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Stormwater Management Model Analysis on the Effectiveness of Low Impact Development Controls for Suburban Lid Designs in Brookings, South Dakota

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STORMWATER MANAGEMENT MODEL ANALYSIS ON THE EFFECTIVENESS OF LOW IMPACT DEVELOPMENT CONTROLS FOR SUBURBAN LID DESIGNS IN BROOKINGS, SOUTH DAKOTA

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by

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DESIGN PAPER ACCEPTANCE PAGE

The undersigned appointed by the dean of the Graduate School, have examined the design entitled

STORMWATER MANAGEMENT MODEL ANALYSIS ON THE EFFECTIVENESS OF LOW IMPACT DEVELOPMENT CONTROLS FOR SUBURBAN LID DESIGNS IN BROOKINGS, SOUTH DAKOTA

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a candidate for the degree of Masters of Science. This design paper is approved as a creditable and independent investigation by the candidate for the master's degree and is acceptable for meeting the design paper requirements for this degree.

Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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DEDICATIONS

Thank you so much to my family and friends for all their help and support. So many long nights and even longer trips between Brookings and Sioux Falls. I do not know how I would have survived without their love and warm meals.

A huge thank to Blake, Leticia, and Vani for beings just amazing classmates, peers, and friends. Over the last few years, they got me through tough moments and kept my spirit up when I really needed a good laugh. Thank you for all your support.

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ABBREVIATIONS

in.	inches
ft.	feet
lbs.	pounds
ft^2	feet square
gal.	gallons
ppb	parts per billion
µg/L	micrograms per liter
mg/L	milligrams per liter
in/hr	inches per hour
USEPA	United States Environmental Protection Agency
BMU	Brookings Municipal Utilities
USGS	United States Geological Survey
SWMM	Stormwater Management Model
SCM	Stormwater Control Measure
LID	Low Impact Development
TSS	Total Suspended Solids
MCLG	Maximum Contaminant Level Goal

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EXECUTIVE SUMARY

STORMWATER MANAGEMENT MODEL ANALYSIS ON THE EFFECTIVENESS OF LOW IMPACT DEVELOPMENT CONTROLS FOR SUBURBAN LID DESIGNS IN BROOKINGS, SOUTH DAKOTA

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Urbanization's influence the features of a watershed's subcatchments. The soil's low permeability causes a decrease in infiltration and storage and an increase in runoff. The management of peak runoff and stormwater quality must follow SCMs. LID controls provide natural practices for handling stormwater management.

This study used the LID controls of traditional drainage, vegetative swales, and bioretention cells to handle the runoff quantity and quality resulting from a 5-year storm event and a 100-year storm event. The SWMM modelled and analyzed the effectiveness of each model to remove the most of three pollutant loads: TSS, lead, and nitrate.

When compared to each other and the initial conditions, the model of bioretention cells (Design C) proved most effective in maintaining the water quality and preventing a significant concentration of TSS and nitrate from leaving the study area of subcatchments. Even though there was an improvement, the LID control of Design C was not managing stormwater quantity and quality most proficiency. Therefore, further study into the parameters of bioretention cells would be required.

CHAPTER I: PROBLEM STATEMENT

The urbanization of an environment drastically changes the features of its surface. As a result, the landscape struggles to manage peak stormwater runoff and maintain the stormwater quality as it infiltrates into the ground (Ercolani et al., 2018; Hsieh, Davis, & Needelman, 2007). The higher the intensity or longer the duration of a storm event, the more important it becomes for the ground to be able to handle the stormwater runoff. Thus, urban projects often include LID to achieve stormwater management and overcome water issues. Any urban project is at least recommended to incorporate LID controls to handle runoff and aid in the storage, infiltration, and evapotranspiration dealing with the stormwater (Davis et al., 2009; Rossman, 2015). Subsequently, the use of LID controls provided a way to reduce the quantity of pollutant loads. Therefore, LID controls reduce the impact of urbanization on a subcatchment.

1. Runoff, Infiltration, & Storage

Among the water processes ongoing in a watershed, infiltration and runoff transfer the largest quantity of stormwater into and through the subcatchments. Storage, while not conveying stormwater, can be heavily influential, since it provides a temporary place to hold stormwater before being absorbed, evaporated, or infiltrated back into surface water or groundwater (Davis et. al, 2009; Shrestha, Hurley, & Wemple, 2018; Trowsdale & Simcock, 2011; Xu & Liu, 2018). The success of the storage on the surface or underground depends on a storm's intensity and the surface features. For most storm events, all three processes should be more than adequate in balancing stormwater movement and maintaining its quality, but that is not always the case when urbanization

changes features about the landscape (Chen, Huang, & Zhang, 2017; Maharjan, Pachel, & Loigu, 2017; Qasim, Motley, & Zhu, 2000).

2. Land Use, Permeability, and Pollutant Loads

Some of these influential landscape features are the land use, soil permeability, and the concentration of surface pollutant loads due to land use. If the storm event duration is longer than expected or more intense, stormwater runoff becomes dominant (Chen, Huang, & Zhang, 2017; Xu & Liu, 2018). Consequentially, the more runoff increases the likelihood of pollutant loads being introduced into the runoff and any water source that receives said runoff.

For less intense storm events, runoff occurs less frequently or on a smaller scale. Rather, infiltration and storage manage most of the stormwater. Thus, infiltration should become the primary method of water movement. Unfortunately, urbanized environments, whether cityscapes or residential suburbs often suffer from poor infiltration for many of its landscapes. Most surfaces of an urban environment have poor permeability. Pavement, rooftops, roads, and many similar surfaces prevent effective infiltration into the soil. That results in pollutant loads either remaining on the surface or being incorporated in the stormwater runoff (Chen, Huang, & Zhang, 2017; Shrestha, Hurley, & Wemple, 2018; Rădulescu, Racoviţeanu, & Swamikannu, 2018; Sadeghi, Loáiciga, & Kharaghani, 2018). LID controls must be implemented to aid in improving infiltration and controlling runoff volume and the direction of its flow. The implementation of LID controls into a development project mediates stormwater runoff and aids in reducing pollutant loads (Li & Davis, 2014).

2. Low Impact Development (LID) Controls

LID has proven to be a widely accepted approach to combating the consequences of urbanization (Shrestha, Hurley, & Wemple, 2018). In an urban environment, LID provides sustainable stormwater control measures (SCMs). These SCMs are the best management practices for mediating stormwater issues that arise when changing a landscape for a construction project. LIDs are often incorporated into urban projects to achieve water conservation. The use of natural features provides a way to preserve the landscape and any aquatic environment and maintain the water cycle and water quality.

LID controls behind SCMs are multifaceted and built to fit the runoff and water quality challenges of the environment. The SWMM Manual Volume III – Water Quality provides some basic LID controls. Many of these are applicable in a suburban environment (Table 1). The addition of these LID controls provides an enhanced capability of the landscape to manage peak flow, and for some LID controls, reduce and maintain the water quality. Furthermore, LID controls can alleviate pressure on urban stormwater infrastructures and reduce downstream erosion and flooding severity (Davis et al., 2009; Rossman, 2015; Rossman & Huber, 2016; Shrestha, Hurley, & Wemple, 2018; Trowsdale & Simcock, 2011; Xu & Liu, 2018).

Table 1: Some of the possible LID controls that can be modeled in SWMM to enhance runoff reduction and pollutant load removal in a suburban environment (Rossman & Huber, 2016).

Bio-retention Cells are depressions that contain vegetation grown in an engineered soil mixture placed above a gravel storage bed. They provide storage, infiltration and evaporation of both direct rainfall and runoff captured from surrounding areas. Street planters and bio-swales are common examples of bio-retention cells.	
Rain Gardens are a type of bio-retention cell consisting of just the engineered soil layer with no gravel bed below it.	
Infiltration Trenches are narrow ditches filled with gravel that intercept runoff from upslope impervious areas. They provide storage volume and additional time for captured runoff to infiltrate into the native soil below.	
Rain Barrels (or ***Cisterns***) are containers that collect roof runoff during storm events and can either release or re-use the rainwater during dry periods.	
Vegetative Swales are channels or depressed areas with sloping sides covered with grass and other vegetation. They slow down the conveyance of collected runoff and allow it more time to infiltrate into the native soil.	

Before the implementation of any LID control, the project area and the LID control should be modeled and analyzed (Li & Davis, 2014; Rădulescu, Racoviţeanu, & Swamikannu, 2018; Trowsdale & Simcock, 2011; Wu et al., 2013). By analyzing the model of a design, the LID controls can be verified as effective, compared against other modeled LID controls or situations, and any parameters for the features evaluated to produce the best results.

3. Stormwater Management Model

Hydrologic and hydraulic models provide essential understanding into LID controls. One modelling program that has repeatedly proven effective for urban subcatchments of a watershed has been the stormwater management model (SWMM) (Chen, Huang, & Zhang, 2017; Mahargan, Pachel & Loigu, 2017; Rossman, 2015; Sadeghi, Loáicga, & Kharaghani, 2018; Wu, et. al, 2013). Hydrologic modeling provides a methodology for analyzing various LID controls to determine the best management practice.

SWMM has proven to be a versatile hydrologic modeling program with it being able to represent an urban environment so accurately (Chen, Huang, & Zhang, 2017; Rossman, 2015). According to Maharjan, Pachel, & Loigu (2017), SWMM can simulate a single-event or a continuous set of flows and various types of pollutant loads. SWMM can adapt to varies environmental factors among different urban environments (Chen, Huang, & Zhang, 2017; Maharjan, Pachel, & Loigu, 2017; Rossman, 2015; Rossman & Huber, 2016). The versatility is due to the comprehensive spectrum of environmental parameters that can be defined in a SWMM simulation. Among the most important are climate, topography, and land use (Rossman, 2015). Additionally, SWMM includes an ability to analyze the presence and distribution of pollutant loads (Rossman, 2015; Rossman & Huber, 2016; Wu et al., 2013; Xu & Liu, 2018). The subcatchment data allows SWMM to track the quantity and quality of stormwater runoff over time from each subcatchment. Even if stormwater enters a drainage system, pipes, or channels, SWMM can provide stormwater data (Maharjan, Pachel, & Loigu, 2017; Rossman, 2015; Xu & Liu, 2018). That defines the environmental limitations and effectively aids in

finding the necessary SCM, so that LID controls can be more accurately designed (Maharjan, Pachel, & Loigu, 2017; Rossman, 2015; Wu et al., 2013).

For this design project, the researcher obtained 6 years' worth of previously collected data for the upstream subcatchments in Brookings, South Dakota. The researcher focused in on the data from three subcatchments in the Indian Hills neighborhood around Arrowhead Park. The data was remodeled, and water quality parameters added, since none existed with the previous model of Brookings, South Dakota. The initial conditions along with three LID controls were modeled in SWMM. Then two single-event simulations: 5-year and 100-year, were run for each of the models. The purpose of this paper was to compare the initial conditions model against three LID control models: traditional drainage model (Design A), vegetative swales model (Design B), and bioretention cells model (Design C). A comparison of all of them provided insight into the effectiveness of each when maintaining the quality of the water and reducing peak runoff rates during wet weather events for a 5-year and a 100-year storm event.

