installation cost is one of the most important considerations for developers when choosing between LID or conventional storm water controls, but focusing on installation costs omits relevant economic information, such as operation and maintenance (O&M) costs. Evaluating projects based on installation costs has advantages of appearing to cost less. The tradeoff for storm water managers is an incomplete and possibly biased description of economic consequences, especially over the life of the LID system (MacMullan and Reich, 2007). Developers may construct the LID system, without considering costs that the owner or operator may accrue due to required maintenance of the system. There are limited studies that evaluate a coherent dataset and perform an exhaustive analysis on both capital, and O&M costs. Ahiablame et al. (2012) suggests that research is needed to create public policy and regulations that address the lack of knowledge and increase awareness of LID treatment through education programs, and government incentives to alleviate high maintenance costs. This master's project seeks to understand the various costs involved with LID treatment technology in order to provide owners and operators a range of LID options that fit into their budget.

This master's project evaluates the connection between the costs and level of TSS removal for various treatment LIDs. By comparing the costs and TSS pollutant removal efficiencies of each LID structure, owners and operators can better understand and select the most cost effective and efficient pollutant prevention solution for treating storm water runoff. This study also compares the physical, chemical, and biological treatment mechanisms for the following LID treatment measures: vegetated swales (bioretention), sand filters, porous pavement, and dry detention basins. Due to the combined physical, chemical, and biological properties involved, vegetated swales are expected to be the most effective at removing sediment in storm water runoff. Dry detention basins are anticipated to be the least costly per volume of storm water runoff the LID is capable of treating due to its open-pit high volume structural design.

2. BACKGROUND

2.1 Human and Environmental Health Effects

Many studies have revealed the negative impacts of human and environmental health from water pollution. Suspended particles, or TSS, can affect the quality of water and can be detrimental to aquatic organisms (Wood and Armitage, 1997; King and Blanton, 2011). The effect of TSS on aquatic organisms can be realized by evaluating the concentration and chemical composition of TSS, the level of exposure to the organism, and the size of the TSS particles (Bilottaa and Braziera, 2008). Heavy metals and pesticides found in industrial or agricultural runoff can sorb to TSS (Bilottaa and Braziera, 2008). Pesticides that sorb to TSS and flow to waterbodies via storm water runoff can lead to dangerous levels of biological oxygen demand (BOD). An increase in BOD increases the demand of dissolved oxygen (DO). Aquatic biota relies on a sufficient concentration of oxygen in the water in order to live (Dadi et al., 2017). These organisms can suffocate due to a high concentration of BOD caused by organic material sorbed to TSS.

Studies in the existing literature have associated TSS with negative ecological impacts, including the death of benthic organisms, a reduction in fish population, and an increase in threat to endangered species (Berkman and Rabeni, 1987; Cooper, 1993; Waters, 1995; Wood and Armitage, 1997; King and Blanton, 2011). Besides pesticides, one other possible explanation for these negative impacts is the association between heavy metals and suspended sediment (Nie et al. 2008; King and Blanton, 2011). Since heavy metals are toxic and are not biodegradable, they can be consumed in the environment and bioaccumulate in aquatic organisms. Bioaccumulation occurs when pollutants accumulate in plant and animal tissues to higher concentrations than in their original environmental location (Weiner, 2013).

Heavy metals have been associated with human health impacts. Khan and Malik (2014) conducted a study on human health effects of untreated or insufficiently treated industrial effluent contaminated with metals and discovered that high metal concentrations affected the normal function of human cells, including those of fetuses, infants, and children. According to the findings of Khan and Malik (2014), higher metal concentrations can lead to the impairment of physiological functions such as reproduction, and the ability of the body to maintain salt and water intake (osmoregulation). The toxicity of heavy metals can also increase the likelihood of developing cancer, and in some instances, death (Dadi et al., 2017). Govindarajalu (2003) conducted a study on people using polluted water in Noyyal River in Southern India, and collected information on the health of 31 villages. Govindarajalu (2003) discovered respiratory issues, allergic reactions, and gastrointestinal complications as a result of the water pollution. Other studies have linked human health issues with contaminated drinking water. An increase in the turbidity of treated drinking water have been associated with an increase of acute gastrointestinal illnesses among children and the elderly (Gaffield et al., 2003). In a study conducted in Long Island Sound, it was discovered that urban storm water runoff is responsible for an estimated 47 percent of the pathogen contamination found in drinking water, likely due to the large loads of bacteria generated from urban and suburban streets, parking lots, and lawns (Gaffield et al, 2003).

The potential human and environmental health effects of high TSS concentration stresses the importance of LID controls for managing urban storm water runoff. Since TSS has been considered to be a surrogate for heavy metal and toxic compounds (Djukic et al., 2016), it is expected that LID treatment measures that are the most effective at lowering the concentration of TSS in storm water effluent will also be the most effective at reducing the impact to aquatic and human health. Gaffield et al. (2003) suggests that reducing storm water runoff and associated pollution from nonpoint sources can be a valuable component of an integrated strategy to protect public health. In an attempt to alleviate environmental and human health impacts associated with storm water pollution, municipalities have set stringent requirements for incorporating LID technology as part of the building permit process for new development projects. Municipalities require storm water that fall onto new urban and commercial development to be reduced volumetrically and treated with LID technology, prior to flowing to local waterbodies.

2.2 Hydrological and Water Quality Benefits of LID Technology

Land development and the increase in urbanization affects the water quality, and water quantity of storm water runoff. It was discovered that an increase of 18 percent of impermeable surfaces in Indianapolis, Indiana over a time span of 18 years caused the annual average runoff volume to increase by 80 percent, and the average annual load for metals to increase by greater than 50 percent (Gaffield et al., 2003). The increase in paved surfaces decreases the ability of storm water from infiltrating ground cover, and naturally treating the storm water, prior to recharging ground water (Ahiablame et al., 2012). As a result, a higher quantity of storm water runoff flows across impermeable surfaces and drains to municipal storm water conveyance systems. This increases the likelihood of overloading the storm conveyance system, which may result in flooding during heavy storm events.

The United States Environmental Protection Agency (2003) notes that storm water runoff increases from 10 percent to 55 percent for development projects that alter natural ground cover to an impervious area (Figure 1). Shallow infiltration of storm water for groundwater recharge is also reduced from 25 percent to 10 percent as a result of post-development impervious cover (USEPA, 2003). LID techniques attempt to restore natural hydrological benefits that would otherwise be absent as part of the development project. In addition to hydrological implications of urbanization, Dodd and Whiles (2004) found that urban land use also influences TSS values in adjacent surface waters. The urbanization of land results in greater TSS loading of receiving waters due to the increase in storm water runoff (King and Blanton, 2011). TSS concentrations in natural undeveloped streams in southern California were found to be twice as low compared to streams in developed areas (Stein and Yoon, 2008). Hydrological impacts and an increase in TSS in storm water runoff stresses the importance of LID technology to mitigate these concerns.

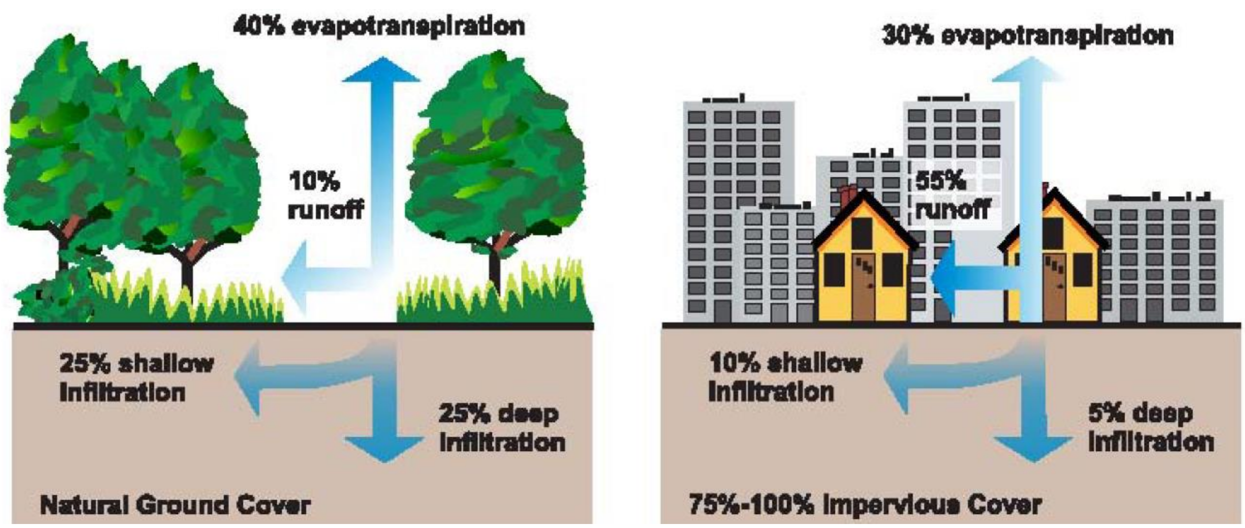


Figure 1 – A comparison and change in volume of storm water runoff between natural ground cover to impervious cover after development (USEPA, 2003). Stormwater runoff increases from 10 percent to 55 percent runoff post-development. Shallow infiltration of stormwater for groundwater recharge is reduced from 25 percent to 10 percent as a result of impervious cover post-development.

LID technology is a land planning and engineering design method applied to storm water management to control system overflow and improve water quality (Gülbaz and Kazezyilmaz-Alhan, 2015). The main goals of LID principles and practices include reducing peak flow and runoff volume, increasing infiltration and groundwater recharge, and improving water quality

(Hunt et al. 2010; Ahiablame et al., 2012). LID technology provides owners and operators the ability to manage rain at the same location in which it falls to the ground, and to treat storm water as a beneficial water source, rather than as wastewater (Gülbaz and Kazezyilmaz-Alhan, 2015). Gülbaz and Kazezyilmaz-Alhan (2015) conducted a study on the Sazlidere Watershed located in Istanbul, Turkey, and discovered that implementing vegetated swales and pervious pavement resulted in a decrease in the peak flow rate and TSS concentration of storm water in the watershed compared to when LID technology was absent. There are numerous studies in the available literature that promote hydrological benefits, as well as the treatment performance for removing TSS. Opposed to the hydrological benefits, this master's project study will focus on the treatment performance aspect of LID technology by evaluating the properties that affect treatment performance for various LID storm water treatment devices.

2.3 Municipal Requirements for LID

Municipalities require the implementation of LID technology to be installed as a structural best management practice (BMP) for new development projects. For example, the California State Water Resources and Control Board (SWRCB) issued a Municipal Regional Stormwater National Pollutant Discharge Elimination System (NPDES) Permit (MRP) for the San Francisco Bay Region (Order No. R2-2015-0049) to regulate storm water discharges from municipalities and local agencies in Alameda, Contra Costa, San Mateo, and Santa Clara counties, and the cities of Fairfield, Suisun City, and Vallejo. Similar municipal permits and requirements have been issued in other regions. As part of Provision C.3 of the MRP, municipal or city planning authorities are required to provide permittees with various storm water treatment options that address soluble and insoluble contaminants in storm water runoff. The MRP also requires municipalities to enforce the implementation of LID techniques to prevent an increase in storm water runoff from new development and redevelopment projects.

The California SWRCB has prepared a C.3 Technical Guidance Manual to assist permittees with LID requirements, including guidance on how to calculate and design for sufficient hydrological benefits. Soil specifications for bioretention LID measures such as vegetated swales are required to achieve an infiltration rate of at least 5 inches per hour, have sufficient moisture content to support plant growth, and consist of 60-70 percent sand, and 30-40 percent compost (SWRCB, 2015).

Since the efficiency of TSS treatment can be affected by the particle size of the treatment media, it is important to understand how the particle distribution of sand and soil used in SWRCB's Standard for bioretention measures compare to other studies available in the existing literature (Barrett, 2005). Figure 2 includes SWRCB sand and compost gradation requirements for bioretention treatment measures. The specific properties that affect treatment performance are discussed in further detail below.

Sieve Size	Percent Passing (by weight)	
	Min	*Max*
3/8 inch	100	100
No. 4	90	100
No. 8	70	100
No. 16	40	95
No. 30	15	70
No. 40 or No.50	5	55
No. 100	0	15
No. 200	0	5

Sieve Size	Percent Passing (by weight)	
	Min	*Max*
1 inch	99	100
1/2 inch	90	100
1/4 inch	40	90
No. 200	1	10

Figure 2 - Sand (left) and Compost (right) gradation requirements by SWRCB for use in LID bioretention storm water treatment measures (SWRCB, 2015)

2.4 Properties that Affect Treatment Performance

The percent removal efficiency of TSS varies across LID structures. Yu et al. (2001) claims that a vegetated swale can remove 72 percent TSS, whereas porous asphalt, according to a study conducted by Houle et al. (2013), can remove up to 99 percent TSS (Yu et al., 2001; Houle et al., 2013). The percent removal efficiency of LIDs also varies across existing literature that studied the same type of LID treatment. For example, 95 percent of TSS was removed by an Austin sand filter compared to 51 percent of TSS removed by a sand filter in a separate study (Barrett, 2005; Houle et al., 2013). In order to gain insight into the reason behind the inconsistencies in the existing literature for TSS removal efficiency, further research into the factors that affect performance for each treatment type is necessary.

The ability of LID technology to remove pollutants from storm water runoff, largely depends on the mechanism of treatment applied. Enhancing water quality can be achieved through pollutant removal mechanics, such as physical filtration or infiltration, chemical sorption (adsorption), and biological processes (Hunt et al., 2010; Ahiablame et al., 2012). The four treatment mechanisms that are evaluated in this master's project study includes sedimentation, infiltration, adsorption, and phytoremediation.

Sedimentation is the process in which particles or sediment are allowed to settle over a period of time (Gaborit et al., 2013). For storm water runoff, sedimentation is a treatment mechanism that allows suspended particles to settle out of the runoff by gravity separation (Middleton and Barrett, 2008). Scholes et al. (2008) defines sedimentation as the vertical movement of discrete or agglomerating suspended sediment particles to the base of a water column, and notes that settling is highly dependent on the retention time of the volume of water flowing through the LID BMP system. According to Weiner (2013), sedimentation involves a two-stage process, coagulation and flocculation. Suspended solids carry an electrostatic charge that keeps them separated (Weiner, 2013). Coagulation is the process in which suspended particles collide, allowing the van der Waals and London attractions to overcome the repulsive energy that keeps them apart. Through coagulation, the suspended particles coalesce to form a larger, heavier particle, known as a floc (Weiner, 2013). Flocculation occurs when floc particles aggregate and become heavy enough to settle out of the water (Weiner, 2013). Clary et al. (2017) suggests that sedimentation is an effective treatment process for TSS removal when combined with infiltration processes.

