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EVALUATION OF LOW IMPACT DEVELOPMENT STORMWATER CONTROL SYSTEMS FOR RUNOFF PEAK FLOW REDUCTION

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EVALUATION OF LOW IMPACT DEVELOPMENT STORMWATER CONTROL SYSTEMS FOR RUNOFF PEAK FLOW REDUCTION

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Table of Contents

List of Figures

List of Tables

Abstract

Extreme precipitation events and increasing impervious surfaces, lead to increased runoff, surcharged storm sewer systems and consequent flooding as well as water quality deterioration, costing not only lives and habitat lost but millions of dollars in damage. Strategies to minimize the negative impacts of stormwater runoff are known as Low Impact Development (LID), which seek to reduce and prevent these impacts through site planning and techniques to mimic as close as possible, a site's pre-developed hydrologic conditions, reducing the quantity of runoff and improving water quality. Such strategies can be evaluated with computer-based stormwater models, coupling a watershed's existing stormwater system with LID techniques.

Undersized stormwater infrastructure is prone to flooding, as is the case for Sunnymeade in Oklahoma City, and the Pearl District in Tulsa. These two sites provide an opportunity to explore the potential of LID for peak flow reduction, using the InfoDrainage stormwater model. Results show that after LID implementation, improvements are representative in reducing storm water flooding within critical areas. Peak flow is considerably reduced in critical areas on the northwest and southwest areas of Sunnymeade, as well as on the north and south ends of Pearl District. Although flooding is still shown in the systems, this transferred onto the LID stormwater control systems, reducing the peak flow in the storm sewer systems from a 100-year storm event to less than a 25-year for Sunnymeade and a 1-year for Pearl District. Sensitivity analysis indicated that the 1-m topographic data, adjusted to urbanization, yields similar results in peak flows as to those of 1-ft survey data for Sunnymeade. Water quality results show a considerable contribution in percent reduction in pollutant loads for both study areas. Overall, LID systems are recommended to be installed in watersheds in Oklahoma given their remarkable potential at decreasing peak flows, with an added value of contributing to pollutant reduction.

Chapter 1: Introduction and Literature Review

Extreme precipitation events, added to extreme land use changes due to urbanization, are triggers for one of the most devastating natural hazards, flooding. The increased imperviousness of the area and urban activities lead to increased runoff, decreased baseflow, reduced groundwater recharge, and water quality deterioration (Liu et al., 2014). Intensified rainfall fueled by climate change has caused nearly $75 billion in flood damage in the U.S. in the past three decades (CNBC, 2021).

Stormwater exceeding the capacity of urban drainage systems can cause urban flooding, resulting in issues, such as traffic interruption, property damage, health issues, economic loss, stream pollution and streamside vegetation deterioration (USGS, 2009; Qin et al., 2013). Large storms have the unfortunate fate of transporting not only large amounts of urban-originated pollutants that travel to natural water sources, but also amounts of water that are big enough to flood cities at large scales. These outcomes due to excess precipitation imply a good reason for better managing stormwater runoff so that the first flush of rain, which is the most significant portion of storms, can be intercepted and treated to reduce the quantity of runoff. In addition, this water management will also reduce pollutant concentration in the receiving waters and all the negative effects to natural habitats that come along with them.

There is a necessity to implement new strategies to minimize and prevent adverse stormwater runoff impacts and to provide water quality treatments or improvements, as close to the source as possible. This necessity brings out strategies that address those issues and work for a greater benefit. Such strategies, known collectively as Low Impact Development or LID, have become a part of urban stormwater management in the United States, marking progress in the gradual transition from centralized to distributed runoff management infrastructure (Vogel et al., 2015). LID seeks to reduce and/or prevent adverse runoff impacts through site planning and techniques that preserve or closely mimic the site's natural or pre-developed hydrologic response to precipitation (New Jersey Stormwater Best Management Practices Manual, 2004). LID practices reduce negative impacts that stormwater runoff from urban areas can have on ecosystems, and its ultimate goal is full, cost-effective implementation to maximize watershed-scale ecosystem services and enhance resilience (Vogel et al., 2015; McLemore et al., 2017).

Prediction of flood hazards is a crucial part of flood risk assessment, flood risk management plans, and the design of flood protection measures (Krvavica & Rubinic, 2020). Flood mapping is a growing interest around the world, given the rising number of natural disasters that have taken place over the last few years. Because of a strong interconnected rainfall-runoff process, as well as rapid advancement computational technology and the availability of high-resolution topographic data, rainfall induced floods are now simulated using integrated hydrologic-hydraulic methods (Hasan et al., 2019; Krvavica & Rubinic, 2020), as will be evaluated, and discussed in this project.

Urban flooding generally happens when heavy rainfall is immediately followed by a restricted drainage system capability (Hasan et al., 2019), as is the case for one of the areas of study in this research, in north Oklahoma City, where flooding has been recurring for high-precipitation events and has been causing property damage, giving this investigation the opportunity to address and asses the issues related to the flooding and how to be able to mitigate them by modeling the current system and evaluating how LID is able to reduce peak runoff. Research is also completed for the area east of downtown Tulsa, in the Pearl District neighborhood, where pond installation has been an ongoing debate between citizens and the government (Krehbiel, 2019), providing an opportunity to explore the extra potential of LID infrastructures coupled with these ponds.

Studies on LID implementation and modeling have been developed throughout the years, which are mostly related to water quality improvement, given the capacities of these techniques in decreasing pollutant concentration in stormwater. However, given the relatively small number of LID studies regarding its impact on peak flow reduction, this project aims to contribute to evaluating the potentials of these structures, which not only have existing water-quality improvement advantages, but also the capabilities to alleviate storm sewer system surcharge.

1.1 Literature Review

In this section, background information regarding the concepts involved in stormwater modeling is provided. This includes stormwater terminology, low impact development techniques with their contribution to water quantity reduction and water quality improvement, different types of stormwater models and one of the main inputs for hydrologic models: elevation data.

1.1.1 Stormwater Runoff

During precipitation events, rain is captured in some percentage by plants, or it is infiltrated into the ground until the soil saturates, and the remainder flows over the land surface as stormwater runoff to the nearest waterways. In urbanized regions, the percentage of rainfall that becomes stormwater runoff is much greater than in non-urban areas, due to increased impervious surfaces, like buildings, roads, and parking area, which force water to flow faster as it runs into the storm sewer system and do not allow it to soak into the ground (USGS, 2009).

Storm sewer systems concentrate runoff into smooth, straight conduits. When this runoff leaves these systems and reaches a stream, its excessive volume and power greatly affect streambanks, damaging streamside vegetation and altering aquatic ecosystems. These increased flows carry a great variety of pollutants, including sediment loads, thermal pollution coming from the impervious surfaces, oil, grease, pesticides, nutrients, bacteria, metals, and petroleum by-products (from leaking vehicles), which can be harmful to humans, plants and animals (Environmental Protection Agency (EPA), 2003; USGS, 2009). Pollution originating over large areas, without a single point of origin and usually carried by stormwater, is considered non-point pollution. In contrast, point sources of pollution come from a single, identifiable point, such as municipal or industrial discharge (USGS, 2009).

1.1.2 Stormwater management

Land development can have severe impacts on stormwater facilities, especially when land is altered from its natural condition to a highly disturbed area with large impervious areas and non-native covers. These impacts include increased stormwater runoff volume, velocity, and pollutant accumulation, and deteriorated water quality in both runoff and contaminated water bodies, such as lakes and rivers. It is frequent for these impacts to be addressed by collecting and conveying the runoff from entire areas with the use of structural conveyance systems, such as ponds, where water is stored and treated prior to discharge downstream (New Jersey Stormwater Best Management Practices Manual, 2004).

The proper management of stormwater runoff is necessary to reduce stream channel erosion, sedimentation, pollution siltation and flooding, which have an impact on communities and ecosystems, including water resources and people. Stormwater management involves measures for the careful application of site design principles, construction techniques to prevent sediments and other pollutants from being released, source control and treatment runoff to reduce pollutants and reduce the impact of post-development or altered hydrology (Field et al., 2004).

1.1.3 Low Impact Development

Rather than responding to the rainfall-runoff processes like centralized structural facilities, low impact development (LID) techniques interact with the entire hydrologic process, contributing to the management of stormwater runoff and pollutants closer to the source and providing site design measurements to reduce the overall impact of land development (New Jersey Stormwater Best Management Practices Manual, 2004). LID is a site design strategy that aims to maintain, replicate, or minimize the change in the pre-development hydrologic conditions using design techniques that create functionally equivalent hydrologic landscapes as well as address maintenance for pollutant removal (Field et al., 2004; Prince George's County et al., 1999). It is generally regarded that LID is a more sustainable solution for urban stormwater management than conventional urban drainage systems (Qin et al., 2013). Hydrologic components of the water cycle such as storage, infiltration, ground water recharge, volume and frequency of discharge are maintained or their changes are kept to the minimum through the use of integrated and distributed micro-scale stormwater retention and detention areas, reduction of impervious surfaces, and the lengthening of flow paths and runoff time (EPA, 2000).

LID techniques rely on distributed runoff management measures that aim to control stormwater with the reduction, infiltration, and reuse of stormwater at the place where it falls (Qin et al., 2013). The benefits of LID include reduction of downstream impact of increased imperviousness since it addresses hydrologic changes caused by development techniques, reduce pollutant loading to receiving water bodies, cost savings which can be achieved by using fewer materials, less labor and area when being treated for stormwater reduction, increased land value, enhance site aesthetics since it sometimes involves natural landscaping, habitat protection, improvement of overall site drainage and air quality, prevention of overly long pooling and creation of mosquito-breeding habitats, and reduce both onsite and downstream flooding (Field et al., 2004; Vogel et al., 2017).

Effective LID includes the use of both structural and nonstructural stormwater management measures, which are a subset of a group of practices and facilities known as Best Management Practices (BMPs). These practices focus on minimizing both the quantitative and qualitative effects on areas that have been heavily altered and moved away from their pre-development hydrologic conditions (New Jersey Stormwater Best Management Practices Manual, 2004). The use of BMPs to control and treat urban stormwater runoff has become a common practice in urban watershed management (Field et al., 2004).

Nonstructural LID-BMPs aim to reduce stormwater runoff impact through sound site planning and design, including proactive practices, such as minimizing land disturbance, regulatory controls that prevent pollution problems by preserving land features to maintain natural drainage characteristics, flattening slopes, utilizing native vegetation and impervious area management. Examples of nonstructural BMPs are public education, planning and management and street/storm drain maintenance. Structural LID-BMPs control and treat runoff close to the runoff's surface or the point of discharge to either the receiving water or the storm sewer system, therefore often smaller in size than standard structural BMPs. These include various types of basins, filters devices and surfaces located on individual lots in residential areas or in commercial, industrial, or institutional development areas, where larger structures are not commonly suitable. An example of LID-BMPs that allow this small size-close to location relationship are bioretention cells. (Field et al., 2004; New Jersey Stormwater Best Management Practices Manual, 2004). An example of non-LID-BMPs are detention and retention ponds. Relevant BMPs, including LID-BMPs to this project are summarized in Table 1.

Table 1. Description for BMPs considered in the research

BMP	Description
LID-BMPs	
Rainwater Harvesting	Rainwater harvesting is the practice of collecting and storing rainwater from roofs or other impervious surfaces in storage tanks during a precipitation event. The stored rainwater is then kept for later use or delayed discharge. Water quality is improved through the controlled release of stormwater as well as with a first flush diverter (City of Tulsa, 2021).
Bioretention cells/rain garden	A bioretention cell (BRC) consists of a shallow excavated pit backfilled with engineered media, topsoil, mulch, and vegetation. It stores, filters, retains, or detains stormwater runoff and then treats ponded runoff through chemical, biological and physical processes (Brown & Hunt, 2011). BRCs are sized to capture runoff from small-to-medium-sized storm events. The surface area of a BRC is typically 3-10 percent of the contributing area, which often has a high percentage of impervious surfaces. They are typically planted with water and drought-tolerant vegetation (McLemore et al., 2017). Rain gardens function similarly to BRCs, but differ in sizes, since they are typically a smaller and a more simplified version of a BRC, typically incorporated in small residential areas.
Pervious Pavement	Pervious pavement is pavement that functions as a structural surface while having the capability of infiltrating stormwater to an aggregate base below where it serves as a reservoir for stormwater soil while distributing surface loads to the in-situ soil. Pervious pavements reduce runoff through storage and exfiltration while improving water quality through filtration and sorption. Various classifications of pervious pavement exist, including pervious asphalt, concrete and pavers. Pervious asphalt differs from conventional asphalt in that it incorporates little to no fines, allowing it to remain porous. Pervious concrete refers to pervious pavement made of aggregate, Portland cement, little to no fines, and additives. Pervious pavers differ from other types of permeable pavement in that it consists of interlocking concrete pavers that are installed in an interlocking configuration (City of Tulsa, 2021).
Non-LID-BMPs	
Wet Detention Pond	Wet detention ponds in this case are referred to as water impoundment structures that intercept stormwater runoff then release it to an open water system at a specified flow rate. They retain permanent pools and typically have retention times sufficient to allow settlement of some portion of the intercepted sediments and attached nutrients or toxics. There is little or no vegetation living within the pooled area, nor are outfalls directed through vegetated areas prior to open water release (Center for Watershed Protection, 2007)
Add-on	
Arch chambers	Arch chambers act as an add-on to bioretention cells, they are an open-bottom plastic infiltration chamber system that allows to meet stormwater runoff reduction and maximize available land as installed below BRC media and subsequently connect back to the storm sewer system (Contech Engineered Solutions, 2021).

1.1.3.1 Low Impact Development in Oklahoma

In the last few years, many stormwater programs in the country have become more sophisticated and environmentally friendly by incorporating streambank protection, groundwater recharge, protection of sensitive receiving waters, control of the overall volume of stormwater runoff, and use of natural systems and site design techniques to control runoff, there has been a particular increase in green infrastructure implementation in the upper Midwest (Vogel et al., 2015). With Oklahoma regulated under the National Pollutant Discharge Elimination System (NPDES) program, LID can help communities improve water quality to meet regulations that are very difficult to achieve using traditional methods for handling stormwater (Vogel et al., 2017).

There is potential for different types of LID techniques and structures across the state, given the variability of rainfall accumulation that occurs throughout the state, as shown in Figure 1. In the western part of Oklahoma where rainfall accumulation and runoff rates are lower for in-state data (Mesonet, 2021), rainwater harvesting is an ideal practice to conserve water. On the contrary, in the eastern part of the state, there is a larger amount of precipitation and consequent runoff that would indicate that rain gardens, pervious pavement, and other practices that encourage infiltration could further benefit groundwater recharge and reduce runoff. In central Oklahoma a combination of practices would be ideal, depending on site location, given the mixed ranges of high and low precipitation rates. It should be noted, however, that that all LID practices can be beneficial in all areas of the state. Urban developments include impervious surfaces, disturbed soils, and managed turf grass which can have multiple impacts on water quality and aquatic life (Vogel et al., 2017).

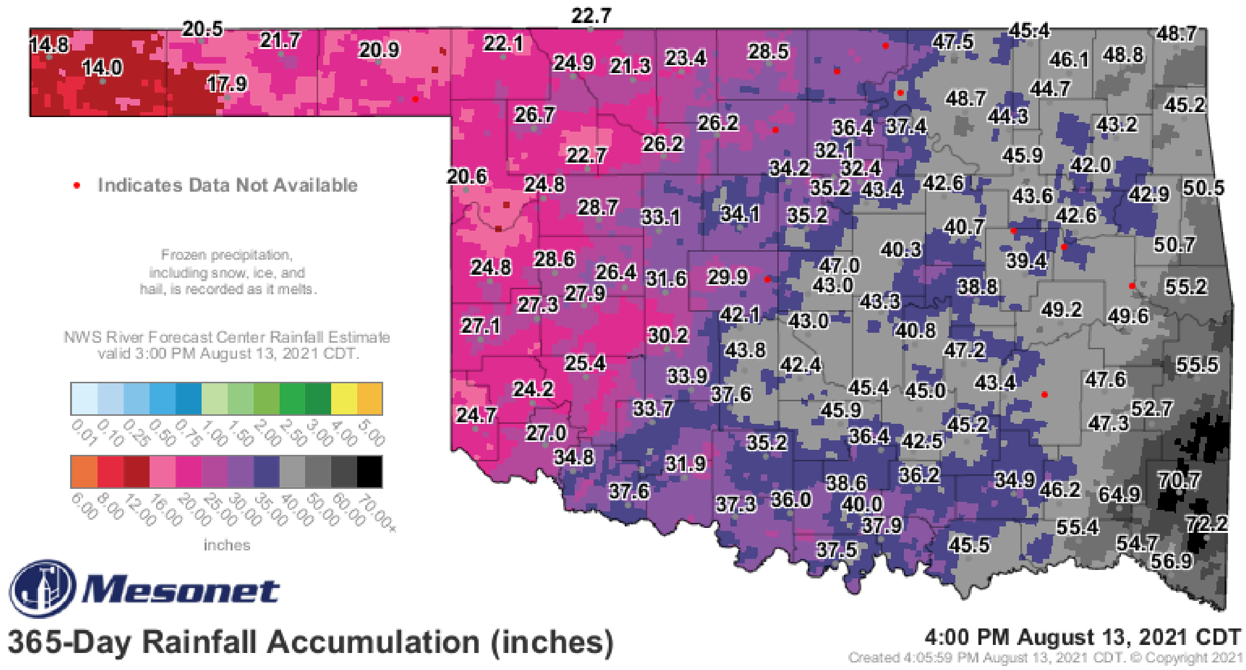


Figure 1. 365-Day Rainfall Accumulation in Oklahoma. Source: (Mesonet, 2021)

1.1.4 Low Impact Development for flood reduction

Urban hydrology and stormwater management have been evolving to improve the urban runoff management for flood protection, public health and environmental protection in many developed countries (Fletcher, Andrieu, & Hamel, 2013). However, according to Li et al., 2016, these types of studies, focusing on stormwater management, are only now emerging in countries like China, giving it great importance to explore methods that can minimize the impacts of urbanization processes on natural environments. In China there has been an increment of investment in urban stormwater management, that is reflected in newly-introduced concepts, such as LID and Sponge Cities (SPC), that aim to address and improve the challenges and problems urban flooding causes. The optimal goals of the SPC is that stormwater generated from rainfall events could be absorbed, stored, infiltrated and cleaned with the natural and/or manmade facilities and the rainfall can then be transformed into a water resource that can be utilized during drought.

With green infrastructures (GI) (an alternative term for LID) practices being implemented in numerous cities to tackle stormwater management issues, Korgaonkar et al. (2021) conducted studies in Tucson, Arizona to model a 3.31 squared kilometer watershed to compared seven different configurations of GI and evaluating its effects on flood mitigation and long-term water availability. They found that GI implementation caused a 1% increase in peak flows at the watershed outlet but predicted reduced on-street accumulated volumes by less than 25%. Current GI configuration may not have a significant impact at the watershed scale, but it does have a localized impact, especially at the street scale for a 25-year design storm (Korgaonkar et al., 2021). A study performed in Windsor, Ontario, included the development, calibration and validation of EPA's Stormwater Management Model (SWMM), testing three different return periods, and evaluating five different implementation scenarios of LID practices, successfully minimizing peak flow in the stormsewers, reducing peak runoff by 13% and total volume by 29% while minimizing costs (Eckart et al., 2018).

1.1.5 Modeling Low Impact Development for water quality

Humans and living beings depend on water for everyday activities, therefore, water quality is a critical component of water resources management. Water quality modeling has many advantages due to its importance to real-life, real-time problems that must be addressed. This type of modeling can provide data where monitoring is not available or is hard to reach or measure. Quality models that are used for planning and management should link management options to meaningful response variables such as pollutant sources and meeting water quality standards, and they should also be appropriate to the complexity of the situation and to the available data (Loucks & van Beek, 2017).

A study made by Qin et al., (2013), found that the performance of LID designs is affected by the structures that are installed and their properties in China. Results vary when different percentages of LID techniques are modeled or when the percentage of the drainage area of the LID components and the storage capacity change.

1.1.6 Stormwater models

Hydrologic, hydraulic, and water quality models all have different purposes and provide a different range of information. The most common, and relevant to this study, modeling software that exists includes models such as, EPA SWMM, Win TR-55, FlowMaster, and the EPA National Stormwater calculator (SWC). The software used in this research is InfoDrainage, developed by Innovyze®.

InfoDrainage and the SWC use the SWMM engine for their hydraulic calculations, the former one is modern, with an advanced graphic interphase and is very user friendly, giving the modeler the capacity to represent an existing (or future) storm sewer system accurately and then connecting LID features at specific points in the watersheds, as opposed to the SWC which is limited in terms that it does not allow for hydraulic routing or the option to choose where LID is to be implemented in the watershed, it is rather a simplistic model that serves for planning purposes in this research.

Win TR-55 is used for hydrological analysis, to better represent an area's curve number and time of concentration, given the appropriate rainfall events, slopes, flow path and land use divisions are provided. FlowMaster is relevant to this research for its hydraulic calculations which contribute to calibrating the InfoDrainage model with flow at the watershed's outfall.

1.1.6.1 InfoDrainage

InfoDrainage is a stormwater design software program that provides the capability of integrating stormwater control structures, including LID, for runoff reduction practices and water quality modeling. It allows the assessment of existing or design storm sewer systems on urban areas, with Computer Aided Design (CAD) and Geographic Information System (GIS) integration (Innovyze, 2021). A case study evaluation was performed by Chow et al., (2014) in Australia to illustrate the use of InfoDrainage (previously named XPDRAINAGE), demonstrating the possibility to describe permeable pavement and swale performance in reducing runoff; the combination of these LID techniques when compared to traditional rainfall storage tanks proved to offer more benefits, in terms of runoff reduction, reduction of carbon emissions and added ammenity values. Additional research is needed on Innovyze's software to contribute to the database on more modern stormwater models for both peak flow and pollutant reductions.

1.1.6.2 EPA SWMM

The EPA Stormwater Management Model (SWMM) is used throughout the world for planning, analysis, and design related to stormwater runoff, combined and sanitary sewers, and other drainage systems. It can be used to evaluate gray infrastructure stormwater control strategies, such as pipes and storm drains, and is a useful tool for creating cost-effective green/gray hybrid stormwater control solutions (EPA, 2020).

Due to climate change, there has been an increase on rainfall intensity and flash floods to accelerated flood inundation in many areas. In a case study performed by Sangeun & Dongwook, (2018), two cities from South Korea, were used to model an urban stormwater inundation simulation with SWMM and a HydroDynamic Model-2D (HDM-2D). They were able to determine the occurrence of a surcharge overflow and the relationship between the flooding wave propagation and the flow interaction with topographical obstacles.

In the Middle East, considering overflow as one of the most frequent concerns in the major cities of Nepal, the implementation of the SWMM model had helped the community with stormwater management in affected areas and has encouraged local people to handle more efficiently the infrastructure management and urban planning to solve the overflow of the area (Keshav et al., 2020). A case study done in Italy had the main objective to simulate rainfall-runoff by comparing it to other models, where the result stated that SWMM predictions were the most accurate with the measured area and pointed out the relevance of the time variance hydrograph as a key feature of the model (Ken-Hang & Abdusselam, 2012).

1.1.6.4 Win TR-55

This model uses the WinTR-20 program as the driving engine for more accurate analysis of the hydrology of the small watershed system being studied (USDA Natural resources conservation service, 2013). A study performed by Bedi et al., (2015) used Win TR-55 to calculate individual curve numbers (CN) for their individual subcatchment areas and to obtain the weighted CN for the watershed to be used in runoff-volume calculations. This CN methodology will be utilized for the research project, as it serves as input for modeling.

1.1.6.5 FlowMaster

The model helps perform hydraulic calculations for dozens of element types, from pipes and open channels to drop inlets and weirs by improving design productivity, ultimately saving project costs. It also helps to interpret and present modelling results with detailed tables, reports, rating curves among others (Bentley, 2021). FlowMaster serves as one of the calibration methods for this project, given its ability to estimate flow through a channel of specific characteristics, when the rainfall or volume of water is provided.

1.1.6.6 EPA SWC

The EPA National Stormwater Calculator (SWC) is a desktop software application that can estimate the annual amount of rainwater and frequency of runoff from a specific site LID controls as well as other green infrastructures. Its computational engine is the EPA Storm Water Management Model (SWMM) (EPA, 2019).

1.1.7 Spatial resolution impact in stormwater modeling

One of the most used and widely available datasets of spatial information are Digital Elevation Models (DEMs). DEMs offer an efficient way to represent the ground surface and allow automated extraction of hydrological features, such as flow direction and flow accumulations, which leads to a proper watershed analysis, thus bringing advantages in terms of processing, cost effectiveness and accuracy assessment (Vaze, Teng, & Spencer, 2010).

Hydrological response is influenced by interactions between rainfall variability in space and time and catchment characteristics. These interactions are more pronounced in urban areas since the high degree of imperviousness and large heterogeneity of watershed characteristics, trigger fast runoff generation. These are reasons why the use of high-resolution data is necessary to investigate hydrological response in urban systems (Faures et al., 1995) (Sempere-Torres et al.,, 1999; Smith et al., 2012; Ochoa-Rodriguez et al., 2015; Zhou et al.,, 2017; Cristiano et al., 2019).

DEM is one the main tools used in hydrological science. It stores terrain information in a grid format and automates the information extraction and analysis process. One of the salient aspects of DEM data is its spatial resolution and over the years, it has led to scientific investigations looking into the effect of DEM resolution on the simulated hydrological response (Sahoo & Jain, 2018). Studies show the effects of DEM resolution on modeling, and how this parameter affects model inputs such as slopes, river network, time of concentration and watershed areas (Zhang & Montgomery, 1994; Sorensen & Seibert, 2007; Fan et al., 2020). Topographic resolutions are also directly related to drainage networks in a river basin, since they are used as a parameter to characterize the hydrological response of a basin (Sahoo & Jain, 2018)., such as the direction where water is flowing and where it accumulates.

1.2 Objectives

The objectives of this study are:

1. To design and model LID implementation into existing overland and enclosed drainage systems; using a stormwater model that shows flood-prone and storm-sewer surcharge areas to optimize localized flood peak reduction in a selected neighborhood of concern in Oklahoma City and Tulsa.
2. To compare model-simulated runoff water quality and quantity improvements for traditional and flood-based LID design criteria, utilizing local design storms.
3. To perform a sensitivity analysis on the InfoDrainage stormwater model for a variety of input variables, such as soil data, media amendments, underdrain diameter, storm duration, and a range of DEM resolutions that vary from publicly available data, at 30-, 10- and 1-meter to site-specific data of 1-foot resolution.

Chapter 2: Methodology

Fulfilling the objectives of this project, included data gathering for the study areas to contribute to model building and subsequent data evaluation and analysis. A hydrology description for each area of interest provided insight on watershed properties, land uses, curve number, time of concentration, subwatershed divisions and rainfall events, which served as input for the stormwater models. The hydrologic model building section describes how real-life data contributed to proper model functioning and accuracy when representing rainfall-runoff processes (Figure 2).

LID implementation required multiple steps until the final recommendation for potential infrastructures was reached based on watershed characteristics (e.g., land use and soil type), price, volume reduction and pollutant reduction. These steps included BMP optimization (McMaine, 2017), placement of the BMPs, and different design specifications for each of the final infrastructures (Figure 3).

Once the potential LID infrastructures were selected based on optimization results and areas of interest, the modeling phase in the InfoDrainage software took place. This process began with building the existing storm sewer system, calibrating it with the available information for each watershed and finally, building the LID system, connecting it into the existing system (Figure 4).

A sensitivity analysis was performed after the modeled LID techniques showed potential success at reducing runoff, comparing four DEM resolutions for the Oklahoma City watershed, including 30-, 10- and 1-meter public data from USGS and an on-site topographical survey performed at 1-foot; the three same public USGS DEMs were used for the Tulsa watershed. This section also included model sensitivity to soil infiltration rates underneath the BMPs, three different types of bioretention cell media, four underdrain pipe diameters (0.5-, 2-, 4-, and 6-in) and 1-day versus 2-day model run time.

Flow charts summarizing the various processes for this methodology are shown in Figures 2 through 4.