CHAPTER II: STUDY AREA

The study was performed on three subcatchments that contained a significant portion of the Indian Hills neighborhood. The neighborhood was in the southwestern area of Brookings, South Dakota. This area was chosen due to a mixture of land use: residential and underdeveloped, and the potential sources for the three pollutant loads being analyzed in SWMM. While the surrounding area was highly residential, most of the lower two subcatchments contained an underdeveloped neighborhood park, Arrowhead Park. In fact, Subcatchment M16-1 and Subcatchment M16-3 each contained a large pond. The presence of these water sources meant LID controls for SCMs were needed to maintain the ponds' water quality. These are ecosystems for the local wildlife and potentially feed into more primary water sources (Figure 1 and Figure 2).

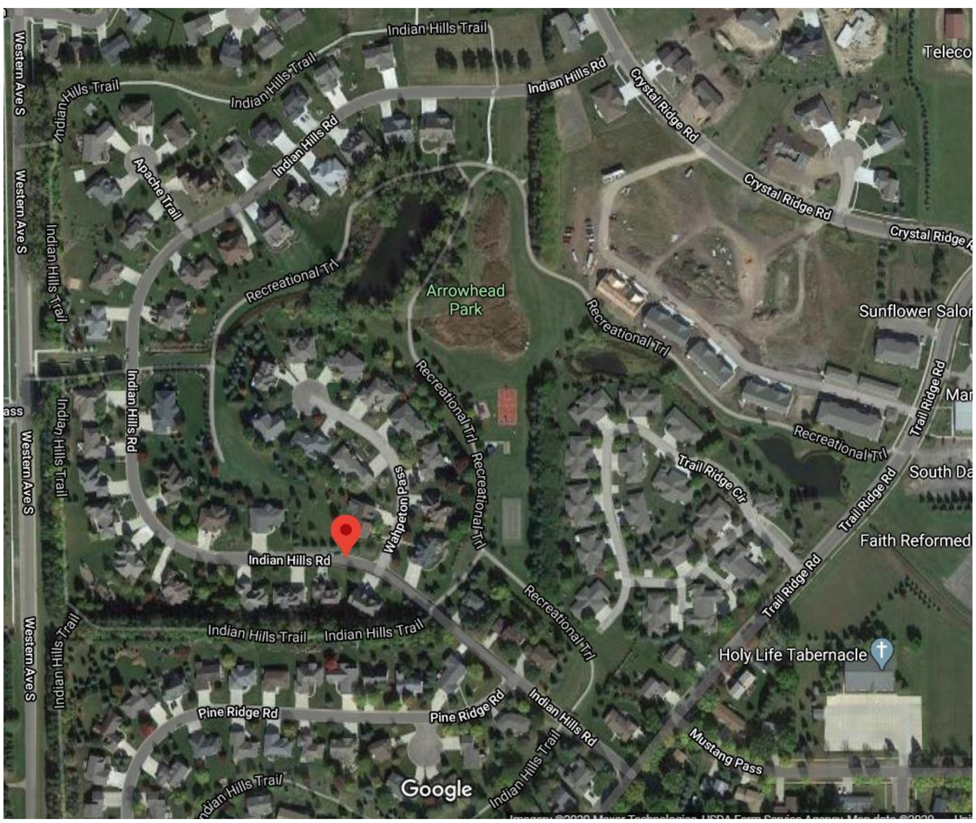

Figure 1: An aerial map of Arrowhead Park in the middle of the Indian Hills neighborhood in Brookings, South Dakota (Arrowhead Park, Brookings, SD, 2020).

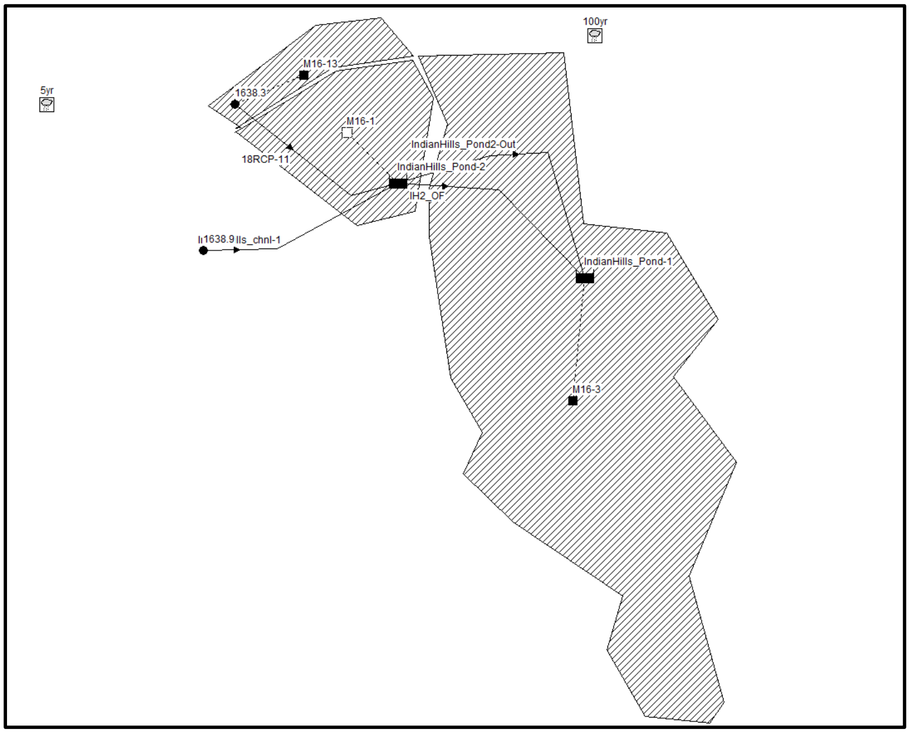

Figure 2: A SWMM model of the initial conditions of the three subcatchments with the two ponds and the two storm events, 5-year and 100-year, rain gages.

1. Land Uses

Urbanization can best be represented through land uses of the watershed's subcatchments. A subcatchment's land use can define the surface's permeability and the concentrations of pollutant loads. As stated in the last section, permeability dictates how well water processes handle runoff and maintain stormwater quality (Wu et al., 2013). The study's subcatchments were comprised of residential and underdeveloped land uses. Each subcatchment contained some percent of each land use.

The residential areas included houses, townhouses, sidewalks, and roadways. Most of the residential areas within the three subcatchments existed within Subcatchment M16-13, which was 95 percent residential. The rest of the residential land use areas existed along the outer rim of the other two subcatchments. These residential areas

primarily consisted of single-family houses, except on the north side of Pond 1 in Subcatchment M16-3. That residential area had a series of townhomes facing away from the pond.

The underdeveloped areas were primarily open green with minimal tree coverage and two medium sized ponds. Neighborhood roads and recreational trails surrounded most of the underdeveloped landscape. The Indian Hills Road lined the north and south sides, and most of the west side of the subcatchments. Recreational Trail, a branching park pathway into the surrounding neighborhood, lined some of the west and the east sides of the park. Only the lower portion of Subcatchment M16-13 contained underdeveloped land use (approximately five percent). Most of the underdeveloped areas were contained in the other subcatchments.

The Subcatchment M16-1 was primarily underdeveloped land use (approximately 60 percent), containing most of Arrowhead Park. The southwest side had a small playground and a basketball court. In the center of the subcatchment is a large, low land depression covered with tall grass and vegetation. In fact, the low land depression led from Pond 2 and Pond 1. The researcher considered that it might act as a dry wetland or a retention pond for larger storm events. In fact, there was an underground pipeline between the dry depression and Pond 1.

Despite having single-family houses on the south side and townhouses on the north side of Pond 1, Subcatchment M16-3 was mostly underdeveloped (70 percent). The Trail Ridge Road ran along the east side of Pond 1. Also, on the northwest side of Pond 1, there was an elongated, shallow depression that ran down the incline from a segment of the Recreational Trail towards Pond 1. This depression appeared to be a type of swale

based on the SWMM model's definition (Rossman & Huber, 2016). It would allow for runoff drainage into Pond 1. However, other than grass, there did not appear to be much vegetation in the depression, so the researcher did not consider it a vegetative swale. Rather, most of the vegetation was on the west side of Pond 1 or the points where the width of Pond 1 narrowed or widened (Arrowhead Park, Brookings, SD, 2020).

2. Landscape

According to USGS topo maps, the elevation of the subcatchments ranged from 1,643 to 1,622 feet (Topographic-Map, n.d.; USGS, 2018). In fact, based on a USGS soil survey, the slope was between 2 and 6 percent. The slope of the landscape can be important in determining design constraints. For example, some LID controls cannot be used if the slope exceeds a certain angle.

Another landscape feature was about the soil composition. Based on a 2019 USDA soil survey, the area of the three subcatchments were primarily (55.3 percent) loam or sandy loam, and less than five percent of the subcatchments consisted of water (Table 2) (USDA, 2019). That meant any soiled surface would have a good permeability relative to its moisture content and any vegetation on it. Additionally, the composition indicated a good soil stability, which influences how well a LID control can enhance infiltration.

Table 2: The soil composition of the three subcatchments based on a 2019 USDA Soil Survey of Brookings County in South Dakota (USDA, 2019).

Soil Type/Name	Portion of Soil Composition (%)
Barnes clay loam	12.8
Doland-Svea loam	20.9
Hamerly-Badger complex	10.8
Svea loam	3.6
Swenoda-Lanona sandy loams	18.1
Vienna-Brookings complex	15.7
Vienna-Brookings complex	13.6
Water	4.6

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3. Water Quality Issues

The capability of a LID control to reduce and maintain an environment's water quality must be one of the primary concerns of any LID. Since there are any number of potential pollutants present in an urban environment, this study focused on three common ones: total suspended solids (TSS), lead, and nitrate. By measuring these for each design modeled, the researcher wanted to analyze how and when the concentrations changed with stormwater runoff, infiltration, and storage.

The primary pollutant was TSS. Particles exist in the water, and the portion that is not soluble in water would be considered TSS. The composition of these solids can be a variety of combinations of soil, chemicals, and biomass. Land use influences the presence of these different suspended solids. In a suburban environment, driveways, roadways, atmospheric depositions, sidewalks, and drainage can cause the formation of TSS. While TSS does not have a direct negative impact on people, its presence potentially would indicate the presence of other more hazardous pollutants. TSS has been known to have hydrophobic compounds attach to them. As a result, they carry these pollutants into the soil and possibly back to water sources in the subcatchment (Qasim, Motley, and Zhu, 2000; Rossman & Huber, 2016; Trowsdale & Simcock, 2011).