Infiltration is the process in which storm water runoff percolates through filter media or the subsurface, such as soil or sand (Chahar et al., 2012). The rate at which infiltration occurs is affected by the characteristics of the soil media (Weiner, 2013). The cations and anions create an electrostatic field around each other that helps to maintain soil structure and sufficient porosity for adequate water infiltration (Weiner, 2013). Pollutant removal occurs through infiltration processes by physical sieving of the filtration media as particulates are removed when storm water passes through the porous substrate or hydraulic barrier (Scholes et al., 2008). Scholes et al. (2008) also suggests that infiltration promotes adsorption, which is an additional mechanism that can be applied in LID technology for storm water pollutant removal via chemical interaction with media substrate.

Adsorption is the main partitioning process that allows chemicals in liquid or air to sorb to organic or mineral surfaces found in solids (Weiner, 2013). For storm water treatment, adsorption is the process in which an ion exchange occurs that involves physical-chemical surface reactions between organic content in the storm water runoff and those found in filter media, such as sand, gravel, or soil (Achak et al., 2009). Adsorption can occur in the gravel matrix of a filter drain, vegetation within a swale, the underground reservoir of porous paving, or in substrate surface during the infiltration of an effluent through the relevant permeable material (Scholes et al., 2008).

Adsorption of pollutants to media substrate is dependent on the particulate surface area and surface composition (Scholes et al., 2008). The level of physical adhesion and/or chemi-sorption is determined by the chemical surface composition of the particle and the organic material that support adsorption of pollutants found in storm water (Scholes et al., 2008). Solubility also determines whether nonionic molecules, such as hydrocarbons, can sorb from the liquid phase to solid surfaces since sorption is much more effective for compounds of low solubility (Weiner, 2013). Dissolved ionic molecules, such as metals, sorb to surface sites by ion exchange (Weiner, 2013). According to Weiner (2013), sorption involves a two-step conceptual model. The first step involves the compound with a larger than zero partitioning coefficient to adsorb from water to the external surface of soil particles. The second step involves the diffusion of the compound from the surface of the soil particle sequestering into the interior of the soil particle, where it is less available for desorption (Weiner, 2013).

Whereas adsorption requires chemical interaction for pollutant removal, phytoremediation, another form of pollutant removal, applies biological mechanisms. Phytoremediation is the process in which plants absorb pollutants in soil through natural uptake through their roots (Leroy et al., 2016). Bioaccumulation in plants can be a useful remediation technique (Weiner, 2013). This type of treatment mechanism is found in LID treatment measures that are vegetated, such as vegetated swales or bioretention devices. Scholes et al. (2008) suggests that vegetation with an elaborate root system of aquatic macrophytes increases the contact between storm water and the uptake of pollutants, such as nitrates and phosphates. The roots can also excrete protons, organic acids, and chelating molecules to increase metal solubilization, and subsequently reduce metal toxicity by plant root uptake (Leroy et al., 2016). Although there are minimal studies in the available literature that show a reduction in TSS by phytoremediation, incorporating vegetation in LID technology can favor the deposition of suspended solids by reducing influent flowrates (Leroy et al., 2016). Since other pollutants tend to sorb to sediment, such as organics and metals, phytoremediation may not necessarily reduce sediment, but can indirectly treat other pollutants that are a function of TSS concentration (Leroy et al., 2016).

The potential for a pollutant to be removed within a treatment system is a function of the type and magnitude of the removal process. A summary of the four treatment mechanisms and their potential (low, medium, or high) to remove pollutants or improve water quality is presented in Table 1. Water quality indicators, including TSS, BOD, chemical oxygen demand (COD), phosphates, and fecal coliforms, all of which can be found in storm water runoff are evaluated for each treatment process. The potential level of treatment for each pollutant category was derived from a study conducted by Scholes et al. (2008). Removal of TSS is dominant in sedimentation and infiltration processes, with less of an impact for the adsorption process, and no impact to TSS by phytoremediation. However, phytoremediation was given a "high" removal potential for nutrients, including nitrates and phosphates, which can adhere to TSS particles. The study notes that filtration and settling mechanisms are two separate and direct removal processes, but adsorption can increase the pollutant removal efficiency when combined with either of the two former processes. Therefore, this suggests that a combination of sedimentation, infiltration, adsorption, and phytoremediation may also prove to be an effective management approach for storm water runoff and treatment.

Table 1 - Potential for direct treatment processes to remove TSS, BOD, COD, nitrates, phosphates and fecal coliforms as derived and adapted from Scholes et al. (2008).

	TSS	BOD	COD	Nitrates	Phosphates	Fecal Coliforms
Settling / Sedimentation	High	Medium	Medium	Low	High	High
Infiltration / Filtration	High	Medium	Medium	Low	High	High
Adsorption	Medium	Medium	Low/ Medium	Low	High	Medium
Phytoremediation / Uptake	N/A	Medium	Low/ Medium	High	High	N/A

N/A = Not Applicable

2.5 Application of Treatment Mechanisms in LID Systems

The level of treatment mechanisms vary across LID treatment technology. Each LID technology can be equipped with one or more mechanisms of treatment. As shown in Table 2, detention basins remove pollutants via sedimentation, a natural and physical treatment method. Sand filters and porous pavement LID technologies utilize sedimentation, infiltration, and adsorption for removal of pollutants, a combination of physical and chemical methods. Lastly, vegetated swales apply all four treatment mechanisms (sedimentation, infiltration, adsorption, and phytoremediation), which is a combination of physical, chemical, and biological treatment processes.

Table 2 - Properties that affect the treatment performance of detention basins, sand filters, porous pavement, and vegetated swales for removing TSS from storm water runoff.

	Sedimentation	Infiltration	Adsorption	Phytoremediation
Detention Basins	•			
Sand Filters	•	•	•	
Porous Pavement	•	•	•	
Vegetated Swales	•	•	•	•

Detention Basins

Detention basins utilize sedimentation as the primary process in which suspended solids, or TSS, are removed from storm water runoff (Middleton and Barrett, 2008). Dry detention basins are shallow depressions are capable of storing storm water runoff for no more than 48 hours (Weiss et al., 2007). Some benefits of dry extended detention basins include the reduction of flooding risk by providing water storage during rain events and alleviating the peak storm flow rate by releasing the collected storm water at a slower rate through a controlled outlet (Weiss et al., 2007). The diameter of the outlet pipe provides static control and limitation of the maximum flow of effluent (Middleton and Barrett, 2008). Factors that affect sedimentation in detention basins include retention time and storm water runoff volume (Gaborit et al., 2013). TSS removal efficiency increases with greater retention time and lower runoff velocity and volume (Gaborit et al., 2013; Takamatsu et al., 2010). Retention time is a function of the outlet pipe diameter, since a larger diameter pipe will release effluent at a greater rate, opposed to a smaller diameter outlet pipe that would decrease the effluent flow rate, and increase the retention time in the basin. Doing so will likely decrease the hydrologic capabilities of the basin because of slower release of water, decreasing available volume in the basin, and preventing a greater flow rate of influent.

The length-to-width ratio of the detention basin and particle density of the influent also affect how TSS is removed. A larger length-to-width ratio will prevent the initial flow of water from discharging directly out of the outlet pipe without sufficient settling time; a process referred to as shortcircuiting (Middleton and Barrett, 2008). When shortcircuiting occurs, higher TSS in the effluent may be observed. To prevent this, developers may increase the length of the detention basin if the availability of land allows. Increasing the length of the basin may also provide sufficient time for particles to aggregate to form larger particles. Greater particle density increases the effectiveness of gravitational settling, as larger particles can settle more effectively than smaller particles (Takamatsu et al., 2010). Overall, detention basins do not detain runoff long enough to allow finer particles to be removed, but utilizing physical and gravitational separation, it can be a low-cost and effective method for removing a fraction of the pollutant load (Weiss et al., 2007). A schematic of a detention basin is shown in Figure 3.

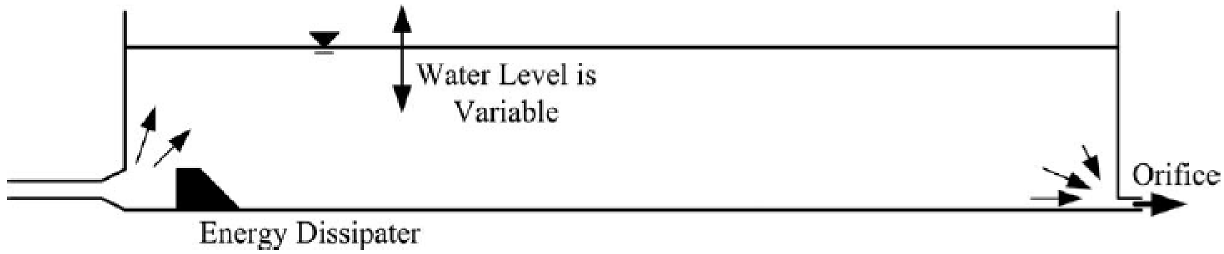


Figure 3 - Schematic of an Extended Dry Detention Basin LID Storm Water Treatment Measure (Takamatsu et al., 2010).

Sand Filters

Sand filter treatment systems utilize a combination of physical removal mechanisms, such as sedimentation and filtration, which are dominant characteristics for TSS removal (Barrett, 2005). The particle size distribution of the sand grain in sand filter systems determine the effectiveness of treating storm water runoff that is collected and discharged as effluent to the storm water conveyance system (Weiss et al., 2007). There are two types of sand filters, Austin sand filters and Delaware sand filters. Austin sand filters are sand-filled areas that filter and release the water to a perforated pipe or underdrain, whereas Delaware sand filters act as low-retention filters that can be placed underground in concrete chambers (Weiss et al., 2007). The performance of sand filters are affected by the size of the sand grain, as only TSS particles smaller in size can move through the spacing of the sand grain, while larger TSS particles are captured on the surface of the sand (Barrett, 2005). The upper layer of sand filters are prone to clogging, which increases the residence time in the filter, but reduces the effective area available for water infiltration (Achak et al., 2009). Kumar et al. (2012) notes that 60 percent of TSS is removed within the first 10 centimeters (cm) of a sand filter, which results in clogging. A longer residence time can increase the sedimentation process, but clogging may increase the amount of maintenance required to maintain the volume of filtering capacity. The sedimentation and infiltration processes in sand filters are mutually beneficial. Once clogging occurs, the infiltration rate decreases, while only smaller particles are allowed to pass through the clogged filter. A slower infiltration rate is also expected to increase the residence time of the runoff, and therefore, increase the efficiency of the sedimentation process, allowing more time for the suspended particles to settle. Sand filters, which use a combination of sedimentation, infiltration, and adsorption mechanisms, can be an effective storm water treatment technique. A schematic of sand filters is shown in Figure 4.

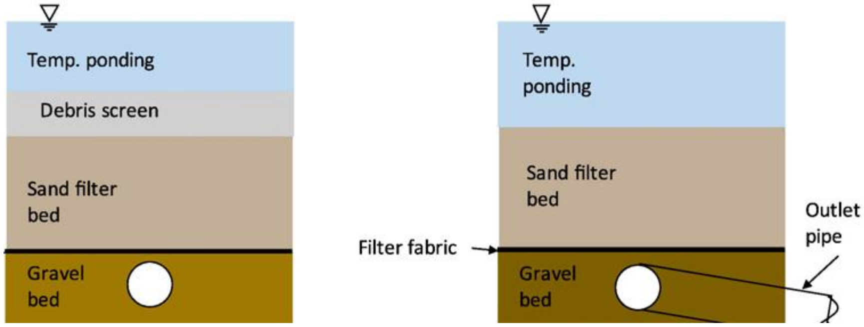


Figure 4 - Schematic of Underground Sand Filter (left) and Perimeter Sand Filter (right) LID Storm Water Treatment Measure (Eckart et al., 2017).

Porous / Permeable Pavement

Permeable pavement LID systems are constructed with a matrix of concrete blocks with voids in between the blocks that allow storm water to infiltrate the system. Beneath the layer of concrete blocks can include a variety of media substrate including sand, gravel, or soil. The media substrate is the primary factor that mitigates the impacts of storm water runoff caused by urban development (Brattebo and Booth, 2003). The hydrologic benefits of porous pavement include volume and peak flow storm water reductions, which is widely known in the available literature to be dependent on the storage capacity and the soil type within the porous pavement structure (Abbott and Comino-Mateos, 2003; Roseen et al., 2012). Geotextile filter fabric and various media types are used beneath the subsurface of porous pavement treatment devices. The crushed stone aides in the filtration of storm water runoff and increases the volume of storage space, and the sand increases the retention time by delaying the release of water into the underlying drain pipe (Roseen et al., 2012). Porous pavement structures are expected to be similar in treatment processes with sand filters, due to the inclusion of sand. Physical and chemical mechanisms reduce the amount of pollutants in storm water effluent by retaining the pollutants in the porous sand reservoir via adsorption, and at the geotextile filter (if present) and subgrade soils (if unlined) (Roseen et al., 2012). The physical separation of TSS from storm water runoff occurs via filtration and adsorption mechanisms. In a study conducted by Brattebo and Booth (2003), it was discovered that porous pavement structures utilized as a parking lot structure significantly reduced the toxicity of storm water runoff below state water quality standards. In contrast, the toxicity of the storm water runoff collected over an asphalt parking lot, which was used as the experimental control, exceeded state water quality standards (Brattebo and Booth, 2003). Since media substrate can affect adsorption and infiltration mechanisms, it is important to characterize and compare media substrate to assess TSS removal performance for porous pavement LID structures.

Suspended sediment in storm water runoff can be strained at the infiltrating surface of the media substrate, depending on the particle size of the TSS and the particle pore size of the media substrate. Media with larger available pore space will remove less contaminants via filtration. A filter cake on the infiltrating surface of the media substrate will form when the particle size of the TSS is larger than the porosity of the substrate (Sansalone et al., 2012). As the filter cake is generated, progressively finer particulate matter (PM) in storm water runoff will be strained, and a reduction in hydraulic conductivity and an increase in head loss for the porous pavement structure is expected (Sansalone et al., 2012). With increased PM straining, effluent PM mass decreases with time (Sansalone et al., 2012). To sustain the hydrological functionality of porous pavement structures, maintenance is required to remove the filter cake when straining is too severe. Maintaining porous pavement structures will be discussed later in this report. A schematic of porous pavement is shown in Figure 5.