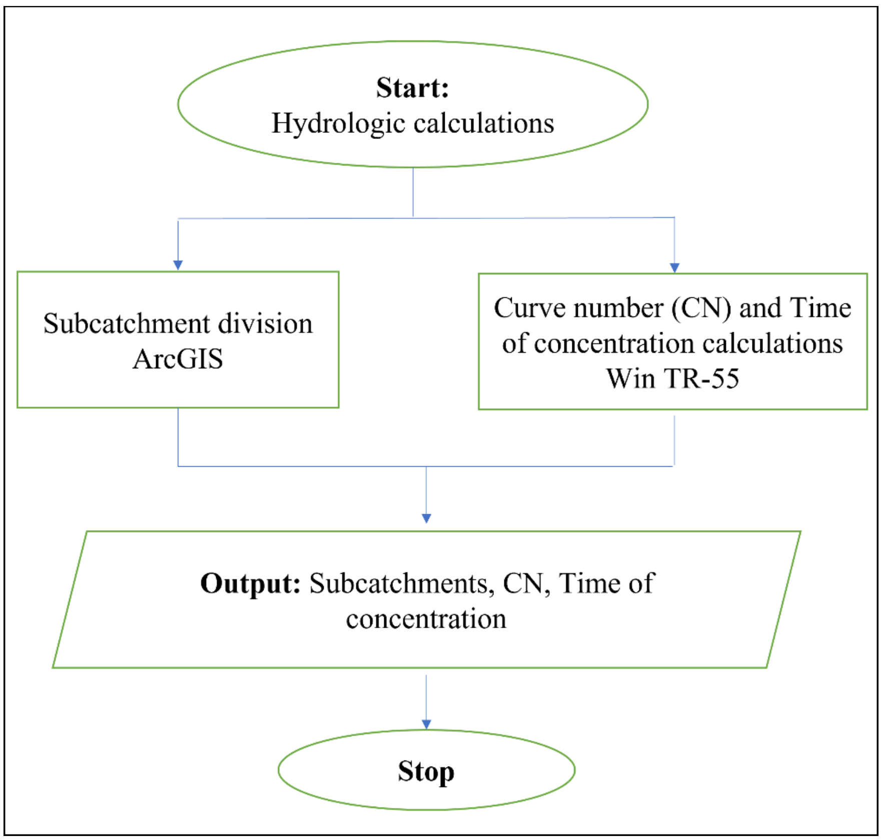


Figure 2. Flow chart of hydrologic calculations

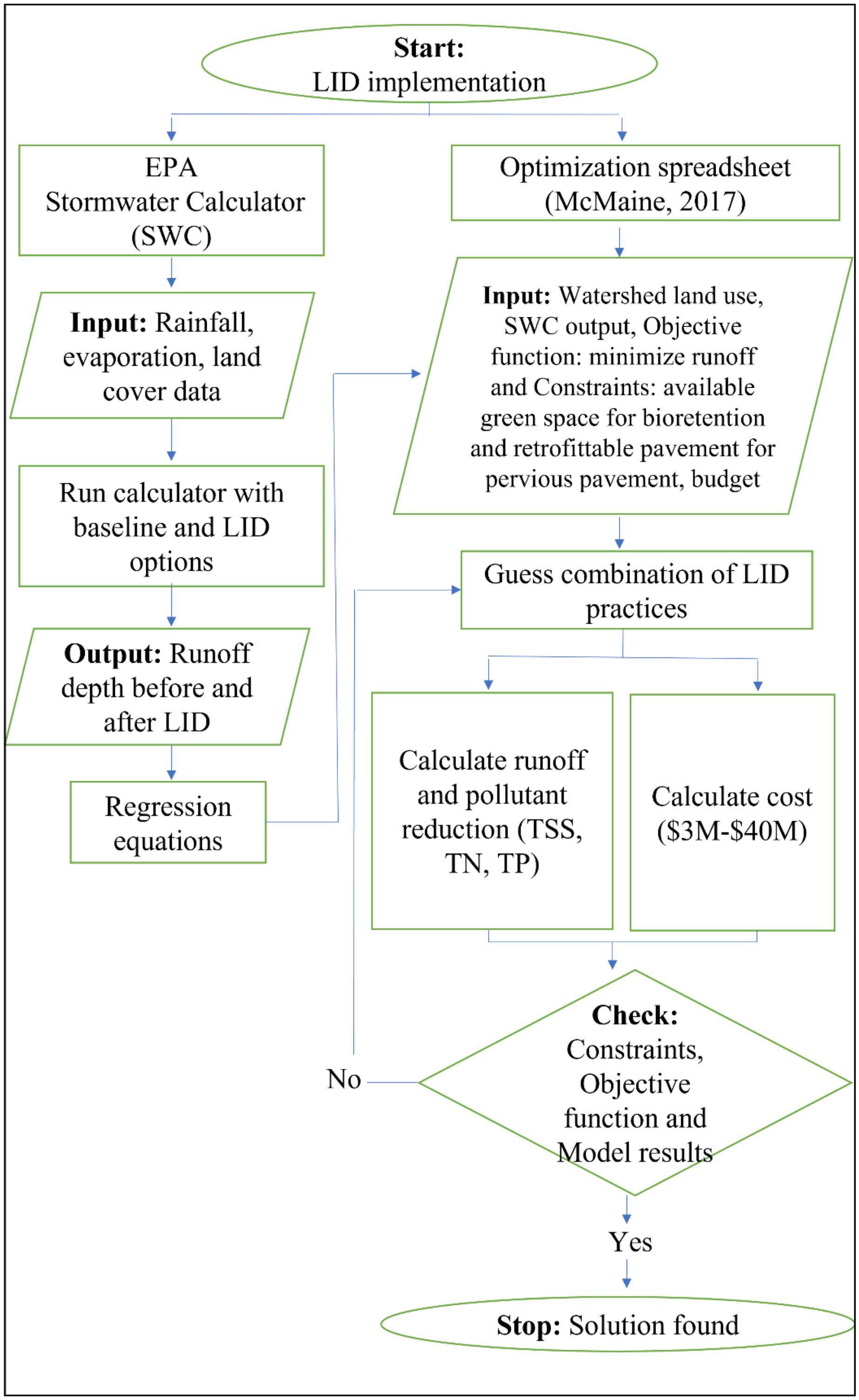


Figure 3. Flow chart of Low Impact Development (LID) Implementation. TSS: Total Suspended Solids, TN: Total Nitrogen, TP: Total Phosphorus

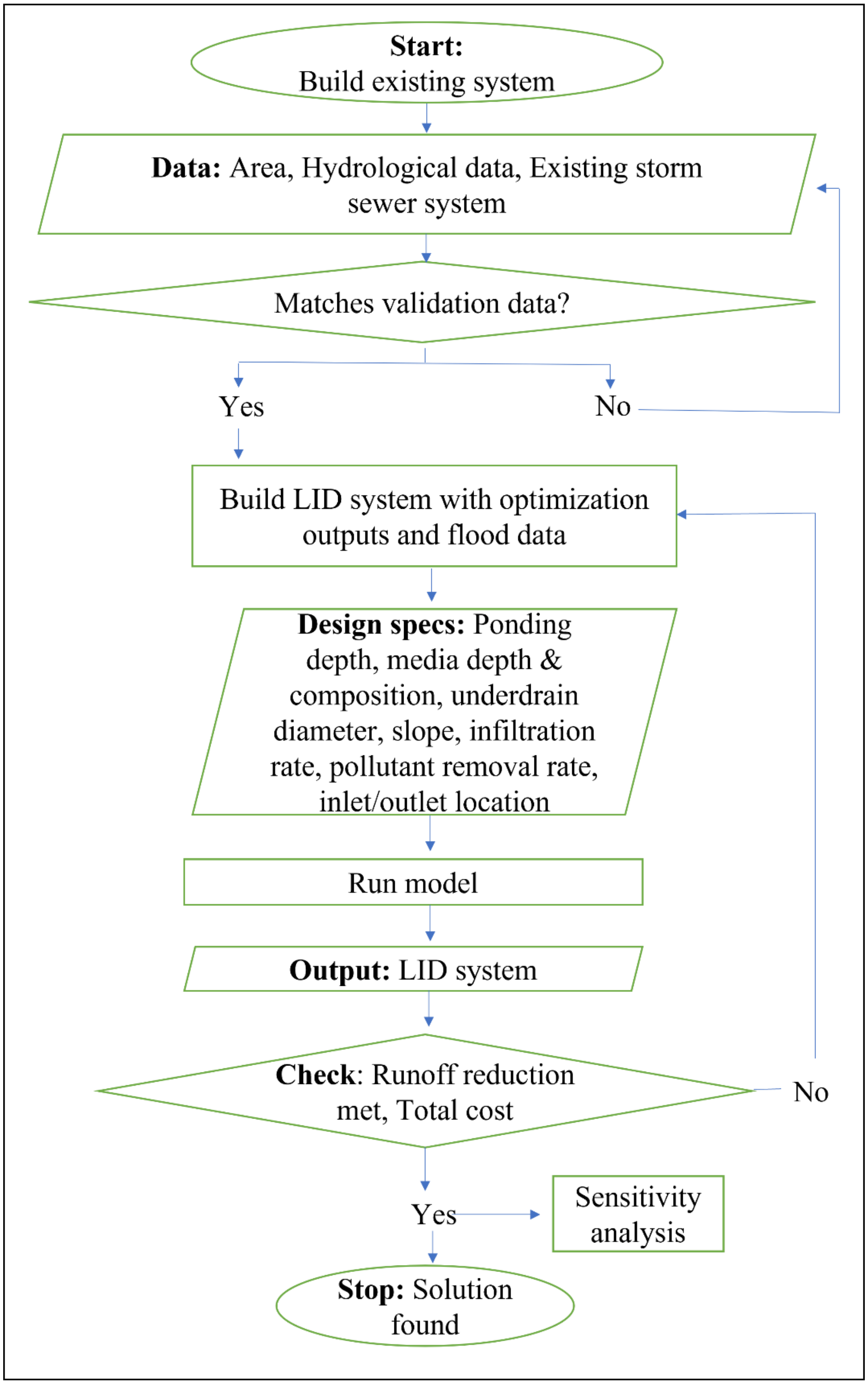


Figure 4. Flow chart of modeling process

2.1 Hydrology

Each of the watersheds was divided into subcatchments, based on the GIS subcatchment division process by Ji & Qiuwen, (2015), which takes into consideration surface cover types of urban catchments, including topography, buildings, and streets, in addition to the natural occurring hydrologic processes in the watershed. Road and conduit networks were the main path for surface and underground flow for storm sewer systems in urban regions acting as the actual flow path of storm runoff; similar to a river network in an undeveloped region, which plays an important role in the rainfall-runoff processes in the watershed.

For this study, multiple resolution DEMs were used (30-, 10-, 1-m and 1-ft), USGS elevation products data were used for the 30-, 10- and 1-m maps (USGS, 2021) while the 1-ft data was obtained through a topographic survey performed by Olsson ® (Olsson, 2021) along with LiDAR data from the City of Oklahoma City. Taking into consideration that the actual runoff and flow processes in urban regions are not only influenced by topography, but also related to the spatial distribution of roads, conduits, and buildings, the original DEM data was adapted from its original version before moving onto flow direction. In urban watersheds, the ideal surface runoff mode is all the storm water flowing to the nearest road by overland flow, until reaching a junction on the ground. The DEM data was modified with the overlay and buffer analysis functions in ArcMap.

The road data was converted from polyline feature layer to raster layer, then overlayed to the DEM layer to get the collection of DEM pixels where the conduits are located. The elevation values of the DEM pixels in the collection are reduced by using the formula:

$$E_a = E_i - D \tag{1}$$

Where E_a is the adjusted elevation of the pixel, E_i is the original elevation of the pixel, and D is the burial depths of the conduits, which the DEM pixels intersect with; the conduit data was obtained from survey and was double checked using Google Earth. However, data for Pearl District only included the pipeline diameter, inlet, manhole and invert elevations were adjusted based on model capacities and available infrastructure data for storm sewers. The buffer analysis tool was used to calculate the buffer area of the conduits at a 12 ft distance on both sides. The buried road layer and original DEM layers were mosaiced together to generate the final DEMs. The hydrology toolbox was used to fill elevation gaps, run flow direction, flow accumulation and the basins tool, to obtain the subcatchment division for each area of interest.

Hydrology analysis was completed using the United Stated Department of Agriculture (USDA) Soil Conservation Service (SCS) TR-55 methodology throughout the watersheds to determine the approximate amount of runoff from specific rainfall events, a Type II SCS Rainfall Distribution was used.

2.1.1 Curve Number

Sub-basins were delineated within the study areas through topographic procedure in Google Earth Pro to appropriately model stormwater reaching the storm sewer system. To determine flow quantity, an SCS Curve Number (CN) was calculated for each subcatchment, based on specific hydrologic soil group, land use, hydrologic condition, and antecedent runoff condition (USDA, 1986). The curve number is focused on soil permeability and existing conditions of the soil, assuming the soil is in normal conditions (not overly saturated or completely dry). The SCS runoff equation is:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{2}$$

Source: (USDA, 1986)

Where Q is runoff (in), P is rainfall (in), S is the potential maximum retention after runoff begins (in) and I_a is initial abstraction (in). I_a is all losses before runoff begins, and includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. Through studies of small agricultural watersheds, I_a was found to be approximated by the empirical equation:

$$I_a = 0.2S \tag{2.1}$$

Source: (USDA, 1986)

S is related to the soil and cover conditions of the watershed through the CN. CN has a range of 0 to 100, and S is related to CN by:

$$S = \frac{1000}{CN} - 10 \tag{2.2}$$

Source: (USDA, 1986)

2.1.2 Time of Concentration

Technical Release 55 (USDA, 1986) requirements for SCS Methodology were followed, including the 6 Min (0.1 Hr) minimum duration for Tc. Time of concentration (Tc) is determined for each drainage area using the Sheet Flow equation (Equation 3), Shallow Concentrated Flow equation (Equations 4.1(unpaved) and 4.2 (paved)) and Channel Flow equation (Equation 5).

$$T_t = \frac{0.007(nL)^{0.8}}{(P_2)^{0.5}S^{0.4}} \tag{3}$$

Where, T_t is travel time (hr), n is the Manning's roughness coefficient (for sheet flow), L is the flow length, $P_2$is the 2-year, 24-hour rainfall (in), and *s* is the slope of hydraulic grade line (land slope, ft/ft). This simplified form of the Manning's kinematic solution is based on shallow steady uniform flow, constant intensity of rainfall excess, rainfall duration of 24 hours, and minor effect on infiltration on travel time.

$$V = 16.1345\sqrt{S} \tag{4.1}$$

$$V = 20.3282\sqrt{S} \tag{4.2}$$

Where, V is the average velocity (ft/s), and S is the slope of hydraulic grade line (land slope, ft/ft). These two equations are based on a solution of the Manning's equation with different assumptions for *n* (Manning's roughness coefficient) and *r* (hydraulic radius, ft). For unpaved areas, *n* is 0.05 and *r* is 0.4; for paved areas, *n* is 0.025 and *r* is 0.2 (Sturm, 2001).

$$V = \frac{1.49r^{\frac{2}{3}}\sqrt{S}}{n} \tag{5}$$

Where, V is the average velocity (ft/s), r is the hydraulic radius (ft), S is the slope of hydraulic grade line (land slope, ft/ft) and n is Manning's roughness coefficient (for open channel flow), for water flowing on the streets and through the corrugated metal pipe and reinforced concrete pipes in the storm sewer system.

The summary table of area, CN, time of concentration and other inputs for the models can be found in Appendix B.

2.2 Low Impact Development Implementation

For decision making on where the LID techniques were to be implemented, optimization methods were required, including the use of the EPA's Stormwater Calculator, an optimization spreadsheet with defined constraints, cost estimations and pollutant removal calculations.

2.2.1 EPA National Stormwater Calculator (SWC)

For the different percentages calculations of impervious area treated by each LID type, the EPA SWC was used. The values calculated from this software were used in the runoff regression for each LID type in the optimization process.

For output results for runoff depths as a function of percent of impervious area treated, a set of inputs and processes was needed: the SWC's site selection tool allows a selection of a point at the centroid of the circle that encompasses the study area.

Required input for the SWC includes rainfall and evaporation data from the closest rain gauge to the study area, percentage land cover data, and running the calculator with no urbanization cover, so that pre-development conditions can be found. A baseline non-LID scenario is also needed by running the simulation with the accurate percent impervious land and no type of infrastructure implemented, which will estimate the maximum depth of runoff produced in the watershed.

The SWC allows to set how much impervious area is treated by each LID practice. Each scenario can be rerun to determine how much runoff is produced when different amounts of impervious area are treated by different LID types. A linear relationship exists between the percent impervious area treated and the depth of runoff produced by each LID practice (McMaine, 2017). The runoff as a percentage of annual rainfall was modeled using the SWC for each of the LID controls: rainwater harvesting cisterns and barrels, rain garden, green roof, street planters, impervious surface disconnection, dry pond, linear bioretention cell, pervious pavement. Any addition of LID will decrease runoff depth. The SWC was run with the parameters set, and with the impervious surface percent treated for each BMP set at 10%, 20%, 40%, 60%, 80% and 100% to obtain a regression for runoff depth for percent of impervious area treated. The regressions yield the runoff produced for a scenario in which impervious area is treated by a singular LID type with the previously mentioned percentages.

2.2.2 Optimization methods

An optimization procedure developed by McMaine, (2017), uses simple, readily available software, such as SWC and Microsoft Excel, to determine the combination of LID practices that maximizes runoff and pollutant reduction, and minimizes cost. This optimization procedure was used as guidance for the modeling process in both study areas. Watershed delineation and base models from the SWC were used to determine runoff under existing conditions. Regression equations, based on SWC output data were built for each LID practice that relate the amount of impervious area treated with runoff reduction. Each regression equation is structured with the y-intercept as the runoff depth of the base model. These equations were used coupled with a cost per area for each practice to determine the optimal combination of LID types that will achieve maximum volume and pollutant reduction at minimum cost.

The optimization spreadsheet is flexible and enables the user to achieve different goals by changing the objective function or adding/modifying constraints. The spreadsheet includes constraints based on physical limitations. Examples on constraints set on the optimization spreadsheet include green roofs and rainwater harvesting which were limited by roof area, and the different types of pervious pavements that were limited to applicable paved areas such as streets, driveways, and areas where gutters can be placed. Similarly, since bioretention occupies green space, this LID types cannot occupy an area greater than the amount of available green space, but it is assumed that they can treat any type of impervious area (McMaine, 2017). Each area was evaluated using aerial views and GIS to determine available space for LID treatments, as well as land ownership information. These limits were defined in the upper and lower limit columns of the optimization spreadsheet.

The objective function focuses in maximizing runoff volume and given the spreadsheet's flexibility, a constraint for minimizing costs is added, while remaining within the capital and maintenance budgets. Finally, all the LID together cannot treat a percentage greater than 100% of the current impervious area. Based on these constraints, the output was the set of BMP combinations, and their corresponding optimum percent of impervious areas treated. An additional optimization constraint was added to maximize pollutant reduction on pollutants such as Total Suspended Solids (TSS), Total Nitrogen (TN) and Total Phosphorus (TP).

The Solver function in Microsoft Excel was used to determine the optimal solution using regression equations for runoff and pollutant reduction and cost. This function uses one of three solving methods: GRG (Generalized Reduced Gradient) Nonlinear, Simplex LP, or Evolutionary, the latter two do not converge to solutions given the high number of variables and complex constraints present in the spreadsheet. The iterative, GRG Nonlinear was found effective in this application (McMaine, 2017). The regression graphs are attached in Appendix D.

2.2.3 BMP Cost Estimation

BMP costs were derived from the available literature and updated to reflect costs in the year 2021 (Table 2) using the equation for the time value of money based on assumed annual inflation rates of 3% (Equation 6). Using the costs according to the literature, the material and installation costs ($/ft^2) were used to calculate the total initial capital cost ($/ft^2) for BMPs requiring excavation and aggregate. The total initial capital costs for these BMPs were based on the excavation depth (ft) and aggregate thickness (ft). For BMPs not requiring excavation and aggregate, the total initial capital costs simply reflect previously published costs of similar projects. The total costs for all the BMPs are calculated by multiplying the previously found cost estimates by the total area of each BMP.

For all the BMPs selected in the optimization, the recurring maintenance costs over a period of 20 years was calculated by assuming an annual inflation rate of 3%. Number of years was assumed to be 20 based on the depreciation rate for land improvements specified by the U.S. Department of the Treasury (2016) (McMaine, 2017). Then the maintenance 20-year present costs as well as the total 20-year present costs were summed to produce the total cost for the optimization output (Equation 6).

$$Present\ Cost\left(\$/_{ft^2}\right) = Capital\ Cost\left(\$/_{ft^2}\right) + Maintenance\ Cost\left(\$/_{ft^2}\right) * \frac{20\ years}{1.03} \quad (6)$$

Source: (McMaine, 2017)

Table 2. Summary table of Best Management Practices costs per square foot

BMP	Installation ($/ft^2)	Annual Maintenance ($/ft^2*year)	Source
Rainwater Harvesting (Cistern)	$0.48	$0.04	(EPA, 2019)
Bioretention	$10.00-$30.00	$0.20	(Clary & Piza, 2017)
Street Planters	$50.00	$0.80	(Green Building Alliance, 2020)
Impervious Surface Disconnection	$0.04	$0.01	(Wisconsin Department of Transportation, 2012)
Pervious Concrete	$12-15	$0.16	(Grupa, 2021)
Pervious Asphalt	$20-23	$0.20	(Grupa, 2021)
Pervious Pavers	$20-23	$0.04	(Grupa, 2021)

2.2.4 Pollutant calculations.

The optimization was run for a target reduction for each of the three pollutants: TSS, TN and TP. Pollutant reductions for each BMP from the literature were incorporated into an equation that yields the mass reduction of each pollutant in kilograms per year. The tables found in Appendix B show the low, median, and high values for percent reduction for each pollutant, these tables were assembled from multiple research papers and resources that used LID for water quality improvement and pollutant reduction.

After justifying the percent reduction of each pollutant from the literature to be used in the optimization, a fractional percentage reduction for each of the three pollutants: TP, TN and TSS was calculated based on the optimum percentage of impervious surface treated by each LID control of the optimization output (Equation 7) (McMaine, 2017; EPA, 2019). The fractional reduction for each LID control in the optimization output was summed to meet the minimum targets for reduction of pollutant loads.

$$fractional\ \%\ reduction = \%\ pollutant\ concentration\ reduction \times \frac{optimum\ \%\ impervious\ area\ treated}{100} \tag{7}$$

Initial concentrations in milligrams per liter of each of the three pollutants were based on the Minnesota Stormwater Manual (Minnesota Pollution Control Agency, 2021) and the SWMM Water Quality Manual (EPA, 2016), these values are seen in Table 3 in the following section. These initial concentrations are used to calculate the mass reductions of each in kilogram per year for each pollutant (Equation 8).

$$mass\ reduction\ \left(\frac{kg}{yr}\right) = inital\ conc.\left(\frac{mg}{L}\right) \times \frac{\%\ conc.reduction}{100} \times \frac{optimum\ \%\ impervious\ area\ treated}{100} \times (Current\ Runoff\ Vol.(gal) - Pre\ Runoff\ Vol.(gal)) \times \frac{0.264}{1000000} \tag{8}$$

2.2.5 Low Impact Development Practice placement

Flooded locations that the model outputs for the existing storm sewer system within the area of study, as well as documented flooding concerns provided by the city of Oklahoma City were considered. Using flood maps, available green area, and previous studies for the pond projects in the city of Tulsa, the potential location of stormwater controls was selected. For both study areas, stormwater structures were designed and located within the right of way of the neighborhood, in areas close to the storm sewer line, as well as large lots where big bioretention cells could be installed.

2.3 Stormwater modeling

The subcatchment hydrology data including each georeferenced area, curve number, time of concentration, initial abstraction, impervious percentage, and pollutant load was input into the preliminary version of the models, meaning, the existing storm sewer system. The pollutant load was calculated for each subcatchment based on initial concentration values for residential, commercial, roofs and green space areas of the SWMM Water Quality Manual. These initial concentrations are presented in Table 3. The subcatchments were attached to their nearest inlet in the existing storm sewer network and analyzed for each design storm.

Table 3. Watershed parameters for Pearl District in SWC

	Phosphorus	**Nitrogen**	**Total Suspended Solids**
Land Use	mg/L	mg/L	mg/L
Commercial	0.20	1.75	69
Residential	0.38	2.64	101
Grassland/ Open lot	0.19	1.51	21
Roofs	0.03	0.42	5

After the subcatchment information was entered, the existing storm sewer line was drawn, based on survey data for pipe sizing, location, and length, and for manhole and inlet structures depths and locations, the latter three parameters, were only provided for the Sunnymeade watershed. Model capabilities do not allow it to run with a rain on grid option, meaning that the only way for the storm sewer line to get water is by connecting the subcatchments or inflows, to their nearest manhole (or BMP for the case of LID modeling) and transporting water to the outfall. With this information, the model can go for a first run of analysis on the behavior of the existing system.

The existing model was developed in the InfoDrainage software (Innovyze, Portland, OR), and validated with the georeferenced complaint reports provided by the City of Oklahoma City, which show areas where the storm sewer system is under performing. The Pearl District model was validated with FEMA's map for the 100-year flood, found on Appendix C, and the flood factor website for the city of Tulsa.

Next steps in the model building process included the use of a pressure transducer located in the reinforced concrete channel box at the intersection of Wellington Avenue and Downing Street in the northeast area of the Sunnymeade watershed, to track the elevation of water at the outfall for the watershed. These elevation measurements were then transformed into the restricting outfall flow for the model using Bentley's FlowMaster program, this model also requires a survey on the concrete channel for distance and slope measurements. For Pearl District, the model was compared with available previous modeling data on this area, which has been done for pond studies by Swift Water Resources Engineering.

2.3.1 Bioretention cell design characterization

A design spreadsheet was used to size the bioretention cells to receive the stormwater volume from the impervious surfaces in the study area (City of Tulsa, 2021), this spreadsheet includes impervious areas and open space to be treated, soil media information, LID design criteria, and design calculations based on BMP area, ponding and media depths, and a total drawdown time of less than 48 hours to prevent mosquito breeding. An example of the inputs for bioretention needed for InfoDrainage are shown in Figures 5-11. Appendix D includes an example of a bioretention cell design spreadsheet.