The second pollutant load was lead. According to the USEPA, lead has a MCLG of zero. This ionic species is not essential to life. Even at low levels, lead can cause anemia, impairment of the nervous system, and potentially cause mental retardation in children or fetuses (BMU, 2017; Qasim, Motley, & Zhu, 2000; Shrestha, Hurley, & Wemple, 2018; Trowsdale & Simcock, 2011). According to Rossman & Huber (2016), depending on the land use in an urban environment, the median presence of lead could be as high as144 µg/L. Since lead particles do not tend to dissolve, they can attach to TSS, and then, inadvertently be swept up in the stormwater runoff.

The third pollutant load was nitrate. Fertilizers and animal waste are common sources for this nitrogen compound. Its water solubility allows it to incorporate into runoff and soil more easily. In less than 10 mg/L concentrations, nitrate is harmless and potentially beneficial, such as helping to lower blood pressure. However, higher concentrations negatively affect the circulatory and respiratory systems of younger children and unborn infants (Qasim, Motley, & Zhu, 2000; Rossman & Huber, 2016; Shrestha, Hurley, & Wemple, 2018). The presence of a neighborhood with well-kept lawns might be a nonpoint source for nitrate. Furthermore, the presence of dogs, birds, and waterfowl in the park demonstrated another nonpoint source in their fecal matter, if not effectively managed (Qasim, Motley, & Zhu, 2000; Shrestha, Hurley, & Wemple, 2018; Trowsdale & Simcock, 2011).

4. Design Constraints

Before modeling, a study area must meet certain constraining standards based upon the LID controls, current or future land uses, and the characteristics of the landscape. If not met, the model of the design might not be as effective. Thus, the

findings would be inaccurate and the recommendation not truly the best solution. Therefore, these must be checked or followed when setting up the models (Table 3).

Table 3: Some of the design constraints for LID controls, land uses, and landscapes.

Design Constraints & Requirements:	
LID controls	• Water table > 6 feet from surface • Presence of trees • Surface slope < 20 % • Vegetative swales length ≥ 100 feet
Land Uses & Landscape	• Presence of ponds/lakes • Residential Vs. Underdeveloped

With LID controls, there are physical landscape traits that need to be met to achieve runoff quantity and quality reduction. The literature discusses some of these based on the environment. For the study area, the water table level, the surface slope, and the minimum vegetative swales length are especially important.

The shallow water table level would allow for oversaturation of the soil. According to SDDENR (2018), based on observed well depths, the water table of the study's area fluctuated between 3 and 9 feet since 2000. Thus, any drainage layer for a LID controls should include drainage pipes. If the ground becomes oversaturated, infiltration would be reduced (SDDENR, 2018; USGS, 2018).

A surface slope of less than 20 percent would also hinder the types of LID controls usable for a landscape. Bioretention cells would be less effective on a steep surface incline. Also, vegetative swales that are placed in a treated area must have a surface slope less than 25 percent. Fortunately, as mentioned before, the slope within the

subcatchments were 2 to 6 percent (Clean Water Services, 2016; USDA, 2019; USGS, 2018).

As for the length of vegetative swales, they must each be at least 100 feet. That length provides a longer detention time to improve infiltration and the capacity for BMP removal. When designing the vegetative swales, the length was set to 100 feet when calculating the area of each unit (Clean Water Services, 2016; Rossman, 2015; Rossman & Huber, 2016).

Outside of the LID control limitations, consideration must be given to the land uses and the presence of the two lakes. Residential areas are primarily impervious. However, those impervious surfaces are roadways, sidewalks, and buildings. These are not necessarily easy to adapt or remove. That limits the amount of area available for LID controls, such as vegetative swales and bioretention cells. Additionally, the ponds in Subcatchment M16-3 and Subcatchment M16-1 take up a portion of the surface, too. In fact, these two ponds act as storage basins for these subcatchments. Most runoff flows into them or infiltrates through the soil and then into them. Thus, these storage basins must be protected from runoff pollutant loads.

When setting up initial concentrations for pollutant load buildup, the researcher referenced a 2017 Brookings Municipal Utilities' (BMU) Water Quality Report and the USEPA standards (BMU, 2017, Qasim, Motley, & Zhu, 2000; Rossman & Huber, 2016). The BMU water report provided a short list of some common contaminants of concern in the Brookings area. These were measured in drinking water and must be maintained with allowable ranges to meet USEPA standards. The researcher based initial concentrations and maximum buildup on the values of these findings and expectations found in other

literature. Since lead is considered dangerous even at an exceptionally low concentration, the goal was 0 ppb (BMU, 2017; Qasim, Motley, & Zhu, 2000). The BMU water report recommended a MCLG of 10 ppm for nitrate (BMU, 2017). The previous literature tended to use an initial TSS concentration of between 50 and 150 mg/L (Davis et al., 2009; Rossman & Huber, 2016; Shrestha, Hurley, and & Wemple, 2018; Trowsdale & Simcock, 2011). As a result, the initial concentrations were set for TSS (100 mg/L), lead (0 µg/L), and nitrate (0.01 mg/L) (BMU, 2017).

After determining the initial concentrations for the three pollutant loads, the SWMM manual recommended relating the pollutant loads to each other. Since TSS will always be present in some form and concentration, it was made the prominent co-pollutant. Nitrate and lead were then dependent on TSS based on the recommendation from the SWMM program manual and previous studies (Table 5) (Qasim, Motley, & Zhu, 2000; Rossman, 2015; Rossman & Huber, 2016; Shrestha, Hurley, Wemple, & 2018). Rossman (2015) also recommended a co-fraction of 0.25, so that was used for both lead and nitrate.

CHAPTER III: DESCRIPTION OF STUDY APPROACH

The study began with an inquiry into SWMM analysis of LID controls and their capabilities to maintain water quality. Certain input parameters about the subcatchments influenced the effectiveness of the LID controls. According to Maharjan, Pachel, and Loigu (2017), previous studies have proven the effectiveness of SWMM in simulating stormwater quality and quantity to determine the performance of LID controls. This study provided insight into a study area located in a small, Midwestern, suburb and show how the addition of one of three LID controls might improve stormwater management.

1. Purpose & Scope of Study

The study area required an improvement in the stormwater management. Thus, the study proposed to use SWMM to model and analyze the initial conditions along with three LID control models. The goal was to figure out which of the three LID controls better maintained the water quality within the subcatchments.

Therefore, SWMM provided hydrological models of all four designs, including the initial conditions. With representative SWMM models, an analysis was run, and each LID control's effectiveness was determined. The initial conditions model provided a current state that needed to be improved upon. Comparisons were made between the initial conditions model and each model of the three LID control designs to show whether there was improvement and by how much. Finally, the models of the LID controls were compared to each other. This comparison was the method used to judge the effectiveness of each design.

2. Design Criteria

The success of the study relied on completing the steps behind the models and their analysis and comparison. First, each design for the study area, including the initial conditions, must be modeled with SWMM based on the determined parameters. Second, each design model must be analyzed in SWMM. These models had two single-event simulations, one for each storm event. Third, a comparison must be made for each LID control model against the initial conditions model to see how the different input parameters affected the results. Fourth, a comparison was made among all the LID control models. Finally, completing the previous design criteria should determine the LID control that demonstrates the most improvement in reducing runoff volume and pollutant load concentration in runoff and external outflow.

3. LID Control Designs

There were three LID control designs that were modeled with SWMM. First, there was a traditional drainage model (Design A). Second, there was the addition of vegetative swales to the initial conditions model (Design B). Third, bioretention cells were added to the initial conditions model (Design C). Each model consisted of three subcatchments. The features for each subcatchment remained largely consistent through each model (Table 4 through Table 8). However, a few of these features were changed since they were relevant input parameters.

Table 4: The physical features of each subcatchment for the initial conditions model both with and without the additional LID controls: vegetative swales and bioretention cells.

Subcatchments	M16-1	M16-13	M16-3
Outlet	IndianHills-Pond-2	1638.3	IndianHills_Pond-1
Area	3	1.8	8.3
Width	380	140	200
%Slope	1.500	0.600	0.900
%Imperv.	12	45	8
N-Imperv	0.013	0.013	0.013
N-Perv	0.240	0.240	0.240
Dstore-Imperv	0.075	0.075	0.075
Dstore-Perv	0.150	0.150	0.150
%Zero-Imperv	25	25	25
Subarea Routing	Outlet	Impervious	Pervious
Percent Routed	100	100	98

Table 5: The infiltration data for each of the three subcatchments: M16-1, M16-13, and M16-3.

Subcatchments	M16-1	M16-13	M16-3
Infiltration Data	Curve Number	Curve Number	Curve Number
Curve Number	61.00	61.00	61.00
Conductivity	0.08	0.08	0.08
Drying Time	7.00	7.00	7.00

Table 6: The breakdown, in percentage, of the land uses for each subcatchment.

Subcatchments	M16-1	M16-13	M16-3
Land Uses	2.00	2.00	2.00
Residential (%)	40.00	95.00	30.00
Underdeveloped (%)	60.00	5.00	70.00

Table 7: The initial conditions for each pollutant load concentration, and how lead and nitrate relate to TSS for all three subcatchments.

Pollutants	TSS	Lead	Nitrate
Units	mg/L	µg/L	mg/L
Initial Concentration	100	0	0.01
Co-Pollutant	-	TSS	TSS
Co-Faction	0	0.25	0.25

Table 8: The buildup and wash off features for land uses based on the three pollutant loads.

Land Uses	Residential			Underdeveloped		
Pollutant Load	TSS	Lead	Nitrate	TSS	Lead	Nitrate
Buildup						
Function	POW	POW	POW	POW	POW	POW
Max. Buildup	50.00	0.00	0.05	25.00	0.00	0.03
Rate Constant	1.00	0.00	1.00	0.50	0.00	0.50
Power Constant	1.00	0.00	1.00	1.00	0.00	1.00
Normalizer	Area	Area	Area	Area	Area	Area
Washoff						
Function	EMC	EMC	EMC	EMC	EMC	EMC
Coefficient	100.00	0.00	100.00	50.00	0.00	50.00

For the traditional drainage model, permeability was adjusted. More specifically, the percent impervious (%Imperv.) changed for each subcatchment. Subcatchment M16-1 and Subcatchment M16-3 had a 90 percent imperviousness for the traditional drainage model. Subcatchment M16-13 had a 95 percent imperviousness for the traditional drainage model. The reason for this change was covered in Chapter V: Traditional Drainage Model (Design A).

For the model with the addition of the vegetative swales, permeability and the presence of a LID control varied. The permeability differed from the traditional drainage model but was the same as the initial conditions model. The presence of the LID control of vegetative swales meant that the BMP removal was added to the buildup processes for the pollutant loads.

The model with the addition of the bioretention cells varied due to its permeability and the presence of a LID control. As with the vegetative swales, the permeability differed from the traditional drainage model but was the same as the initial conditions model. The presence of the LID control of bioretention cells meant a shift in

the buildup, since BMP removal was significant, and in the depth of stormwater since an initial LID stage existed before the total precipitation.