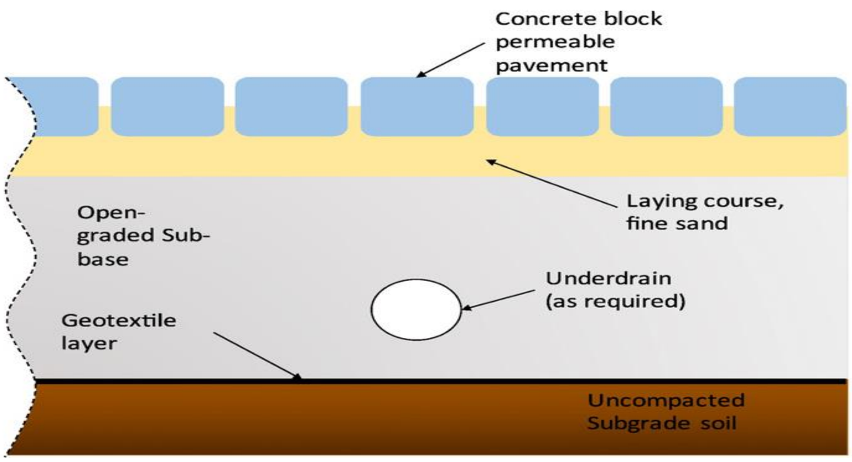


Figure 5 - Schematic of Pervious Pavement LID Storm Water Treatment Measure (Eckart et al., 2017)

Vegetated Swales / Bioretention

Vegetated swales are shallow channels with vegetative growth on the side slopes and bottom width, designed to retain storm water runoff and remove storm water pollutants through filter media (Bloorchian et al., 2016). Vegetated swales or bioretention LID technology is the most complex of the systems previously discussed. Vegetated swales utilize a combination of sedimentation, infiltration, adsorption, and phytoremediation mechanisms to treat pollutants in storm water runoff (Yadav et al., 2012; Papaevangelou et al., 2017). Depending on the permeability of the media substrate used, a bioretention system may include a perforated underdrain that collects and discharges the infiltrated water to the storm water conveyance system (Weiss et al., 2007). The infiltrated water can recharge shallow groundwater and decrease the pollutant load discharged to the storm drain network (Brown and Hunt, 2011). The vegetation helps to remove the water through uptake, while the runoff infiltrates into the soil or media substrate (Weiss et al., 2007). A schematic of a vegetated swale or bioretention system is shown in Figure 6.

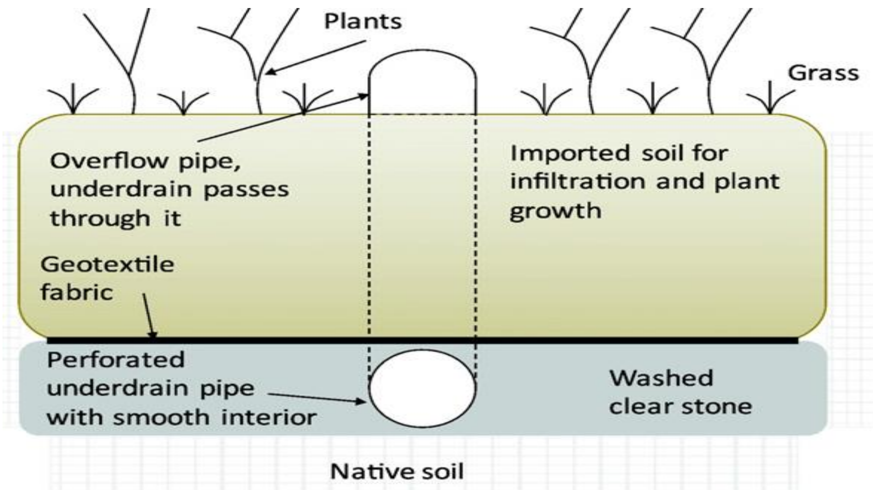


Figure 6 - Schematic of Bioretention LID Storm Water Treatment Measure (Eckart et al, 2017).

The pollutant removal efficiency of bioretention treatment may be affected by factors such as the shape of the swale and the media materials used for substrate (Xu et al., 2017). Soil is a fine filter media compared to rapid sand filtration, which could provide adequate PM removal, as large particles can be filtered by the media surface, and smaller particles can be captured by sedimentation, infiltration, or adsorption mechanisms (Hunt et al., 2011). In a study conducted by Goh et al. (2016), the bioretention swale achieved an effluent TSS average removal efficiency of 83.8 percent. Higher removal efficiencies were observed with high pollutant loadings in the influent, while low pollutant loadings resulted in lower removal efficiency, likely due to easier removal of larger particles in the storm water runoff. This is consistent with porous pavement and sand filter LID systems.

The length and slope of the swales affect TSS removal performance; the most effective swale was designed with a minimum of 75 meters (m) in length and a maximum 3 percent longitudinal slope (Yu et al., 2011). The installation of check dams, or devices that delay the flow of water, such as a stack of cobblestones laid across the width of the swale, also improve swale

TSS removal performance (Yu et al., 2011) due to increased sedimentation. TSS removal efficiency is also affected by air temperature; an increased temperature can lead to poor sedimentation due to increased diffusion and Brownian motion (Goh et al., 2016). Although, the impact of temperature on TSS removal is expected to be minor.

Vegetated swales achieve high removal efficiency of pollutants when dense and fully developed vegetation is present (Backstrom, 2002; Ahiablame et al., 2012). The more pervious the soil used in a vegetated swale, the greater the infiltration of storm water runoff into the swale (Bloorchian et al., 2016). Therefore, plants incorporated into swales can favor the deposition of TSS by reducing the velocity of the influent, and thereby increasing the sedimentation process by allowing the TSS particles to interact and settle out (Leroy et al., 2016). Maintaining healthy vegetation cover with a thick organic layer of soil helps to increase the treatment of storm water as it percolates into the ground via infiltration (Paule-Mercado et al., 2017). The infiltration treatment mechanism for vegetated swales is dependent on soil hydrological conditions and the interaction between the organic content in the media substrate and the existing vegetation (Bloorchian et al., 2016).

Papaevangelou et al. (2017) performed a study on the removal of chromium in constructed wetlands, which have very similar treatment mechanisms compared to vegetated swales. Like vegetated swales, constructed wetlands utilize physical, chemical and biological treatment mechanisms to remove contaminants from water. These processes occur between the interaction between the vegetation, media substrate, and the pollutants (Kadlec and Wallace, 2009; Papaevangelou et al., 2017). The vegetated systems demonstrated better removal of chromium, compared to the control system without vegetation. The vegetation provides surface area for biofilm growth and metal binding through their roots, stems, and leaves (Papaevangelou et al., 2017). However, Papaevangelou et al. (2017) notes that the porous media was the most prevalent for chromium removal compared to that of the vegetation, which was relatively low in comparison. Plants are a supplement to the porous media as the abundance of vegetation provide additional organic matter from plant decay, and root exudation (Lizama Allende et al., 2014; Papaevangelou et al., 2017). Without plants, organic matter diminishes due to microbial consumption (Papaevangelou et al., 2017). A higher retention capacity of metal accumulation in the porous media occurs when high organic matter is available (Sultana et al., 2015; Papaevangelou et al., 2017). This aligns with California's MRP technical guidance that recommends a combination of sand and compost (high infiltration, high organic content) for the top surface layer of bioretention devices (SWRCB, 2015). Along with mechanisms of treatment, there are other factors that affect the performance of a treatment system, as noted in the following section.

2.6 TSS Particle Size Distribution in Urban Storm Water Runoff

The particle size distribution (PSD) of TSS in storm water runoff plays a critical role in determining treatment selection. Storm water treatment systems are designed with specific filter media as well as filter mesh in order to target pollutants based on the fraction of their particle size (Charters et al., 2015). In a study conducted by Charters et al. (2015), the following was suggested:

- Regardless of drainage area characteristics (concrete roof, copper roof, galvanized roof, asphalt road), median PSD was similar across the drainage areas, and independent of the influent concentration of TSS;
- Treatment systems require consideration of a wide-range of influent PSD observed over numerous storm events to limit uncertainty in treatment system performance;
- Due to the large variation in PSD for storm water runoff, treatment devices with a short retention time presents a performance risk of not providing sufficient TSS removal across all rain events; and,
- Systems that provide a train of treatment devices or treatment mechanisms can provide a comprehensive approach to managing a range of particle size pollutants.

Winston and Hunt (2017) conducted a study on 43 road runoff events and found that median particle size varied from 31 micrometers (μm) to 144 μm. There were approximately 40 percent of fines (particles less than 63 um) found in runoff in Charters et al. (2015), and approximately 12 percent of fines discovered in a study by Gjukic et al. (2016). The differences in fines discovered in the storm water runoff in the two studies suggest that PSD is dependent on location and land use.

Djukic et al. (2016) also discovered that the smaller fractions of solid particles in urban runoff contain higher quantities of contaminants due to the large surface area per unit mass that provide the smaller particles with better adsorption capabilities. Finer fractions of TSS contain higher concentrations of both heavy metals and nutrients (Djukic et al., 2016). Smaller particles also have lower densities and a higher organic content that allow them to absorb to pollutants, such as metals, more effectively. Purvis et al. (2018) also discovered that the concentration of bacteria, including enterocci and fecal coliform were positively correlated to the concentration of TSS; higher concentration of bacteria was observed with higher TSS concentration. As noted by Charters et al. (2015), it is imperative that a treatment system has the capability to remove a wide range of PSDs, including the smaller fractions of TSS that tend to adsorb pollutants and contribute to negative human health and environmental impacts. As part of this Master's project study, the four treatment mechanisms (sedimentation, infiltration, adsorption, phytoremediation) and the four applications of these mechanisms (detention basins, sand filters, porous pavement, vegetated swales) will be evaluated for TSS removal and how PSD may play a role in treatment performance.

2.7 Factors that Affect Treatment Costs

One of the goals of LID storm water treatment measures include the reduction of costs for the construction and maintenance of storm water infrastructure, such as municipal or city piping conveyance systems (Ahiablame et al., 2012). As surface runoff increases due to an increase in impermeable surfaces from development projects, municipalities are challenged with having to upgrade their storm water conveyance system infrastructure to prevent system overflow, which may be costly. Efforts to reduce flooding and improve drainage are the most significant areas of contribution to costs for managing storm water measures (Visitacion et al., 2009). LID storm water systems can reduce the input load on the storm water conveyance system and result in significant cost savings (Roy et al., 2008). LIDs reduce the amount of storm water runoff at the source, as rain falls onto the new development area and drains to the LID device. Some LIDs are designed with overflow pipes that drain to the municipal storm drain system once the volume capacity of the LID has been reached. Other LIDs are designed to directly recharge ground water without ever reaching the storm water conveyance system, decreasing the need for existing infrastructure upgrades. Nonetheless, Ahiablame et al. (2012) associated high costs with maintaining LID structures. The level of demand LID maintenance can be on monetary budgets for owners and operators has not been simplified, due to the many factors that can impact costs.

Factors that affect treatment costs may include selection of materials, construction and installation costs, and operation and maintenance costs. Since these costs can vary based on selection of LID, the size of the LID, and the materials used as media substrate, it is important to standardize these costs be considering the volume of runoff each LID is capable of storing at any given time. Previous studies estimate the cost associated with hydraulic benefits of each LID, as cost per cubic meter of runoff volume the LID is capable of reducing ($\$/m^3$). In a study conducted by Joksimovic and Alam (2014) capital costs for constructing LIDs were $4,308,214 for pervious pavement and $523,985 for a vegetated swale (Joksimovic and Alam, 2014). Based on this study, pervious pavement appeared to be more costly than the vegetated swale by a factor of eight (8). When standardizing these costs with the amount of runoff volume the treatment device is capable of reducing, the cost of pervious pavement was approximately $\$157/m^3$ of runoff reduced, and the cost of the vegetated swale was approximately $\$15/m^3$ of runoff reduced. The standardization in cost creates more value for the vegetated swale, as the cost of pervious pavement is now more than the vegetated swale by a factor of ten (10).

Costs vary for each LID and are dependent on the amount of maintenance required. Houle et al. (2013) found that maintenance costs were lower for bioretention and porous asphalt pavement structures compared to dry detention basins (Houle et al., 2013). As shown in Table 3 below, replacing media substrate is a maintenance requirement for sand filters, porous pavement, and vegetated swales when enough sediment compromises the efficiency of the LID device. If enough sediment clogs the surface area of each filter medium, the infiltration of storm water runoff will decrease. Therefore, it is important to routinely remove accumulated sediment from each LID device, and replace the media substrate that may have been removed as a result of removing the accumulated sediment. Sansalone et al. (2012) suggests that cleaning the filter cake on porous pavement with a sweeper or vacuum would be sufficient. Vegetated swales or bioretention devices are the only LID technology of the four evaluated in this master's project study that requires landscape maintenance. Landscaping is required to prune excessively tall vegetation and remove weeds, which may otherwise affect the phytoremediation capability of the specific bioretention plants that fair well with water intake and pollutant removal.

Table 3 – Applicability of costs and maintenance requirements associated with LIDs for detention basins, sand filters, porous pavement, and vegetated swales (bioretention).

LID Costs			Maintenance		
	Capital and Installation	Operational Costs	Media Substrate Replacement	Accumulated Sediment Removal	Landscaping
Detention Basin	Yes	No	No	Yes	No
Sand Filter	Yes	No	Yes	Yes	No
Porous Pavement	Yes	No	Yes	Yes	No
Vegetated Swales	Yes	No	Yes	Yes	Yes

3. METHODOLOGY

3.1 Data Collection and Analysis – TSS, Percent Removal Efficiency

One of the goals for this study was to establish how well LID treatment systems remove TSS from storm water runoff. Vegetated swales (bioretention), porous pavement, sand filters, and dry detention basins were selected for this study due to differences in treatment properties. The mechanisms for LID treatment that were evaluated as part of this study include sedimentation, infiltration, adsorption, and phytoremediation. Operators need to understand how these properties can affect treatment performance in order to select appropriate treatment measures based on their water quality needs.

TSS removal efficiencies, as a percentage of removal, were collected from primary literature from studies listed in Table 4 below.

Table 4 - A list of sources where TSS removal efficiencies were collected for detention basins, sand filters, porous pavement, and vegetated swale LID treatment systems.