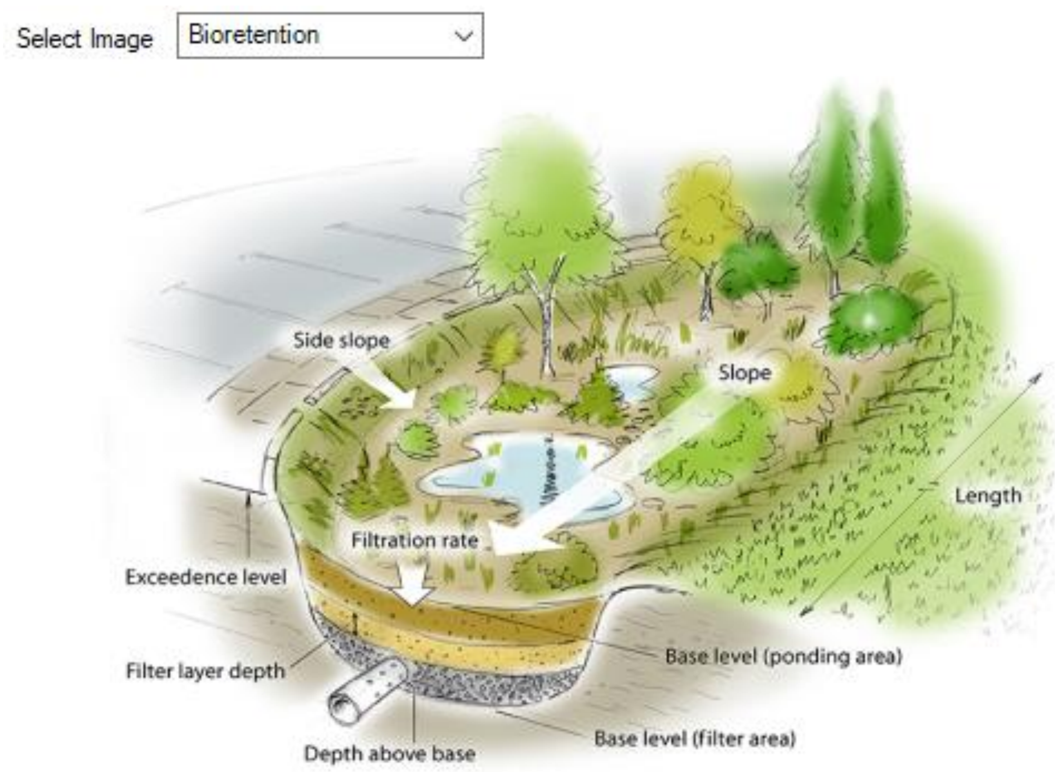


Figure 5. Example of bioretention cell in InfoDrainage (example shown for Sunnymeade – 1ft - clay soil model) (Innovyze, 2021)

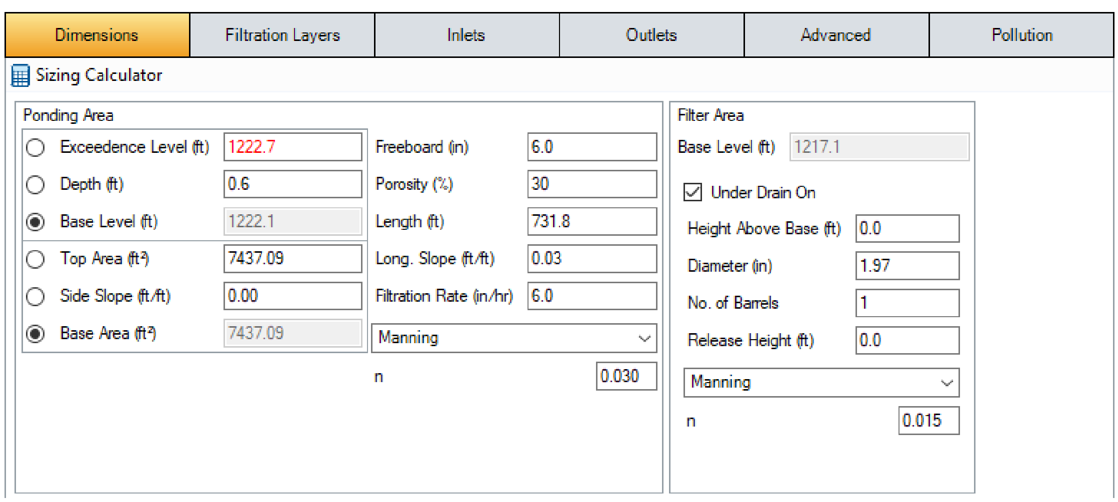


Figure 6. Example of bioretention cell Dimensions tab in InfoDrainage (example shown for Sunnymeade – 1ft -clay soil model) (Innovyze, 2021)

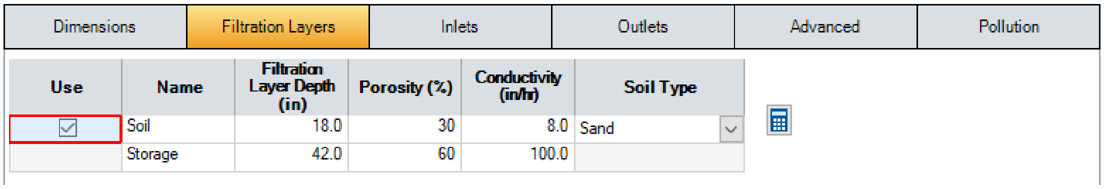


Figure 7. Example of bioretention cell Filtration Layers tab in InfoDrainage (example shown for Sunnymeade – 1ft -clay soil model) (Innovyze, 2021)

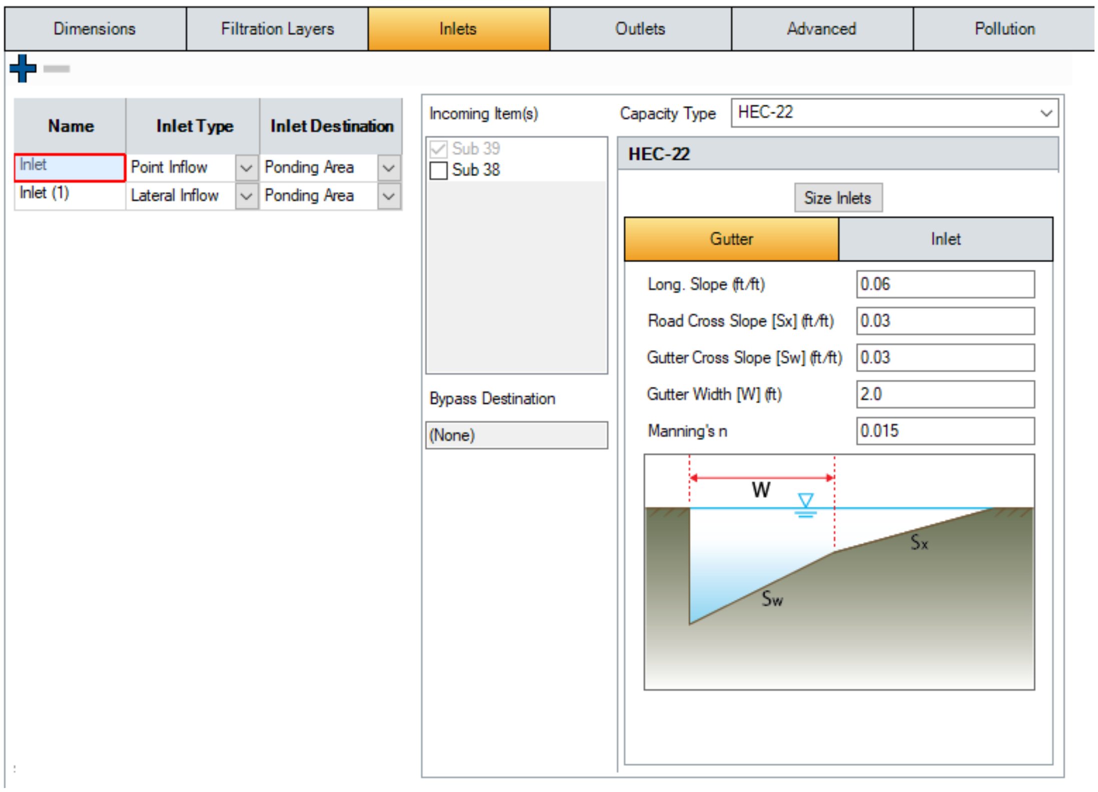


Figure 8. Example of bioretention cell Inlets tab in InfoDrainage (example shown for Sunnymeade – 1ft -clay soil model) (Innovyze, 2021)

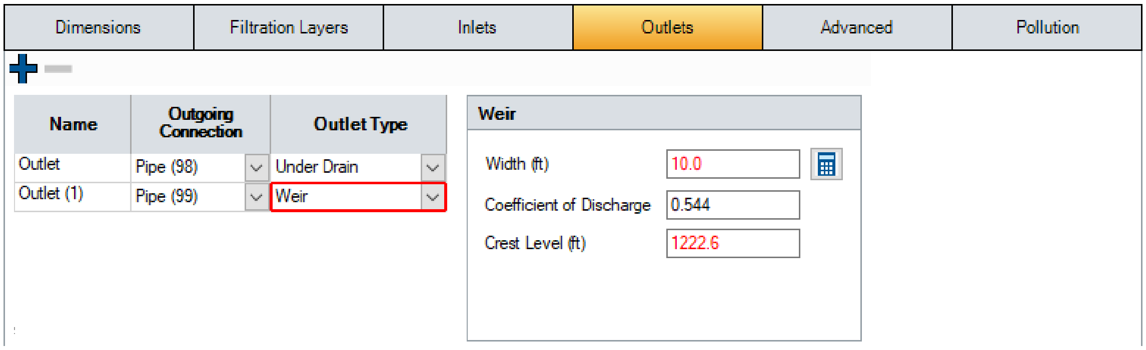


Figure 9. Example of bioretention cell Outlets tab in InfoDrainage (example shown for Sunnymeade – 1ft -clay soil model) (Innovyze, 2021)

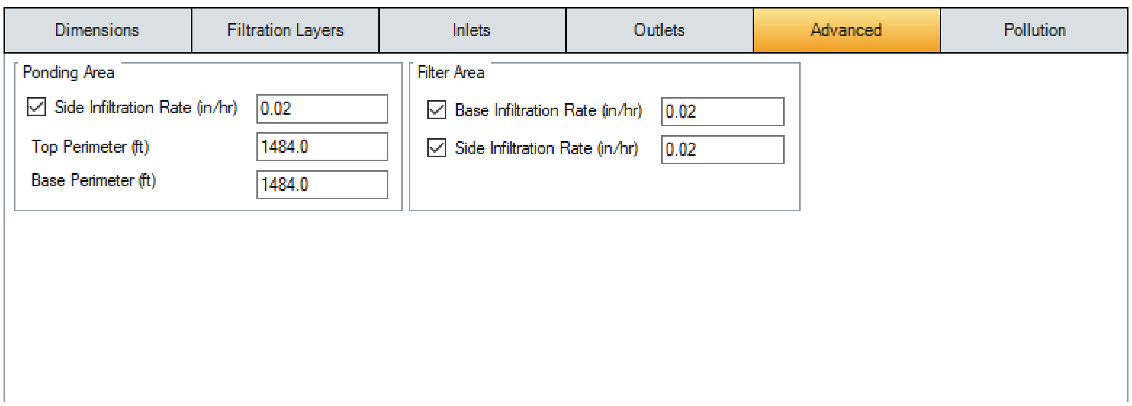


Figure 10. Example of bioretention cell Advanced tab in InfoDrainage (example shown for Sunnymeade – 1ft -clay soil model) (Innovyze, 2021)

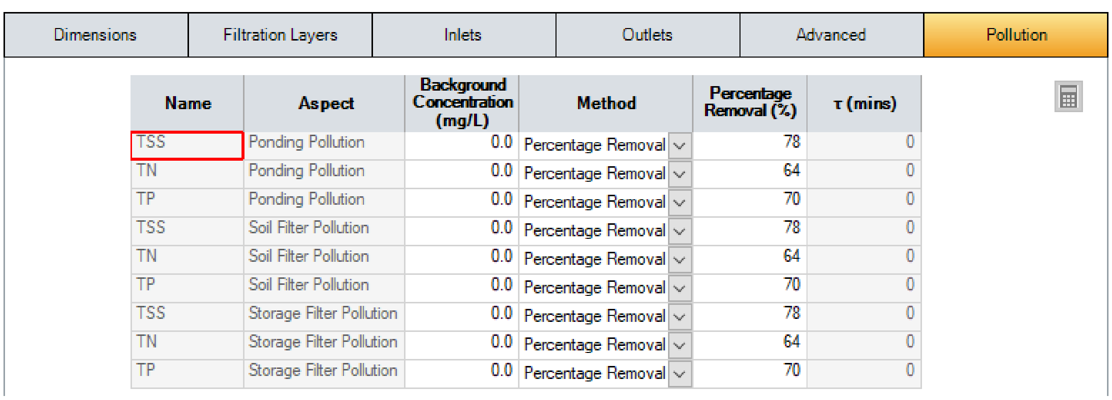


Figure 11. Example of bioretention cell Pollution tab in InfoDrainage (example shown for Sunnymeade – 1ft -clay soil model) (Innovyze, 2021)

2.4 Sensitivity Analysis

Sensitivity analysis determines how different values of an independent variable affect a particular dependent variable under a given set of assumptions (Kenton, 2021). It provides users of mathematical and simulation models with tools to evaluate the dependency of the model output from the model input, and to investigate how important is each model input in determining the output (Iooss & Saltelli, 2016). For this study, this analysis was performed to evaluate model sensitivity, first to different resolution DEMs when used as input for both study areas. Therefore, the results on peak flow and pollutant load reduction in the areas of interest, were compared between the various DEMs for each watershed, for Sunnymeade, given there was a 1-ft survey done, this model (the baseline model) was compared to lower resolution DEMs (30-, 10- and 1-m), consequently performing a cost-effective analysis in terms of the availability and possibility of performing a survey, compared to using publicly available data. For Pearl District, since there was no survey, the model could only be compared between the three finest publicly available DEM resolutions.

Other variables such as soil type, BRC amendments, more specifically, the layer on top of a bioretention cell, right below the ponding layer and above the storage layer, underdrains, and storm duration were be changed one at a time by a specified percentage, to analyze how each of those affect model outputs, these variations in the model were evaluated by comparing bioretention cell drainage performance, in terms of how long it took for the cell to go to half its flooded depth and the maximum level of water on it.

Soil types were included in the sensitivity analysis, and they changed based upon the different types of soil surrounding the study areas on the B horizon, this was changed by varying the soil infiltration rate underneath the BMP, making soil infiltration the second input variable.

BRC amendments were changed for different types of possible media on top of the bioretention cells, making changes in the porosity and conductivity if the media as the third input variable to be studied. Underdrains connecting bioretention cells with one and another were changed to a 0.5-, 2-, 4- and 6-inch diameter to analyze their potential to handle the different storms. Finally, storm duration was compared between a 24- and 48-hour storm to analyze peak flow times and peak runoff values.

Chapter 3: Study Areas

Data collection and pre-processing involved site descriptions for the watershed areas located in Oklahoma City and Tulsa, including hydrologic data, soil data, topographic data, and a description of the existing storm sewer systems, as well as analyzing the potential these areas have for improving their hydrologic conditions with BMP installation. This provided the necessary information to perform the existing drainage system evaluation and assess the potential location for LID placement.

This research study used data collected onsite as well as online for background information on the watershed's properties and hydrologic conditions. The following section includes site descriptions for the two watersheds, with their corresponding storms, subcatchment divisions, soil properties, SWC inputs, budget constraints, existing storm sewer network, and potential LID technique locations.

3.1 Study area locations in Oklahoma

The Sunnymeade watershed, north Oklahoma City, east of Lake Hefner; analysis included a concrete-lined channel within the City of The Village as the outfall. For the Pearl District watershed, downtown Tulsa, the outfall was set south of the watershed at the pond in Centennial Park. The location of the two watersheds in the state of Oklahoma is shown in Figure 12.

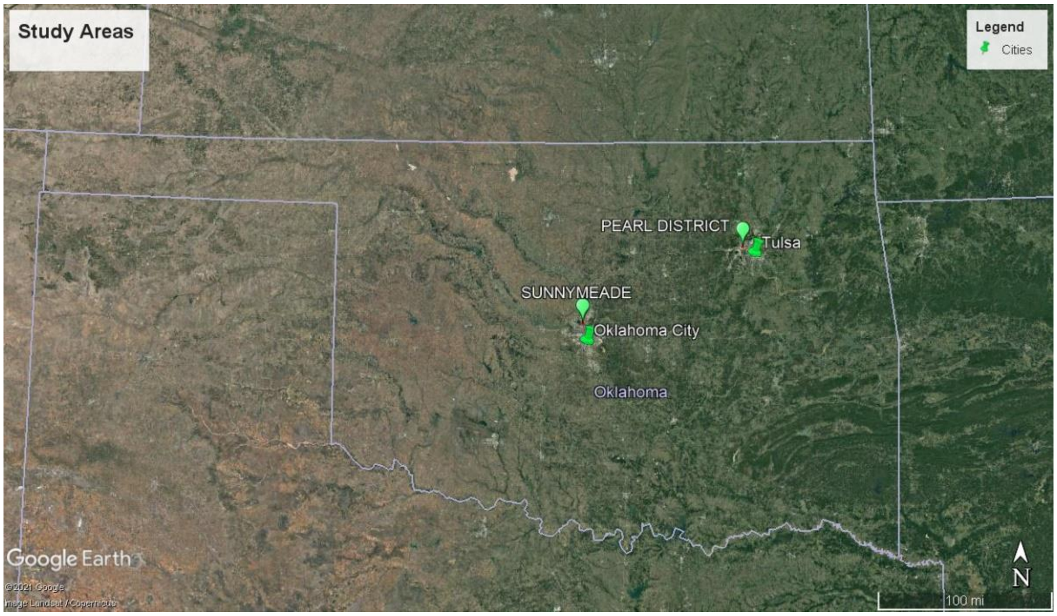


Figure 12. Study area locations in Oklahoma (Google Earth, 2021)

3.2 Oklahoma City: Sunnymeade neighborhood

This section describes all the data used for the methodology section for the Oklahoma City site.

3.2.1 Hydrologic data - Sunnymeade

For Oklahoma County, where the Sunnymeade is located, the National Atmospheric and Oceanic Administration (NOAA) storm data was used, the storms are presented in Table 4.

Table 4. National Atmospheric and Oceanic Administration (NOAA) 24-Hour Storm Events for Oklahoma City (NOAA, 2021)

Return interval (years)	**Rainfall depth (in)**
1	3.0
5	4.9
10	5.7
25	6.8
50	7.7
100	8.7

The Sunnymeade watershed (Figure 13), with a contributing drainage area of 358 acres, is primarily developed residential with minor segments of commercial property and impervious areas such as parking lots and paved streets. The total land use percentage is observed in Table 5. The general direction of stormwater flow is from southwest to northeast. The stormwater flow from Nichols Hills Suburban Tracts subdivision is collected and conveyed by a storm sewer system that outfalls into the concrete-lined channel beginning at Downing Street and Village Drive within the City of The Village. The residential area in The Village is directly located at the upstream of the concrete channel, and the area only utilizes a curb and gutter system to convey stormwater overland.

Table 5. Land use division for the Sunnymeade neighborhood in Oklahoma City, Oklahoma

Component	**Area (Acre)**	**% Of total**	**% Impervious Area**
Streets	120.99	34%	50%
Driveways/Parking Lots	29.45	8%	12%
Roofs	89.23	25%	37%
Total Impervious	239.66	67%	100%
Pervious Area	118.65	33%	
Total	358.31	100%	

Figure 13. Sunnymeade watershed in Oklahoma City, The Village and Nichols Hills in the state of Oklahoma. Base map: (ESRI, 2021)

The USDA National Resources Conservation Service soil survey reports of Oklahoma County indicates three soil types within the study area (USDA, 2021). It consists of Type D soils with a slow infiltration rate when thoroughly wet. The Type D soil consists of fine particles in a particular size that impedes the downward movement of water. The rate of water transmission in

Type D soil is very slow, which increases surface runoff. Appendix A includes soil reports from the USDA.

For this neighborhood, the project area of Nichols Hills Suburban Tracts subdivision as well as the residential area in The Village directly are located at the upstream of the outfall channel. These distinct drainage areas convey stormwater to the existing storm sewer system inlets through residential area with homes, lawns, asphalt streets, and earthen drainage ditches.

The Nichols Hills Suburban Tracts roadside ditches convey most of the subdivision storm water runoff to existing inlets. The entire network drains into a double cell reinforced concrete box located on the northeast end of the watershed, which discharges northeast into a concrete-lined channel at the intersection of Downing Street and Village Drive.

The 75-acre area of The Village within the project boundary does not have an enclosed storm sewer and therefore, stormwater is conveyed in the roadway curb and gutter system. Village Drive becomes the collecting drainage channel during storm events and conveys flow to the northeast to Downing Street where stormwater is collected by the concrete-lined channel. Even though the lack of a storm sewer system and consequent flooding in this area of the watershed, LID is not implemented in this city given the project if focused in Oklahoma City, additional to this, the InfoDrainage model requires for LID to be connected to the storm sewer system to receive water and therefore this area cannot be modeled. Figure 14 shows the existing storm sewer system and inlets for the watershed.

Figure 14. Existing storm sewer system and inlets for Sunnymeade in Oklahoma City, Oklahoma. Base map: (ESRI, 2021)

Hydrology for the Oklahoma City study area established 45 separate sub-basins (Figure 15) for the 77 inlets within the overall drainage area; each of these subcatchments was individually delineated to obtain building, street, and lawn/grass percentages.

Figure 15. Subwatershed division for Sunnymeade in Oklahoma City, Oklahoma. Base map: (Google Earth, 2021)

3.2.2 Low Impact Development Implementation data – Sunnymeade

As the first step in LID implementation is the SWC modeling, the inputs necessary for this are presented in Table 6. An overall land use percentage is also needed as a summary of Table 5 with a total percent impervious of 67% and 33% lawn.

Table 6. Watershed parameters for Sunnymeade in US EPA Stormwater Calculator. (USDA: United States Department of Agriculture; LID: Low Impact Development)

Parameter	Input	Observation
Runoff Potential	D – High runoff potential	Data from Web Soil Survey (USDA Natural resources conservation service, 2013)
Soil Drainage	0.63 in/hr	Silty loam/Clay below urban complex (Tulsa LID Manual 2021)
Topography	Moderately Flat (5%)	Based on site's topography SWC map. Measured by surface slope (feet of drop per 100 feet of length)
Time Period	Near term	Years 2020-2049
Years to Analyze	20	
Design storm	3.7 in.	2-year storm for Oklahoma City (NOAA, 2021)

As part of the optimization process, after the SWC is ran, the optimization spreadsheet requires as one of its constraints, a total capital cost. For this city's project, the limit budget for modeling was set to $4M due to a local limit price for construction.

For LID modeling purposes, the potential locations for BMPs were selected based on the documented flooding complaint data provided by Oklahoma City, shown in Figure 16.

Figure 16. Flood complaint areas for Sunnymeade. Base map: (ESRI, 2021)

3.2.3 Sensitivity Analysis data - Sunnymeade

For soil types, the infiltration rate of the soil underneath the bioretention cells was changed, comparing clay, silty clay, silt loam and sandy loam for Sunnymeade. For bioretention cell media, the conductivity and porosity values of the soil layer inside the bioretention were changed between sandy, sandy loam and loam, to evaluate different types of media to place on top of the bioretention storage layer. Infiltration rates and porosities used are shown in Table 7. Infiltration data was obtained from the Tulsa LID Manual (2021), porosity and conductivity from USDA (USDA, 2007; USDA, 2008).

Table 7. Soil infiltration and porosity data for Sunnymeade

Soil/Media type	**Infiltration rate (in/hr)**	
Clay	0.02	
Silty clay	0.14	
Silt loam	0.63	
Sandy loam	1.98	
	Porosity (%)	**Conductivity (in/hr)**
Sand	30	6
Sandy loam	2	5.6
Loam	23.3	3.94

The 1-ft survey data for the Sunnymeade neighborhood and the 1-, 10- and 30-m DEMs from USGS are shown in Figure 17.

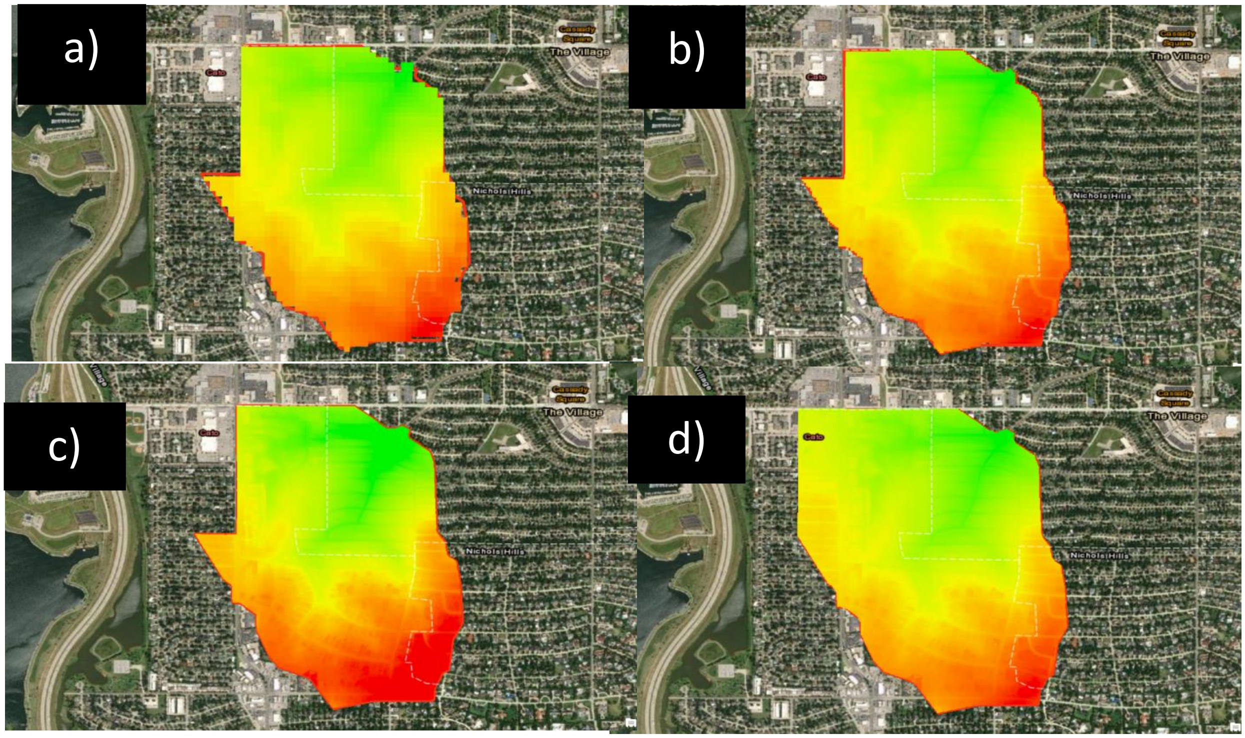


Figure 17. Digital Elevation Models (DEMs) for Sunnymeade in Oklahoma City, Oklahoma. A) 30m, b) 10m, c) 1m, d) 1ft, where red is the highest elevation and green is the lowest elevation (ESRI, 2021).

3.3 Tulsa: Pearl District neighborhood

This section describes the data used for the methodology in the Tulsa neighborhood.

3.3.1 Hydrologic data – Pearl District

The storm data for Tulsa County from NOAA, used for the Pearl District is shown in Table 8.

Table 8. National Atmospheric and Oceanic Administration (NOAA) 24-Hour Storm Events for Tulsa (NOAA, 2021)

Return interval (years)	Rainfall depth (in)
1	3.2
5	5.1
10	6.1
25	7.1
50	7.9
100	8.8

The Pearl District watershed (Figure 18) has a contributing area of 395 acres, it is primarily developed commercial, with residential properties and impervious areas such as train tracks, parking lots and streets (Table 9). The general direction of stormwater flow is from northeast to southwest. This area is known for its pond construction controversy, given that the city owns several buildings and has purchased homes for pond development that will play a major role in resolving Tulsa's likelihood of flooding (Pearl District Association, 2015; Canfield, 2019; Krehbiel, 2019). Precipitation is collected by a storm sewer system that varies in pipe diameters from 6 to 108 inches in size, discharging in Centennial Park Pond, which eventually outfalls the Arkansas River.