4. *Assessment of the Designs*

The assessment of each modeled LID control design must be based on the results from the simulations performed in SWMM. First, the calculated surface runoff depth should be less than the surface runoff depth of the initial conditions, or at least one of the lowest surface runoff depths. Additionally, a larger infiltration loss depth than surface runoff depth would be representative in an improved removal of pollutant loads. Of course, a higher infiltration loss depth does not mean the final storage has to be small. Rather, it should be larger than surface runoff depth.

Second, there should be no external outflow. An external outflow would mean that a volume of stormwater was leaving the subcatchments. Depending on the pollutant load concentrations in surface runoff, a significant concentration of pollutant loads would be leaving the study area for another subcatchment or water source. That would be undesirable for maintaining the water quality.

Third, the surface runoff quality should be less than for the initial conditions model. A lower value would mean there was less of those pollutant loads in surface runoff. In fact, an assessment of the other water processes should show buildup of the pollutant loads to be mostly in BMP removal and the remaining buildup.

5. *Modeling the Designs*

The process of modeling each design remained consistent across all four models (Figure 3). First, the researcher followed the SWMM program's tutorials for project

setup, constructing a SWMM model, and setting up the properties for the necessary SWMM objects. According to Rossman (2015), most of these values in the SWMM tutorial were usable for most subcatchment models. The result was a base theoretical model that the researcher could alter and add to from existing data.

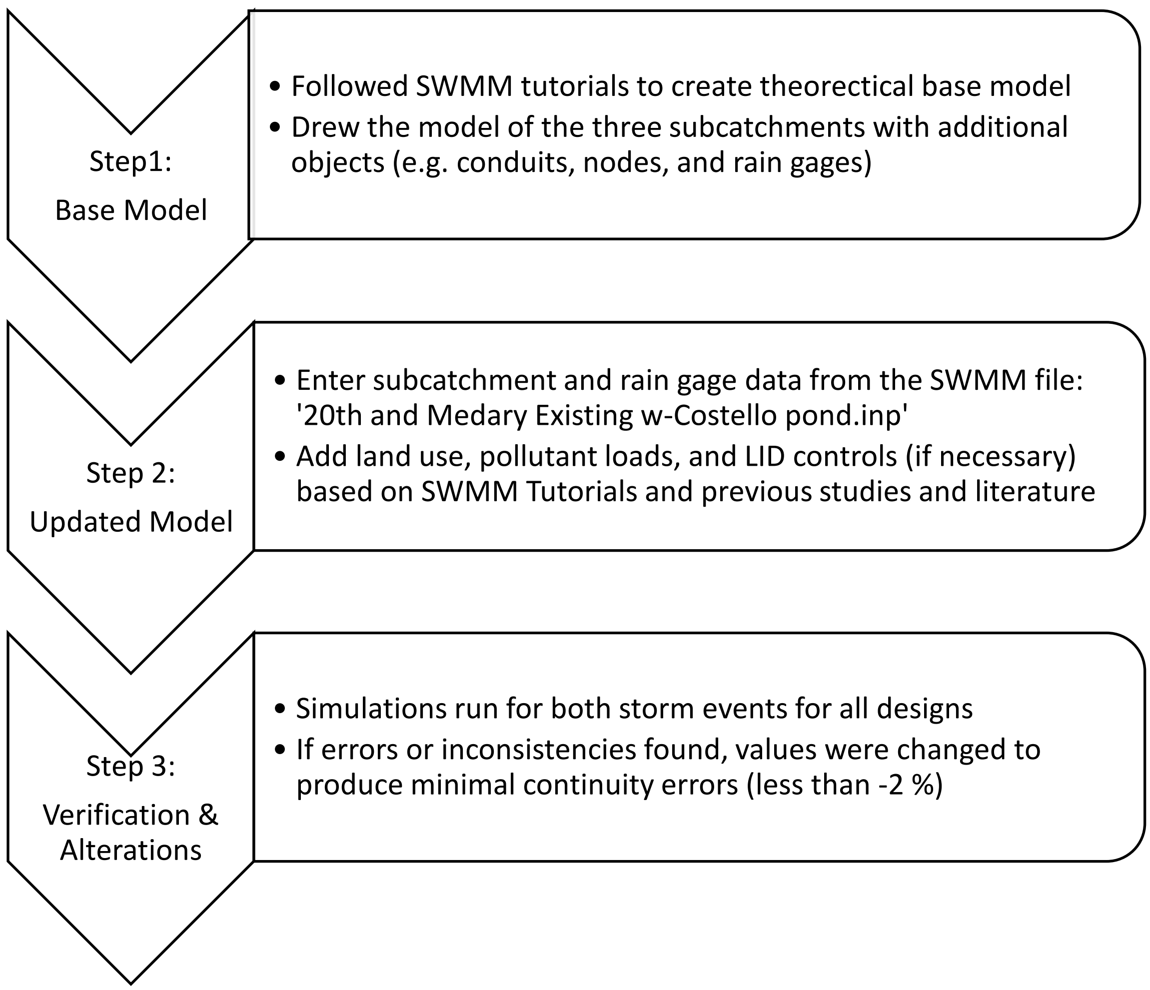

Figure 3: The process of creating the models for the four designs run for the two storm events.

Second, the existing data from the SWMM file with 6 years of subcatchment data was entered. That meant some values from the SWMM tutorial were changed to fit with the existing data on the study area. However, not all the data required for the study was present. Any data not provided (e.g., pollutant loads) was based on the SWMM manual

tutorials and previous studies and literature. The drawing of the three subcatchments' model was based on the existing data's model (Figure 2).

Third, that data was coordinated across the designs, and altered or added if the design required different values (e.g., %Imperv. for traditional drainage design). The literature on LID and some of these LID controls helped to define some of these parameters. However, in some cases test simulations were run to verify whether the values entered were applicable and produced consistent results. The results were analyzed to check for any issues. Some adjustments were made to values when issues were found.

CHAPTER IV: INITIAL CONDITIONS MODEL

The first step in determining the effectiveness of LID controls was to model and analyze the initial conditions in SWMM. Two single-event SWMM simulations were run – one for each storm event. Calculating the flow depth and volume and the presence of pollutant loads in SWMM analysis provided insight into how the initial conditions handle two storm event intensities. The results presented a datum state of the subcatchments to compare against the other modeled subcatchments' designs.

1. Input Parameters

The initial conditions laid out the parameters for the subcatchments, their land uses, and potential pollutant load concentrations. SWMM analyzed the model with a 5-year storm event and a 100-year storm event based on the rain gage data. Before any alterations, a simulation was run for both storm events to show a base situation of the subcatchments together (Table 4 through Table 8).

2. Output of the Model

For each storm event, the water processes created quantity and quality factors related to runoff. As stated previously, the processes with the most significant influence are runoff, infiltration, and storage (e.g., lakes, depressions, and ground storage). During each of these processes, SWMM calculated the quantity of water in terms of runoff and the mass of pollutant loads present. The sum of infiltration, surface runoff, and final storage should equal the total precipitation. The evapotranspiration was considered negligible in this study and verified since SWMM calculated no significant amount. The model showed that for both storm events, the water process quantities did equal precipitation. The most influential for the initial conditions model was the infiltration loss

with 0.215 in. for a 5-year storm event and 0.351 in. for a 100-year storm event (Table 9). Still, the final storage depth was larger than the surface runoff depth. That was a good sign, since a larger storage compared to stormwater runoff was preferred.

Table 9: The runoff quantity data from two SWMM simulations run for 5-year and 100-year storm events of the initial conditions model.

Storm Event	**5-year**	**100-year**
Total Precipitation (in.)	0.260	0.435
Infiltration Loss (in.)	0.215	0.351
Evaporation Loss (in.)	0	0
Surface Runoff (in.)	0.017	0.032
Final Storage (in.)	0.028	0.053

When it came down to the mass of the three pollutant loads, TSS and nitrate showed significant concentrations. The concentrations of lead were insignificant in comparison to the other two pollutant loads. In fact, lead only appeared significant in surface buildup and surface runoff. For a 5-year storm event, there was more surface buildup for nitrate than TSS. The same was true for a 100-year storm event. Though, the surface runoff quantity for TSS was four times larger than for nitrate for a 5-year storm event and a 100-year storm event. Thus, surface runoff removed more TSS than nitrate. However, the larger initial concentration was a reason for this shift, since the initial buildup of TSS (46.25 lbs.) and nitrate (0.501 lbs.) were just as large a difference as surface runoff (Table 10).

Table 10: The runoff quality data for the concentrations of the three pollutant loads: TSS, lead, and nitrate from two SWMM simulations run for 5-year and 100-year storm events of the initial conditions model.

Storm Event	**5-year**			**100-year**		
Pollutant Load:	**TSS**	**Lead**	**Nitrate**	**TSS**	**Lead**	**Nitrate**
Initial Buildup (lbs.)	46.250	0	0.501	46.250	0	0.501
Surface Buildup (lbs.)	0.574	0.001	1.088	0.202	0	2.097
Infiltration Loss (lbs.)	0	0	0	0	0	0
BMP Removal	0	0	0	0	0	0
Surface Runoff (lbs.)	4.353	0.001	1.324	8.388	0	2.369
Remaining Buildup (lbs.)	42.471	0	0.265	38.064	0	0.229

The volume of through outflow and the inflow concentration of the pollutant loads present varied between the two storm events. While the volume of dry weather inflow was insignificant, the volume of a wet weather inflow showed significance. However, according to the final stored volume, the runoff was the only routing source in the initial conditions model. There were no external inflows or outflows based on SWMM calculations (Table 11).

Table 11: The flow volumes for different inflows and outflows from two SWMM simulations run for 5-year and 100-year storm events of the initial conditions model.

Storm Event	**5-year**	**100-year**
Dry Weather Inflow (gal.)	0	0
Wet Weather Inflow (gal.)	6000	11000
External Inflow (gal.)	0	0
External Outflow (gal.)	0	0
Final Stored Volume (gal.)	6000	11000

For the initial conditions model, TSS and nitrate had the most significant quantities for the wet weather inflow. In fact, according to the simulation, no other water process was significant enough to change the value, so it was equal to the final stored volume for both storm events. As with the volume, the 5-year storm even had a significantly larger concentration of TSS than nitrate – about four times. The 100-year storm event had the same difference between TSS concentration and nitrate concentration. Despite no other sources of significant inflow, the mass concentration of TSS and nitrate were both larger for the final stored mass when compared to the wet weather inflow quantity for both storm events (Table 11 and Table 12).

Table 12: The flow quality, mass concentrations of the three pollutant loads, data from two SWMM simulations run for 5-year and 100-year storm events of the initial design.