Source of Data	Detention Basins	Sand Filters	Porous Pavement	Vegetated Swales
Barrett, 2005	●	●		●
Braswell et al., 2018			●	
Brown and Hunt, 2011				●
Clary et al., 2017	●	●		
Davis, 2007				●
Goh et al., 2016				●
Hogland et al., 1987			●	
Houle et al., 2013	●	●	●	●
Jiang et al., 2015			●	
Kumar et al., 2012		●		
Lucke and Nichols, 2015				●
Middleton and Barrett, 2008	●	●		
Purvis et al., 2018				●
Roseen et al., 2012			●	
Sansalone et al., 2012			●	
Scholes et al., 2008	●			●
Shrestha et al., 2018				●
Torrens et al., 2009		●		
Weiss et al., 2007	●	●		●
Wilson et al., 2011		●		

Each of the literature articles in Table 4 have studied LID treatment measures for at least one of the four LIDs evaluated in this study, and provide an average TSS removal efficiency for the LID. The average TSS removal efficiencies that were collected from these studies were tabulated, and a single-factor analysis of variance (ANOVA) computed with XLStat was performed for each LID. An ANOVA allowed a comparison of the TSS removal efficiencies, and determined if there was a significant difference in the means generated from previous studies between the four treatment types. Prior to running the ANOVA, outlier analysis was performed, and four outliers in the vegetated swale dataset were removed. Data has been tested for normality and homogeneity of variances using Q-Q plots in XLStat, and all four treatment datasets confirmed a normal distribution as noted in Figure 7. Standard deviations were inconsistent, therefore a non-parametric Kruskal-Wallis test was also performed in XLStat to verify the results from the standard ANOVA test. Probability values less than 0.05 have been considered to imply a significant difference among treatment types.

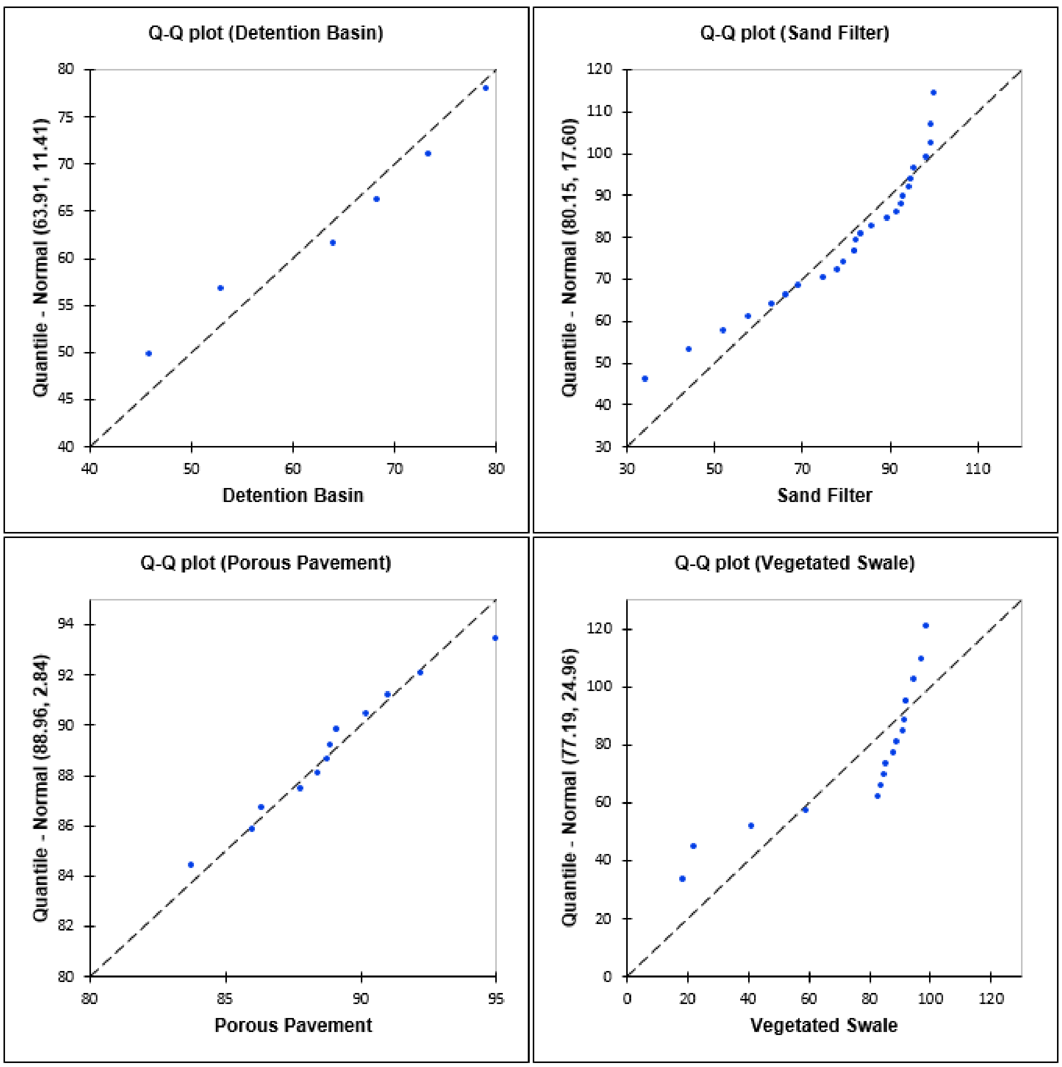


Figure 7 - Quantile-Quantile (Q-Q) Plots of TSS Removal Efficiencies for Four LID Treatment Systems, data collected from primary literature. Data collected shows normal distribution, but with outliers present. Outliers were removed prior to conducting the single-factor ANOVA test.

In addition, a bar graph was utilized for a visual comparison of the means of Percent TSS Removal across the different studies. A bar graph was generated for each LID treatment measure. It is important to understand whether past studies for LID treatment for TSS generated comparable results. Considering the varying physical, chemical, and biological properties of each treatment device was a valuable aspect of this study. If there are significant differences in the data from past studies, it is also important to understand the potential causes of the inconsistencies in the data. Therefore, to observe trends or potential explanations for the differences in TSS removal efficiencies across different studies for the same LID system, additional data was collected, tabulated, and compared. For detention basins, the influent and effluent TSS concentrations, design retention time, design length-to-width ratio, influent flow rate, outlet pipe diameter, and the TSS particle size of the influent were all considered. For sand filters, the influent and effluent TSS concentrations, sand grain size, sand media depth, and sand porosity were factors that were evaluated in the primary literature. For porous pavement, the influent and effluent TSS concentrations, the initial and final hydraulic conductivity, surface loading rate, and retention time were considered. Finally, for vegetated swales, the following factors were evaluated: the influent and effluent TSS concentrations, type of media substrate, media depth, soil additives (if any), and the type and amount of plant species.

Box plots were generated for a visual comparison of TSS removal efficiencies across the four treatment types, and to review the range of removal for each LID. Bar graphs were also generated for the four treatment types showing effluent concentrations that were available in the primary literature in order to assess water quality achievability.

3.2 Data Collection and Analysis – Capital and Operation and Maintenance Costs

A second goal for this study is to realize the capital, installation, and operation and maintenance costs associated with LID treatment measures. Operators need to understand the variability in costs associated with treatment measures to make better informed financial decisions for treating their storm water runoff. It should be noted that a few studies in the current literature have conducted life cycle analyses (LCA) on LID technology that include an evaluation of both economic and environmental externality costs (Xu et al., 2017; Chui and Zhan, 2016). Factors that were considered in these studies include capital and O&M costs, transportation and raw material costs, energy costs, and environmental, social, and economic benefits. Since one of the goals of this master's project study is to convey capital and maintenance costs associated with LID technology, life cycle externality costs were not analyzed, nor evaluated. The intent of this master's project study is to provide owners and operators with a sufficient evaluation of capital and maintenance expenditures associated with LIDs. From this, owners and operators can make informed storm water management choices for their operation and business needs.

Capital and O&M costs for each LID storm water treatment measure were considered as part of this study. These costs were standardized by previous studies available in the primary literature as cost per volume of runoff reduced or that the LID is capable of treating, in cubic meters ($/m^3). Financial data was collected from the studies noted in Table 5 below.

Table 5 - A list of sources where capital and O&M costs were collected for detention basins, sand filters, porous pavement, and vegetated swale LID treatment systems.

Source of Data	Detention Basins	Sand Filters	Porous Pavement	Vegetated Swales
Barrett, 2005	●	●		●
Houle et al., 2013	●	●	●	●
Joksimovic and Alam, 2014			●	●

Each of these articles have studied LID treatment measures for at least one of the four LIDs evaluated in this study, and provide an average cost per cubic meter of runoff capacity for the LID. The average costs that were collected from these studies were tabulated, and presented in a bar graph for visual comparison.

3.3 Analyzing the Optimization of Costs and Treatment Efficiency

The primary intent of this master's project study is to assess the cost effectiveness of each LID storm water treatment measure. In order to do so, costs and TSS treatment efficiencies must be compared. Based on the data collected for costs and TSS removal efficiencies, a critical analysis will be prepared and recommendations will be provided for LID treatment selection.

4. DATA ANALYSIS AND DISCUSSION

4.1 Total Suspended Solids, Percent Removal Efficiency

Detention Basins

A large variation of TSS removal efficiencies for detention basins were observed across existing studies. As shown in Figures 8 and 9 below, the lowest reduction in TSS concentration of 45.8 percent was observed by Middleton and Barrett (2008), while the largest reduction in TSS concentration of 79 percent was observed by Houle et al. (2013).

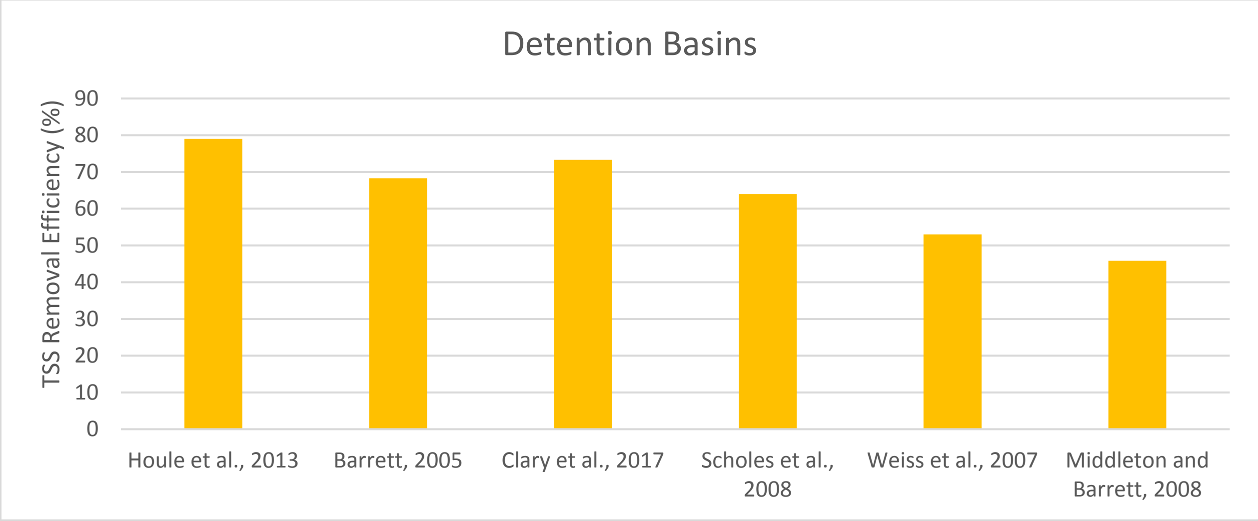


Figure 8 - TSS Percent Removal Efficiency for Detention Basins, as derived from previous studies

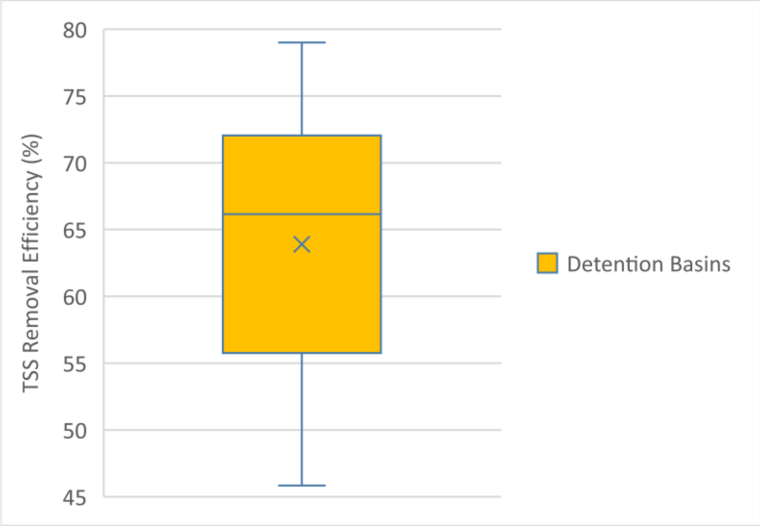


Figure 9 - Box Plot of TSS Removal Efficiencies for Detention Basin Systems, derived from current literature

These differences are likely due to the design of the detention basin in each study, including factors such as retention time, length-to-width ratio, and the outlet pipe diameter (Table 6). Houle et al. (2013) utilized a mound of gravel at the outlet of the basin, in order to provide coarse filtration to the storm water runoff prior to discharging out of the basin. This may explain a smaller TSS effluent concentration compared to studies performed by Barrett (2005), and Middleton and Barrett (2008). Since Middleton and Barrett (2008) installed a 6-inch pipe at the outlet of the basin for their study, one can expect that the outflow rate was likely greater than the outflow of Houle et al. (2013)'s gravel outlet. A greater outflow rate decreases the residence time in the basin, and prevents settling or sedimentation from occurring. Middleton and Barrett (2008) performed their study with a retention time of 12 hours, compared to the detention times of 24-28 hours (Houle et al, 2013), and 72 hours (Barrett, 2005), which may explain the larger TSS concentration in the effluent compared to the other studies. Comparing Middleton and Barrett (2008) with Houle et al. (2013), the two studies share similar influent concentrations, but different outlet concentrations, likely due to a combination of the longer residence time and gravel outlet structure in the study conducted by Houle et al. (2013).

Table 6 - TSS removal efficiency by LID detention basins. Data derived from multiple authors in the current literature.