Table 9. Land use division for the Pearl District neighborhood in the city of Tulsa, Oklahoma

Component	**Area (Acre)**	**% Of total**	**% Impervious Area**
Streets	67	17%	36%
Parking	61	15%	32%
Commercial	40.6	10%	22%
Houses	13	3%	7%
Train tracks	6	2%	3%
Total Impervious	187	48%	100%
Total Pervious	206.16	52%	
Total	393	100%	

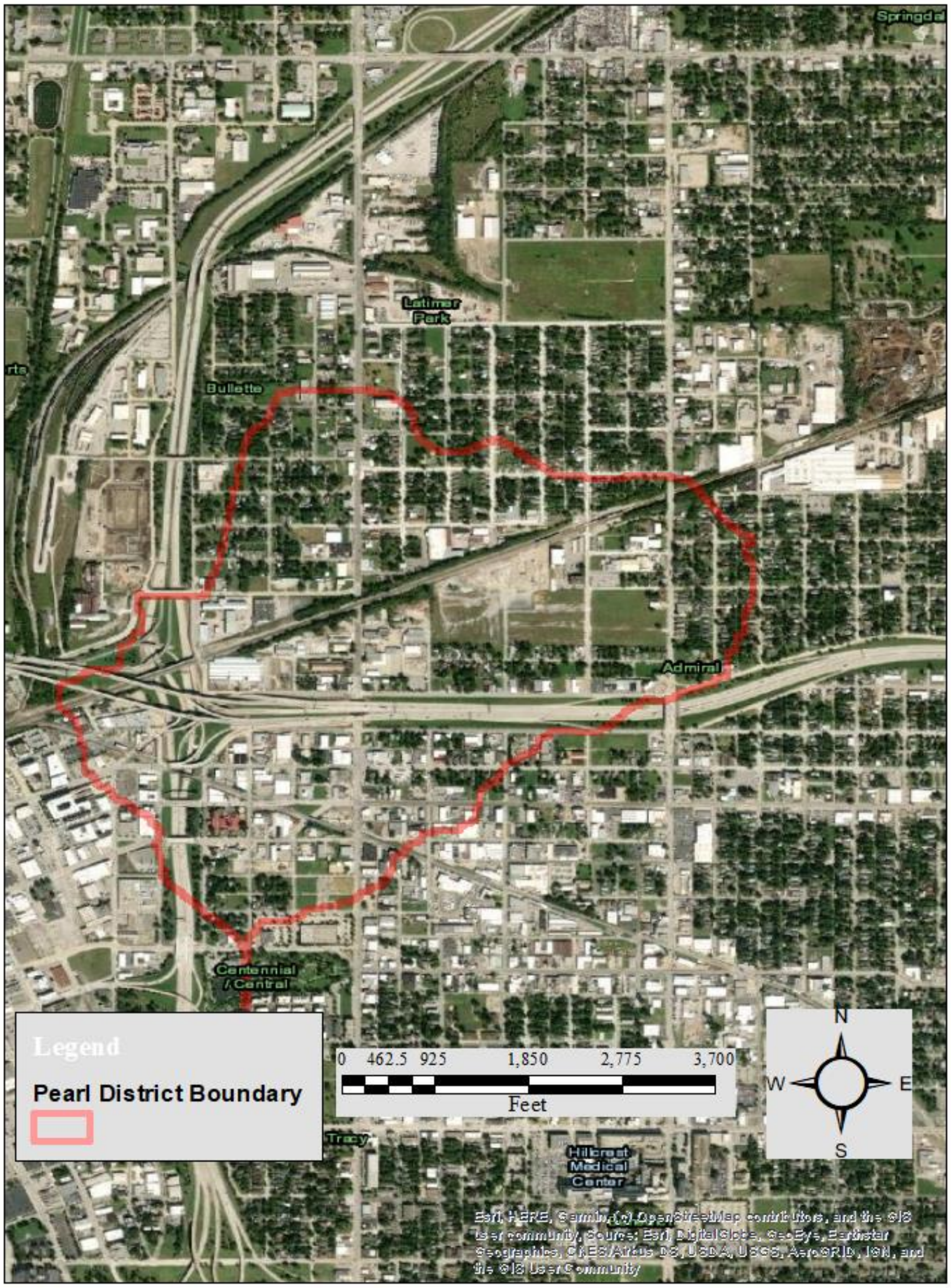


Figure 18. Pearl District watershed in Tulsa, Oklahoma (ESRI, 2021)

The USDA National Resources Conservation Service soil survey reports of Tulsa County indicate three soil types within the study area, all relating to urban land use (USDA, 2021). The watershed consists of Type D soils with a slow infiltration rate, given its silt loam/silty clay characteristic. Appendix A includes soil reports.

The existing storm sewer system for the Pearl District neighborhood was obtained from the City of Tulsa from the input for the modelling process for the Elm Basin in Tulsa and was cropped to match the extent of the Pearl District watershed. It is an enclosed storm sewer system with multiple outlets throughout the watershed. One of the main storm sewer lines extends across the watershed from Haskell Street and North Utica Avenue through Admiral Place, Admiral Boulevard, across I-244 until it reaches the pond underneath South Owasso Avenue, another major branch of the system is underneath St. Louis Avenue and Utica Avenue, travelling west to North Peoria Avenue until East Admiral Place where it meets the previously mentioned sewer line. One other main pipeline extends from north to south on the center of the watershed. The system for Pearl District is observed in Figure 19.

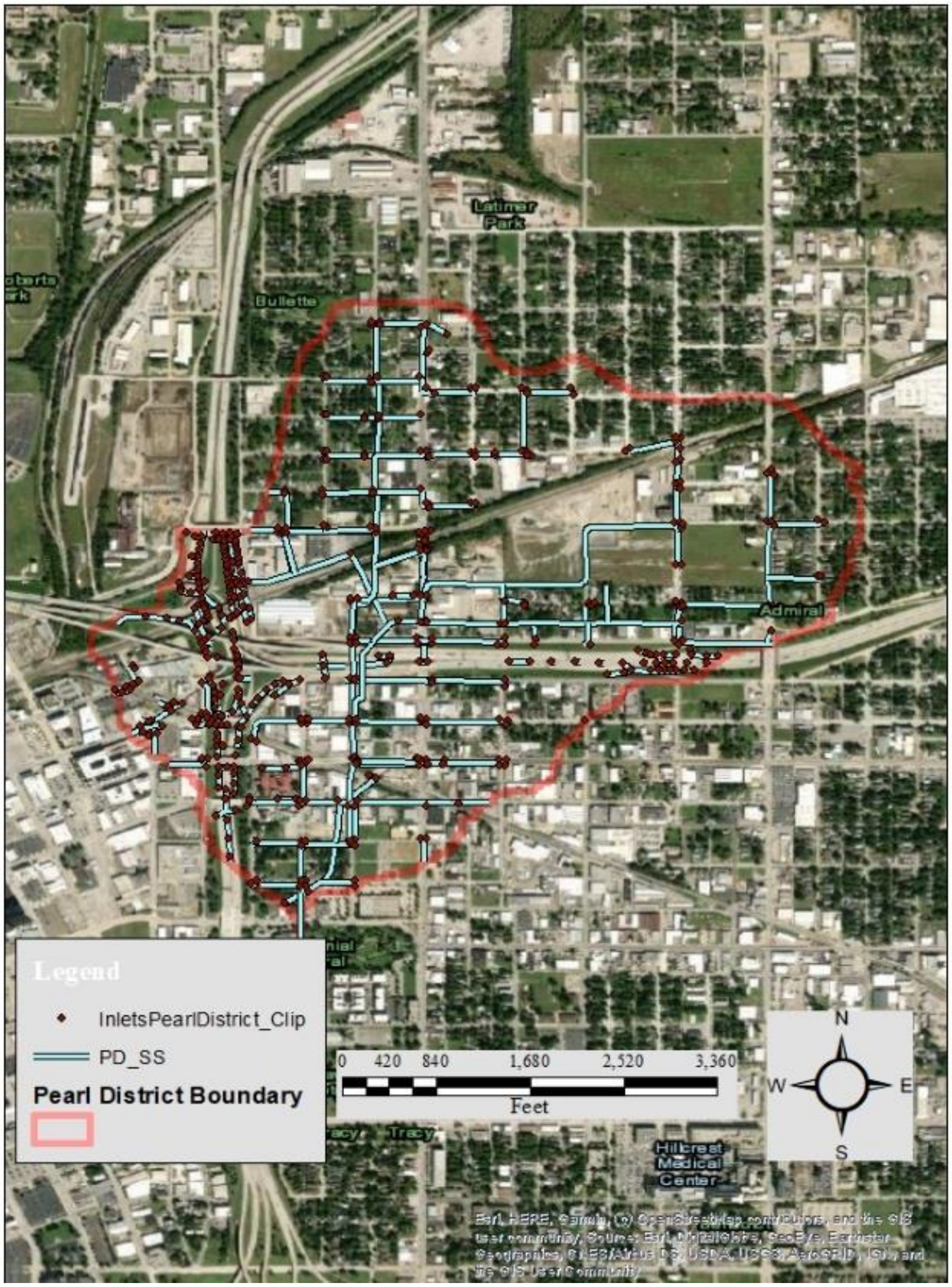


Figure 19. Existing storm sewer system and inlets for Pearl District in Tulsa, Oklahoma (ESRI, 2021)

Hydrology for the Pearl District in Tulsa yielded 91 separate subcatchments (Figure 20) for the 487 inlets in the watershed; each of these areas was also individually delineated to get individual land use data.

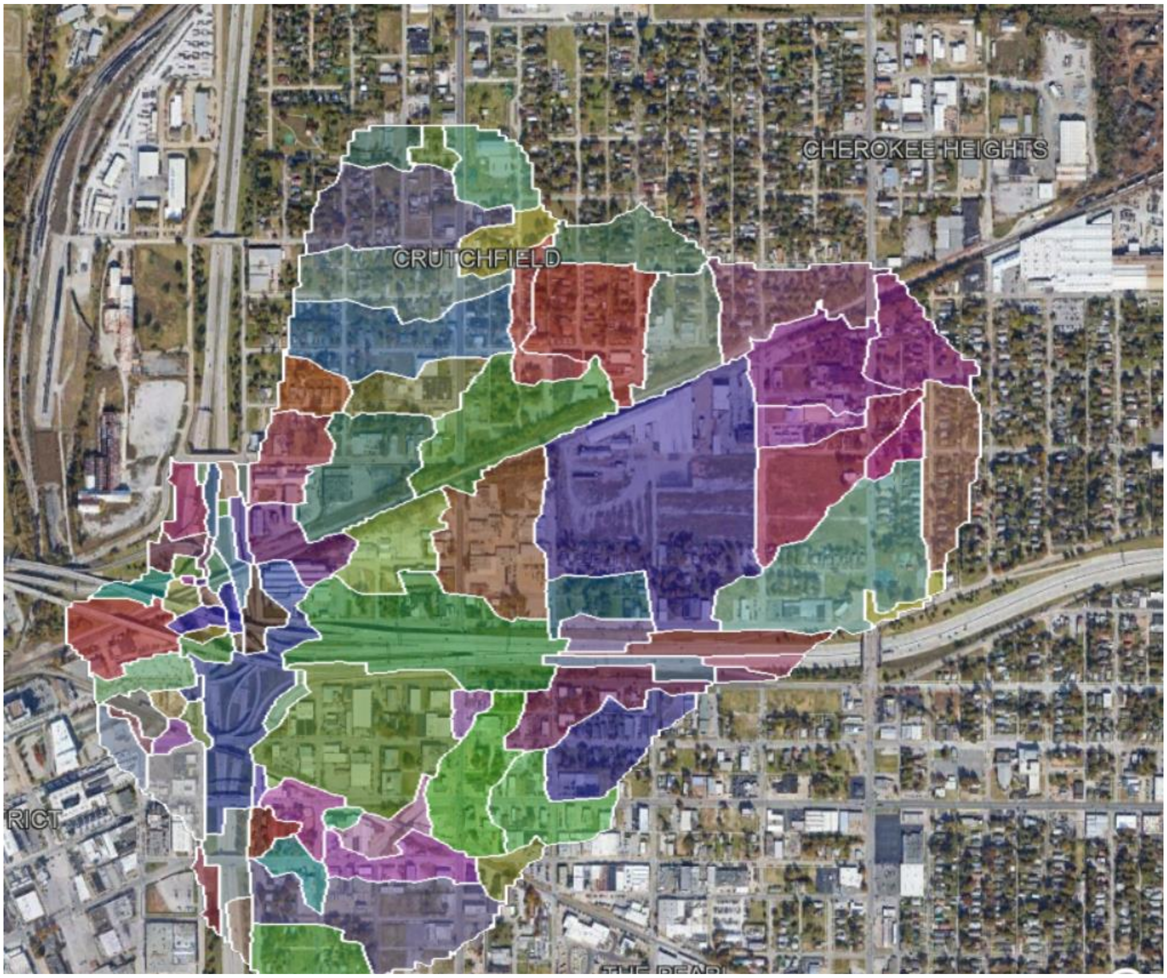


Figure 20. Subwatershed division for Pearl District in Tulsa, Oklahoma (Google Earth, 2021)

3.3.2 Low Impact Development Implementation data – Pearl District

The inputs necessary for SWC modeling are presented in Table 10. An overall land use percentage is also needed as a summary of Table 9 with a total percent impervious of 48% and 52% lawn.

Table 10. Watershed parameters for Pearl District in US EPA Stormwater Calculator. (USDA: United States Department of Agriculture; LID: Low Impact Development)

Parameter	Input	Observation
Runoff Potential	D – High runoff potential	Data from Web Soil Survey (USDA Natural resources conservation service, 2013)
Soil Drainage	0.22 in/hr	Silty clay loam (Tulsa LID Manual 2021)
Topography	Flat (2%)	Based on site's topography SWC map. Measured by surface slope (feet of drop per 100 feet of length)
Time Period	Near term	Years 2020-2049
Years to Analyze	20	
Design storm	3.9 in.	2-year storm for Tulsa (NOAA, 2021)

For Tulsa there was no mandatory budget constraint, it was minimized to $4M in the models, for comparison purposes with Oklahoma City, as they yield similar BMP outputs in the optimization process.

For LID modeling purposes, the potential locations for BMPs were selected based on the 100-year flood maps and flooding locator websites, shown in Figure 21.

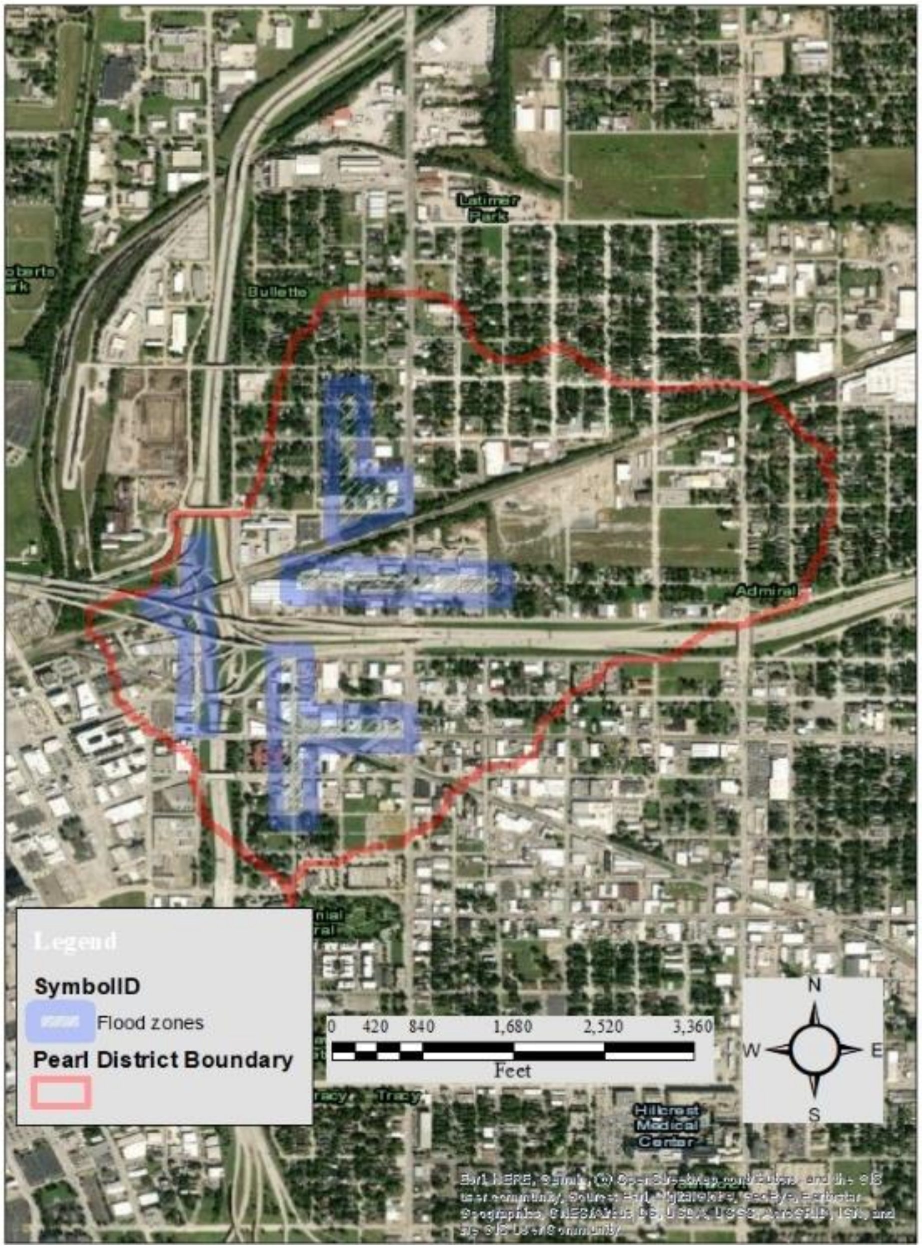


Figure 21. Flood-prone areas for Pearl District in Tulsa, Oklahoma (ESRI, 2021)

3.3.3 Sensitivity Analysis data – Pearl District

For soil types, the infiltration rate of the soil underneath the bioretention cells was changed, comparing silty clay loam, silt loam and sandy loam. For bioretention cell media, the conductivity and porosity values of the soil layer inside the bioretention were changed between sandy, sandy loam and loam, similarly to Sunnymeade. Infiltration rates and porosities used are shown in Table 11. Infiltration data was obtained from the Tulsa LID Manual (2021), porosity and conductivity from USDA (USDA, 2007; USDA, 2008).

Table 11. Soil infiltration and porosity data for Pearl District

Soil/Media type	**Infiltration rate (in/hr)**	
Clay	0.02	
Silty clay	0.14	
Silt loam	0.63	
Sandy loam	1.98	
	Porosity (%)	**Conductivity (in/hr)**
Sand	30	6
Sandy loam	2	5.6
Loam	23.3	3.94

The 1-, 10- and 30-m DEMs from USGS are shown in Figure 22.

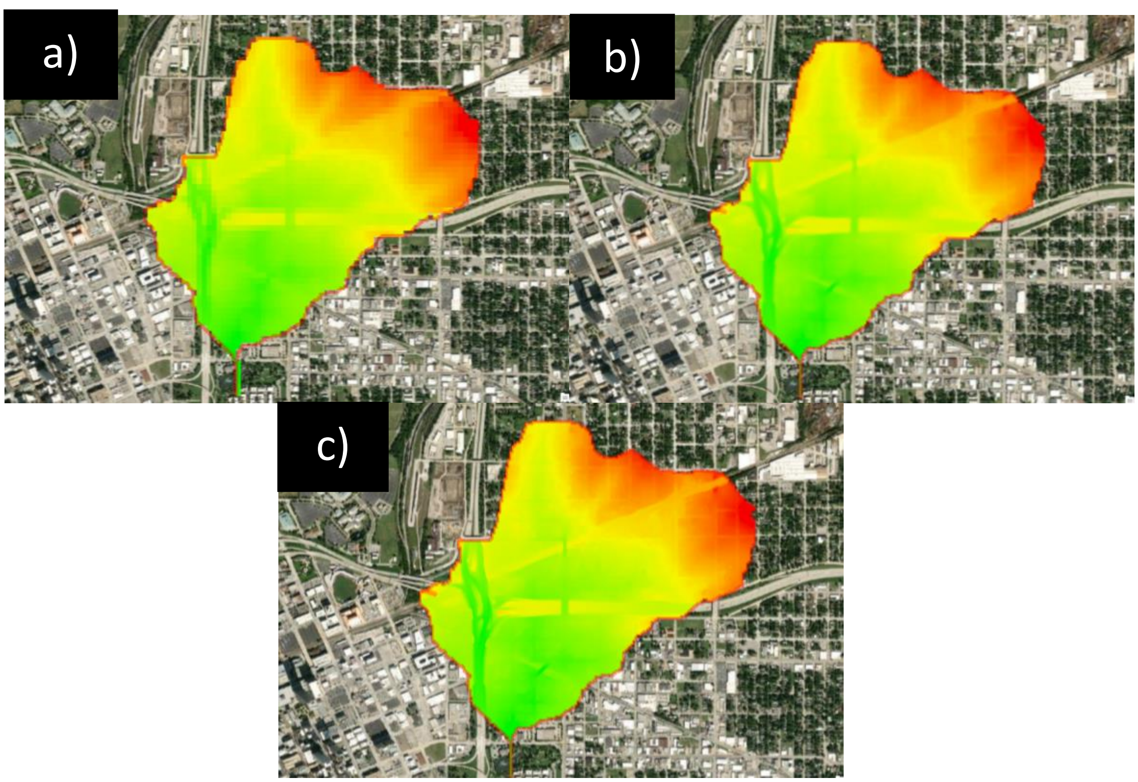


Figure 22. Digital Elevation Models (DEMs) for Pearl District in Tulsa, Oklahoma. A) 30m, b) 10m, c) 1m, where red is the highest elevation and green is the lowest (ESRI, 2021).

Chapter 4: Results and Discussion

Determining the hydrological responses of a watershed is complicated and depends on characteristics such as physical and meteorological (Fan et al., 2020), the former ones include land use, terrain slopes, and drainage systems, the latter one referring to the different storms which take place in a watershed depending on its recurrence interval or return period. The distribution of physical land uses throughout the watershed, as well as the multiple scenarios ran in this study, effect the output of the hydrological modeling, such as peak flow, flow depths, flooded areas and drain times. Therefore, the impact of resolution, soil, bioretention media, underdrain and storm duration is discussed herein. Results from both sites major pipelines and critical areas are shown in this section, complete aerial views, cross sections, tables, and hydrographs are in Appendix E.

4.1 Optimization

Optimization spreadsheet summary results are discussed in this section after this process was performed at each site for prices ranging from $3M to $40M for BMPs that included: rainwater harvesting cistern, bioretention cells (linear and open lot), pervious concrete, pervious pavers, and pervious asphalt. The original optimization spreadsheet (McMaine, 2017) includes more stormwater controls in its list, but they were removed (or added) to meet each site's individual needs, such as available space, costs, and infrastructure. The lowest price limit was set to meet the local initial budget constraint to observe what options for LID practices were most cost-effective. The maximum budget was obtained so that 100% of the impervious area would be treated. Optimization spreadsheets in detail are in Appendix D.

The result summary from the optimization process for the highest capital cost for the Sunnymeade neighborhood in Oklahoma City and Pearl District in Tulsa, is shown in Table 12.

Table 12. Summary of optimization results for Sunnymeade and Pearl District from Microsoft Excel Optimization spreadsheet for the highest capital cost considered ($40,000,000). (BMP: Best Management Practice, TSS: Total Suspended Solids, TN: Total Nitrogen, TP: Total Phosphorus) (McMaine, 2017)

Place	**BMP**		**Percent Reduction**			**$/kg**	**$/gram**	**$/ gram**	**Total capital cost**	**Percent runoff volume reduced**
	1	**2**	**TSS%**	**TN%**	**TP%**	**TSS**	**TN**	**TP**	**$**	**%**
Sunnymeade	Open-lot Bioretention 12% Linear Bioretention 50%	Pervious Concrete Gutter 10.1% Pervious concrete streets 5.9%	100	69	83	15,841	820	5,205	40,000,000	52
Pearl District	Open-lot Bioretention 30% Linear Bioretention 50%	Pervious Concrete Streets 11.1%	100	66	93	18,695	928	5,204	40,000,000	39

The results include the area, BMP output to treat the impervious surfaces, percent reduction and cost per unit reduction for the pollutants TSS, TN and TP and percent reduction of runoff volume, detailed graphs on these results for a range of prices is shown in Figures 23-27. The summary table also includes the total capital cost, with optimization price estimations. These BMP outputs contribute as a planning tool for the modeling process, and they do not accurately reflect the totality of LID design in terms of pricing or pollutant reduction. Its purpose is to be a guide for the most suitable and cost-effective BMP, which for Pearl District was (in order from most to least optimal) open lot bioretention (open-lot BRC) and linear bioretention cells (LBC), the latter refers to bioretention placement mostly in front of houses within the right-of-way. For Sunnymeade, the optimal BMPs were open-lot BRC, pervious concrete gutter (PCG), LBC and pervious concrete streets (PC streets).

These results also show remarkable pollutant reduction in both neighborhoods, given that bioretention has high removal rates, 78% for TSS, 64% for TN and 70% for TP, and since during the optimization it is coupled with permeable pavement, removal rates are increased, these latter removal rates are 72% for TSS and 25% for both TN and TP. These two practices, included in green infrastructures, are being implemented in numerous projects to tackle stormwater management issues (Korgaonkar et al., 2021).

Due to budget constraints for both projects, ease on finding available green space over retrofittable pavement and modelling results, PCGs are considered as a future Phase II, rather than the original baseline models. These coupled models of both stormwater controls could enhance pollution and peak flow reduction, and the neighborhoods landscape.

While aiming to reduce as much runoff volume as possible as one of the main goals of this research, it is important to highlight, the higher potential that exists at Sunnymeade to store the water in the bioretention cells and the permeable concrete gutters to alleviate the storm sewer system. This is not the case in this phase of the project for Pearl District, given the high amount of commercial impervious surface, and significant right of way, this percent reduction only reaches 39% of the volume based only on optimization.

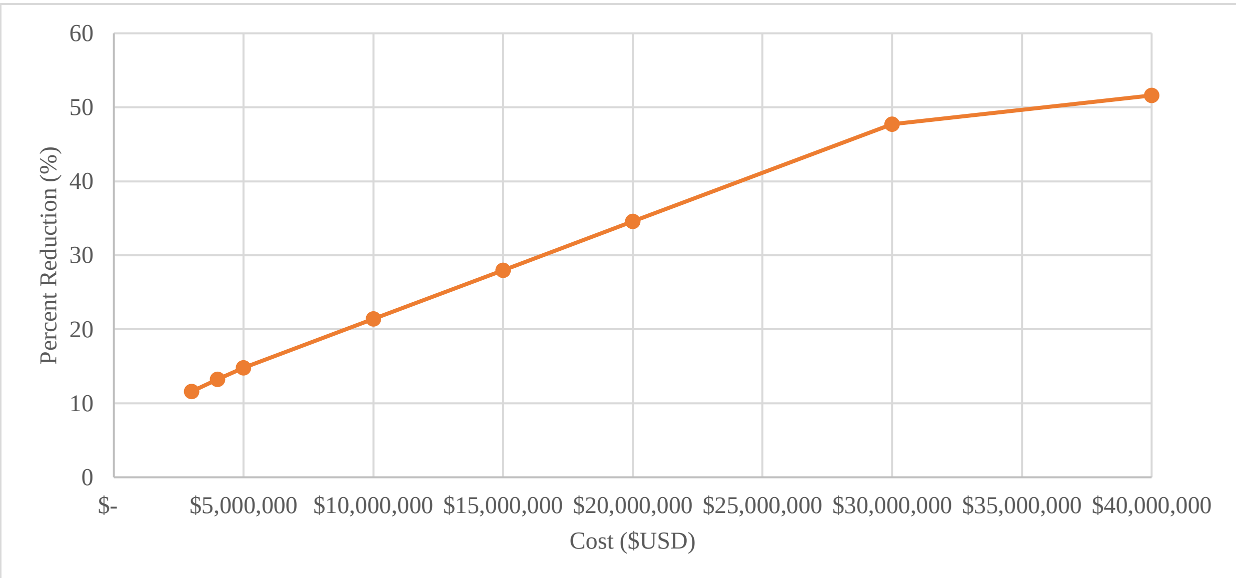


Figure 23. Total runoff reduction percentage from Optimization spreadsheet results for Sunnymeade

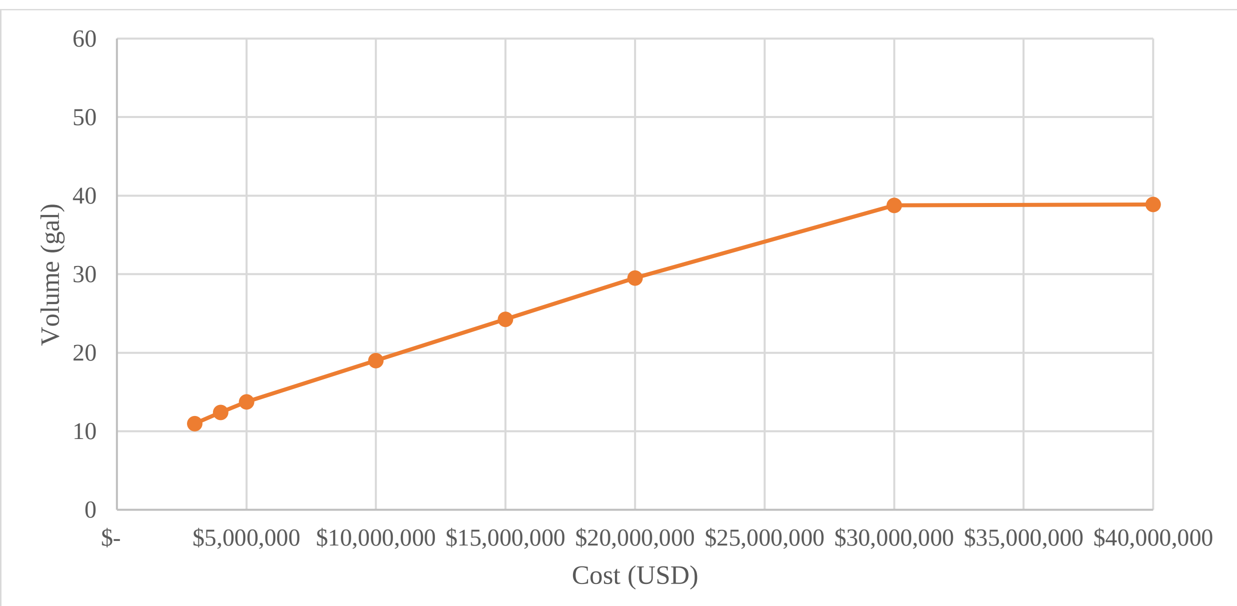


Figure 24. Total runoff reduction percentage from Optimization spreadsheet results for Pearl District

These results illustrate a rectangular hyperbola between the capital cost and percent of volume runoff reduction for both sites. For Pearl District, after $30M, the volume reduction reaches a limit of 40% for the chosen combination of potential stormwater controls and consequently flattens the linear slope of the graph, similarly, after $30M in Sunnymeade, the slope of the relationship between cost and percent reduction changes, this is because the watershed can only receive and treat a maximum amount of precipitation, and even though the total cost increases for a different combination of LID techniques, the amount of impervious area that can be treated has a maximum as well. Optimization also shows that when the maximum budget in Sunnymeade is applied, the pre-development runoff depth is reduced to 77% with LID the maximum possible amount of the impervious area, going from 21.7 in to 4.96 in. For Pearl District this value is reduced by 81% (from 17.5 in to 3.21 in).