Storm Event	**5-year**			**100-year**		
Pollutant Load:	**TSS**	**Lead**	**Nitrate**	**TSS**	**Lead**	**Nitrate**
Dry Weather Inflow (lbs.)	0	0	0	0	0	0
Wet Weather Inflow (lbs.)	4.259	0.001	1.264	8.215	0.002	2.251
External Inflow (lbs.)	0	0	0	0	0	0
External Outflow (lbs.)	0	0	0	0	0	0
Final Stored Mass (lbs.)	4.262	0.001	1.265	8.220	0.002	2.252

Based on the analysis of the initial conditions model, more TSS was washed away in surface runoff than any other pollutant load. Since many other pollutants can travel with TSS, its effective removal became even more important. However, the analysis of the initial conditions model did also show a significance in the concentration of nitrate, depending on the storm event and the water process containing the nitrate. As for lead, the concentration of TSS and nitrate were more significant than it. Thus, the analyses of the LID control design models would be more focused on TSS and nitrate concentrations for both storm events. Furthermore, the desired level of maintenance of the water quality in the subcatchments was not being achieved for the initial conditions. Thus, the LID controls models must show some level of improvement for this result, too.

CHAPTER V: TRADITIONAL DRAINAGE MODEL (DESIGN A)

A traditional drainage system (Design A) was modeled as channels in series. The corridor of waterways led from Subcatchment M16-13, through Subcatchment M16-1, and out through Subcatchment M16-3 (Figure 4). Unlike the initial conditions model, the traditional drainage model was assumed to have less infiltration. The depth of infiltration and surface runoff should be quite different from the initial conditions model, but the pollutant load concentrations might be a different case entirely.

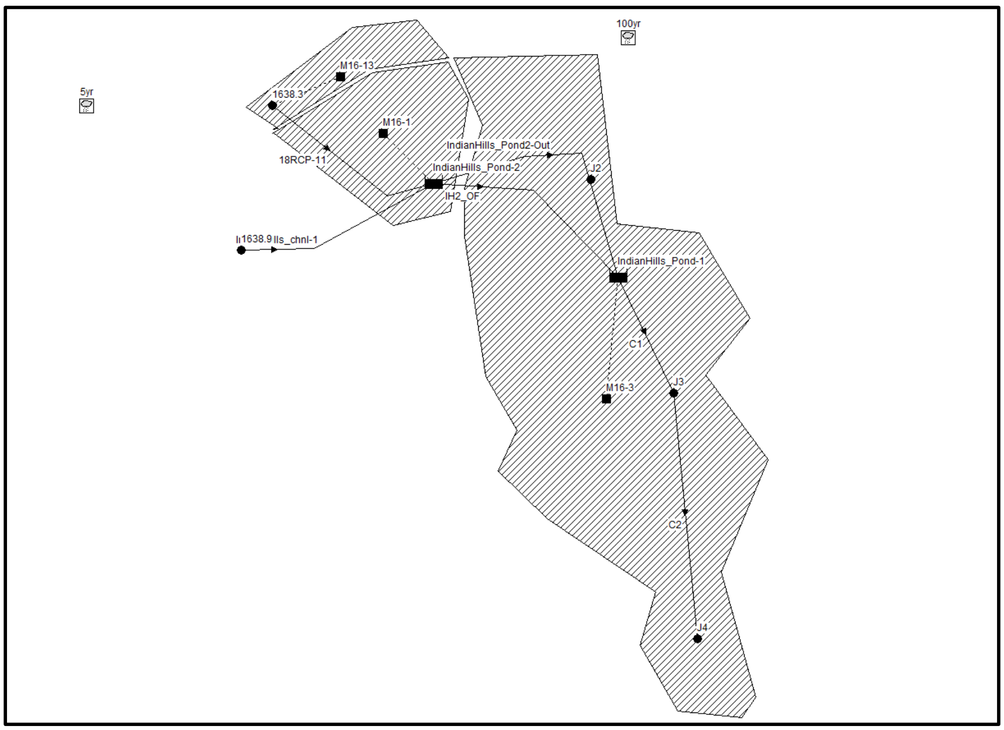

Figure 4: The model of the traditional drainage through the three catchments along with the two storm events, 5-year and 10-year, rain gages.

1. Model Conceptualization

The model for Design A was designed to replicate a series of channels directing the flow of water from one subcatchment to the next. Along the way, each pond acted as a temporary basin. However, to contain the influence of outside contaminated runoff, the

only one external inflow source was the Indian Hills channel that fed directly into Pond 2. Based on the initial conditions model, the Indian Hills channel did not supply a significant external inflow. Thus, the Design B simulations showed no external inflow, too. The stormwater was directed along the conduits from Subcatchment M16-13 to the south side of Subcatchment M16-3 through additional junction points (Figure 4). These conduits acted as channels, directing the stormwater runoff flow into and out of the ponds, and then out of the study area.

Another assumption was that the %Imperv. significantly increased from the initial conditions model. The reason for the change in the %Imperv. was using a conservative assumption that traditional drainage was meant to reduce, if not eliminate, stormwater runoff. Thus, the surface was not capable of managing the stormwater through other water processes. Additionally, traditional drainage systems were more concerned about hydraulic impact than the water quality impact (Davis et al., 2009; Hsieh, Davis, & Needelman, 2007; Ercolani et al., 2018). For this study, if the water never flowed along the surface, there was less of a chance of becoming contaminated from surface pollutant loads. Other than these changes in the model and assumptions, the rest of the subcatchment characteristics were left the same.

2. Input Parameters

As stated before, most of the subcatchment characteristics remained the same as the initial conditions model (Table 5 through Table 8). The only characteristic that changed was the %Imperv. Subcatchment M16-1 and Subcatchment M16-3 were made 90 percent impervious, while Subcatchment M16-13 was made 95 percent impervious

(Table 13). The rest of each subcatchment's characteristics were the same as the initial conditions model.

Table 13: The physical characteristics of each subcatchment for the initial conditions model both with and without the additional LID control: vegetative swales and bioretention cells.

Subcatchments	M16-1	M16-13	M16-3
Outlet	IndianHills-Pond-2	1638.3	IndianHills_Pond-1
Area	3	1.8	8.3
Width	380	140	200
%Slope	1.500	0.600	0.900
%Imperv.	90	95	90
N-Imperv	0.013	0.013	0.013
N-Perv	0.240	0.240	0.240
Dstore-Imperv	0.075	0.075	0.075
Dstore-Perv	0.150	0.150	0.150
%Zero-Imperv	25	25	25
Subarea Routing	Outlet	Impervious	Pervious
Percent Routed	100	100	98

3. Output of Traditional Drainage Model

This model demonstrated that most of its stormwater was moved through surface runoff for both storm event. In fact, surface runoff depth was almost an entire magnitude larger than infiltration depth. Still, a significant amount remained in the final storage depth. The 100-year storm event had 0.02 more inches than the 5-year storm event. That may be due to how the conduits were routing the stormwater to the ponds. Instead of most of the water being infiltrated into the soil, the stormwater runoff was captured in storage structures on the surface of the subcatchments (Table 14).

Table 14: The runoff quantity data from two SWMM simulations run for 5-year and 100-year storm events for Design A.

Storm Event	**5-year**	**100-year**
Total Precipitation (in.)	0.260	0.435
Infiltration Loss (in.)	0.023	0.038
Evaporation Loss (in.)	0	0
Surface Runoff (in.)	0.103	0.235
Final Storage (in.)	0.134	0.164

The model's pollutant load concentrations were primarily picked up via surface runoff. The surface runoff concentrations for TSS was 48.7 percent of the initial buildup concentration for the 5-year storm event. For the 100-year storm event, 91.7 percent of the initial buildup concentration was picked up via surface runoff. SWMM calculated that 100 percent of the nitrate concentration from initial buildup and surface buildup were picked up via surface runoff (Table 15). The runoff removed more of the surface buildup and may have left with the external outflow that was 7000 gal. for the 5-year storm event and 36,000 gal. for the 100-year storm event (Table 16).

Table 15: The runoff quality data for the concentrations of the three pollutant loads from two SWMM simulations for Design A.

Storm Event	**5-year**			**100-year**		
Pollutant Load:	**TSS**	**Lead**	**Nitrate**	**TSS**	**Lead**	**Nitrate**
Initial Buildup (lbs.)	46.250	0	0.501	46.250	0	0.501
Surface Buildup (lbs.)	0.190	0.006	5.626	0.137	0.011	10.604
Infiltration Loss (lbs.)	0	0	0	0	0	0
BMP Removal (lbs.)	0	0	0	0	0	0
Surface Runoff (lbs.)	22.506	0.006	6.127	42.414	0.011	11.105
Remaining Buildup (lbs.)	23.935	0	0	3.973	0	0

Table 16: The flow volume of inflow and outflow data from two SWMM simulations run for 5-year and 100-year storm events for Design A.

Storm Event	**5-year**	**100-year**
Dry Weather Inflow (gal.)	0	0
Wet Weather Inflow (gal.)	36000	82000
External Inflow (gal.)	0	0
External Outflow (gal.)	7000	36000
Final Stored Volume (gal)	29000	46000

Similarly, the masses of pollutants in inflows and outflows were significant. The wet weather inflow concentration of TSS was four times as large as nitrate. Even the external outflow mass of TSS was four times as large as the mass of nitrate in the external outflow. Still, most of the mass of TSS and nitrate after the external outflow

remained in the final stored amount. Despite the external outflow, the final stored mass was also significantly large (Table 17).

Table 17: The flow quality mass concentration data from two SWMM simulations run for 5-year and 100-year storm events for Design A.

Storm Event	**5-year**			**100-year**		
Pollutant Load:	**TSS**	**Lead**	**Nitrate**	**TSS**	**Lead**	**Nitrate**
Dry Weather Inflow (lbs.)	0	0	0	0	0	0
Wet Weather Inflow (lbs.)	22.009	0.006	5.939	41.804	0.010	10.893
External Inflow (lbs.)	0	0	0	0	0	0
External Outflow (lbs.)	4.101	0.001	1.208	20.392	0.005	5.406
Final Stored Mass (lbs.)	17.941	0.004	4.741	21.511	0.005	5.514

CHAPTER VI: VEGETATIVE SWALES MODEL (DESIGN B)

The second LID control model created and analyzed in SWMM was the vegetative swales model (Design B). This design model started by using the initial conditions model as a base (Figure 2). The subcatchments' parameters are the same as in the initial conditions model, except now the LID control parameters have been added for a vegetative swale. The goal was to increase the permeability of the subcatchments to subsequently increase infiltration and reduce pollutant load concentrations being picked up in surface runoff.

1. Model Conceptualization

The vegetative swales were added to each subcatchment to increase the amount of permeable surface. Despite some of the landscapes in Subcatchment M16-1 and Subcatchment M16-3 having features resembling LID controls or other SCMs, the findings showed a lack of effectiveness for the initial conditions. Thus, the study area was modified with the addition of vegetative swales to improve infiltration and reduce pollutant load concentration in surface runoff and final storage. The addition of vegetative swales meant the LID control quantity under the parameters of each subcatchment was increased to one type of LID control.