Detention Basins	TSS Reduction (%)	TSS Conc. of Influent (mg/L)	TSS Conc. of Effluent (mg/L)	Design Retention Time (hours)	Design Length-to-Width Ratio	Influent Flow Rate (cfs)	Outlet Pipe Diameter (inches)	TSS Particle Size of Influent
Barrett, 2005	68.30	114	36.14	72	3.0	-	-	-
Clary et al., 2017	73.3	-	-	-	-	-	-	-
Houle et al., 2013	79	77	16	24-48	1.5	1	Gravel	-
Middleton and Barrett, 2008	45.83	72	39	12	-	-	6	-
Scholes et al., 2008	64	-	-	-	-	-	-	-
Weiss et al., 2007	53	-	-	-	-	-	-	-

According to Middleton and Barrett (2008), a larger length-to-width ratio is recommended for optimal TSS removal. Houle et al. (2013)'s design consisted of a detention basin of 46 feet wide and 70 feet long, an approximate length-to-width ratio of 1.5. Barrett (2005) implemented a length-to-width ratio of 3.0, twice as long as that of Middleton and Barrett (2008). Since Barrett (2005) resulted in a higher effluent of 36 milligrams per liter (mg/L) compared to 16 mg/L from Houle et al. (2013), this may suggest that short-circuiting plays a limited role in overall TSS removal. Though, this determination cannot be made with confidence due to the lack of available data between the studies. A higher effluent observed in Barrett (2005) may be a result from a higher TSS concentration in the influent; 114 mg/L, Barrett (2005) compared to 77 mg/L, Houle et al. (2013).

It is clear that the removal of TSS from storm water runoff through the use of detention basins is highly variable and dependent on multiple factors. There were no data available in the existing scientific literature that included an exhaustive review of factors, including influent flow rate, and how the size of the TSS particles can impact the TSS removal in detention basins. When designing a detention basin, these factors should be considered in order to target a sufficient reduction in pollutants that will meet water quality standards. The TSS removal rates are clearly variable across the various studies available in the existing literature. Caution should be taken when designing a detention basin, due to the uncertainty of the many factors involved. Since sedimentation is the primary removal mechanism in detention basins, one would need to assess how factors can influence the sedimentation process. Sedimentation occuring in detention basins can be affected by retention time, length-to-width ratio of the basin, the influent flow rate, the size of the outlet pipe, and the particle size distribution of the influent, but the studies found as part of this Master's Project did not adequately address these factors. Due to the limited data available in these studies, it is difficult to make a direct comparison amongst these studies to effectively evaluate differences observed in TSS removal.

Sand Filters

From the data collected from studies available in the current literature, TSS reduction in sand filters appear to be highly variable. As shown in Figures 10 and 11 below, in Kumar et al. (2012), the TSS reduction was measured to achieve a 34.2 percent reduction in Test "C", and was the lowest reduction in TSS achieved compared to the other studies. Kumar et al. (2012) also achieved the highest TSS removal in Test "G" with 100 percent of TSS removed. A range of 34.2 to 100 percent is a wide range of variability. Like detention basins, the reduction in TSS can be affected by various factors, and must be accounted for when designing sand filters to meet specific water quality needs. The factors that were analyzed as part of this Master's Project study include sand grain size, sand media depth, and the porosity of the sand media.

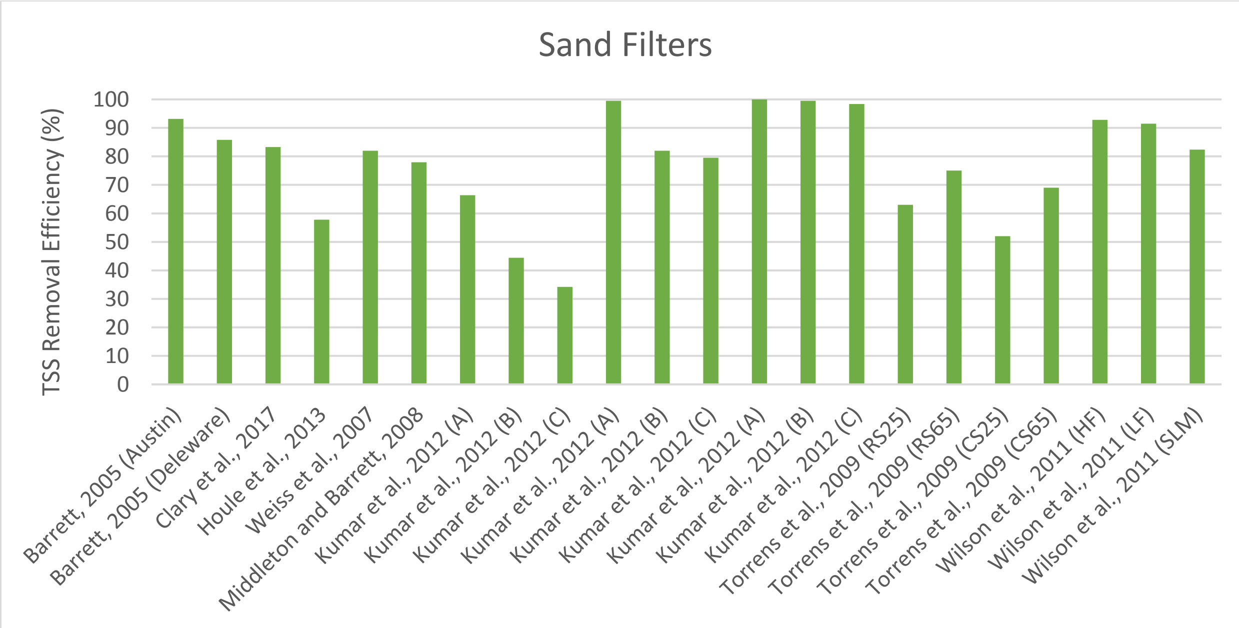


Figure 10 - TSS Percent Removal Efficiency for Sand Filters, as derived from previous studies

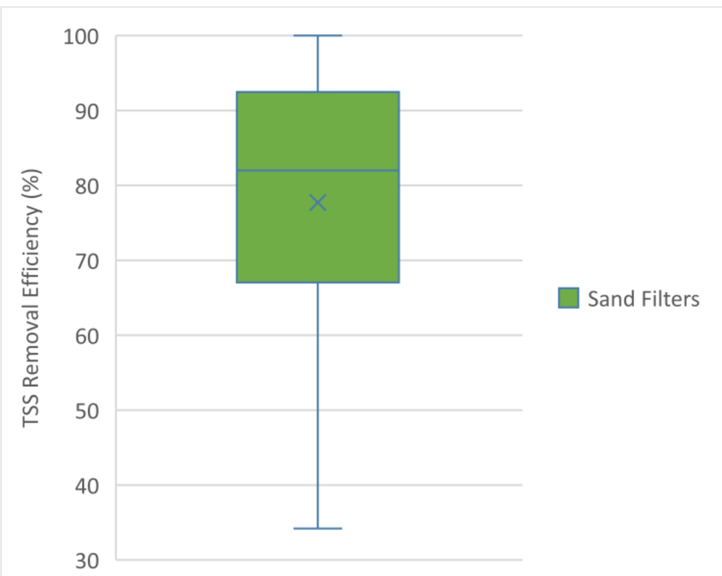


Figure 11 - Box Plot of TSS Removal Efficiencies for Sand Filter Systems, derived from current literature

TSS removal efficiency increases with an increase in sand media depth. Kumar et al. (2012) conducted a study on sand filters with media depths of 10 centimeters (cm), 35 cm, and 55 cm. As noted in Table 7 below, for sand grain size ranging from 0.5 to 0.7 millimeters (mm) and a constant influent concentration of 250 mg/L in all tests, TSS removal efficiency increased from 44.4 percent (Test "B") to 82.0 percent (Test "E") to 99.5 percent (Test "H") with increasing media depth of 10, 35, and 55 cm, respectively. This observation is consistent with other studies.

Table 7 - TSS removal efficiency by LID sand filters. Data derived from multiple authors in the current literature.

Sand Filters	TSS Reduction (%)	TSS Conc. of Influent (mg/L)	TSS Conc. of Effluent (mg/L)	Sand Grain Size (mm)	Sand Media Depth (cm)	Sand Porosity (%)
Barrett, 2005 (Austin)	93.16	114	7.8	-	-	-
Barrett, 2005 (Delaware)	85.79	114	16.2	-	-	-
Clary et al., 2017	83.3	-	-	-	-	-
Houle et al., 2013	57.78	45	19	-	-	-
Kumar et al., 2012 (A)	66.4	250	84	0.3-0.5	10	-
Kumar et al., 2012 (B)	44.4	250	139	0.5-0.7	10	-
Kumar et al., 2012 (C)	34.2	250	164.5	0.7-1.0	10	-
Kumar et al., 2012 (D)	99.53	250	1.18	0.3-0.5	35	-
Kumar et al., 2012 (E)	82.0	250	45	0.5-0.7	35	-
Kumar et al., 2012 (F)	79.5	250	51.25	0.7-1.0	35	-
Kumar et al., 2012 (G)	100	250	0	0.3-0.5	55	-
Kumar et al., 2012 (H)	99.5	250	1.25	0.5-0.7	55	-
Kumar et al., 2012 (I)	98.4	250	4.0	0.7-1.0	55	-
Middleton and Barrett, 2008	77.95	39	8.6	-	-	-
Torrens et al., 2009 (RS25)	63	48.11	17.8	River Sand	25	0.42
Torrens et al., 2009 (RS65)	75	46.0	11.5	River Sand	65	0.42
Torrens et al., 2009 (CS25)	52	54.79	26.3	Crushed S.	25	0.44
Torrens et al., 2009 (CS65)	69	63.55	19.7	Crushed S.	65	0.44
Weiss et al., 2007	82	-	-	-	-	-
Wilson et al., 2011 (HF)	92.8	198.61	14.3	Fine[1]	550[2]	-
Wilson et al., 2011 (LF)	91.5	81.18	6.9	Fine[1]	550[2]	-
Wilson et al., 2011 (SLM)	82.4	78.98	13.9	Medium[1]	300[2]	-
Wilson et al., 2011 (HM)	94.8	200	10.4	Medium[1]	550[2]	-
Wilson et al., 2011 (LM)	89.6	81.73	8.5	Medium[1]	550[2]	-
Wilson et al., 2011 (HC)	95.4	200	9.2	Coarse[1]	550[2]	-
Wilson et al., 2011 (LC)	94.6	81.48	4.4	Coarse[1]	550[2]	-

[1]Sand Grain Size not indicated, general description provided. [2]lateral/horizontal flow sand filter

Torrens et al. (2009) completed a study using River Sand and Crushed Sand as a filtering medium for storm water filtration. Regardless of the type of sand used, a reduction in TSS was achieved to a greater extent in the 65 cm filter, compared to the 25 cm filter. TSS removal efficiency increased from 63 to 75 percent using River Sand, and from 52 to 69 percent using Crushed Sand when depth of sand media was increased from 25 cm to 65 cm. Lastly, Wilson et al. (2011) utilized a horizontal/lateral sand filter consisting of 300 cm and 550 cm of sand media, with "medium" sized sand. With approximately 80 mg/L of TSS in the influent for both tests, Test "LM" achieved a higher removal efficiency of 89.6 percent with the 550 cm filter, compared to Test "SLM" with a removal efficiency of 82.4 percent with the 300 cm filter. Since the primary removal mechanisms for sand filters are infiltration and filtration, this observation in the data is validated. The more sand media available, the more filtration capacity is available for storm water runoff to percolate through. However, one must not isolate the efficiency of sand filters to be dependent only on sand media depth.

TSS removal efficiency increases with a decrease in sand grain size. In the study conducted by Kumar et al. (2012), tests were conducted using a constant TSS influent concentration and sand media depth for sand grain sizes ranging from 0.7-1.0 mm, 0.5-0.7 mm, and 0.3-0.5 mm. With sand depth of 10 cm, TSS removal efficiency increased from 34.2 to 44.4 to 66.4 percent with decreasing sand grain size. This observation is independent of media depth. Similar results and improvement in TSS reduction are observed, regardless of media depth. With sand depth of 35 cm, TSS removal efficiency increased from 79.5 to 82.0 to 99.53 percent with decreasing sand grain size. A similar trend occurred with a sand depth of 55 cm, although improvements in TSS reduction were marginal, which suggests that an optimal design for media depth is between 35 cm and 55 cm in depth. Torrens et al. (2009) completed tests using river sand and crushed sand with porosity values of 0.42 and 0.44, respectively. Torrens et al. (2009) cannot be directly compared to Kumar et al. (2012) since the exact sand grain size is unknown, but grain size in Torrens et al. (2009) can be evaluated by making an inference by assuming a larger porosity value to equate to a larger sand grain size. The filtering efficiency increases when the pore space between the sand particles are smaller (Barrett, 2005; Weiss et al., 2007). Therefore, it is correct to assume that river sand has a smaller grain size than crushed sand. For a filter of 25 cm in media depth, TSS was reduced by 63 percent using river sand, compared to a 52 percent reduction using the presumed larger crushed sand (Torrens et al, 2009). For a filter of 65 cm in media depth, TSS was reduced by 75 percent using river sand, compared to a 69 percent reduction using the presumed larger crushed sand (Torrens et al, 2009). This trend is apparent even with lower influent concentrations of TSS observed in the river sand tests; the calculated percent reduction for TSS is a secondary characteristic of sand filters, and depends on the average influent concentration observed (Barrett, 2005). This dependence will be discussed later in this section.

It is important to note an inconsistency discovered in the study conducted by Wilson et al. (2011). Tests were completed using “fine”, “medium”, and “coarse” sand, and contrary to studies by Torrens et al. (2009) and Kumar et al. (2012), an opposite trend of TSS removal was observed. With approximately 200 mg/L of TSS in the influent, and a media depth of 550 cm, TSS removal efficiency increased from 92.8 (Fine) to 94.8 (Medium) to 95.4 percent (Coarse), which is conflicting from what would be expected with increasing sand grain size. These results may suggest that other factors may be involved that influence TSS removal. It is uncertain whether horizontal or lateral filters are capable of achieving similar results to that of the common vertical sand filter. This particular sand filter is also much larger in media depth, which may suggest that differences in sand grain size may not be the primary removal property of sand filters to consider once the sand media exceeds a certain depth. Additional research is needed to provide more insight into horizontal sand filter treatment and whether there are any significant differences observed in TSS reduction as a result of different sand media size. Additionally, PSD of TSS in the influent for each of the fine, medium, and coarse sand tests may have been diverse. Since PSD data was not provided, it is uncertain whether PSD may have had a substantial effect on TSS reduction in Wilson et al (2011). Since PSD is dependent on location and land use, PSD is very much a possibility for differences observed across the data collected (Charters et al., 2015; Djukic et al., 2016. Barrett (2005) suggests that since there is no sufficient data available to determine the particle size of the influent retained in the filter media, one can expect differences in TSS removal with differences in PSD runoff at other sites. In order to provide insight into the inconsistencies observed in Wilson et al. (2011), additional data would be needed to assess how the combination of PSD, grain size, media depth, and horizontal treatment all factor into TSS removal.