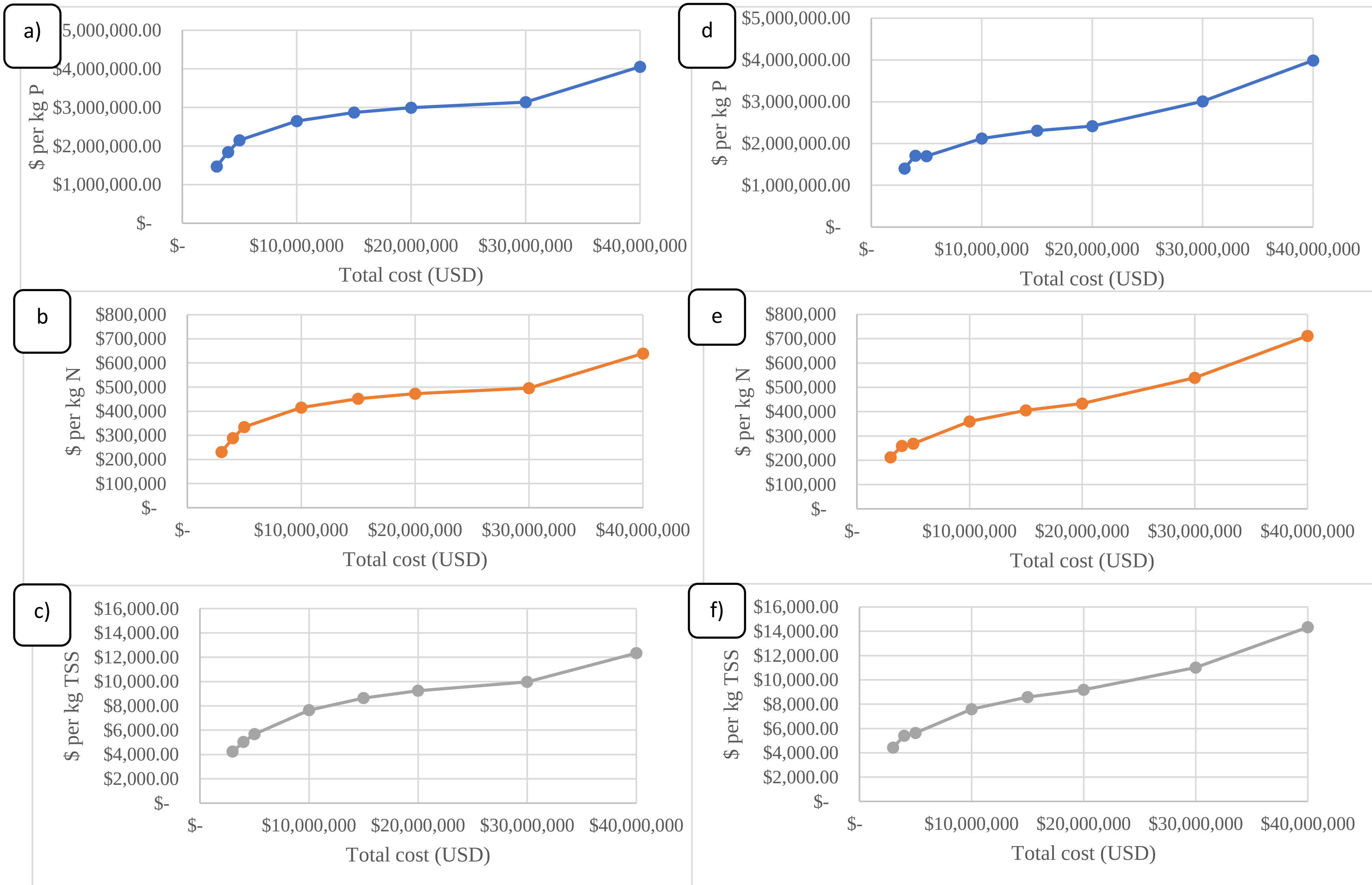


Figure 25. Cost per kilogram of pollutant removed from Optimization spreadsheet results. a-c) Sunnymeade, d-f) Pearl District. (P: Phosphorus, N: Nitrogen, TSS: Total Suspended Solids)

Figure 25 is evidence that even though both sites follow a positive trend, the relationship between price per kilogram of pollutant removed is unique for each of the study areas. In Sunnymeade the cost per kilogram removed of P ranges from $1.4M to $4M, for N it ranges between $230K and $640K, and for TSS between $4K and $12K. For Pearl District prices range between $1.4M and $4M per kilogram of phosphorus removed, between $200K and $700K per kilogram of nitrogen and $4k to $14k for TSS.

To conclude the optimization section, it is observed from Figures 26 and 27 that TSS reduction in Sunnymeade is not only higher than the other two pollutants for this area but is also higher than what is predicted in Pearl District. While combining PCG, which has a TSS removal rate of 72% and BRC with a TSS removal rate of 78%, this pollutant's reduction is significant in the Oklahoma City neighborhood, as opposed to TP and TN which have removal rates of 25% with PCG and 70% and 64% respectively with BRC. This low pollutant removal rate with PCG in this area is the reasoning behind the gap between TSS and the other two pollutants. For the highest cost option, reduction rates are 100% for TSS, 83% for TP and 69% for TN. Since this process was optimized to maximize volume reduction, instead of water quality, removal rates are not as high as they would be if the objective function was changed to maximize nitrogen removal, for which case, BRC would be best. Since Sunnymeade has a considerable impervious area for streets and parking areas (42%), this allows the watershed to be suitable for PCG and pervious concrete streets with the higher cost options, which means there is no need to replace entire streets or parking lots, which would increase costs even further.

For Pearl District, it can be observed that the consistent use of both LBC and BRC plus low percentages of PCG throughout the different capital cost runs, yields similar curves in pollutant reduction for all three pollutants. For the $40M budget option, reduction rates are 100%, 93% and 65% for TSS, TP and TN respectively.

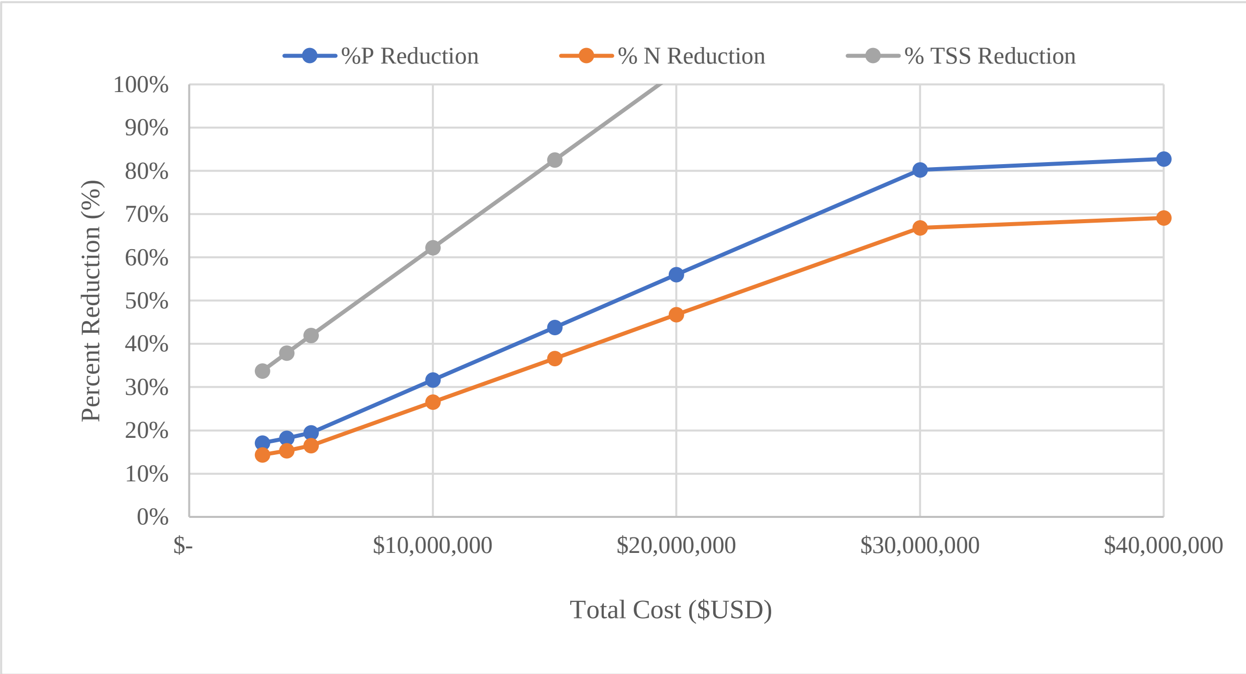


Figure 26. Pollutant percent removal from Optimization spreadsheet results for Sunnymeade (P: Phosphorus, N: Nitrogen, TSS: Total Suspended Solids)

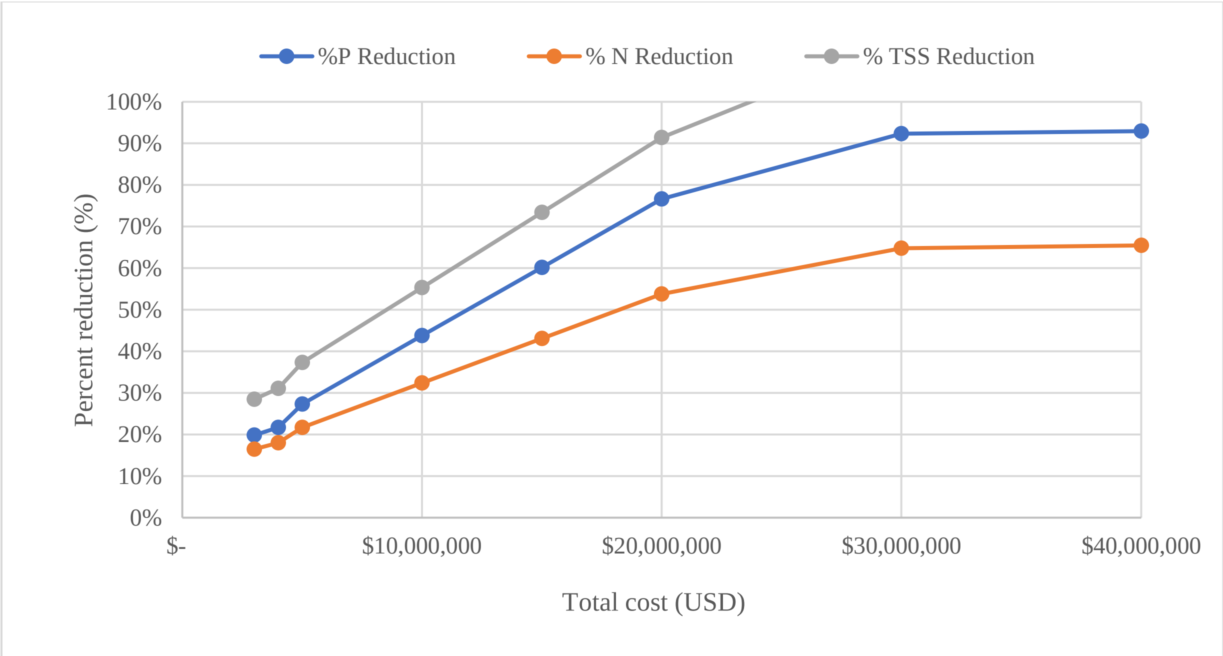


Figure 27. Pollutant percent removal from Optimization spreadsheet results for Pearl District (P: Phosphorus, N: Nitrogen, TSS: Total Suspended Solids)

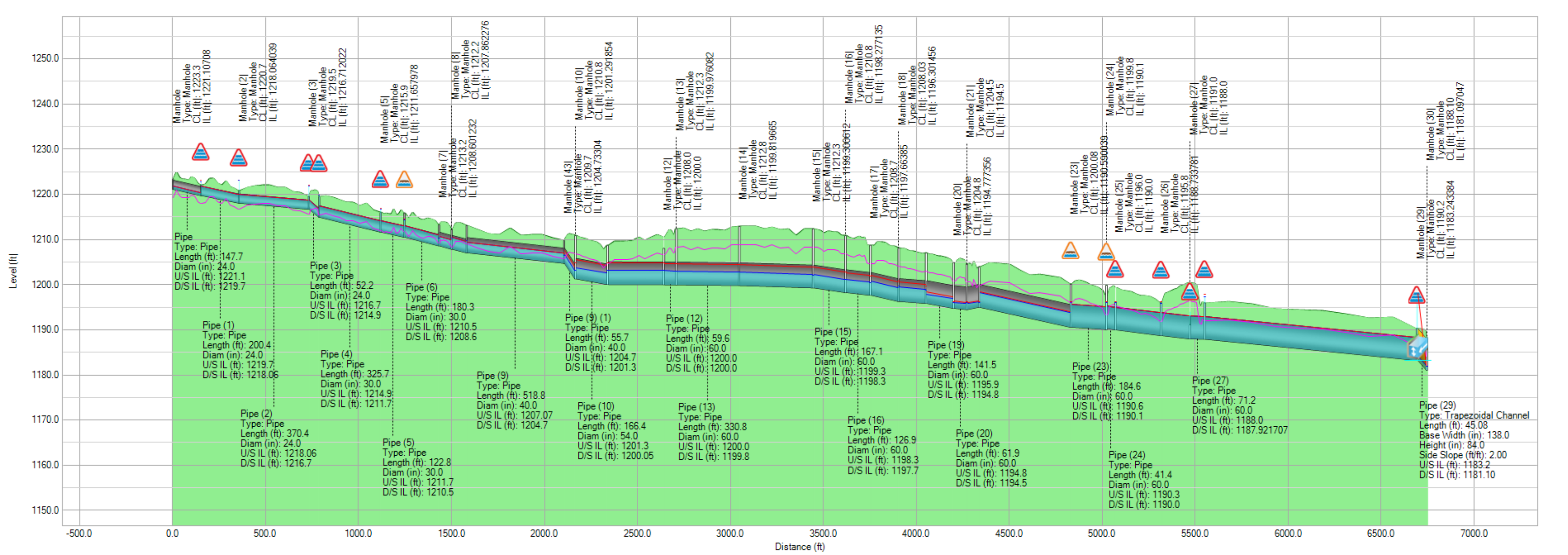
4.2 Runoff modeling

Modeling in the InfoDrainage software was developed based on optimization spreadsheet results and cost estimations. Models for both cities were designed and ran based on the lowest cost options ($4M). Additional modeling for Sunnymeade was done to evaluate different low-cost options which combine two kinds of stormwater controls (BRC and PCG), and a higher cost option of $20M to see the watershed's response to BMP placement on the maximum area possible, i.e. implementing LBC and BRC on as much available green space and PCG suitable areas as possible. This further evaluation of cost comparison was not performed for Pearl District due to lack of flooded areas and suitable areas for BMP installation.

4.2.1 Sunnymeade existing

The modeling for the existing system in Oklahoma City shows widespread flooding at primary concern areas, including the Drakestone and Greystone intersection and Elmhurst and Dorchester intersection, beginning at a 5-year storm event and surcharging the existing storm sewer system. For Sunnymeade and Croydon intersection, modeling shows system surcharging occurring as early as the 10-year event with overland flooding occurring more often after this storm event. A flood map example for the 10-year storm event is observed in Figure 28. In Figure 29, a cross section example of this system's main trunk line is shown, from south to north (Guilford Lane to Sunnymeade Place), to evidence the flooding that occurs in the system. The complete inundation patterns can be observed in flood maps in Appendix E. These results agree with the locations of flooding complaints provided by the city and shown on Figure 16. The upstream area (on the left of this figure) and the downstream (on the right) flood consequently to the areas of the watershed that had most complaints.

Figure 28. Flood map for the 10-year storm event, 1-ft model in the Sunnymeade watershed in Oklahoma City, Oklahoma. Areas in blue are the existing storm sewer system, areas in red represent flooding in the system (Google Earth, 2021; Innovyze, 2021)



Junction	Manhole	Manhole (2)	Manhole (3)	Manhole (5)	Manhole (7)	Manhole (43)	Manhole (12)	Manhole (14)	Manhole (15)	Manhole (17)	Manhole (20)	Manhole (23)	Manhole (26)	Manhole (29)
Type	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole
CL (ft)	1223.3	1220.7	1219.5	1215.9	1213.2	1209.7	1208.0	1212.8	1212.3	1208.7	1204.8	1200.08	1195.8	1190.2
IL (ft)	1221.10708	1218.064039	1216.712022	1211.657978	1208.601232	1204.73304	1200.0	1199.819665	1199.300612	1197.66385	1194.777356	1190.590039	1188.733781	1183.243384

Connection	Pipe	Pipe (2)	Pipe (3)	Pipe (4)	Pipe (5)	Pipe (7)	Pipe (9)	Pipe (9) (1)	Pipe (11)	Pipe (13)	Pipe (14)	Pipe (15)	Pipe (17)	Pipe (19)	Pipe (22)	Pipe (23)	Pipe (25)	Pipe (27)	Pipe (28)	Pipe (29)
Type	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Trapezoidal Channel
Length (ft)	147.7	370.4	52.2	325.7	122.8	61.9	518.8	55.7	295.1	330.8	388.9	167.1	144.1	141.5	485.6	184.6	237.7	71.2	1134.3	45.08
Diam (in)	24.0	24.0	24.0	30.0	30.0	36.0	40.0	40.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	138.0
Height (in)																				84.0
U/S IL (ft)	1221.1	1218.06	1216.7	1214.9	1211.7	1208.6	1207.07	1204.7	1200.05	1200.0	1199.8	1199.3	1197.7	1195.9	1195.003	1190.6	1190.0	1188.0	1187.9	1183.2
D/S IL (ft)	1219.7	1216.7	1214.9	1211.7	1210.5	1207.9	1204.7	1201.3	1200.0	1199.8	1199.3	1198.3	1196.3	1194.8	1190.6	1190.1	1188.7	1187.921707	1183.2	1181.10
SWC																				
Type																				
EL (ft)																				
BL (ft)																				

Figure 29. Elmhurst and Dorchester down to Sunnymeade and Croydon ending at watershed's outlet, Main storm sewer line cross section for the 10-year storm event in the Sunnymeade watershed in Oklahoma City, Oklahoma. Triangular shapes over the landline indicate flood warning (orange) and flooding (red) (Innovyze, 2021)

4.2.2 Pearl District existing

Modeling for the storm sewer system shows flooding in six areas, three of which are in the 100-year flood plain, and where it was expected to happen from Figure 21, and none in other areas of the system, this may be due to the reliability on publicly available data and lack of proper surveying on the storm sewer system for this area of the project, since most of the pipe slopes were automatically calculated by the model, as well as having a standard manhole size throughout the watershed. These flooded areas are spread throughout the basin, north, on East King Street and North Owasso Street, east, near a playground area on East Admiral Place and North Utica Avenue, as well as on East Admiral Place and North Trenton Avenue; south, a couple of blocks away from the proposed pond area by the City of Tulsa on East 3rd Street and South Owasso Avenue, and in the center of the watershed, north of the train tracks and on I-244. Flooding begins on all flood-prone area from the 5-year storm event. The flood map for the 10-year storm event and an example pipeline cross section of one of the areas of concern are shown in Figures 30 and 31 respectively.

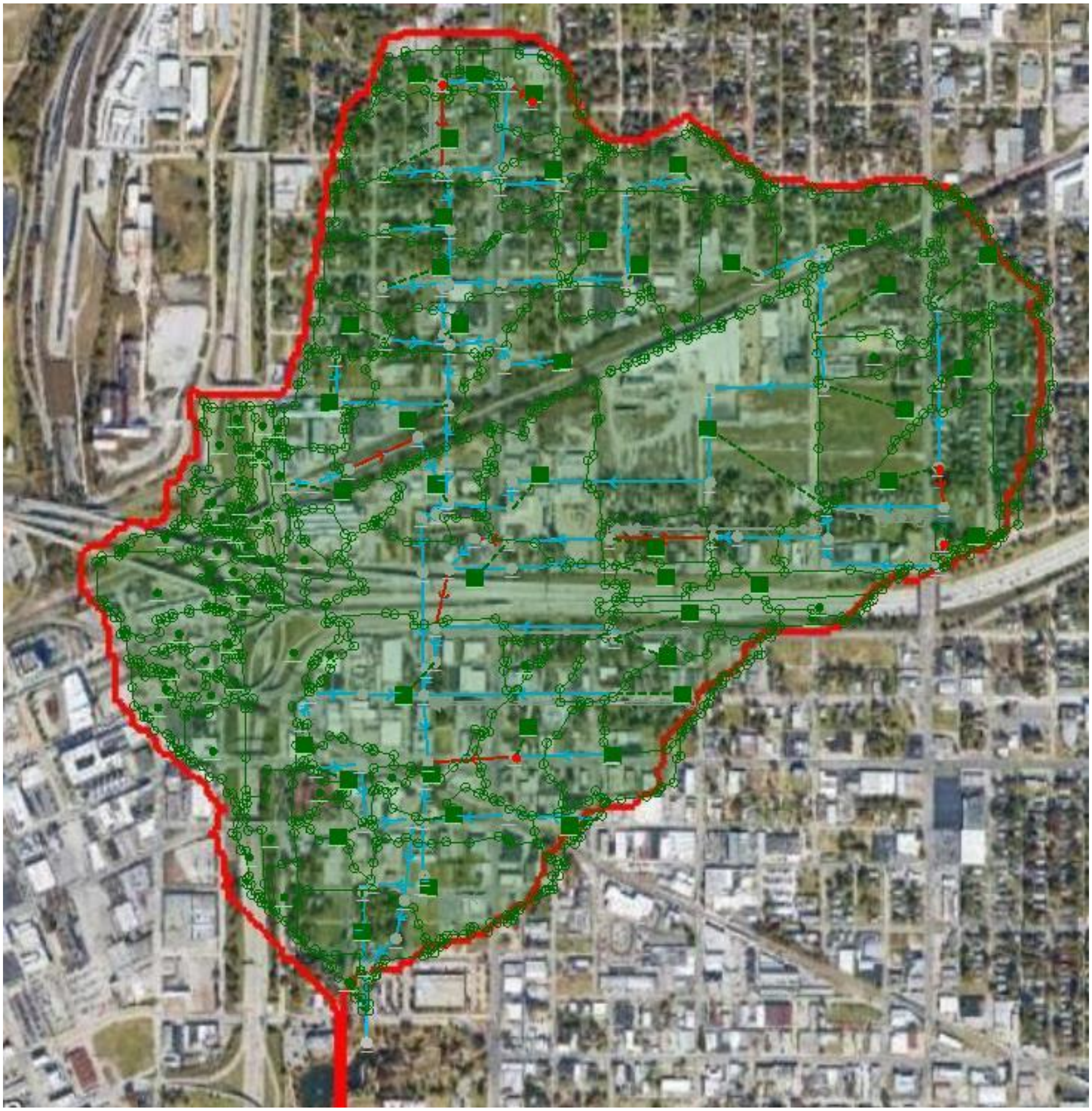
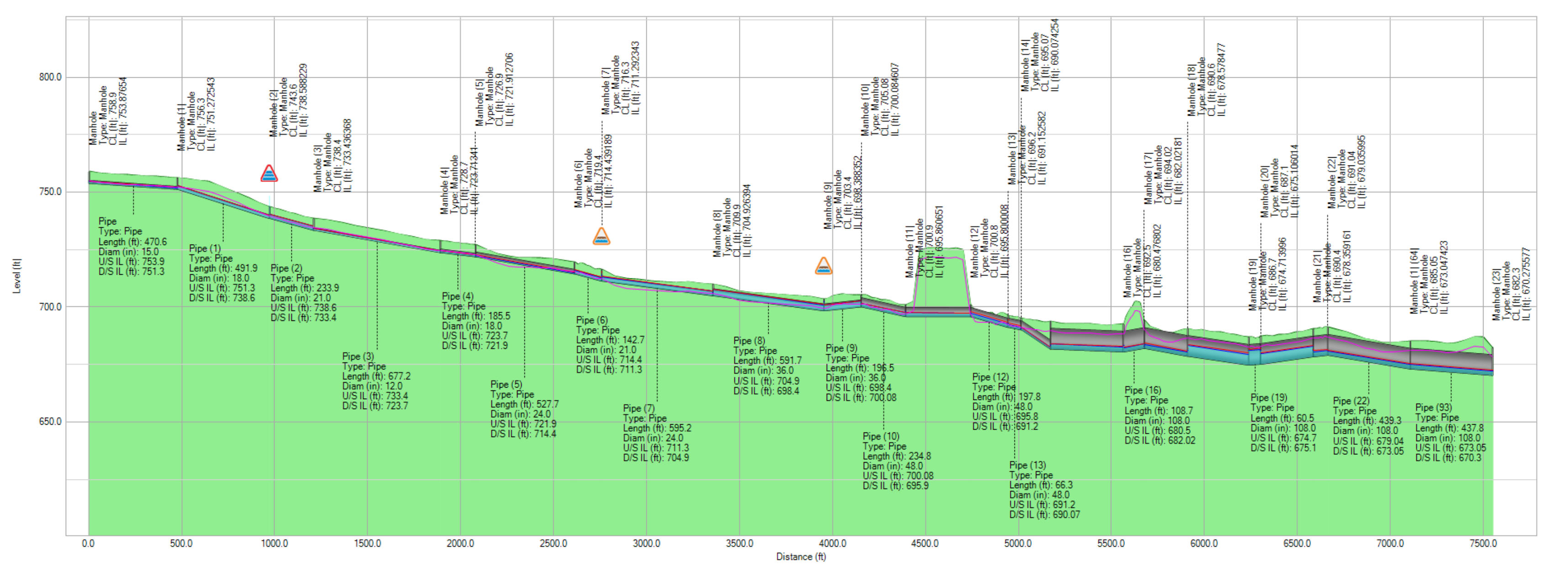


Figure 30. Flood map for the 10-year storm event, 1m model in the Pearl District watershed in Tulsa, Oklahoma. Areas in blue are the existing storm sewer system, areas in red represent flooding in the system (Google Earth, 2021; Innovyze, 2021)



Junction	Manhole (1)	Manhole (2)	Manhole (4)	Manhole (6)	Manhole (8)	Manhole (9)	Manhole (11)	Manhole (12)	Manhole (15)	Manhole (16)	Manhole (18)	Manhole (19)	Manhole (21)	Manhole (1) (64)	Manhole (23)
Type	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole	Manhole
CL (ft)	756.3	743.6	728.7	719.4	709.9	703.4	700.9	700.8	693.7	692.5	690.6	686.7	690.4	685.05	682.3
IL (ft)	751.272543	738.588229	723.71341	714.439189	704.926394	698.388352	695.860651	695.800008	681.737614	680.476802	678.578477	674.713996	678.359161	673.047423	670.275577

Connection	Pipe	Pipe (1)	Pipe (2)	Pipe (3)	Pipe (4)	Pipe (5)	Pipe (6)	Pipe (7)	Pipe (8)	Pipe (9)
Type	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe
Length (ft)	470.6	491.9	233.9	677.2	185.5	527.7	142.7	595.2	591.7	196.5
Diam (in)	15.0	18.0	21.0	12.0	18.0	24.0	21.0	24.0	36.0	36.0
U/S IL (ft)	753.9	751.3	738.6	733.4	723.7	721.9	714.4	711.3	704.9	698.4
D/S IL (ft)	751.3	738.6	733.4	723.7	721.9	714.4	711.3	704.9	698.4	700.08

Connection	Pipe (10)	Pipe (11)	Pipe (12)	Pipe (14)	Pipe (15)	Pipe (16)	Pipe (18)	Pipe (20)	Pipe (22)	Pipe (93)
Type	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe	Pipe
Length (ft)	234.8	345.8	197.8	153.9	388.02	108.7	324.7	278.5	439.3	437.8
Diam (in)	48.0	48.0	48.0	48.0	108.0	108.0	108.0	108.0	108.0	108.0
U/S IL (ft)	700.08	695.9	695.8	690.07	681.7	680.5	678.6	675.1	679.04	673.05
D/S IL (ft)	695.9	695.8	691.2	681.7	680.5	682.02	674.7	678.4	673.05	670.3

SWC	
Type	
EL (ft)	
BL (ft)	

Figure 31. East King Street and North Owasso Street down to East 5th Place and South Owasso Avenue cross section for the 10-year storm event in the Pearl District watershed in Tulsa, Oklahoma. Triangular shapes over the landline indicate flood warning (orange) and flooding (red) (Innovyze, 2021)

Slope is very important in how quickly a drainage channel will convey water, and therefore, it influences the sensitivity of a watershed to precipitation events of various time durations. Watersheds with steep slopes will tend to result in rapid runoff responses to local rainfall excess and consequently higher peak discharges. On the other hand, for a watershed with a flat slope, the response to the same storm will not be as rapid (Elmoustafa, 2012). This tendency and relationship between slopes and peak flow, could have had an influence in the modeling of these watersheds; given the steeper and more accurate slopes of Sunnymeade, this neighborhood floods in more areas for the different storms than Pearl District, where slopes are flatter in potential areas of interest due to the publicly available DEM data and the assumptions that had to be made given the lack of survey data.