2. Input Parameters

Within the LID control settings, most parameters of the vegetative swales were inputted to be the same (Table 18). The reason for the consistent parameters, except for one, was to eliminate the possible influence of too many variant parameters for this model. The only varied parameter of the vegetative swales was the unit area for each

vegetative swale (Table 19). These areas were based upon which of the three subcatchments contained each vegetative swale. The values of these features were either known or based the SWMM manual (Rossman, 2015; Rossman & Huber, 2016). These areas influence the percentage of the subcatchment used for the LID controls. As mentioned in the Design Constraints section of Chapter II: Study Area, each subcatchment had a limited amount of space. Subcatchment M16-1 had the least amount. Most of that subcatchment's land use was residential. As stated before, the residential areas made up of houses, roadways, and sidewalks. Even if some of it can be changed to incorporate vegetative swales, roadways and sidewalks are not likely to be among the surfaces altered.

Table 18: The parameters of the LID control for vegetative swales that were held for all vegetative swales used in each subcatchment.

Vegetative Swales – VS1		
Features:		Units
Berm Height	5	In
Vegetative Volume Fraction	0.1	
Surface Roughness (n)	0.06	
Surface Slope	3	%
Swales Side Slope	2.3	(Run/Rise)

Table 19: The LID control parameters for vegetative swales that were held constant or varied for each subcatchment: M16-1, M16-3, and M16-13.

LID Controls for VS1			
Subcatchment	M16-1	M16-13	M16-3
Area of Each Unit (ft^2)	1200	600	2000
Number of Units	10	10	10
% of Subcatchment Occupied	9.183	7.652	5.532
Surface Width per Unit (ft)	6	6	6
% Initially Saturated	35	35	35
% Impervious Area Treated	60	60	60
% Pervious Area Treated	30	30	30

3. Output of Model

Infiltration was the primary water process used to transport stormwater for Design B. In fact, far more stormwater infiltrated than either surface runoff or final storage for both storm events. The final storage for both storm events was 10 times smaller than infiltration. Fortunately, final storage was still at least 0.008 inches deeper than surface runoff (Table 20).

Table 20: The runoff quantity data from two SWMM simulations run for 5-year and 100-year storm events for the LID control of Design B.

Storm Event	5-year	100-year
Total Precipitation (in.)	0.26	0.435
Infiltration Loss (in.)	0.21	0.343
Evaporation Loss (in.)	0	0
Surface Runoff (in.)	0.021	0.039
Final Storage (in.)	0.029	0.052

As for the buildup of pollutant loads, TSS and nitrate were still more significant than lead. For both storm events, there was more surface buildup of nitrate than TSS. Interestingly, there was a similar ratio of BMP removal between the two pollutant load concentrations. Despite that BMP removal, still a significantly larger amount of TSS was in the surface runoff buildup. Fortunately, due to the BMP removal, the remaining buildup was close to the initial buildup, showing only minimal loss due to surface runoff (Table 21).

Table 21: The runoff quality data of the concentrations of the three pollutant loads from two SWMM simulations for the LID control of Design B.

Storm Event	5-year			100-year		
Pollutant Load:	**TSS**	**Lead**	**Nitrate**	**TSS**	**Lead**	**Nitrate**
Initial Buildup (lbs.)	46.250	0	0.501	46.250	0	0.501
Surface Buildup (lbs.)	0.636	0	1	0.206	0.002	1.936
Infiltration Loss (lbs.)	0	0	0	0	0	
BMP Removal (lbs.)	0.653	0	0.281	1.150	0	0.449
Surface Runoff (lbs.)	3.349	0	0.954	6.595	0.002	1.755
Remaining Buildup (lbs.)	42.885	0	0.267	38.710	0	0.233

Between the two storm events, the amount of wet weather inflow doubled from the 5-year to 100-year. Similarly, the concentration of TSS and nitrate in wet weather inflow doubled between the two storm events. SWMM never calculated any external inflow or outflow, so there was no significant loss in the volume of the flow rate. Based on the flow quality, the concentration of the wet weather inflow made up the stored mass of both pollutant loads (Table 22 and Table 23).

Table 22: The flow volume of inflows and outflows from two SWMM simulations for the LID control of Design B.

Storm Event	**5-year**	**100-year**
Dry Weather Inflow (gal.)	0	0
Wet Weather Inflow (gal.)	7000	14000
External Inflow (gal.)	0	0
External Outflow (gal.)	0	0
Final Stored Volume (gal.)	7000	14000

Table 23: The flow quality mass concentration data from two SWMM simulations run for the LID control of Design B.

Storm Event	**5-year**			**100-year**		
Pollutant Load:	**TSS**	**Lead**	**Nitrate**	**TSS**	**Lead**	**Nitrate**
Dry Weather Inflow (lbs.)	0	0	0	0	0	0
Wet Weather Inflow (lbs.)	3.308	0	0.938	6.532	0.002	1.737
External Inflow (lbs.)	0	0	0	0	0	0
External Outflow (lbs.)	0	0	0	0	0	0
Final Stored Mass (lbs.)	3.311	0	0.939	6.536	0	1.738

Therefore, the addition of vegetative swales demonstrated an effectiveness in stormwater management. Further research would be needed to see the parameters that need to be adjusted. Still, if the parameters could be mediated vegetative swales mighty produce an effective decrease in TSS and nitrate concentrations.

CHAPTER VII: BIORETENTION CELLS MODEL (DESIGN C)

The third LID control was bioretention cells. As with the vegetative swales, bioretention cells were modeled to determine their effectiveness in reducing the peak runoff and the concentration of the three pollutant loads. The base of the model was the same as the initial conditions. Then, one type of LID control was added to each subcatchment. The parameters of the bioretention cells were inputted, so that the form of the bioretention cells was consistent. SWMM analyzed the model and calculated the depth, the flow volume, and the concentration of the three pollutant loads for both storm events.

1. Model Conceptualization

Bioretention cells reduce peak runoff and aid in the infiltration of stormwater as pollutant loads are removed. The structure of the bioretention cells can vary, depending on the need (Davis et al, 2009; Li & Davis, 2014; Rossman, 2015; Rossman & Huber, 2016; Trowsdale & Simcock, 2011). The bioretention cell structure used for this design model was the depression in the soil with multiple layers (Figure 5). Each layer aids in controlling infiltration, removing pollutant loads, temporarily storing stormwater runoff, and reducing the risk of flooding. Many studies have demonstrated the success and usefulness of this bioretention structure, particularly when dealing with nitrogen compounds and TSS (Shrestha, Hurley, & Wemple, 2018; Trowsdale & Simcock, 2011)

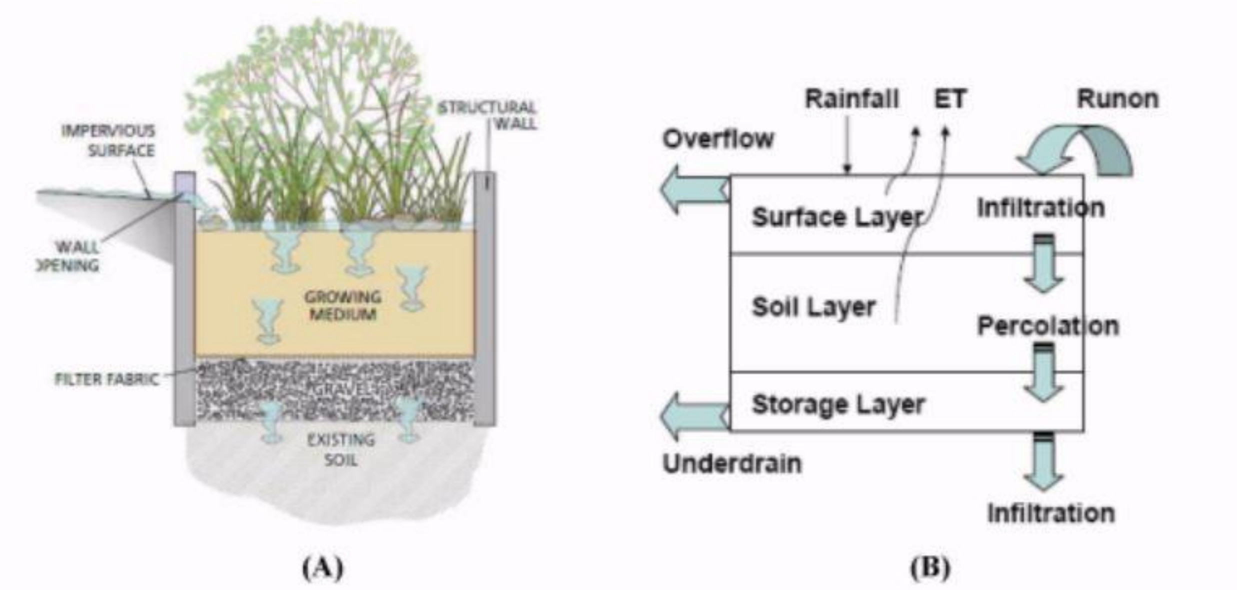

Figure 5: (A) The diagram for a basic bioretention system, and (B) the processes into the bioretention system and through its layers (Rossman & Huber, 2016).

2. *Input Parameters*

The parameters behind the bioretention cells focus on each layer as well as the overall size and quantity of them for each subcatchment. The parameters of the layers were kept consistent. Their values were based on recommendation from the SWMM Manual and previous studies (Davis et al., 2009; Rossman, 2015; Rossman & Huber, 2016; Shrestha, Hurley, & Wemple, 2018; Trowsdale & Simcock, 2011). The values used for this study's bioretention cells and its layers included physical details as well as soil characteristics (Table 24 and Table 25).

Table 24: The soil and storage layers' parameters of Design C for this study.

Soil Layer	
Thickness (in)	20
Porosity (Vol. Fraction)	0.32
Field Capacity (Vol. Fraction)	0.22
Wilting Point (Vol. Fraction)	0.1
Conductivity (in/hr)	0.25
Conductivity Slope	40
Suction Head (in.)	6.2
Storage Layer	
Thickness (in.)	12
Void Ratio	0.5
Seepage Rate (in/hr.)	0.11
Clogging Factor	0

Table 25: The bioretention cell's drainage layer parameters and its pollutant removal ability for Design C in this study.

Drain Layer	
Flow Coefficient	0
Flow Exponent	0.5
Offset (in)	6
Open Level	0
Closed Level	0
Pollutant Removals	
TSS	80%
Lead	55%
Nitrate	70%

Additionally, the sizes and number of bioretention cells per subcatchment were estimated and modeled to fit the ability of each subcatchment. As stated previously in the Chapter VI: Vegetative Swales (Design B) and Chapter II: Study Area, the unit area was limited based on the available space and land use. The unit area was dependent on the subcatchment (Table 26 and Table 27).

Table 26: The surface features of the bioretention cell used for Design C.

Surface Parameters	
Berm Height (in.)	5
Vegetation Volume Fraction	0.1
Surface Roughness	0.06
Surface Slope (%)	3

Table 27: The bioretention cell's parameters, including the unit area for each subcatchment.