Differences in TSS reduction observed can also be explained by evaluating the influent and effluent TSS concentration of the storm water runoff. Sand filters have consistent TSS removal performance as results indicate a constant effluent concentration for a filter of the same sand type and sand depth (Barrett, 2005). This suggests that the calculated percent reduction for TSS is a secondary characteristic of the treatment type and depends on the specific average influent concentration observed. Since sand filters provide relatively constant TSS effluent concentrations, the percent removal would appear to be much lower for storms with low influent concentrations and higher for storms with high influent concentrations. This dependence on influent concentration may help explain the wide range of TSS percent removals (85% to 93%) reported in the literature for similar treatment types. The studies conducted by Houle et al. (2013) and Barrett (2005) observed similar effluent concentrations of TSS, but since Houle et al. (2013) had a lower influent concentration of TSS, a lower TSS removal efficiency was also observed. This TSS reduction dependence on influent concentration is also clearly apparent in Wilson et al. (2011). When comparing fine, medium, and coarse sand filters with a constant media depth, effluent concentrations of TSS were generally consistent across all tests of the same sand type, but TSS removal efficiencies were higher for all tests with approximately 200 mg/L TSS in the influent compared to approximately 80 mg/L TSS in the influent (Wilson et al., 2011).

Porous / Permeable Pavement

From the data collected from studies available in the current literature, there was much less variability in TSS reduction for porous pavement / permeable pavement LID structures compared to any of the other LID treatment systems. As noted in Figures 12 and 13 below, the lowest reduction in TSS was observed in Sansalone et al. (2012) (Test "L") with a reduction of 83.77 percent. Hogland et al. (1987) achieved the greatest removal efficiency, with a 95 percent reduction in TSS.

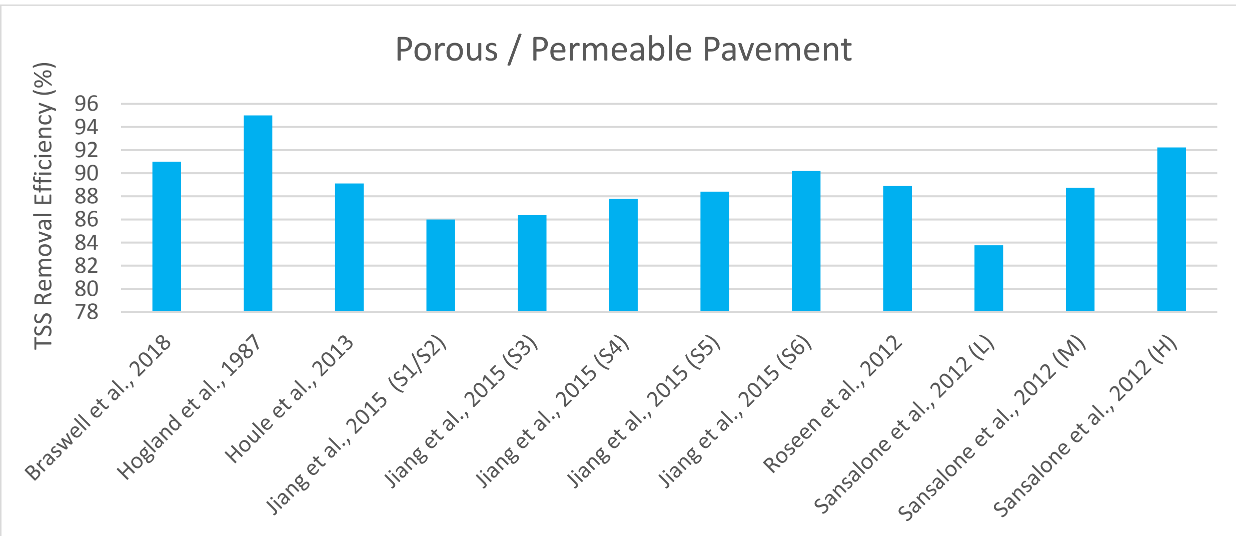


Figure 12 - TSS Percent Removal Efficiency for Porous / Permeable Pavement LID structures, as derived from previous studies

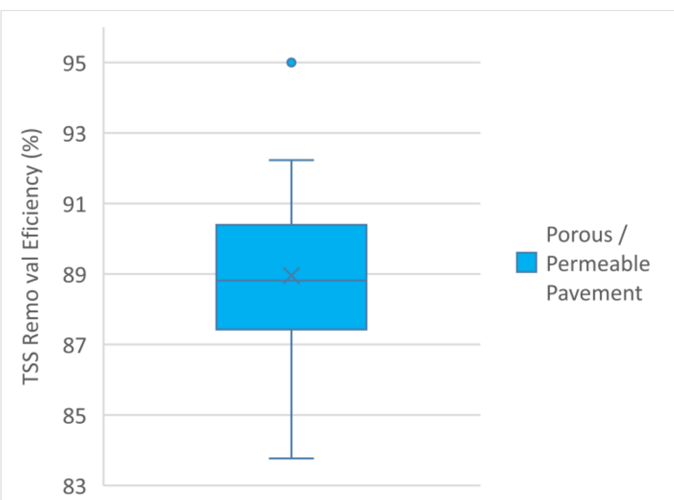


Figure 13 - Box Plot of TSS Removal Efficiencies for Porous / Permeable Pavement Systems, derived from current literature

The concentration of TSS in the influent and the hydraulic conductivity through the sand media are factors that can influence TSS reduction in porous pavement structures. In a study conducted by Sansalone et al. (2012), the efficiency of porous pavement LID structure for TSS removal was dependent on the TSS concentration of the influent. With a constant surface loading rate of 22 liters per square meter (L/m^2), the percent reduction in TSS increased from 84 percent to 92 percent when the influent concentration of TSS was increased from 47 mg/L to 190 mg/L (Table 8). A greater removal efficiency was observed with a higher TSS loading in the influent. This is likely a result from increased clogging and a decrease in infiltration expected with a higher TSS load. This assumption is supported by the decrease in hydraulic conductivity observed with a higher TSS loading. When the influent of TSS was 47 mg/L, it took approximately 250 hours for the hydraulic conductivity to drop from 3.1×10^{-1} mm/s to lower than 10^{-3} mm/s, compared to the 136 hours required for the hydraulic conductivity to drop lower than 10^{-3} mm/s with an influent of 190 mg/L TSS (Sansalone et al., 2012). The faster reduction in hydraulic conductivity suggests that higher TSS loadings increase clogging. When clogging occurs, it decreases the rate of infiltration due to less surface area available, and in turn, promotes higher TSS reduction as observed in the effluent. This can also be a result of the consistency in TSS effluent concentrations from all three tests, which is well known in the literature to be the case for sand filters (Barrett, 2005; Houle et al., 2013; Roseen et al., 2012; Wilson et al., 2011). Sand is the primary media substrate used in porous pavement structures, so exhibiting effluent consistency is also a characteristic of porous pavement structures.

Table 8 - TSS removal efficiency by LID porous pavement. Data derived from multiple authors in the current literature.

Porous / Permeable Pavement	TSS Reduction (%)	TSS Conc. of Influent (mg/L)	TSS Conc. of Effluent (mg/L)	Initial Hydraulic Conductivity (mm/s)	Final Hydraulic Conductivity (mm/s)	Surface Loading Rate (L/m^2)	Retention Time (min)
Braswell et al., 2018	91	-	-	-	-	-	-
Hogland et al., 1987	95	378	18	-	-	-	-
Houle et al., 2013	89.11	101	11	-	-	-	-
*Jiang et al., 2015 (S1/S2)	85.99	785	110	-	-	-	Immediate
*Jiang et al., 2015 (S3)	86.37	785	107	-	-	-	10
*Jiang et al., 2015 (S4)	87.78	785	96	-	-	-	20
*Jiang et al., 2015 (S5)	88.41	785	91	-	-	-	40
*Jiang et al., 2015 (S6)	90.19	785	77	-	-	-	70
Roseen et al., 2012	88.89	54	6	-	-	-	-
Sansalone et al., 2012 (L)	83.77	47.25	7.67	3.23×10^{-1}	6.97×10^{-4}	22.28	-
Sansalone et al., 2012 (M)	88.74	93.58	10.53	3.04×10^{-1}	7.92×10^{-4}	22.17	-
Sansalone et al., 2012 (H)	92.23	190.76	14.82	3.24×10^{-1}	5.58×10^{-4}	22.35	-

*In Table 7 of Jiang et al. (2015), based on review of the data and graphs within, TSS and Turbidity values appear to be switched. The data shown in Table 8 above are true TSS concentrations from Jiang et al. (2015), but are misrepresented and listed as Turbidity measurements in Table 7 of the journal article.

Effluent consistency was observed in all of the studies noted in Table 8 above, as results indicate effluent concentrations below 20 mg/L TSS, with the exception of Jiang et al. (2015). Since the study was conducted in a laboratory experiment, Jiang et al. (2015) noted that compaction of the permeable pavement materials could not be completed due to laboratory equipment limitations, and a lower effluent concentration and a higher TSS removal efficiency would be expected in a full-sized porous pavement system. This may explain the reasoning behind the higher effluent concentration observed in Jiang et al. (2015) compared to the other studies.

Retention time is also a factor that can influence the removal of TSS from porous pavement systems. As noted in Jiang et al. (2015) and Figure 14 below, TSS concentration decreased by 86 percent after initial infiltration through the porous pavement system, and continued to decrease to a total TSS reduction of 90.1 percent over a 70 minute duration. Jiang et al. (2015) notes that this increase in TSS removal is mainly due to smaller TSS particles being intercepted and adsorbed by materials in porous pavement during the infiltration process, indicating that filtration and adsorption are the mechanisms occurring during TSS removal. Smaller particles have more surface area for adsorption to occur (Djukic et al., 2016; Purvis et al., 2018).

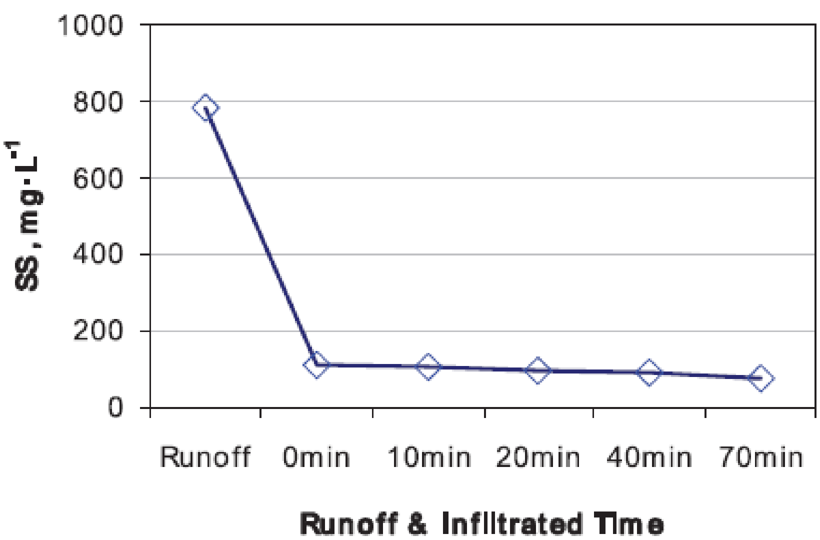
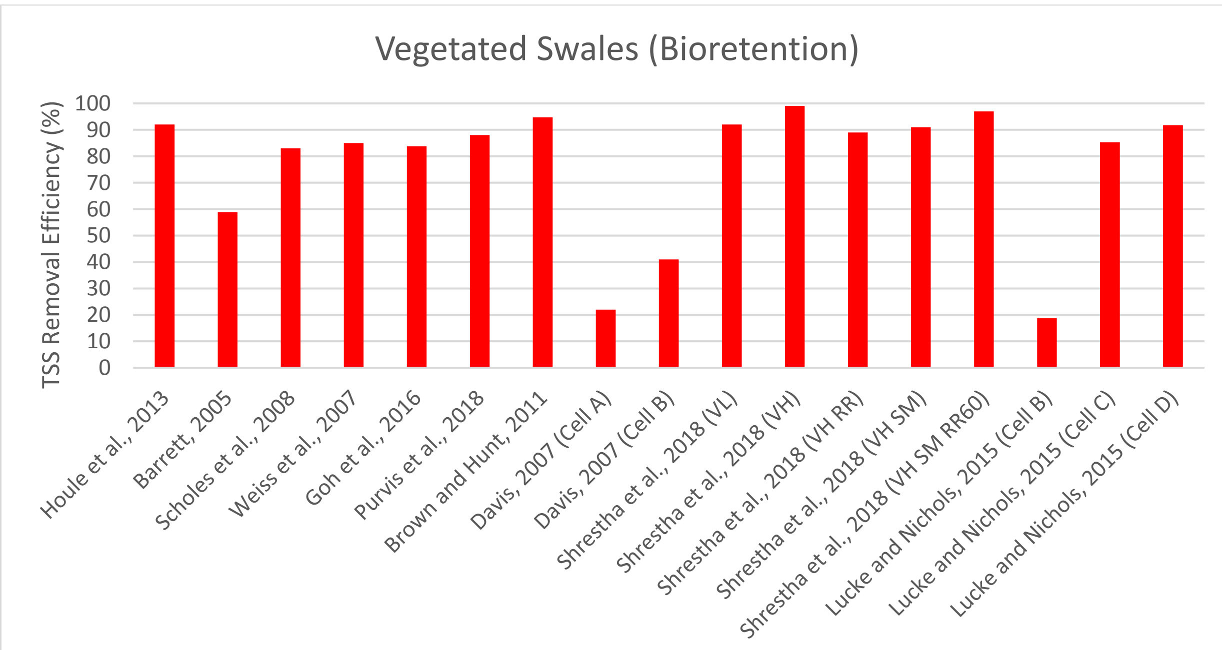


Figure 14 - TSS concentration of pavement runoff before and after infiltrated in permeable pavement with different sampling time (Jiang et al., 2015)

Since sand filters and porous pavement systems share similar mechanisms of removal, porous pavement systems likely exhibit the same properties as sand filters, and require a combination of influent concentration, PSD, grain size, retention time, and media depth to consider to evaluate how TSS removal may be affected. Since all of these factors alter the efficiency of TSS removal, it is important for owners and operators of porous pavement and sand filter LID systems to analyze the characteristics of the storm water runoff for their location and land use to assess whether water quality limitations can be achieved by these systems.