4.2.3 LID-based system

Given the results from the optimization spreadsheet, known cost-effectiveness and high storage capacity and pollutant removal rates for bioretention cells, these stormwater control types are modeled for both watersheds to minimize both flow and pollutant concentration from the system (Vogel et al., 2017; PennState Extension, 2019; BMP Database, 2020; Minnesota Pollution Control Agency, 2021). It is important to highlight that the optimization procedure and stormwater modeling, when coupled, imply an iterative process is made between the two. Initial optimization results may suggest stormwater controls that are not able to meet the peak flow reduction goal and therefore when modeled, these preliminary results, yield to optimization adjustments to re-evaluate and maximize the LID stormwater controls that when treating the impervious areas, provide the best results. As previously mentioned, the selected baseline models are based on the $4M version of the optimization results. Additional models including PCG structures are also included for Sunnymeade.

Standard BRC design includes space for ponding at the surface which allows time for stormwater to infiltrate into the pervious media (City of Tulsa, 2021). It is recommended that a bioretention cell is designed for the ponding surface to drain within 24 hours to sustain plant growth and reduce mosquito habitat (Minnesota Pollution Control Agency; City of Tulsa). In situ soils may be used as filter media in the bioretention cell if stormwater infiltrates within 24 hours, otherwise, engineered media can increase the infiltration rate if native soils are not suitable.

Given that the native soils at the site are clay soils with an estimated infiltration rate of 0.02 in/hr for Sunnymeade, an engineered media is needed in the design. For Pearl District, the soil at the top layer is silt loam (infiltration rate of 0.63 in/hr), which is moderate, but multiple infiltration tests would need to be performed to confirm its draining capacity, deeper than at 11 inches or more, soil is silty clay loam (infiltration rate of 0.22 in/hr), which would most likely require engineered media as well to meet the drain time maximum. For the media a 90% washed sand and 10% compost media layer will have an estimated infiltration rate of 6 in/hr (used on the model) based on the bulk density of sand in the mixture (Saxton & Rawls, 2006). The 10% organic matter included in the filter media layer supports turfgrass growth at the surface of the cell.

Below the surface storage and filter media layers, there is usually an aggregate layer of #57 washed stone that serves as a storage for stormwater as it exfiltrates into the surrounding soils. Typically, bioretention cells simply include an underdrain to increase drainage efficiency, but with flood reduction as the focus of this project, a subsurface detention system, such as the Chambermaxx® Stormwater Chamber System (Contech Engineered Solutions, Edmond, OK, 2021), may be introduced additional to the underdrains, to the design for increased storage in Sunnymeade. The device is a 4-ft wide, corrugated, open-bottom plastic infiltration chamber system designed to maximize storage in a bioretention cell before discharging into the surrounding soil. The chamber system design guide indicates that 6 inches of aggregate stone must exist above and below the 2.5 ft tall chamber.

This was integrated into a standard BRC design that includes a minimum of 2-inch choker stone later between the aggregate stone layer and filter media layer to prevent fines from clogging the system. 4 inches of aggregate will be backfilled above the device and 6 inches below the device (Figure 32). Without the chamber system for the Tulsa neighborhood, the cross section for the bioretention cells is shown in Figure 33.

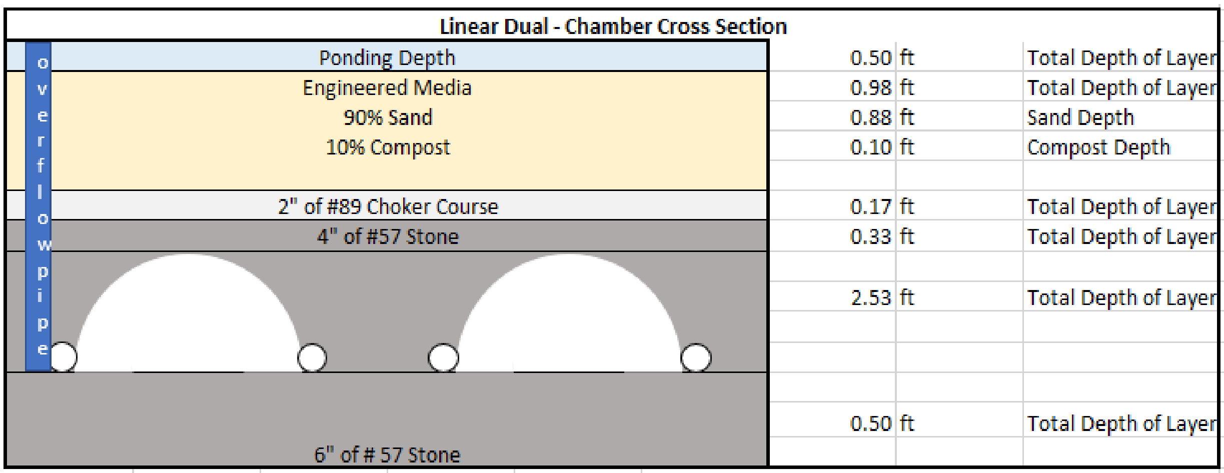


Figure 32. Bioretention cell cross-section with arch chambers and design specs for Sunnymeade

Single Chamber BRC Cross-Section			
Ponding Depth	0.50	ft	Total Depth of Layer
Engineered Media	0.98	ft	Total Depth of Layer
90% Sand	0.88	ft	Sand Depth
10% Compost	0.10	ft	Compost Depth
2" of #89 Choker Course	0.17	ft	Total Depth of Layer
4" of #57 Stone	0.33	ft	Total Depth of Layer
30" of #57 stone	2.53	ft	Total Depth of Layer
6" of # 57 Stone	0.50	ft	Total Depth of Layer

Figure 33. Bioretention cell cross-section and design specs for Pearl District

The combined surface ponding, filter media, choker course, aggregate above and below the standardized arch chamber device and the subsurface storage device itself amounts to a 5 ft depth, this depth remains the same for the Pearl District bioretention cells for storage maximization. These design dimensions meet the recommended drawdown time of 48 hours or less. Additional design components include a nonwoven geotextile barrier to separate the cell from the surrounding soils that filters fines and prevents clogging of the drainage system. For sides of the bioretention cell that are adjacent to roads an impermeable barrier is to be installed to prevent stormwater migration into the road base (Tulsa LID Manual, 2021). Each bioretention cell has a 6 in ponding depth with 4.5 ft of backfilled media and rock. The stormwater holding capacity for each linear foot (10' x 1' x 5') of the bioretention cell is 24.5 ft^3, which includes the ponding depth, chamber space as well as the rock and media pore space. For example, a 100 ft long linear bioretention cell accepting stormwater from a ¼ acre residential lot would have 2445 ft^3 of stormwater storage capacity. The cells are designed with an inlet that would direct ponded stormwater overflow to the subsurface storage chambers via a vertical overflow pipe, and the underdrains connect linear bioretention cells to one another while contributing to drainage efficiency. Each individual chamber has 75.1 ft^3 of storage capacity where water is stored until the water drains into the native soil via the open bottom of the chamber.

Permeable pavement (PP or PCG for this project), infiltrates stormwater while functioning as a structural surface. An aggregate base under the PP serves a reserve for stormwater storage and distributes surface loads to the in-situ soil. The subgrade is not compacted during construction stages to promote exfiltration. Benefits of PP include runoff volume and peak flow rate reductions, water quality improvement, ground water recharge promotion and suitable for retrofitting (Tulsa LID manual).

PCG for Sunnymeade was designed to treat 8% and 10% of the impervious surfaces for the $4M and $20M model respectively. This implied 9781 linear feet of PCG on streets where curb was present and a street of particular interest (N Wellington Avenue) where PCG would be suitable, the width is maxed out at 4 ft for the gutter areas and at 12 ft for the PC street. The infiltration rate of PP is set at the minimum value of 100 in/hr. The PC Street has a stormwater volume capacity of 82268 ft^3 and the PCGs have a combined volume capacity of 15314 ft^3, these calculations are from the permeable pavement design spreadsheet from the Tulsa LID Manual and can be found in Appendix D. Both PC designs have a total depth of 3.3 ft, with a 0.5 ft pervious concrete aggregate layer made with crushed limestone, 2 in of #3 stone for the choker course, 2.5 ft of aggregate storage made with #57 stone and 8 in diameter underdrain. The design cross section is shown in Figure 34.

Single Chamber BRC Cross-Section with ChamberMaxx (x2)			
Permeable pavement	0.50	ft	Total Depth of Layer
2" of #3 Choker Course	0.16	ft	Total Depth of Layer
Aggregate storage	2.50	ft	Total Depth of Layer
	8.00	in	Underdrain
Aggregate storage	0.16	ft	
			Soil

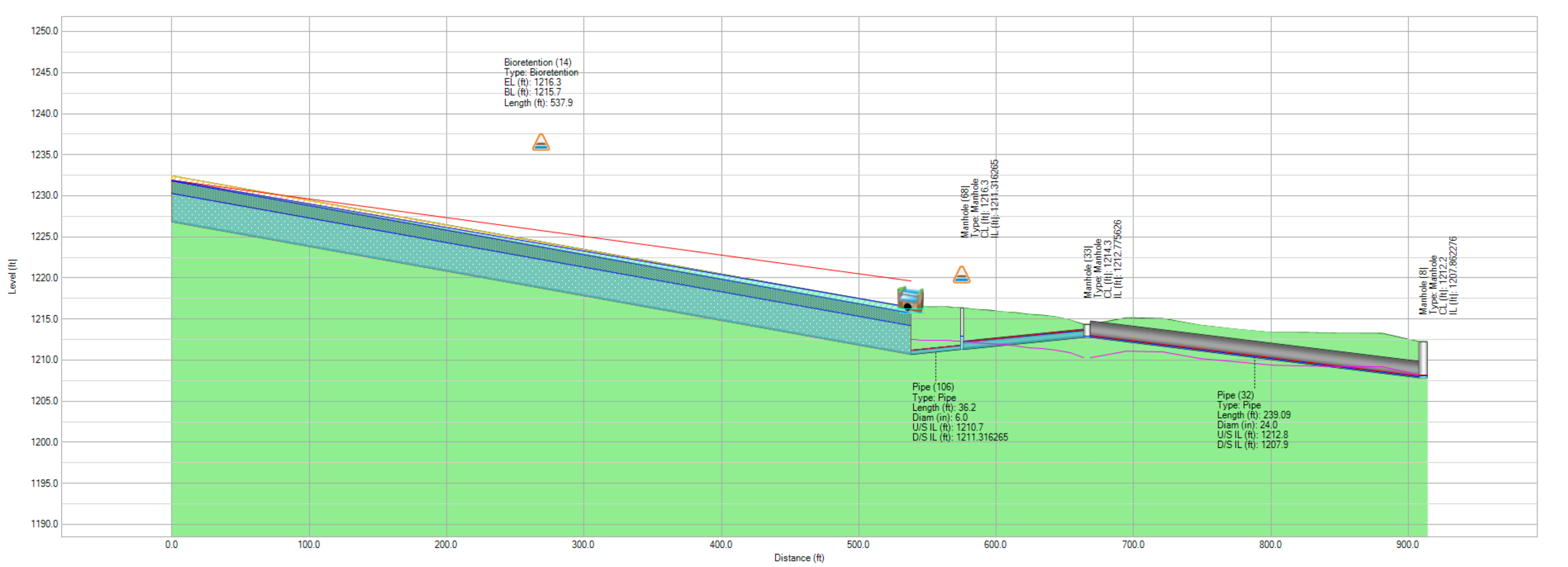
Figure 34. Pervious concrete gutter cross-section and design specs for Sunnymeade

4.2.4 Sunnymeade proposed LID system

For Phase I of this research study, open-lot BRC was selected as the main LID control to be implemented in Sunnymeade, due to the ease of constructing in the neighborhoods right-of-way and to make use of large open lot areas that are available. Phase II of the project included modeling the original optimization results, with 3 model options: open lot BRC and LBC (baseline model), open-lot BRC, PCG and PC street with the $4M budget, and a <$20M model that combines open-lot BRC, LBC, PCG and PC street throughout the entire watershed.

BRCs provide an ideal solution to treat the existing system for Sunnymeade thanks to the available open lots and extended right-of-way areas in front of the neighborhood houses. For Phase I (baseline model), approximately 12,788 feet of existing roadside ditches were identified for double-cell (two arch chambers) LBC placement for runoff storage and slow-release conveyance to the existing stormwater pipe network. Two large areas were identified for a multi-cell open-lot BRC beneath the open lots at the southwest corner of the Sunnymeade and Croydon intersection and below Guilchester Park at Guilford and Dorchester intersection. The proposed open-lot BRC + LBC LID system example for the 10-year storm is shown in Figures 35 and 36 and detailed with different storms in Appendix E.

Figure 35. Proposed LID $4M open-lot bioretention + linear bioretention system in Sunnymeade, Oklahoma City, Oklahoma for 10-year storm event. Areas in blue are the existing storm sewer system, areas in orange are the LID system (Google Earth 2021; Innovyze, 2021)



Junction		Manhole (68)		Manhole (33)		Manhole (8)
Type		Manhole		Manhole		Manhole
CL (ft)		1216.3		1214.3		1212.2
IL (ft)		1211.316265		1212.775626		1207.862276
Connection		Pipe (106)	Pipe (104)		Pipe (32)	
Type		Pipe	Pipe		Pipe	
Length (ft)		36.2	87.5		239.09	
Diam (in)		6.0	12.0		24.0	
U/S IL (ft)		1210.7	1211.3		1212.8	
D/S IL (ft)		1211.316265	1212.775626		1207.9	
SWC	Bioretention (14)					
Type	Bioretention					
EL (ft)	1216.3					
BL (ft)	1210.7					

Figure 36. Proposed $4M open-lot bioretention + linear bioretention system cross-section in Sunnymeade & Croydon intersection in Sunnymeade, Oklahoma City, Oklahoma for 10-year storm event. Triangular shapes over the landline indicate flood warning (orange) (Innovyze, 2021)

With the inclusion of LBCs and the two large open-lot BRCs, a significant reduction in peak flow rate through the existing storm sewer becomes apparent as well as a minimization of surcharged induced flooding. Table 13 shows the results of the proposed system compared with existing. In these tables, flood depth is described by the model as the level of water above the invert level of the junction where flooding is occurring, meaning a manhole is surcharging. A summary Table (14) on the percent flow reduction achieved with the LID system for the different storms is presented. This results though highly variable, evidence that LID, when placed on the right areas with the right space, can accomplish excellent peak flow reduction and greatly reduce flood depths.

Table 13. Runoff System Comparison Table for Areas of Interest – Sunnymeade $4M open-lot bioretention + linear bioretention (EX: Existing system, PR: Proposed LID system, 1-YR: 1-year storm event, 5-YR: 5-year storm event, 10-YR: 10-year storm event, 25-YR: 25-year storm event, 50-YR: 50-year storm event, 100-YR: 100-year storm event)

System Comparison Table - 1 ft model - Clay soil							
Historic Flooding Location		EX 1-YR	PR 1-YR	EX 5-YR	PR 5-YR	EX 10-YR	PR 10-YR
Sunnymeade & Croydon	Peak Flow (cfs)	35.8	26	65.4	51.1	77	59.6
	Flood Depth (ft)	0	0	0	0	0.14	0
Drakestone & Greystone	Peak Flow (cfs)	25.1	24.4	32.3	31.5	33	32.2
	Flood Depth (ft)	0	0	0.45	0	0.92	0.4
Elmhurst & Dorchester	Peak Flow (cfs)	17.5	1.31	21.5	1.36	22.1	1.38
	Flood Depth (ft)	0	0	1.8	0	2.4	0

Historic Flooding Location		EX 25-YR	PR 25-YR	EX 50-YR	PR 50-YR	EX 100-YR	PR 100-YR
Sunnymeade & Croydon	Peak Flow (cfs)	92.6	67.26	105.6	77.7	120.6	88.7
	Flood Depth (ft)	0.43	0.41	0.69	0.67	0.95	0.92
Drakestone & Greystone	Peak Flow (cfs)	37.1	36.5	37.7	37.1	38.7	38.3
	Flood Depth (ft)	1.63	1.2	2.44	1.7	3	1.9
Elmhurst & Dorchester	Peak Flow (cfs)	22.6	1.39	23	1.42	23.1	1.45
	Flood Depth (ft)	3.3	0	4	0	4.8	0

Table 14. Peak flow reduction for areas of interest - Sunnymeade $4M open-lot bioretention + linear bioretention

Location	Peak flow reduction (%)
Sunnymeade & Croydon	22-27
Drakestone & Greystone	1-3
Elmhurst & Dorchester	94-95

Based on model capacity, much of the flooding that occurred on the storm sewer system, no longer occurs in the proposed model due to the LBCs and BRCs receiving the majority of surface runoff through the project area. Retention occurs in the arch chambers within the LBCs and open-lot BRC with controlled release to the existing storm sewer system. Comparison model output of existing and proposed flow through the existing system main trunkline for the different storms is included in Appendix E. With these implementations, particularly near the watersheds outlet, on Sunnymeade and Croydon, peak flow reduction has noteworthy results, decreasing the 100-year storm peak flow down to less than a 25-year storm, yielding a 30% flow reduction, the 50-year storm is decreased to a 10-year, 25-year storm down to a 7-year storm, 10-year storm down to a 4-year and reducing the 5- and 1-year storm events by 22% and 27% respectively. According to these results, the BRC system has a greater impact on bigger storms rather than the smaller ones. On Drakestone & Greystone the flow is not reduced as much as it is on the other areas due to the lack of green space for LBC placement, added to the considerable flooding that occurs in this point of the watershed, further reduction may be achieved if construction was made in the city of Nichols Hills, since its runoff contributes to the surcharged storm sewer system. On the southwest area, in Elmhurst & Dorchester where there is more pervious area, the maximum runoff reduction percentages are obtained, the flow is reduced by 92%, reducing all the storms to less than a 1-year storm.

The reasoning for the large variation between the peak flow reductions may lie in the available space each of the key areas have for bioretention cell placement. For example, Drakestone & Greystone is the most flooded area out of the three, but it does not have much surrounding space for bioretention construction and therefore peak flow is not reduced as much as in the other areas. On the contrary, Elmhurst & Dorchester does not flood as much, but has bigger house lot areas that allow for larger bioretention placement and modeling, which can be observed from Figure 35.

For Phase II of this model, based on optimizations costs and results, the open-lot BRC + LBC model was compared to a $4M optimization alternative model with open lot BRC plus PCGs and PC on N Wellington Ave, and an $18M model with open-lot BRC, LBC, PCG and PC Streets. The best performing combination of stormwater controls for the most downstream point of interest in the watershed was the latter combination of LBC, open-lot BRC and PC (both gutter and streets), though it performs similarly to the $4M baseline model, since there is only a limited amount of water that is introduced into the model and therefore retained. The open-lot BRC, PCG and PC street combination reduced less flow due to the budgetary constraint and the lack of curb in the neighborhood, which did not allow for much placement of this latter BMPs. The total flow reduction differences for each of the three areas of interest are observed in Figures 37-39. For Elmhurst and Dorchester (the most upstream point) there was no area applicable for the open-lot BRC, PCG and PC street model.

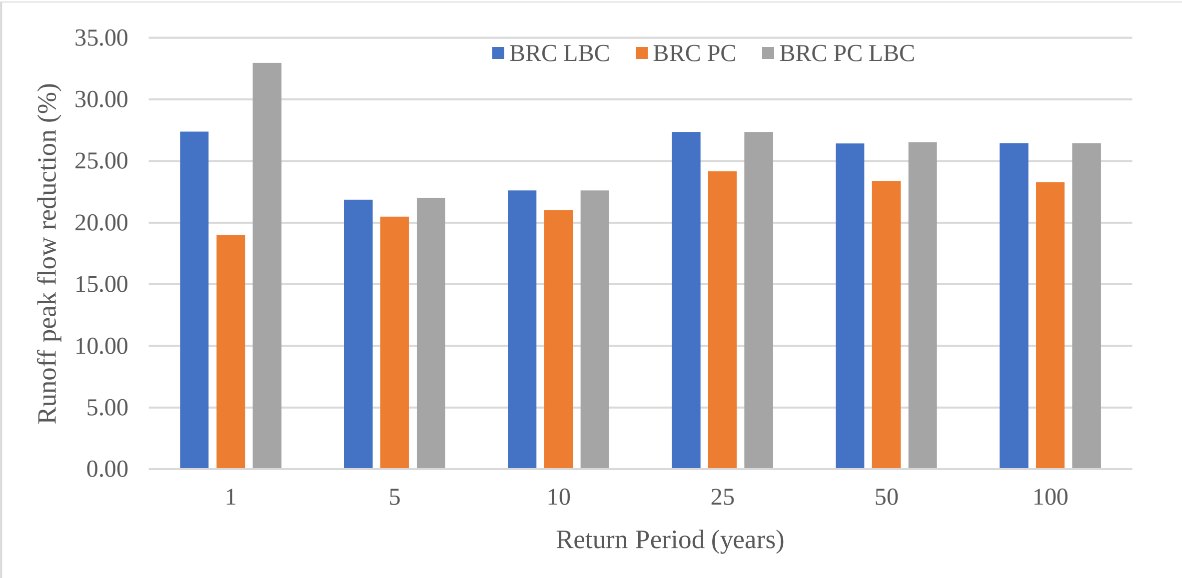


Figure 37. Sunnymeade &Croydon runoff peak flow reduction comparison between the three cost models ($4M baseline, $4M optimization alternative, $18M). (BRC Open-lot BRC, LBC: Linear Bioretention, PC: Permeable concrete)

For Drakestone & Greystone, overall, the $18M combination model, performs best, though the maximum percent flow reduction remains below 3%, as it does in the baseline $4M model, as observed in Figure 35. This better performance is directly related to the fact that the PCGs are in the southeast corner of the watershed, near this flood concern area, and being able to store and infiltrate rain that would otherwise fall directly onto the subcatchments on this area and consequently into the storm sewer system.

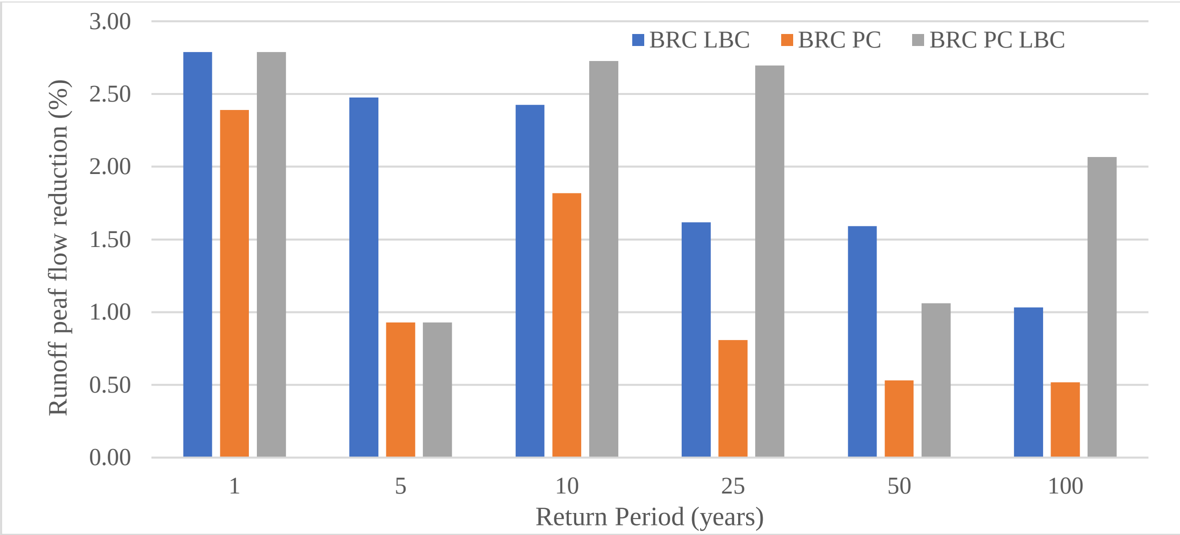


Figure 38. Drakestone & Greystone runoff peak flow reduction comparison between the three cost models ($4M baseline, $4M optimization alternative, $18M). (BRC Open-lot BRC, LBC: Linear Bioretention, PC: Permeable concrete)

For the watershed's upstream area, in Elmhurst & Dorchester (Figure 36), the two available models ($4M baseline open-lot BRC and LBC, and $18M open-lot BRC, LBC and PC) perform the same, given the available area for LBC placement in this area did not change from one model to another.

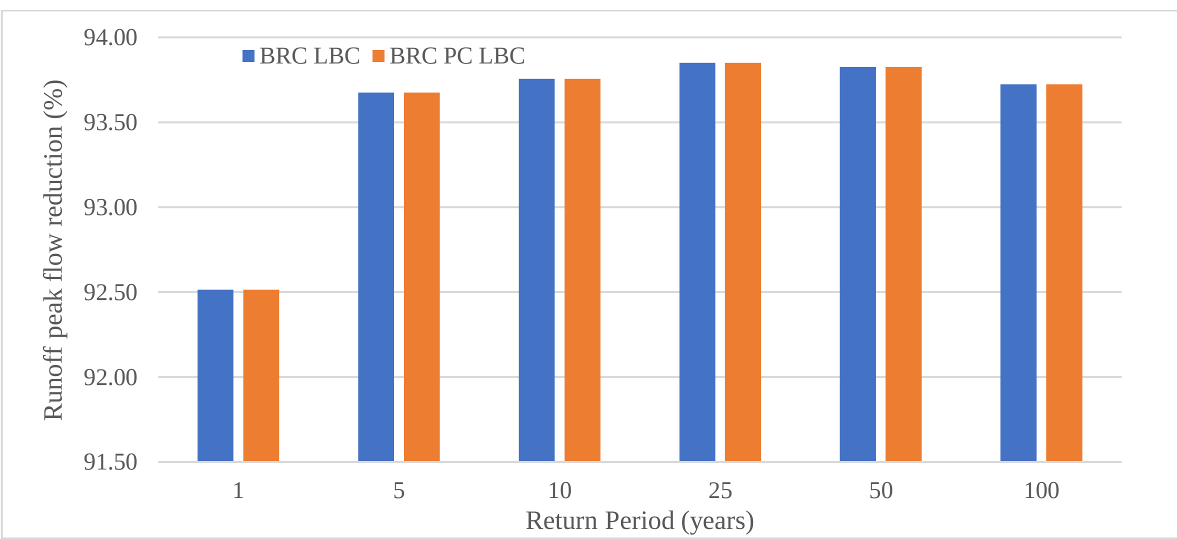


Figure 39. Elmhurst & Dorchester runoff peak flow reduction comparison between the wo cost models ($4M baseline, $18M). (BRC Open-lot BRC, LBC: Linear Bioretention, PC: Permeable concrete)

Figures 40 and 41 evidence the difference between the LID systems and their ability to alleviate the storm sewer system. Comparing with Figure 35 (the baseline $4M model), to the alternative $4M option (open-lot BRC and PCGs), the former one, has a better performance at peak flow reduction, as less flooding is seen in the system when LID is placed, opposed to the four red, or flooded areas seen in Figure 40, where for the 10-year storm, the storm sewer system significantly floods near Elmhurst & Dorchester, and in Greystone and Drakestone. These results are evidence of the iterative process between optimization and modeling, as the optimization's cheapest options did not result in remarkable peak flow reduction. As for the $18M model (Figure 41), the storm sewer system for the 10-year storm event, appears as there is almost no flooding in the system occurring at all, except for a couple of pipes in the Greystone and Drakestone flood complaint area.