Subcatchment Features			
Area (ft^2)	**M16-13**	**M16-1**	**M16-3**
	600	1200	2000
Number of Units	10		
Surface Width Per Unit (ft)	6		
Initial Saturation (%)	35		
Impervious Area Treated (%)	60		
Pervious Area Treated (%)	30		

3. Output of Model

When analyzed with SWMM, the bioretention cells model determined infiltration managed about 94 percent of the total precipitation for a 5-year storm event and about 86 percent for a 100-year storm event. Of the 0.015 in. remaining for a 5-year storm event, less than half was surface runoff depth. Most of the remaining was incorporated into the initial LID storage (0.329 in.) as final storage (0.338 in.). The 100-year storm event had a similar pattern with the water processes (Table 28). That was primarily due to the bioretention cells additional capacity to store stormwater in the depression and in its storage layer. The additional capacity to retain more stormwater runoff and infiltration and for a longer period would be beneficial in maintaining water quality.

Table 28: The runoff quantity data from two SWMM simulations run for the LID control of Design C.

Storm Event	5-year	100-year
Initial LID Storage (in.)	0.329	0.329
Total Precipitation (in.)	0.260	0.435
Infiltration Loss (in.)	0.245	0.372
Evaporation Loss (in.)	0	0
Surface Runoff (in.)	0.006	0.012
Final Storage (in.)	0.338	0.381

Since the infiltration was relatively large, a significant concentration of TSS and nitrate from the initial buildup and surface buildup were removed through BMP removal of the bioretention cells. As for the surface runoff, the depth was one to two magnitudes smaller than any other water process for this model's simulations of the storm events. This small surface runoff depth probably contributed to the relatively small TSS and nitrate concentration found in the surface runoff (Table 28 and Table 29). Considering the remaining buildup concentrations for the pollutant loads of TSS and nitrate, a significant amount of the two pollutant loads remained in the storage. In other words, less of these two pollutant loads were being washed away by surface runoff and into the ponds or neighboring subcatchments.

Table 29: The runoff quality data for the concentrations of the three pollutant loads from two SWMM simulations for the LID control of Design C.

Storm Event	5-year			100-year		
Pollutant Load:	TSS	Lead	Nitrate	TSS	Lead	Nitrate
Initial Buildup (lbs.)	46.25	0	0.501	46.250	0	0.501
Surface Buildup (lbs.)	0.626	0	1	0.206	0.002	1.936
Infiltration Loss (lbs.)	0	0	0	0	0	0
BMP Removal (lbs.)	2.832	0	0.908	5.444	0.001	1.600
Surface Runoff (lbs.)	1.17	0	0.326	2.301	0.001	0.605
Remaining Buildup (lbs.)	42.885	0	0.267	38.710	0	0.233

Even the routing of the pollutants showed no significant concentration leaving through external outflows. The concentration of the final stored mass almost equals the

wet weather inflow concentration (Table 30). Between the two storm events, the wet weather inflow concentration almost doubles from 5-year to 100-year (Table 31).

Table 30: The flow volume of inflows and outflows from two SWMM simulations run for the LID control of Design C.

Storm Event	5-year	100-year
Dry Weather Inflow (gal.)	0	0
Wet Weather Inflow (gal.)	2000	4000
External Inflow (gal.)	0	0
External Outflow (gal.)	0	0
Final Stored Volume (gal.)	2000	4000

Table 31: The flow quality mass concentration data from two SWMM simulations for the LID control of Design C.

Storm Event	5-year			100-year		
Pollutant Load:	TSS	Lead	Nitrate	TSS	Lead	Nitrate
Dry Weather Inflow (lbs.)	0	0	0	0	0	0
Wet Weather Inflow (lbs.)	1.142	0	0.307	2.262	0	0.585
External Inflow (lbs.)	0	0	0	0	0	0
External Outflow (lbs.)	0	0	0	0	0	0
Final Stored Mass (lbs.)	1.144	0	0.308	2.264	0	0.585

The effectiveness of bioretention cells model suggested that this LID control might be a good choice. However, a comparison of all the modeled designs would be required first. The parameters of infiltration depth, surface runoff depth, external outflow volume, concentration of TSS and nitrate for BMP removal, surface runoff, and final storage must be considered. Although, the literature does support the versatility of this LID control (Davis et al., 2009; Li & Davis, 2014; Rossman & Huber, 2016).

CHAPTER VIII: COMPARISON OF MODEL RESULTS

The initial conditions design of the three subcatchments showed an ineffectiveness in maintaining water quality for the subcatchments' model. While the initial design's infiltration handled most of the water movement for both storm events, a significant concentration of TSS (4.353 lbs.) and nitrate (1.324 lbs.) was still washed away with surface runoff for the 5-year storm event, including a portion of the TSS initial buildup and the TSS and nitrate surface buildups. That surface runoff concentration could contaminate water sources and other subcatchments. When the three LID control designs were analyzed and compared, each showed an improvement on different aspects of the initial design's stormwater management.

1. Design A – Traditional Drainage Model

Design A was meant to focus on directing the flow of stormwater. The stormwater was meant to be picked up in Subcatchment M16-1. Then, the series of channels carried the stormwater flow into Subcatchment M16-13, emptying into Pond 2. Next the stormwater flow left Pond 2 along two possible channel pathways that both were directed to Pond 2 in Subcatchment M16-3. Finally, the stormwater flow was carried out of the study area. As a result, SWMM's calculations should be very different from the initial conditions model.

Among the runoff quantity of stormwater showed the reverse of the desired outcome of the flow parameters for both storm events: 5-year and 100-year. The infiltration depth was 10 times too small compared to the initial conditions and the surface runoff depth was about 10 times too large. Neither showed a significant influence from evaporation depth. Despite that, Design A did contain a larger final storage depth.

In fact, the magnitude differences in infiltration depth and surface runoff depth were the same for the final storage (Table 32). Thus, the similar difference between infiltration and surface runoff depths provided enough final storage depth to remain.

Table 32: The runoff quantities of the initial conditions model and Design A (Traditional Drainage Model) for comparison for both storm events

5-year		
Model:	**Initial Conditions**	**Traditional Drainage**
	Depth (in.)	**Depth (in.)**
Total Precipitation	0.260	0.260
Infiltration Loss	0.215	0.023
Evaporation Loss	0	0
Surface Runoff	0.017	0.103
Final Storage	0.028	0.134
100-year		
Model:	**Initial Conditions**	**Traditional Drainage**
	Depth (in.)	**Depth (in.)**
Total Precipitation	0.435	0.435
Infiltration Loss	0.351	0.038
Evaporation Loss	0	0
Surface Runoff	0.032	0.235
Final Storage	0.053	0.164

The quality of the runoff showed a shift in the concentration of TSS and nitrate for both storm events. The surface buildup for both the initial conditions model and Design A were nitrate. The concentration of nitrate in surface buildup was 5 times larger for Design A than the initial conditions model. In comparison, the TSS was a higher concentration for surface runoff, about four times the quantity. Interestingly, despite the higher concentration of TSS in surface runoff, its concentration in the remaining buildup was still significantly higher for both the initial conditions model and Design A. However, the initial conditions model showed a more significant remaining buildup than Design A. Thus, Design A was not better at retaining the pollutant load concentrations of TSS or nitrate (Table 33).

Table 33: The runoff qualities of the TSS and nitrate pollutant load concentrations for the initial conditions model and Design A (Traditional Drainage Model) for comparison for both storm events.

5-year				
Model:	**Initial Conditions**		**Traditional Drainage**	
Pollutant Load	TSS (lbs.)	Nitrate (lbs.)	TSS (lbs.)	Nitrate (lbs.)
Initial Buildup	46.250	0.501	46.250	0.501
Surface Buildup	0.574	1.088	0.190	5.626
Surface Runoff	4.353	1.324	22.506	6.127
Remaining Buildup	42.471	0.265	23.935	0
100-year				
Pollutant Load	TSS (lbs.)	Nitrate(lbs.)	TSS (lbs.)	Nitrate (lbs.)
Initial Buildup	46.250	0.501	46.250	0.501
Surface Buildup	0.202	2.097	0.137	10.604
Surface Runoff	8.388	2.369	42.414	11.105
Remaining Buildup	38.604	0.229	3.973	0

2. *Design B – Vegetative Swales Model*

When comparing Design B to the initial conditions model, there were improvements across flow, depth, and concentration. The differences were not as obvious as between initial conditions model and Design A. The change ranged from 0.001 to 0.01. Still, there was still improvement.

The depth of the surface runoff decreased by 0.005 inches, and the infiltration increased by 0.004 inches for a 5-year storm event. For the 100-year storm event, the infiltration depth was 0.008 inches smaller for Design B, and its surface runoff was 0.007 inches larger. Still, the final storage depth was larger for Design B for a 5-year storm event but smaller for the 100-year storm event (Table 34).

Table 34: The runoff quantities of the initial conditions model and Design B (Vegetative Swales Model) for comparison for both storm events

5-year		
Model:	**Initial Conditions**	**Vegetative Swales**
	Depth (in.)	**Depth (in.)**
Total Precipitation	0.260	0.260
Infiltration Loss	0.215	0.210
Evaporation Loss	0	0
Surface Runoff	0.017	0.021
Final Storage	0.028	0.029
100-year		
Model:	**Initial Conditions**	**Vegetative Swales**
	Depth (in.)	**Depth (in.)**
Total Precipitation	0.435	0.435
Infiltration Loss	0.351	0.343
Evaporation Loss	0	0
Surface Runoff	0.032	0.039
Final Storage	0.053	0.052

When it came to the runoff quality, there was a reduction in the concentration of both TSS and nitrate with Design B. The surface buildup for TSS increased (0.062 lbs. for 5-year and 0.004 lbs. for 100-year) and for nitrate decreased (0.088 lbs. for 5-year and 0.161 lbs. for 100-year). The concentration of surface runoff decreased for each pollutant load for both storm events. The addition of the BMP removal with the vegetative swales helped reduce stormwater runoff concentrations of TSS and nitrate. However, there was not a significant difference between the two models for both storm events when it came to the remaining buildup concentration. In fact, the remaining buildup was higher for Design B than the initial conditions model (Table 35).

Table 35: The runoff qualities of the TSS and nitrate pollutant load concentrations for the initial conditions model and Design B (Vegetative Swales Model) for comparison for both storm events.