Vegetated Swales

Vegetated swales were observed to have the greatest variation in TSS removal compared to the other three LID treatment systems, ranging from 18.71 to 99 percent as noted in Figures 15 and 16 below. Factors that may have influenced the large range of TSS removal include influent concentration, type of media substrate, depth of media substrate, amount of vegetation in the swale, and overall design of the swale.



* Lucke and Nichols, 2015 (Cell A) not shown due to negative TSS removal efficiency due to design flaw

Figure 15 - TSS Percent Removal Efficiency for Vegetated Swales / Bioretention LID structures, as derived from previous studies

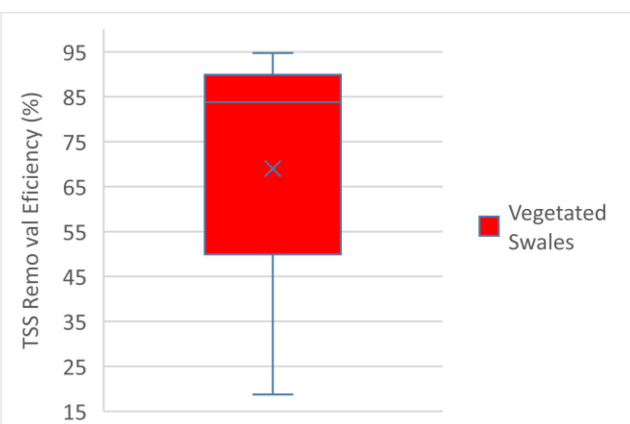


Figure 16 - Box Plot of TSS Removal Efficiencies for Vegetated Swale Bioretention Systems, derived from current literature

TSS removal efficiency is dependent on the concentration of TSS in the influent. Comparing VH SM RR60 (enhanced rainfall and runoff) with VH SM, a higher TSS reduction was observed for VH SM RR60, although the effluent of VH SM RR60 (20 mg/L) was slightly higher than that of VH SM (6 mg/L). Since all variables were constant other than influent flowrate, this suggests that TSS reduction varies based on the influent TSS concentration. Low TSS removals were observed in Davis (2007) with a 22 percent removal in Cell A and 41 percent in Cell B. Both Cell A and B were able to achieve an effluent concentration below 20 mg/L, but since the influent concentration was already relatively low in TSS (23.7 mg/L and 19.2 mg/L), the reduction in TSS appears to be very low (David, 2007). Cells A and B in Luck and Nichols (2015) share similar results, with a TSS reduction less than 20 percent. The four tests between Cells A and B of Davis (2007) and Luck and Nichols (2015) demonstrated the lowest reduction in TSS out of all studies assessed as part of this master's project study for vegetated swales, with the exception of the study conducted by Barrett (2005), which achieved a 58.88 percent reduction in TSS. All other studies achieved an 83 percent or greater reduction in TSS.

The lower TSS removal observed in Barrett (2005) highlights the importance of media substrate selection for the removal of TSS in vegetated swales. Barrett (2005) utilized natural soil as the primary media substrate in the vegetated swale, which is not a common type of media for bioretention vegetated swales, as it is recommended that the media substrate include 60-70 percent sand, and 30-40 percent compost to increase infiltration and adsorption mechanisms (SWRCB, 2015). Shrestha et al. (2018) was able to achieve an 89 to 99 percent removal by applying a similar sand-to-compost ratio (Table 9). Adding newspaper or SorbtiveMedia™ in a portion of the media substrate did not have any significant differences in TSS removal, but altering the media substrate can ensure better removal efficiencies for nutrient removal, such as nitrogen and phosphorus (Davis, 2007; Shrestha et al., 2018). A consistent media depth was observed in all studies with depth data available, ranging from 90 to 110 cm, suggesting that 90 cm is the ideal minimum media depth for pollutant removal.

Table 9 - TSS removal efficiency by LID vegetated swales (bioretention). Data derived from multiple authors in the current literature.

Vegetated Swales / Bioretention	TSS Reduction (%)	TSS Conc. of Influent (mg/L)	TSS Conc. of Effluent (mg/L)	Media Substrate	Media Depth (cm)	Soil Additive	Plant Species
Barrett, 2005	58.88	114	67.12	Soil only	-	-	Grass
Brown and Hunt, 2011	94.74	152	8	Sod, Sandy Clay Loam	110.0	N/A	Centipede Turf
Davis, 2007 (Cell A)	22	23.7	18.5	50% Sand 30% Topsoil 20% Mulch	90.0	N/A	Grass, Shrubs, Small Trees
Davis, 2007 (Cell B)	41	19.2	11.3	50% Sand 30% Topsoil 20% Mulch	90.0	30 cm of 0.017:1 Newspaper: Sand Mix	Grass, Shrubs, Small Trees
Goh et al., 2016	83.8	-	-	-	-	-	-
Houle et al., 2013	92	-	-	-	-	N/A	-
Lucke and Nichols, 2015 (Cell A)	-279.31	9.67	36.67	Sandy Loam	90	N/A	Lomandra Longifolia
Lucke and Nichols, 2015 (Cell B)	18.71	46.33	37.67	Sandy Loam	90	N/A	Lomandra Longifolia
Lucke and Nichols, 2015 (Cell C)	85.29	204	30	Sandy Loam	90	N/A	Lomandra Longifolia
Lucke and Nichols, 2015 (Cell D)	91.80	231.67	19	Sandy Loam	90	N/A	Lomandra Longifolia
Purvis et al., 2018	88	35.1	4.2	-	90.0	N/A	Thin-cut Sod
Scholes et al., 2008	83	-	-	-	-	-	-
Shrestha et al., 2018 (VL)	92	164	14	Sand & Compost	91.5	N/A	Two (2) Native Perennials
Shrestha et al., 2018 (VH)	99	266	3	Sand & Compost	91.5	N/A	Seven (7) Native Perennials
Shrestha et al., 2018 (VH RR)	89	358	38	Sand & Compost	91.5	N/A	Seven (7) Native Perennials
Shrestha et al., 2018 (VH SM)	91	65	6	Sand & Compost	91.5	Sorbtive Media™	Seven (7) Native Perennials
Shrestha et al., 2018 (VH SM RR60)	97	620	20	Sand & Compost	91.5	Sorbtive Media™	Seven (7) Native Perennials
Weiss et al., 2007	85	-	-	-	-	-	-

VH = vegetation high diversity, RR = enhanced rainfall + runoff, SM = SorbtiveMedia, VL = vegetation low diversity

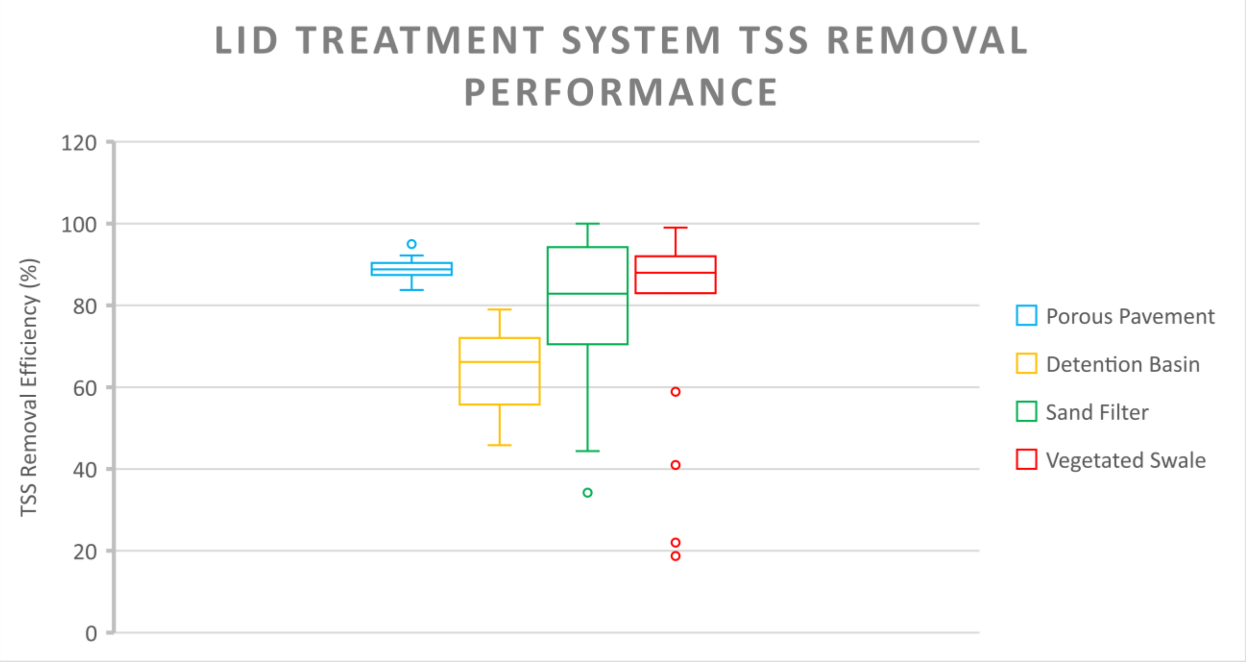
Vegetation did not remove TSS through phytoremediation, but indirectly increased the removal efficiency in vegetated swales. In a study conducted by Shrestha et al. (2018), TSS removal was measured for a bioretention / vegetated swale consisting of two (2) native perennial plant species (VL) and a bioretention / vegetated swale consisting of seven (7) native perennial plant species (VH). As noted in Table 9 above, the results indicate higher TSS removal occurred in the swale with the greater number of plant species (99% VH, 92% VL). The VH swale had a greater influent TSS concentration, as well as a lower effluent TSS concentration compared to VL, which suggests that the incorporation of plants may have favored the deposition of suspended solids by increasing the sedimentation process, also noted to hold true in Leroy et al. (2016). Various types of vegetation were utilized in other studies as noted in Table 9 above, but it is unclear whether the differing vegetation made an impact to the TSS removal efficiencies in those studies. Other factors, such as influent concentration, media depth, and type of media would have to be consistent across the studies in order to independently evaluate vegetation's effect on TSS removal.

The volume runoff capacity of the swale affects overall TSS removal. In Purvis et al. (2018), TSS influent was measured at 35.1 mg/L, and 4.2 mg/L at the outlet of the perforated underdrain pipe, achieving an 88 percent reduction in TSS. Storm water that reached volume capacity in the swale and overflowed into the overflow pipe was measured with a TSS concentration of 31.6 mg/L, achieving only a TSS reduction of 10 percent. Assuming sedimentation is the primary mechanism involved in the overflow process, these findings indicate that infiltration and/or adsorption is the dominant processes over sedimentation due to the higher reduction in TSS measured at the underdrain. This is important for owners and operators of vegetated swales to understand that the volume capacity of the swale will also have an effect on TSS concentrations in the effluent during overflow conditions. If the capacity of the swale is minimal, overflow conditions may occur sooner during high flow events, which will limit the potential of TSS removal.

The geotextile fabric appears to be a crucial element for the design of bioretention vegetated swales. During my review of Lucke and Nichols (2015)'s designed experimentation with four roadside bioretention basins, Basin A was tested with a low influent TSS concentration compared to Basins C and D. Lucke and Nichols (2015) noted a negative removal efficiency for TSS in Basin A and a low removal efficiency for Basin B (Table 9). The study noted that the bioretention basins were found to export higher concentrations of TSS compared to the TSS concentration in the influent (Test A). After conducting a critical analysis of the study as part of this master's project study, it was discovered that the bioretention basins were not properly designed. As observed in Eckart et al. (2017), a geotextile layer is normally placed above the gravel layer that houses the perforated underdrain in vegetated swales and bioretention systems. The explanation for low or negative TSS removal efficiencies in Basins A and B in the study conducted by Lucke and Nichols (2015) can be explained by deficient design regarding the absence of the geotextile layer potentially causing media substrate to exit in the effluent. The only other explanation for the observed differences in TSS removal for this study is due to differences in the influent TSS concentration, since there are no differences in design between the four systems.

LID Treatment System Comparison

A box plot was prepared in order to visually observe the variation in TSS removal efficiency (%) across all four LID treatment systems. Figure 17 below shows that vegetated swales have the largest variation in the TSS removal efficiencies collected from existing primary literature, while porous pavement has the least. However, when excluding outliers in the data collected for vegetated swales, the variation is similar to that of porous pavement structures. Detention basins are the only LID systems that failed to achieve at least an 80 percent reduction in TSS from the data collected. As noted in previous sections of this report, TSS removal can be influenced by numerous variables, and the variations observed in the box plots for each LID system are likely caused by factors that include, but are not limited to, influent concentration, PSD of the influent and media substrate, media substrate selection, and engineering design.



*Lucke and Nichols, 2015 (Cell A) for bioretention not shown due to negative TSS removal efficiency due to presumed design flaw

Figure 17 - Box plots showing a comparison of the TSS removal efficiencies collected for the primary literature for four LID treatment systems

A single-factor analysis of variance (ANOVA) was conducted using the data collected across all four LID systems. Four (4) outliers, as identified by outlier analysis, were removed from the data for vegetated swales prior to conducting the ANOVA. Results indicate that a significant difference exists amongst the means for TSS reduction efficiencies between at least two treatment types. The results of the ANOVA are provided in the Table 10 below.

Table 10 – Single Factor Analysis of Variance (ANOVA) results for TSS Removal Efficiencies (%) for Detention Basin, Sand Filter, Porous Pavement, and Vegetated Swale LID treatment systems. Data derived from existing primary literature, as noted in Tables 6 through 9 of this report. ANOVA computed using XLStat.

Source	df	SS	MS	F	p-value
Model	3	3473.592	1157.864	6.643	**0.001**
Error	53	9238.010	174.302		
Corrected Total	56	12711.602			

df = degrees of freedom, SS = sum of squares, MS = mean square
F = (MS for between groups)/(MS for within groups)

A normal distribution across the data for each treatment type was confirmed, but standard deviations of the four treatments were not the same. Due to differences in variance, a Kruskal-Wallis test was performed to verify the standard ANOVA test, and results indicate (p-value = 0.005) that a significant difference exists, so the treatment type does indeed an impact on TSS removal.