Figure 40. Proposed LID $4M open-lot bioretention + pervious concrete gutter and street system in Sunnymeade, Oklahoma City, Oklahoma for a 10-year storm event. Areas in blue are the existing storm sewer system, areas in red represent flooding in the system, areas in orange are the LID system (Google Earth 2021; Innovyze, 2021)

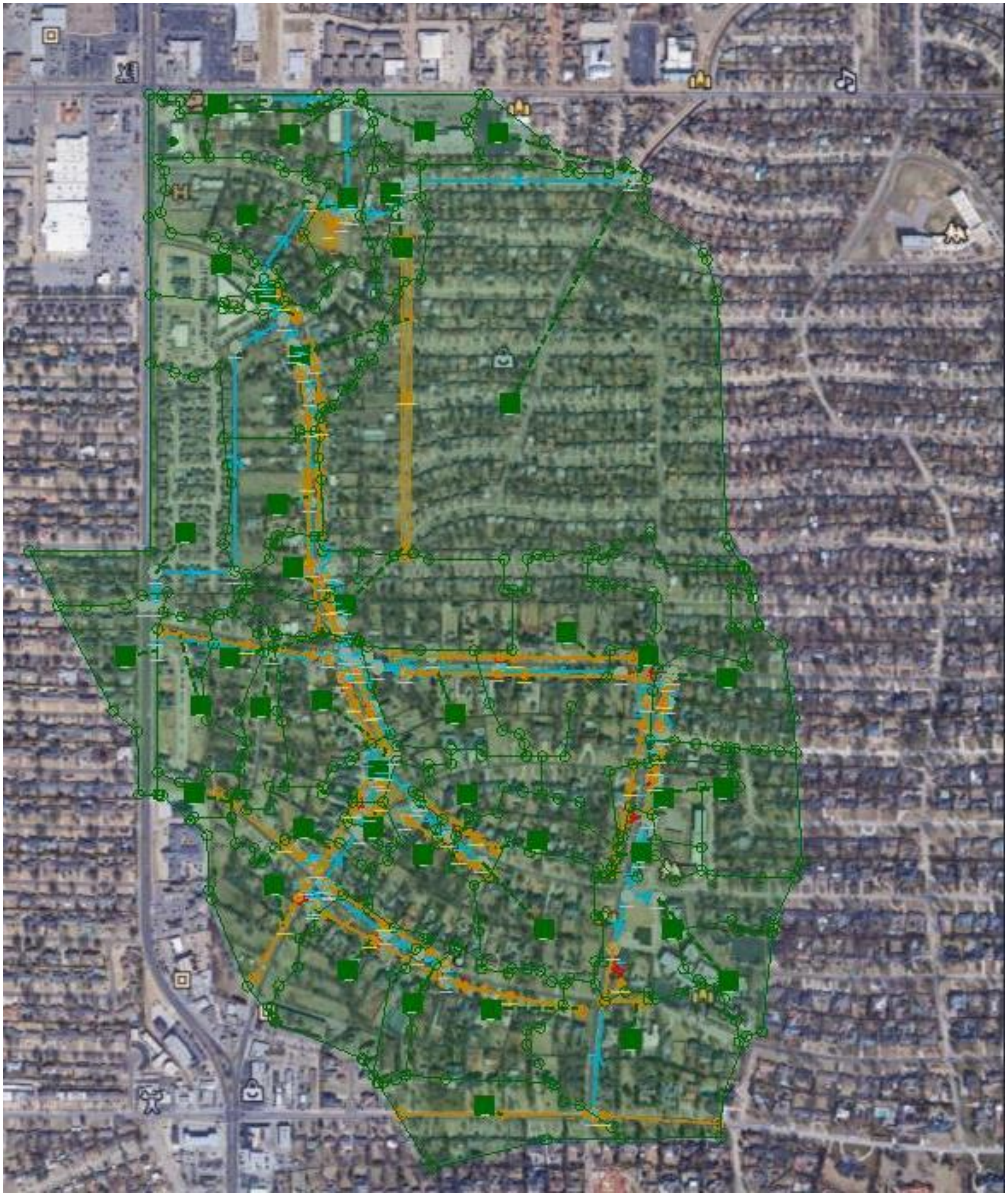


Figure 41. Proposed LID $18M open-lot bioretention + linear bioretention + pervious concrete gutter and street system in Sunnymeade, Oklahoma City, Oklahoma for a 10-year storm event. Areas in blue are the existing storm sewer system, areas in red represent flooding in the system, areas in orange are the LID system (Google Earth 2021; Innovyze, 2021)

4.2.5 Pearl District proposed LID system

Approximately 5,105 feet of existing right-of-way grassy areas were identified for LBC placement plus two open-lot BRC potential areas with areas that add up to 16,982 ft^2. Given the lack of surface pipes on this watershed (as there are on Sunnymeade), the underdrains and connections between cells and back into the storm sewer system would have to be underground and require manned inspection for manhole depth and proper inlet size. Three main areas were identified for LBC, primarily on three of the areas of concern from the existing system: East Independence Street and North Owasso Avenue, East Admiral Place and North Utica Avenue, and East 3rd Street and South Owasso Avenue. There are not many big open lots for large bioretention cells that are not privately owned, therefore the open-lot BRCs of this system were placed along the right of way of big green spaces and some lots owned by the City. The LID system is shown in Figures 42 and 43 for the 10-year storm as well as in Appendix E for multiple storm events.

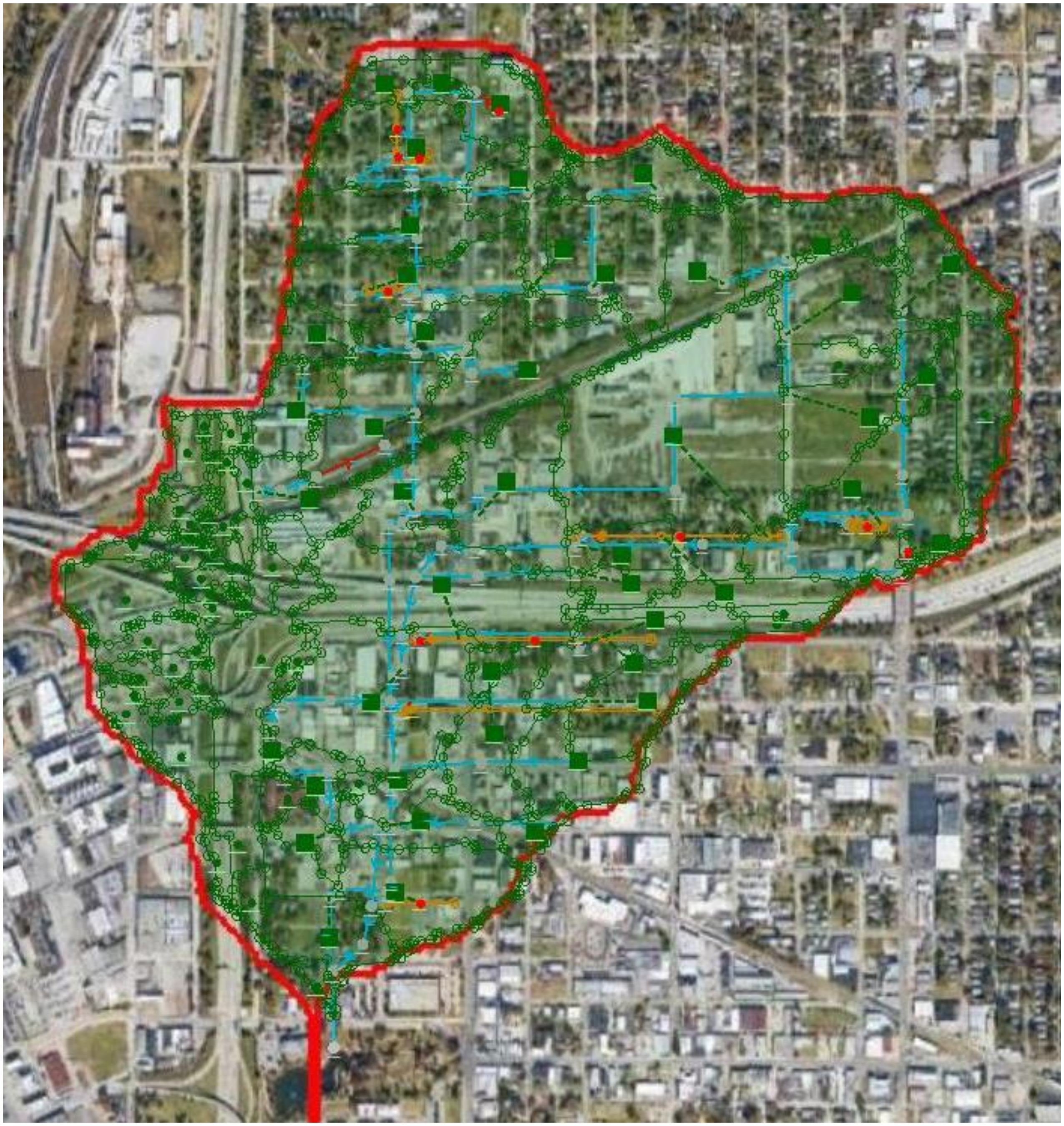
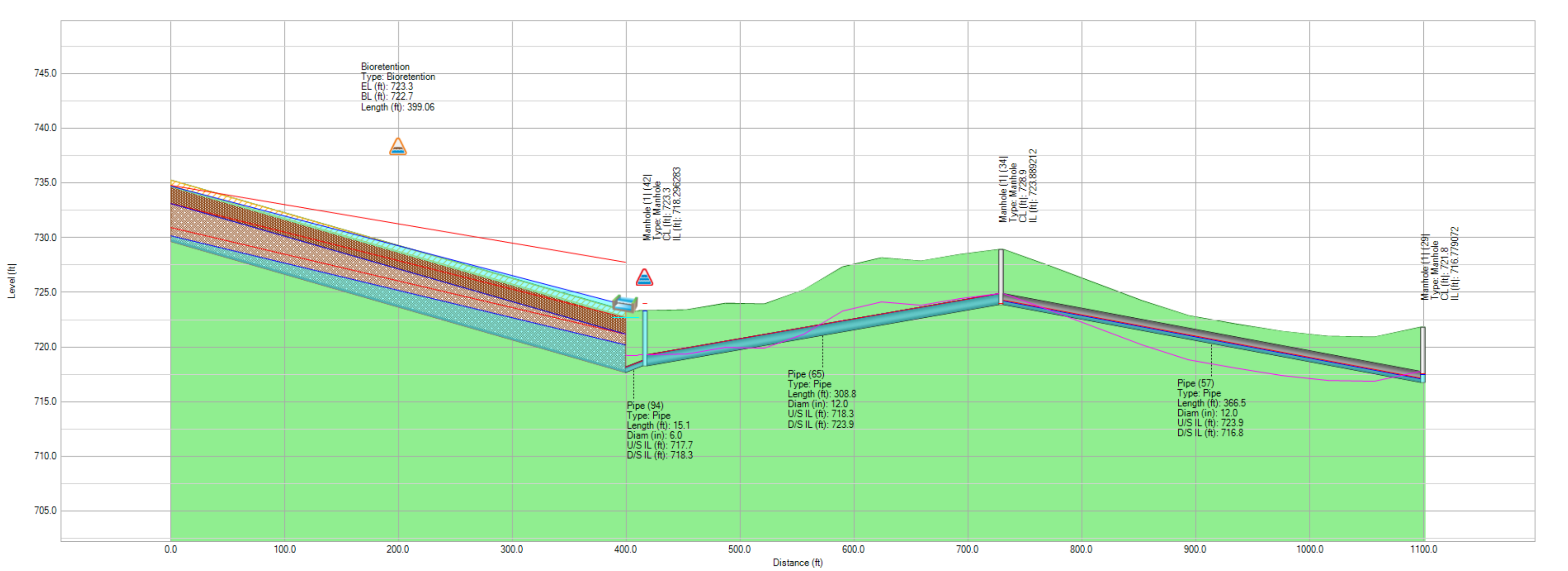


Figure 42. Proposed LID $4M open-lot bioretention + linear bioretention system in Pearl District, Tulsa, Oklahoma for 10-year storm event. Areas in blue are the existing storm sewer system, areas in red represent flooding in the system, areas in orange are the LID system (Google Earth, 2021; Innovyze, 2021)



Junction		Manhole (1) (42)			Manhole (1) (34)		Manhole (1) (29)
Type		Manhole			Manhole		Manhole
CL (ft)		723.3			728.9		721.8
IL (ft)		718.296283			723.889212		716.779072
Connection			Pipe (94)	Pipe (65)		Pipe (57)	
Type			Pipe	Pipe		Pipe	
Length (ft)			15.1	308.8		366.5	
Diam (in)			6.0	12.0		12.0	
U/S IL (ft)			717.7	718.3		723.9	
D/S IL (ft)			718.3	723.9		716.8	
SWC	Bioretention						
Type	Bioretention						
EL (ft)	723.3						
BL (ft)	717.7						

Figure 43. Proposed LID $4M open lot-bioretention cross-section in East King Street and North Owasso Street in Pearl District, Tulsa, Oklahoma for 10-year storm event. Triangular shapes over the landline indicate flood warning (orange) (Innovyze, 2021)

Tables 15 and 16 show the results of the proposed system versus existing, and the summary table for percent of flow reduction. Comparing these results as to those of the pond modeling, there is over-estimation on flood depths of the model, given it reaches exceedance levels as high as 6.72 ft, when the pond model reflects a maximum depth of 2-ft for the 100-year storm. This error or over estimation can be due to the non-exact data that was input for the storm sewer system, and the assumptions that were made to keep the pipes and manholes underground, invert levels or manhole/inlet diameters and widths could have been miscalculated. Nonetheless, the reached levels of peak flow reduction are significant and surpass the optimization's initial estimates.

Table 15. Runoff System Comparison Table for Areas of Interest – Pearl District $4M open-lot bioretention + linear bioretention (EX: Existing system, PR: Proposed LID system, 1-YR: 1-year storm event, 5-YR: 5-year storm event, 10-YR: 10-year storm event, 25-YR: 25-year storm event, 50-YR: 50-year storm event, 100-YR: 100-year storm event)

System Comparison Table - 1m model - Silty Clay Loam soil - 1m							
Historic Flooding Location		EX 1-YR	PR 1-YR	EX 5-YR	PR 5-YR	EX 10-YR	PR 10-YR
E Independence & N Owasso	Peak Flow (cfs)	6.37	1.56	7.8	2.25	7.8	2.25
	Flood Depth (ft)	0	0	0	0	0	0
E Admiral & N Utica	Peak Flow (cfs)	28.61	6.51	33.39	6.95	35.99	6.95
	Flood Depth (ft)	1.95	0	5.7	0	7.9	0
E 3rd and S Norfolk	Peak Flow (cfs)	15.29	3.47	16.63	3.47	17.26	3.47
	Flood Depth (ft)	1.32	0	3.04	0	4	0

Historic Flooding Location		EX 25-YR	PR 25-YR	EX 50-YR	PR 50-YR	EX 100-YR	PR 100-YR
E Independence & N Owasso	Peak Flow (cfs)	7.8	2.25	7.9	2.26	7.95	2.26
	Flood Depth (ft)	0	0	0	0	0	0
E Admiral & N Utica	Peak Flow (cfs)	38.46	6.96	40.35	6.96	42.09	6.97
	Flood Depth (ft)	10.12	0	11.92	0	13.5	0
E 3rd and S Owasso	Peak Flow (cfs)	17.94	3.47	18.48	3.47	19.1	3.47
	Flood Depth (ft)	5	0	5.82	0	6.72	0

Table 16. Peak flow reduction for areas of interest – Pearl District $4M open-lot bioretention + linear bioretention

Location	**Peak flow reduction (%)**
E Independence & N Owasso	71-75
E Admiral & N Utica	77-83
E 3rd and S Owasso	77-81

On East Independence Street and North Owasso Avenue the 1-year storm shows smaller flows than the rest of the storms, which remain consistent, this may be a direct response of the model to smaller storms, resulting in smaller peak flows, whereas from the 5-year storm going forward, the flow on the pipe does not change as the bigger storms don't have a remarkable impact on this upstream area of the watershed.

Given that this watershed does not flood as much compared to Sunnymeade, the LBCs are effective in moving the flooded areas from the storm sewer system to the cells and reducing all the exceeded water levels in the system, it is observed in both figures (39 and 40), and the tables, that peak flow reduction is significantly reduced. Despite the lack of large areas for bioretention cell placement, the linear ones provide a good alternative for stormwater management. With the used available data, peak flow reduction for this neighborhood reduces the all-storm peak flows down to <1-year in all areas of interest in the watershed. It is important to mention that Pearl District modeling, could not include a 45-acre area on the west side of the watershed, over I-244 and I-75 due to lack of connection data for the storm sewer system, which could influence the high peak flow reduction numbers for the model.

4.3 Water quality modeling

The key areas for flow reduction on each of the watersheds were kept as the focus points for water quality evaluation. Therefore, pollutant load was measured in the same pipes and manholes as flow and flood depth were measured at.

4.3.1 Sunnymeade

As observed in Table 17, the total pollutant load increases as the intensity of the storm increase. The reasoning behind the bigger loads for Sunnymeade and Croydon compared to Elmhurst & Dorchester is due to their locations, given the latter one is on the upstream side of the watershed, whereas Sunnymeade and Croydon is almost at the outfall. The pollutant reduction percentage in Drakestone and Greystone is lower, for the same reason peak flow reduction is, there is not as much space for bioretention placement as is in the other two areas. Load reduction is significantly influenced by the location of the junction where it is measured at, and how much its upstream stormwater control can capture.

Table 17. Water Quality Comparison Table for Areas of Interest – Sunnymeade $4M open-lot bioretention + linear bioretention (EX: Existing system, PR: Proposed LID system, 1-YR: 1-year storm event, 5-YR: 5-year storm event, 10-YR: 10-year storm event, 25-YR: 25-year storm event, 50-YR: 50-year storm event, 100-YR: 100-year storm event. TSS: Total Suspended Solids, TN: Total Nitrogen, TP: Total Phosphorus)

Historic Flooding Location		EX 1-YR	PR 1-YR	EX 5-YR	PR 5-YR	EX 10-YR	PR 10-YR
Sunnymeade & Croydon	TSS (lbs)	510.9	402.3	953.7	746.3	1145.4	894.1
	TN (lbs)	16.9	13.3	31.6	24.7	38	29.6
	TP (lbs)	2.2	1.7	4.2	3.2	5	3.8
Drakestone & Greystone	TSS (lbs)	498.7	365.9	879.5	674.9	1037	801.1
	TN (lbs)	15.4	11	27.1	20.2	31.9	24
	TP (lbs)	2.1	1.5	3.9	2.8	4.4	3.4
Elmhurst & Dorchester	TSS (lbs)	209.1	0.1	410.3	0.3	497.2	1.2
	TN (lbs)	7.7	0	15.2	0	18.4	0.1
	TP (lbs)	1.1	0	2.1	0	2.5	0

Historic Flooding Location		EX 25-YR	PR 25-YR	EX 50-YR	PR 50-YR	EX 100-YR	PR 100-YR
Sunnymeade & Croydon	TSS (lbs)	1408.4	1097.5	1624.5	1264.3	1864.8	1450.3
	TN (lbs)	46.7	36.3	53.9	41.8	61.9	47.9
	TP (lbs)	6.2	4.7	7.1	5.4	8.2	6.2
Drakestone & Greystone	TSS (lbs)	1250.6	977.9	1422.4	1122.2	1610.8	1282.1
	TN (lbs)	38.4	29.2	43.7	33.5	49.4	38.3
	TP (lbs)	5.3	4.1	6.1	4.7	6.9	5.4
Elmhurst & Dorchester	TSS (lbs)	617.4	3.2	716.2	2.1	826.3	2.6
	TN (lbs)	22.8	0.2	26.5	0.1	30.6	0.2
	TP (lbs)	3.1	0	3.6	0	4.2	0

Table 18 shows evidence of removal rates throughout the watershed, ranging between 22% and 100% for all pollutants, location depending. Similarly to the peak flow reduction, Elmhurst & Dorchester shows the highest possible pollutant load reduction, whereas on the downstream side of the watershed the percent removal rates are between 21% and 24% for all three pollutants. Full load (lbs) tables are in Appendix D.

Table 18. Pollutant load reduction for areas of interest – Sunnymeade $4M open-lot bioretention + linear bioretention (TSS: Total Suspended Solids, TN: Total Nitrogen, TP: Total Phosphorus, %red: percent reduction)

		Storm return period (years)					
Historic Flooding Location		1	5	10	25	50	100
Sunnymeade & Croydon	TSS (% reduction)	21	22	22	22	22	22
	TN (% reduction)	21	22	22	22	22	23
	TP (% reduction)	23	24	24	24	24	24
Drakestone & Greystone	TSS (% reduction)	27	23	23	22	21	20
	TN (% reduction)	29	25	25	24	23	22
	TP (% reduction)	29	28	23	23	23	22
Elmhurst & Dorchester	TSS (% reduction)	100	100	100	99	100	100
	TN (% reduction)	100	100	99	99	100	99
	TP (% reduction)	100	100	100	100	100	100

For the Phase II modelling results, the three stormwater control combinations yielded different pollutant reduction results for the areas of concern, as observed when comparing table 18-20. For Sunnymeade & Croydon and Elmhurst & Dorchester removal rates are the same for the $4M baseline model and the $18M model, congruently with the peak flow reduction results. For the Sunnymeade area, the removal rates are reduced to a range between 17%-18% for TSS, 17%-10% for TN and 18%-20% for TP for the alternative $4M model, since there is less bioretention in this model, these reductions are reduced. For Drakestone and Greystone the results are between 2%-5% different comparing the $4M baseline model and the $18M one and have a 10%-14% difference for TSS, 12%-17% for TN and 12%-19% for TP between the $4M baseline and the $4M alternative.

Table 19. Pollutant load reduction for areas of interest – Sunnymeade $4M open-lot bioretention + pervious concrete gutter (TSS: Total Suspended Solids, TN: Total Nitrogen, TP: Total Phosphorus)

		Storm return period (years)					
Historic Flooding Location		1	5	10	25	50	100
Sunnymeade & Croydon	TSS (% reduction)	17	17	18	18	18	18
	TN (% reduction)	17	18	18	18	19	19
	TP (% reduction)	18	19	20	19	20	20
Drakestone & Greystone	TSS (% reduction)	13	12	12	11	11	10
	TN (% reduction)	12	12	11	11	11	11
	TP (% reduction)	10	13	9	9	10	10

Table 20. Pollutant load reduction for areas of interest – Sunnymeade $18M open-lot bioretention + linear bioretention + pervious concrete gutter and streets (TSS: Total Suspended Solids, TN: Total Nitrogen, TP: Total Phosphorus)

		Storm return period (years)					
Historic Flooding Location		1	5	10	25	50	100
Sunnymeade & Croydon	TSS (% reduction)	21	22	22	22	22	22
	TN (% reduction)	21	22	22	22	22	23
	TP (% reduction)	23	24	24	24	24	24
Drakestone & Greystone	TSS (% reduction)	25	22	22	21	20	20
	TN (% reduction)	24	22	21	21	21	20
	TP (% reduction)	24	23	20	19	20	19
Elmhurst & Dorchester	TSS (% reduction)	100	100	100	99	100	100
	TN (% reduction)	100	100	99	99	100	99
	TP (% reduction)	100	100	100	100	100	100

4.3.2 Pearl District

Table 21 shows similar results to Sunnymeade in terms of total load accumulation, depending on the location of the area of interest. E 3rd St and S Owasso Avenue is near the outfall of the watershed, as opposed to E Independence & N Owasso Ave. E Admiral Pl & N Utica Ave is on the east side of the watershed, however, it receives flow and pollutants from most of that entire area given how large the subcatchments are on that end.

Table 21. Water Quality Comparison Table for Areas of Interest – Pearl District $4M open-lot bioretention + linear bioretention (EX: Existing system, PR: Proposed LID system, 1-YR: 1-year storm event, 5-YR: 5-year storm event, 10-YR: 10-year storm event, 25-YR: 25-year storm event, 50-YR: 50-year storm event, 100-YR: 100-year storm event. TSS: Total Suspended Solids, TN: Total Nitrogen, TP: Total Phosphorus)

System Comparison Table - 1m model - Silty Clay Loam soil - 1 day- Water Quality 1m								
Historic Flooding Location		EX 1-YR	PR 1-YR	EX 5-YR	PR 5-YR	EX 10-YR	PR 10-YR
E Independence & N Owasso	TSS (lbs)	73	26.3	118.1	42.6	140.4	50.7
	TN (lbs)	3	1	4.9	1.7	5.8	2
	TP (lbs)	0.4	0.1	0.6	0.2	0.7	0.3
E Admiral & N Utica	TSS (lbs)	471.5	72.2	824.2	119.6	1010.8	143.3
	TN (lbs)	19.8	3	34.5	5	42.4	6
	TP (lbs)	2.6	0.4	4.5	0.7	5.5	0.8
E 3rd and S Owasso	TSS (lbs)	365	84.9	609.2	131.8	737.9	156
	TN (lbs)	11.2	2.4	18.7	3.8	22.7	4.5
	TP (lbs)	1.4	0.3	2.3	0.4	2.8	0.5

Historic Flooding Location		EX 25-YR	PR 25-YR	EX 50-YR	PR 50-YR	EX 100-YR	PR 100-YR
E Independence & N Owasso	TSS (lbs)	161.9	58.5	178.7	64.7	197.3	71.4
	TN (lbs)	6.7	2.3	7.4	2.5	8.2	2.8
	TP (lbs)	0.9	0.3	0.9	0.3	1	0.4
E Admiral & N Utica	TSS (lbs)	1197.5	166.5	1346.8	184.6	1514.6	204.7
	TN (lbs)	50.2	7	56.5	7.7	63.5	8.6
	TP (lbs)	6.5	0.9	7.3	1	8.2	1.1
E 3rd and S Owasso	TSS (lbs)	866.3	179.7	968.8	198.3	1083.6	218.8
	TN (lbs)	26.6	5.2	29.8	5.7	33.3	6.3
	TP (lbs)	3.3	0.6	3.7	0.7	4.2	0.7

Table 22 shows evidence of removal rates behaving differently throughout the watershed, between 64% and 80% for TSS, 66% and 85% for TN and 60% and 87% for TP. The highest removal rates are achieved on the upstream of the watershed in E Admiral Pl and N Utica Ave, where one open-lot BRC is installed. The downstream area of the watershed on E 3rd St and S

Owasso Ave, shows high removal rates as well, considering it has a high pollutant load for its location, which is a cause of multiple LBCs placed on near multiple parts of the storm sewer system in this area. Full load (lbs) tables are in Appendix D.

Table 22. Pollutant load reduction for areas of interest – Pearl District $4M open-lot bioretention + linear bioretention (TSS: Total Suspended Solids, TN: Total Nitrogen, TP: Total Phosphorus)

		Storm return period (years)					
Historic Flooding Location		1	5	10	25	50	100
E Independence & N Owasso	TSS (% reduction)	64	64	64	64	64	64
	TN (% reduction)	67	65	66	66	66	66
	TP (% reduction)	75	67	57	67	67	60
E Admiral & N Utica	TSS (% reduction)	85	85	86	86	86	86
	TN (% reduction)	85	86	86	86	86	86
	TP (% reduction)	85	84	85	86	86	87
E 3rd and S Owasso	TSS (% reduction)	77	78	79	79	80	80
	TN (% reduction)	79	80	80	80	81	81
	TP (% reduction)	79	83	82	82	81	83

4.4 Sensitivity analysis

Results showing the different alternatives to the baseline models ($4M) are presented in this section. The variation in topographic resolution provides the most variable results for both watersheds, in the existing and proposed LID systems. The result variation when changing smaller, more detailed parameters, such as soil infiltration, underdrains, and amendment variation for bioretention, are also smaller in terms of not affecting the overall flow values of the storm sewer system, or the conditions of flooding at which the baseline model is at. Therefore, no new flood areas are found, nor flooded areas are taken off, which is the contrary case for the DEM evaluation.