5-year				
Model:	**Initial Conditions**		**Vegetative Swales**	
Pollutant Load	TSS (lbs.)	Nitrate (lbs.)	TSS (lbs.)	Nitrate (lbs.)
Initial Buildup	46.250	0.501	46.250	0.501
Surface Buildup	0.574	1.088	0.636	1.000
BMP Removal	0	0	0.653	0.281
Surface Runoff	4.353	1.324	3.349	0.954
Remaining Buildup	42.471	0.265	42.885	0.267
100-year				
Pollutant Load	TSS (lbs.)	Nitrate(lbs.)	TSS (lbs.)	Nitrate (lbs.)
Initial Buildup	46.250	0.501	46.250	0.501
Surface Buildup	0.202	2.097	0.206	1.936
BMP Removal	0	0	1.150	0.449
Surface Runoff	8.388	2.369	6.595	1.755
Remaining Buildup	38.604	0.229	38.710	0.233

3. Design C – Bioretention Cells Model

When compared against the initial conditions model, Design C provided more obvious improvement on the water processes and the concentrations of TSS and nitrate. For both storm events, the infiltration depth increased by 0.030 in. for a 5-year storm event and 0.021 in. for a 100-year storm event. The change in surface runoff depth was ten times smaller for both storm events. Even the final storage depth was 10 times larger than with the initial conditions (Table 36). That was despite the wet weather flow being about a third of the volume of the initial conditions for both storm events.

Table 36: The runoff quantities of the initial conditions model and Design C (Bioretention Cells Model) for comparison for both storm events

5-year		
Model:	**Initial Conditions**	**Bioretention Cells**
	Depth (in.)	**Depth (in.)**
Initial LID Stage	0	0.329
Total Precipitation	0.260	0.260
Infiltration Loss	0.215	0.245
Evaporation Loss	0	0
Surface Runoff	0.017	0.006
Final Storage	0.028	0.338
100-year		
Model:	**Initial Conditions**	**Bioretention Cells**
	Depth (in.)	**Depth (in.)**
Initial LID Stage	0	0.329
Total Precipitation	0.435	0.435
Infiltration Loss	0.351	0.372
Evaporation Loss	0	0
Surface Runoff	0.032	0.012
Final Storage	0.053	0.381

The pollutant load concentrations varied based on the pollutant load and the water process. The TSS concentration for surface runoff was lower for Design C. That was due to the significant BMP removal that did not exist for the initial conditions. Thus, the remaining buildup for TSS was larger. Nitrate also saw a smaller concentration in the surface runoff due to BMP removal. This pollutant load also had a significant larger remaining buildup. However, the surface buildup for TSS was smaller for the initial conditions but only by about 0.052 lbs. Even considering the mass quantity of the wet weather inflow for both storm events, the TSS quantity was a fourth of the mass from the initial conditions model. Similarly, the nitrate quantity was about a fourth of the mass quantity of the initial conditions model (Table 37).

Table 37: The runoff qualities of the TSS and nitrate pollutant load concentrations for the initial conditions model and Design C (Bioretention Cells Model) for comparison for both storm events.

5-year				
Model:	**Initial Conditions**		**Bioretention Cells**	
Pollutant Load	TSS (lbs.)	Nitrate (lbs.)	TSS (lbs.)	Nitrate (lbs.)
Initial Buildup	46.250	0.501	46.250	0.501
Surface Buildup	0.574	1.088	0.626	1.000
BMP Removal	0	0	2.832	0.908
Surface Runoff	4.353	1.324	1.170	0.326
Remaining Buildup	42.471	0.265	42.885	0.267
100-year				
Pollutant Load	TSS (lbs.)	Nitrate(lbs.)	TSS (lbs.)	Nitrate (lbs.)
Initial Buildup	46.250	0.501	46.250	0.501
Surface Buildup	0.202	2.097	0.206	1.936
BMP Removal	0	0	5.444	1.600
Surface Runoff	8.388	2.369	2.301	0.605
Remaining Buildup	38.604	0.229	38.710	0.233

4. Design B & Design C Comparison

Since Design A fell short of improving on any of the key results when compared to the initial conditions model, the choice was narrowed to Design B and Design C. Both had shown the potential for a more effective stormwater management of the study area. Thus, Design B and Design C were compared to each other.

First, the water processes that occurred with any significance were distinct between Design B and Design C. The infiltration depth was larger for Design C than Design B by 0.035 in. for a 5-year storm event and 0.029 in for a 100-year storm event. The surface runoff was significantly smaller for Design C than for Design B by a magnitude of 10 for a 5-year storm event and 0.027 in. for a 100-year storm event (Table 38). As a result, the final storage depth was larger for Design C than Design B.

Table 38: The runoff quantities of the Design B (Vegetative Swales Model) and Design C (Bioretention Cells Model) for comparison for both storm events

	5-year	
Model:	**Vegetative Swales**	**Bioretention Cells**
	Depth (in.)	**Depth (in.)**
Initial LID Stage	0	0.329
Total Precipitation	0.260	0.260
Infiltration Loss	0.210	0.245
Evaporation Loss	0	0
Surface Runoff	0.021	0.006
Final Storage	0.029	0.338
	100-year	
Model:	Vegetative Swales	**Bioretention Cells**
	Depth (in.)	**Depth (in.)**
Initial LID Stage	0	0.329
Total Precipitation	0.435	0.435
Infiltration Loss	0.343	0.372
Evaporation Loss	0	0
Surface Runoff	0.039	0.012
Final Storage	0.052	0.381

Second, the quality of the water processes showed the differences were with BMP removal and surface runoff. The success of BMP removal for TSS and nitrate for Design C was about two times bigger than for Design B. One of the reasons for that had to do with Design C having a lower surface buildup for the 5-year storm event. As a result, the concentration of TSS and nitrate in surface runoff for Design C was a third of the concentrations in Design B. BMP removal influenced this significant difference (Table 39). However, despite that, the remaining buildup of TSS and nitrate are the same for both LID controls. Likely that was due to so many of the common parameters set the same (Table 18, Table 19, Table 26, and Table 27).

Table 39: The runoff qualities of the TSS and nitrate pollutant load concentrations for Design B (Vegetative Swales Model) and Design C (Bioretention Cells Model) for comparison for both storm events.

5-year				
Model:	**Vegetative Swales**		**Bioretention Cells**	
Pollutant Load	TSS (lbs.)	Nitrate (lbs.)	TSS (lbs.)	Nitrate (lbs.)
Initial Buildup	46.250	0.501	46.250	0.501
Surface Buildup	0.636	1.000	0.626	1.000
BMP Removal	0.653	0.281	2.832	0.908
Surface Runoff	3.349	0.954	1.170	0.326
Remaining Buildup	42.885	0.267	42.885	0.267
100-year				
Pollutant Load	TSS (lbs.)	Nitrate(lbs.)	TSS (lbs.)	Nitrate (lbs.)
Initial Buildup	46.250	0.501	46.250	0.501
Surface Buildup	0.206	1.936	0.206	1.936
BMP Removal	1.150	0.449	5.444	1.600
Surface Runoff	6.595	1.755	2.301	0.605
Remaining Buildup	38.710	0.233	38.710	0.233

Third, the final storage volumes were lower for Design C than Design B. Thus, the LID control managed the entire flow without any leaving the study area. The mass quantity of TSS, lead, and nitrate were also smaller for Design C than Design B. For both storm events, the flow volume of Design B was more than 3 times as large as Design C. Therefore, Design C was better able to control the wet weather inflow (Table 22 and Table 30).

CHAPTER IX: RECOMMENDATIONS

The study found that the additions to the initial conditions model were more effective in managing the pollutant loads of TSS and nitrate. The concentration allowed to buildup on the surface was less, resulting in a lower amount in surface runoff. Consequently, the remaining buildup was slightly higher than the initial conditions, so more TSS and nitrate remained in the subcatchments instead of washing into another subcatchment.

Lead never became significant enough compared to the other two pollutant load concentrations. Even when it became detectable, the concentration found in surface buildup would leave in the surface runoff regardless of design. There was no significant concentration left behind in final stored mass.

Now, between these two LID controls, Design C proved to be more effective in managing the water quality as well as the peak stormwater flows. Therefore, the researcher would recommend looking into bioretention cells as an addition to the initial conditions. Of course, further study into bioretention cells and their parameters would be required. The Design C used in this analysis was not as effective as it could have been based on previous studies.

The next step should be to study which of the bioretention cells' parameters were most influential in improving the removal of these pollutant loads. Also, since there was some pre-existing SCMs, some consideration might need to be given to them. Their placement could be diverging the stormwater runoff flow. If so, then most of the stormwater was not being effectively directed to maintain the water quality. If these characteristics and the bioretention cells' parameters could be more thoroughly studied,

the researcher would be confident in a significant difference in the peak flow and water quality management of these subcatchments.

APPENDICES

Data Sources -20th and Medary Existing w-Costello pond.inp

The primary source of data on the subcatchments used in this study came from a previously created SWMM file created by Thad Drietz, a city engineer from Brookings, South Dakota. He had been collecting and updating the data in the model for more than six years. The subcatchments cover most of the city, focusing in on the area between Medary Avenue and 20th Street. Besides hydraulic information on the subcatchments, the model contained precipitation gages, including for a 5-year and 100-year storm event. See attached digital file under the name given in the title.

Data Sources – dpp-initialdesign.inp

This SWMM file was based on hydraulic data from a previous SWMM file and the addition of water quality and LID data recommended from the SWMM manual and previous studies (Li & Davis, 2014; Rossman, 2015; Rossman & Huber, 2016; Sadeghi, Loáiciga, & Kharaghani, 2018). This was the initial conditions of the study area and SWMM modeled it to use as a comparison against the LID control designs (Design A, Design B, and Design C). See attached digital file under the name given in the title.

Data Sources – dpp-traditionaldrainage.inp

This SWMM file was a combination of the same initial conditions model with some additions. New conduits were added to drain the stormwater runoff. Also, changes were made to the imperviousness percentages of each subcatchment. The result modeled was that of a traditional drainage (Design A). See attached digital file under the name given in the title.

Data Sources – dpp-vegswale.inp

This SWMM file was a combination of the ‘initialdesign.inp’ file with the addition of vegetative swales (Design B). The characteristics of the vegetative swales were decided based on the SWMM manual and previous literature on vegetative swales (Rossman, 2015). The result was a model that incorporated several vegetative swales that aided in handling the peak flow and water quality maintenance. The model appeared in the SWMM 5.1 program just like the initial conditions model. Each subcatchment now included a LID control of vegetative swales. See attached digital file under the name given in the title.

Data Sources – dpp-bioretentioncell.inp

This SWMM file was a combination of the ‘initialdesign.inp’ file with the addition of bioretention cells (Design C). The characteristics of the bioretention cells were based upon the SWMM manual and previous literature on bioretention cells (Rossman, 2015; Rossman & Huber, 2016). The result was a model that incorporated several bioretention cells to manage peak flow and maintain water quality. The model looked the same as the initial design model, but each subcatchment now included a LID control for bioretention cells. See attached digital file under the name given in the title.

Sample Table Spreadsheets

The simulation analysis provided data on the results for each design. Within each design, the data corresponded to the three pollutant loads and the runoff. Each design was then run for each storm event: 5-year and 10-year, to correspond with the precipitation gage data. This data as well as some characteristics data on each subcatchment, each

design, and each LID control, if used for the design, was tabulated. These tables can be found in the file: TablesDesignPaper.pdf, as a collection of spreadsheets on the design models. These were used for the tables in the paper and to easily compare the findings from the simulation analysis among the designs. See attached digital file under the file named previously mentioned.

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