Since a significant difference exists, a Tukey's honest significant difference (HSD) test was computed to determine and narrow the mean TSS removal efficiencies that are significantly different from each other. Results are included in Table 11 below. Tukey’s HSD test specifies that a significant difference exists in the mean TSS removal efficiency for detention basins compared to any of the mean TSS removal efficiencies for vegetated swales, sand filters, and porous pavement LID systems. There were no significant differences in mean TSS removal efficiency between vegetated swales, porous pavement, and sand filter systems.

Table 11 - Tukey (HSD) / Analysis of the differences between the categories with a confidence interval of 95 percent

Contrast	Difference	Standardized Difference	Critical Value	p-value	Significant
Vegetated Swale vs Detention Basin	26.220	4.024	2.652	**0.001**	**Yes**
Vegetated Swale vs Sand Filter	9.971	2.223	2.652	0.130	No
Vegetated Swale vs Porous Pavement	1.169	0.221	2.652	0.996	No
Porous Pavement vs Detention Basin	25.052	3.795	2.652	**0.002**	**Yes**
Porous Pavement vs Sand Filter	8.802	1.910	2.652	0.236	No
Sand Filter vs Detention basin	16.249	2.717	2.652	**0.043**	**Yes**
Tukey's d critical value:			3.751		

Since detention basins utilize sedimentation as the primary process for TSS removal, and the removal efficiency for detention basins are significantly different than that of sand filters, porous pavement, and vegetated swales, one can infer that a combination of sedimentation, filtration, and adsorption mechanisms are capable of removing a higher amount of solids from stormwater runoff compared to sedimentation alone. Since there were no significant difference in TSS removal for vegetated swales when compared to porous pavement and sand filter systems, phytoremediation may not be a critical aspect for TSS removal in LID systems. Owners and operators that seek treatment with higher TSS removal efficiencies are encouraged to remove detention basins as an option, as the other three LID systems can achieve a greater reduction in TSS.

Since there are no significant differences between the means of TSS removal for vegetated swales, porous pavement, and sand filters, owners and operators are recommended to consider the LID treatment systems that can achieve the water quality standard required for their application. An example of this is discussed in the next section.

4.2 Treatment System Effluent

Since sand filters, porous pavement, and vegetated swales were all observed to have a removal efficiency dependent on influent concentration, it is also important for owners and operators to understand the water quality limitations of each LID system. Relying on TSS removal efficiencies may be misleading if the TSS concentration in the influent is very low. Davis (2007) suggests that from a discharge water quality perspective, performance of the system should be examined in terms of effluent water quality. Effluent TSS concentrations from Tables 6 through 9 are presented in graphical form in Figure 18 below.

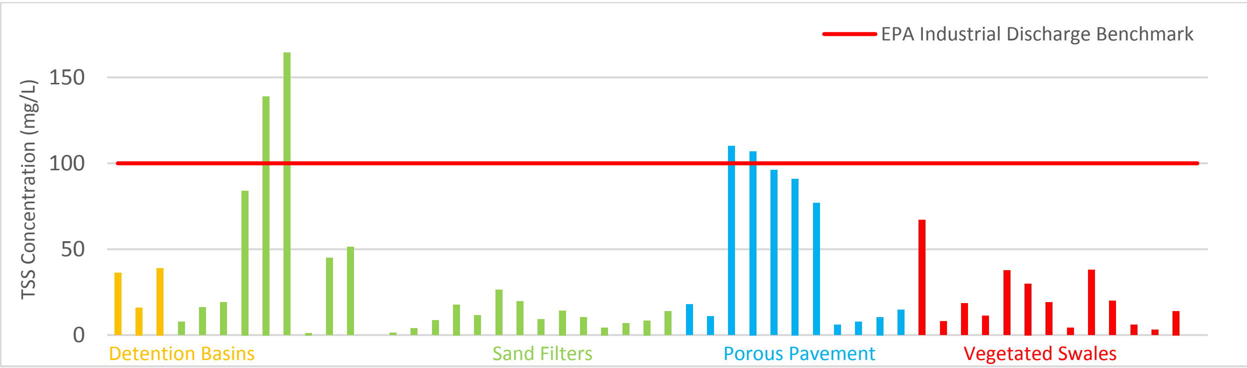


Figure 18 - Effluent TSS Concentrations achieved from four LID Treatment Systems. Data derived from existing literature and from Tables 6 through 9 of this report.

Detention basins, porous pavement, sand filters, and vegetated swales are all capable of achieving an effluent concentration well below the USEPA's 100 mg/L threshold for industrial facility discharges. Porous pavement and sand filters were noted to have treatment tests that exceeded this threshold, but as noted in previous sections of this report, the elevated TSS concentrations in the effluent are due to insufficient media substrate depth, and these systems can be improved with an ideal engineering design (Jiang et al, 2015; Kumar et al, 2012).

4.3 Financial Costs of LID Systems

After reviewing the current primary literature for cost information on LID treatment systems, it is clear that the availability of capital and O&M costs is limited. Houle et al. (2013) is the only primary article that included a cost comparison of all four LID treatment types, which includes detention basins, sand filters, porous pavement, and vegetated swales. Barrett (2005) conducted a cost comparison involving detention basins, sand filters, and vegetated swales, but did not compare porous pavement systems. Costs from Barrett (2005) and Houle et al. (2013) cannot be directly compared due to insufficient information available from both studies to evaluate differences observed in costs, but the trend in overall cost comparison may be more valuable. Barrett (2005) noted that detention basins were the least costly when considering construction and O&M costs, and the volumetric runoff reduction of the system. Vegetated swales were the second least costly, while sand filters were the most costly (Barrett, 2005). A similar trend was observed in Houle et al. (2013); from least costly to most expensive: detention basins, vegetated swales, sand filters, and porous pavement (Figure 19).

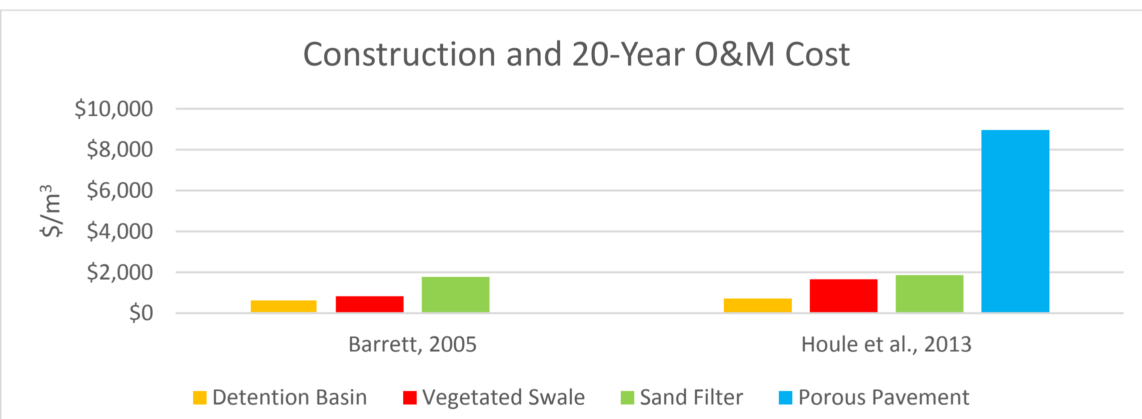


Figure 19 - Construction / Capital and O&M Costs for detention basins, sand filters, porous pavement, and vegetated swales as derived from Barrett (2005) and Houle et al. (2013). Detention basins were the least costly, with vegetated swales second least costly, and porous pavement the most expensive to construct and maintain.

Joksimovic and Alam (2014) did not evaluate O&M costs, but noted that vegetated swales were much more cost effective compared to porous pavement systems when considering capital costs and the volumetric capacity of the system. In Table 12 below, Joksimovic and Alam (2014) has the highest capital costs for porous pavement and a vegetated swale, but the lowest capital cost per capacity of volumetric runoff, which suggests that the larger the system installed, the more cost effective the system is, due to increased runoff capacity. This may be due to better purchase value for materials when buying in higher quantity, as well as better value from the construction company for scaling larger projects, but due to limited information available, these assumptions are uncertain.

Table 12 – Costs for LID treatment measures

LID Treatment Type	Capital / Construction Cost	Construction Cost of the Design Storm ($/m^3)	Annual O&M Cost	Annual O&M Cost of the Design Storm ($/m^3)	Construction and O&M Cost (20-Year) ($/m^3)	Literature Source
Detention Basin	$172,737	$590	$3,120	$83	$673	Barrett, 2005
Delaware Sand Filter	$230,145	$1,912	$2,910	$78	$1,990	Barrett, 2005
Austin Sand Filter	$242,799	$1,447	$2,910	$78	$1,525	Barrett, 2005
Vegetated Swale	$57,818	$752	$2,750	$74	$826	Barrett, 2005
Detention Basin	$40,700	$417	$6,150	$15	$712	Houle et al., 2013
Sand Filter	$37,700	$386	$7,210	$74	$1,862	Houle et al., 2013
Porous Pavement	$65,700	$4,940	$2,670	$201	$8,955	Houle et al., 2013
Vegetated Swale	$63,200	$647	$4,940	$51	$1,658	Houle et al., 2013
Porous Pavement	$4,308,214	$157	-	-	-	Joksimovic and Alam, 2014
Vegetated Swale	$2,024,786	$29	-	-	-	Joksimovic and Alam, 2014

4.4 Optimization of Costs and Treatment Efficiency

Results of the ANOVA and Tukey tests for TSS removal efficiency as shown in Tables 10 and 11 in previous sections of this report conclude that there are no significant differences in TSS removal between porous pavement, sand filters, and vegetated swales. Though, detention basins statistically have less TSS removal capabilities than the other three (3) LID systems. If owners and operators are seeking an LID storm water treatment system with higher TSS removal efficiency, but strives for the treatment system that would cost least in capital and maintenance costs over a 20-year time period, it is recommended to select vegetated swales (bioretention) as the LID for installation. Detention basins are the least costly per volumetric runoff capacity the system is capable of treating, but has the least efficient removal for TSS. Since vegetated swales, porous pavement, and sand filters are not statistically different in their removal capabilities, vegetated swales are the most cost effective option to achieve water quality requirements and reduce the most storm water runoff. These results must be taken with caution, as there is limited data available in the primary literature to properly evaluate costs. Though, the findings of this study has promise, as both Barrett (2005) and Houle et al. (2013) indicate similar overall trend in results, regardless of the factors that were evaluated in each study to come to their respective conclusions.

5. CONCLUSION AND RECOMMENDATIONS

An increase in development and urbanization has increased the volume of storm water runoff because percolation into natural and permeable ground cover is reduced. When rain falls to the ground, it picks up pollutants, including TSS, and travels with the flow of storm water through storm sewers, and eventually to local waterbodies. TSS is known to cause both human and environmental health problems. In order to manage rainfall volume and provide treatment to storm water runoff, municipalities require new development projects to include onsite LID treatment systems to treat the storm water that falls in the footprint of the new development site.

Existing studies have shown that LID storm water measures are effective in reducing runoff and improving water quality, but studies that can assist decision makers in selecting the most effective practices for their water quality needs is limited. One of the goals for this master’s project was to provide greater insight into the LID treatment systems that are the most efficient at removing TSS from storm water runoff. There are minimal studies that evaluate a coherent dataset and perform an exhaustive analysis on both capital, and O&M costs of LID treatment systems. A second goal for this master’s project study was to assess the least costly options for LID systems. Achieving these two goals will provide decision makers with the knowledge required to select the most efficient and least costly LID option that can be integrated into their storm water management program.

Due to the combined physical, chemical, and biological properties involved, vegetated swales were expected to be the most effective at removing sediment in storm water runoff. Results of the single-factor ANOVA indicate that there were no significant differences observed in TSS removal efficiencies between vegetated swales, sand filters, and porous pavement, but detention basins were statistically different from the 3 other systems. Therefore, the original hypotheses was only partially correct.

Properties that affect treatment performance include sedimentation, infiltration / filtration, adsorption, and phytoremediation mechanisms. Since detention basins resulted in the least efficient removal for TSS, results suggest that combining filtration and adsorption mechanisms favor TSS removal over sedimentation. Since vegetated swales did not statistically differ in TSS removal from sand filters and porous pavement systems, results suggest that phytoremediation is not an effective removal mechanism for TSS.

Each LID treatment system has various factors that can influence the efficiency of TSS removal. These factors include, but are not limited to, influent concentration, PSD of the influent and media substrate, media substrate selection, hydraulic conductivity, and engineering design. Decision makers are recommended to review TSS removal efficiency requirements, as well as to consider water quality limitations for their operation prior to exploring LID treatment options. All four LID systems have the potential to meet water quality standards, and the design of the system can be altered to meet specific water quality criteria.

Dry detention basins were anticipated to be the least costly per volume of storm water runoff the LID is capable of treating due to its open-pit high volume structural design. Based on a review of the limited primary literature available, this hypotheses was correct. When considering capital and O&M costs, detention basins were noted to be the least costly in Houle et al. (2013) and Barrett (2005), while sand filters and porous pavement systems were the most expensive per volumetric runoff capacity of the system. Costs can vary based on the size of the system, materials used, location, and maintenance requirements.

If owners and operators are seeking an LID storm water treatment system with higher TSS removal efficiency, but strives for the treatment system that would cost least in capital and maintenance costs over a 20-year time period, it is recommended to select vegetated swales (bioretention) as the LID to install. Detention basins are the least costly per volumetric runoff capacity the system is capable of treating, but has the least efficient removal for TSS. Since vegetated swales, porous pavement, and sand filters are not statistically different in their TSS removal capabilities, vegetated swales are the most cost effective option to achieve water quality requirements and reduce storm water runoff into municipal conveyance systems.

Since there were only two studies in the existing scientific literature that were comparable for capital and maintenance costs, the results of this master's project study should be taken with caution in respect to costs. Additional data on capital and maintenance costs are needed to analyze a larger dataset to verify the findings of my master's project study. TSS removal efficiencies were widely studied and were available in the scientific literature for each LID system, but there remains a gap in the costs associated with LID systems. Future research should be aimed at closing the gap on costs, to increase the data available in the scientific literature, and to allow future studies to generate findings based on statistical analyses. Future studies should aim to conduct an ANOVA test on LID costs to confirm whether a significant difference exists between treatment types.

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