4.4.1 DEM resolution

The InfoDrainage outputs showed that resolution variability of the DEM can affect the amount of basin runoff, as is also seen in other studies (Fan et al., 2020), where increasing the DEM size, decreases the mean slope of the watershed, as is the case for multiple areas of interest on both watersheds. Qualitatively, there is generally more flooded areas on the coarser resolutions than the finer ones.

4.4.1.1 Sunnymeade

For this watershed, the main outlier is the 30 m DEM, although the differences do not differ by large percentages quantitatively speaking. It has been researched that flat areas, such as Oklahoma for some processes perform well under grid resolutions of 25 m, whereas more mountainous regions, will most likely require as high a resolution as it can get (Vaze et al., 2010). Results between the 30 m and the other resolutions vary by a maximum of 23% and as low as 2%, as shown in Figures 44-47, which is acceptable considering the difference in running time of the model. The 10-m data also performed well, with a range of 1-10% of difference to the 1-ft model. The differences between the 1-m model and the 1-ft range between 0.03% and 6%. The finest resolution of 1-ft, though most accurate, has the highest computational cost, takes the longest and is slower when working with it, given it has so many data points. These results mean a disadvantage to this high-resolution DEM, considering that similar results were obtained with the 1-m DEM, the survey 1-ft data could be eliminated for future studies from a cost-benefit stand point, given it not only costs money, but time and computer capabilities.

Referring to this former statement, having a detailed 1-ft model, not only topographically but also in terms of the storm sewer system survey, allowed this watershed to be as close to reality as it could, whereas major adjustments had to be manually done to the 10 m and 30 m models.

In Figures 44 and 45, the existing system flow values are graphed for Sunnymeade and Croydon and Drakestone and Greystone. For Sunnymeade, the 1-ft, 1-m and 10-m perform similarly, meaning a cost-effective solution and likely potential for these resolutions to be used in future designs shall survey options not be available. Model errors exist, which could be the reasoning behind the 30-meter model not always being the one with the lowest flows. The watershed presents variability in terms of resolution results, but overall, the 1-m DEM performs almost as good as the 1-ft model.

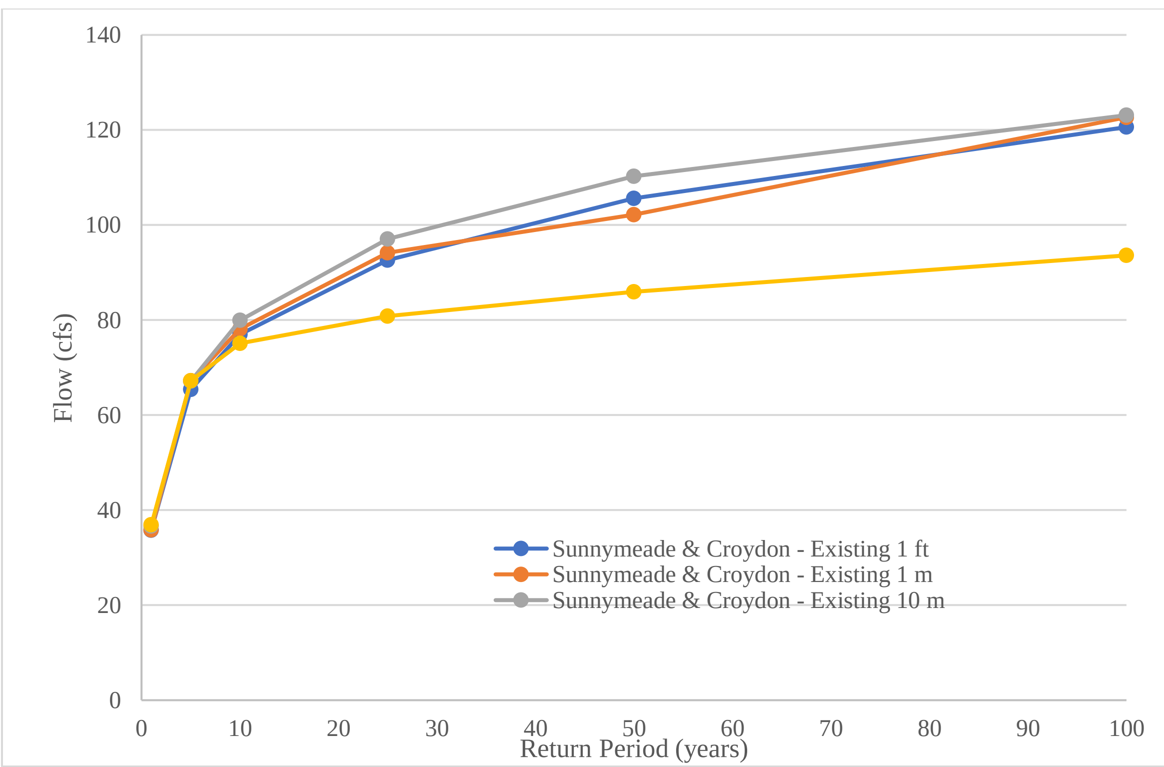


Figure 44. Sunnymeade and Croydon existing system flow data comparison for DEM resolutions

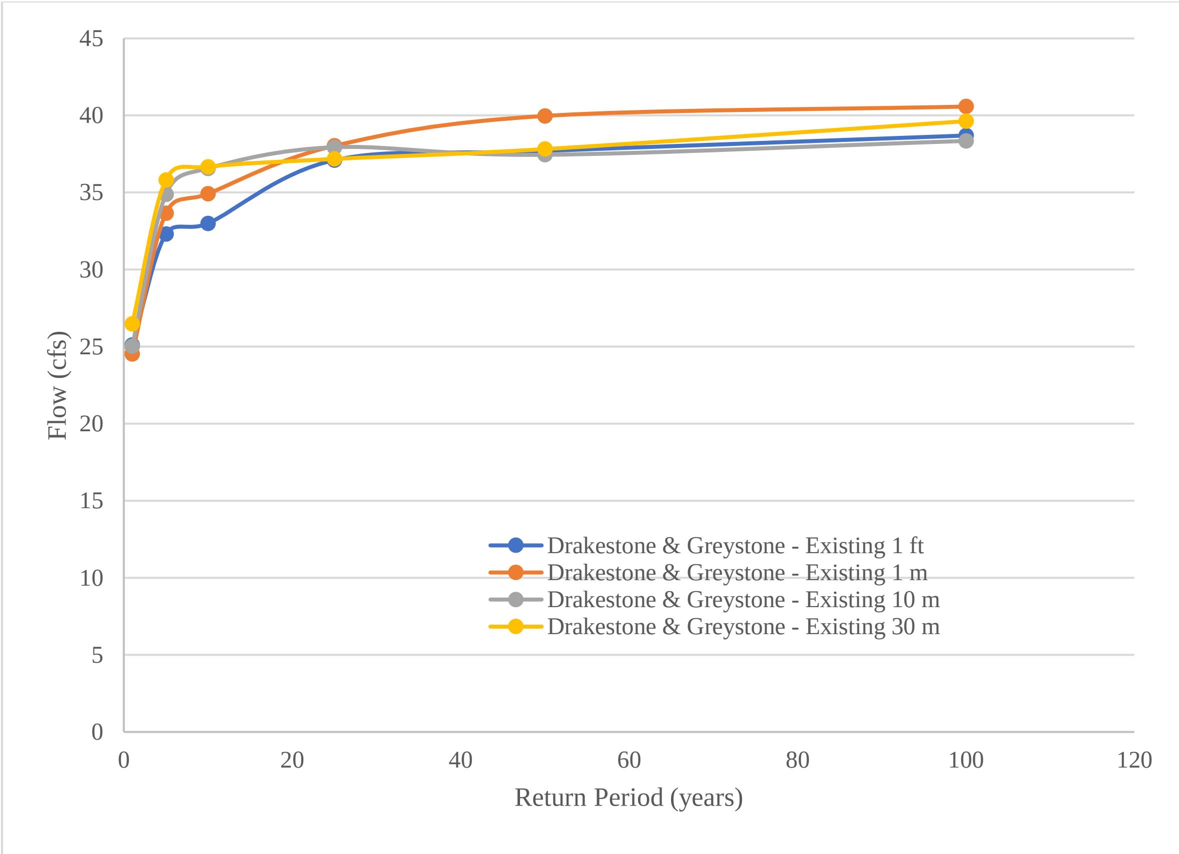


Figure 45. Drakestone & Greystone Croydon existing system flow data comparison for DEM resolutions

Figures 46 and 47 display the small differences between the resolutions in the LID models; with the slightly reduced flow in these areas, the percent difference is also smaller between the resolutions and maxes out at 10%.

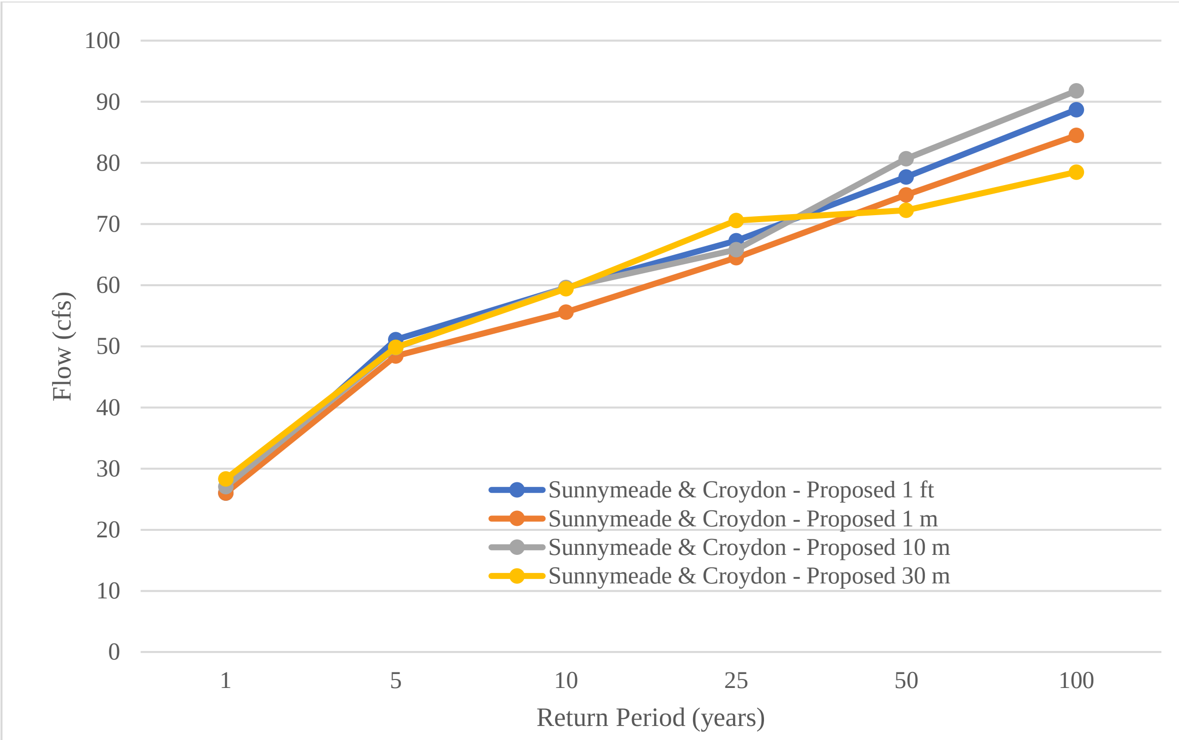


Figure 46. Sunnymeade and Croydon proposed $4M open-lot bioretention + linear bioretention LID system flow data for DEM resolutions

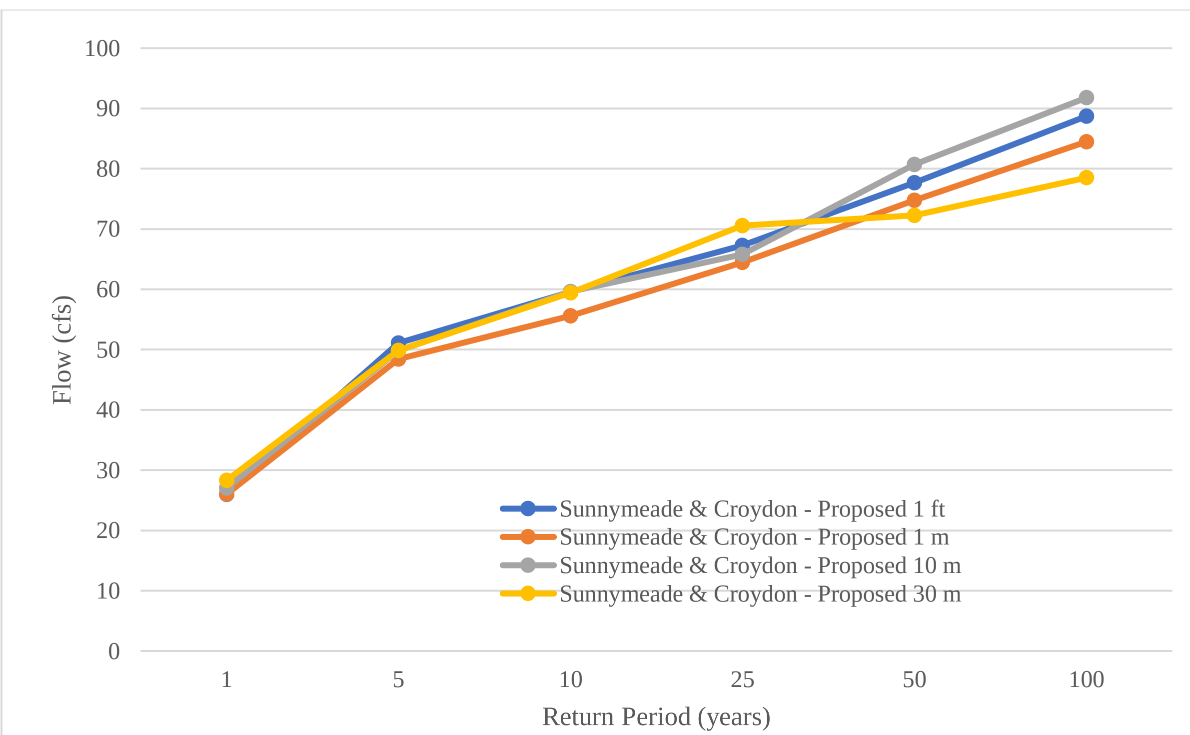


Figure 47. Drakestone & Greystone Croydon proposed $4M open-lot bioretention + linear bioretention LID system flow data comparison for DEM resolutions

Results details on water quality variations between the resolutions are in Appendix E, but the difference between models did not surpass 2%, meaning that terrain and slope data has little to no effect on total pollutant loads for this watershed.

More qualitative results are observed in Figure 48, where the 30-m model alerts of more flooded areas than the rest of the models, notably, against the 1-ft model. Previous studies have shown that slope and pixel elevation changes, can influence the formation and directions of reaches (Fan et al., 2020), affecting the flow path and consequently model output.

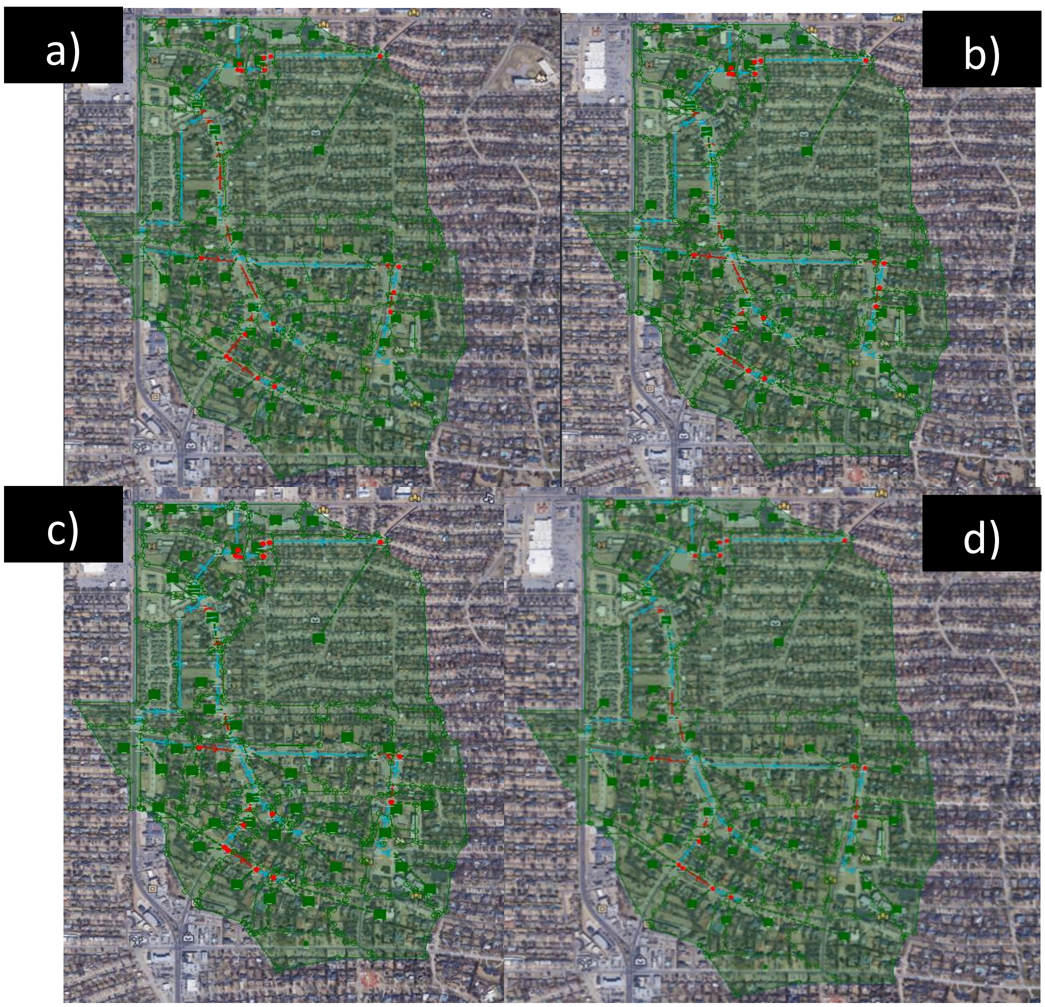


Figure 48. 10-year storm existing Sunnymeade for DEM resolutions in Oklahoma City, Oklahoma. A) 30m, b) 10m, c) 1m, d) 1ft. Areas in blue are the existing storm sewer system, areas in red represent flooding in the system (Google Earth, 2021; Innovyze, 2021)

4.4.1.2 Pearl District

In agreement to previous studies (Nazari-Sharabian et al., 2019; Al-Khafaji & Saeed, 2019; Fan et al., 2020) runoff depth and flow are decreased as the DEM cell size increased. Which occurs because when the DEM increases, the mean slope of the area is decreased, in turn, decreasing the amount of water velocity and runoff. The 10-m and 30-m models perform almost the exact same for these 2 points of interest and 4 moments of the storm (Figures 49-52), though yielding results no larger than a 3% difference with the 1-m model.

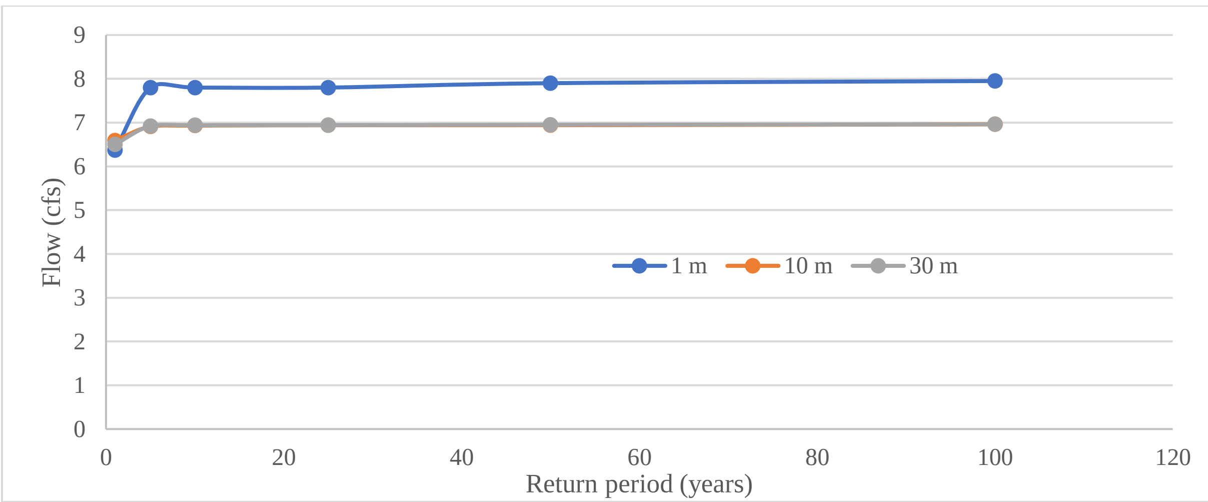


Figure 49. E Independence St & N Owasso Ave existing system flow data comparison for DEM resolutions

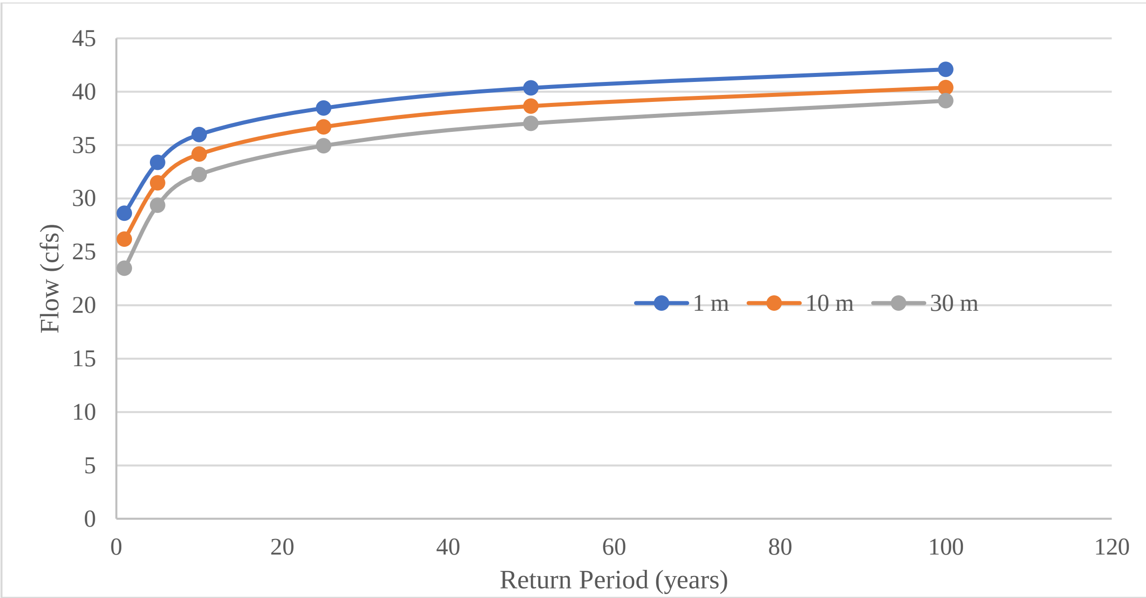


Figure 50. E Admiral Pl & N Utica Ave existing system flow data comparison for DEM resolutions

The LID system shows a difference of less than 1% between the models, with the 30-m as the fastest but most different one, whereas on the existing system, the differences were bigger, even though they did not surpass 8%.

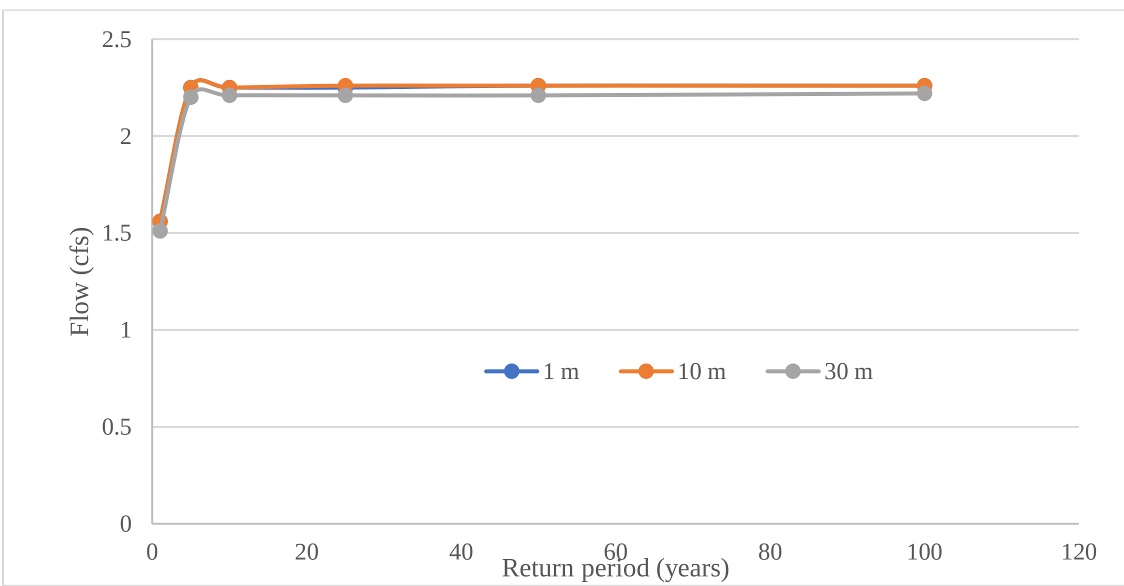


Figure 51. E Independence St & N Owasso Ave proposed $4M open-lot bioretention + linear bioretention LID system flow data for DEM resolution

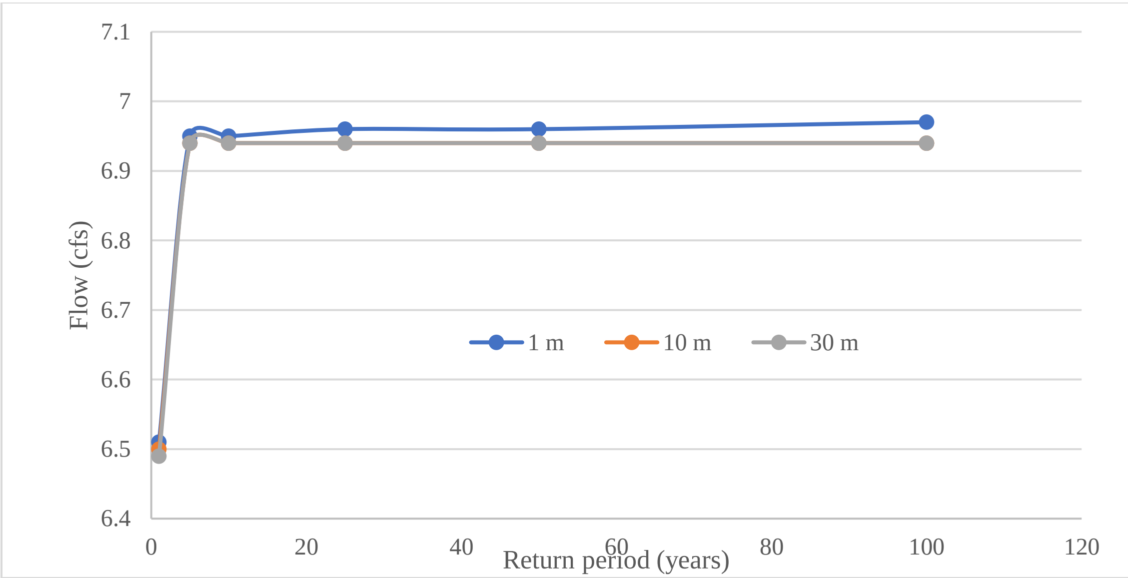


Figure 52. E Admiral Pl & N Utica Ave proposed $4M open-lot bioretention + linear bioretention LID system flow data for DEM resolution

As in Sunnymeade, Figure 53a, evidences a much larger number of flooded areas for the Pearl District Watershed at 30m; areas which are still on the flood-prone zone, meaning the model is interpreting the bigger DEM cell sizes as bigger areas where water can accumulate and create flooding potential.

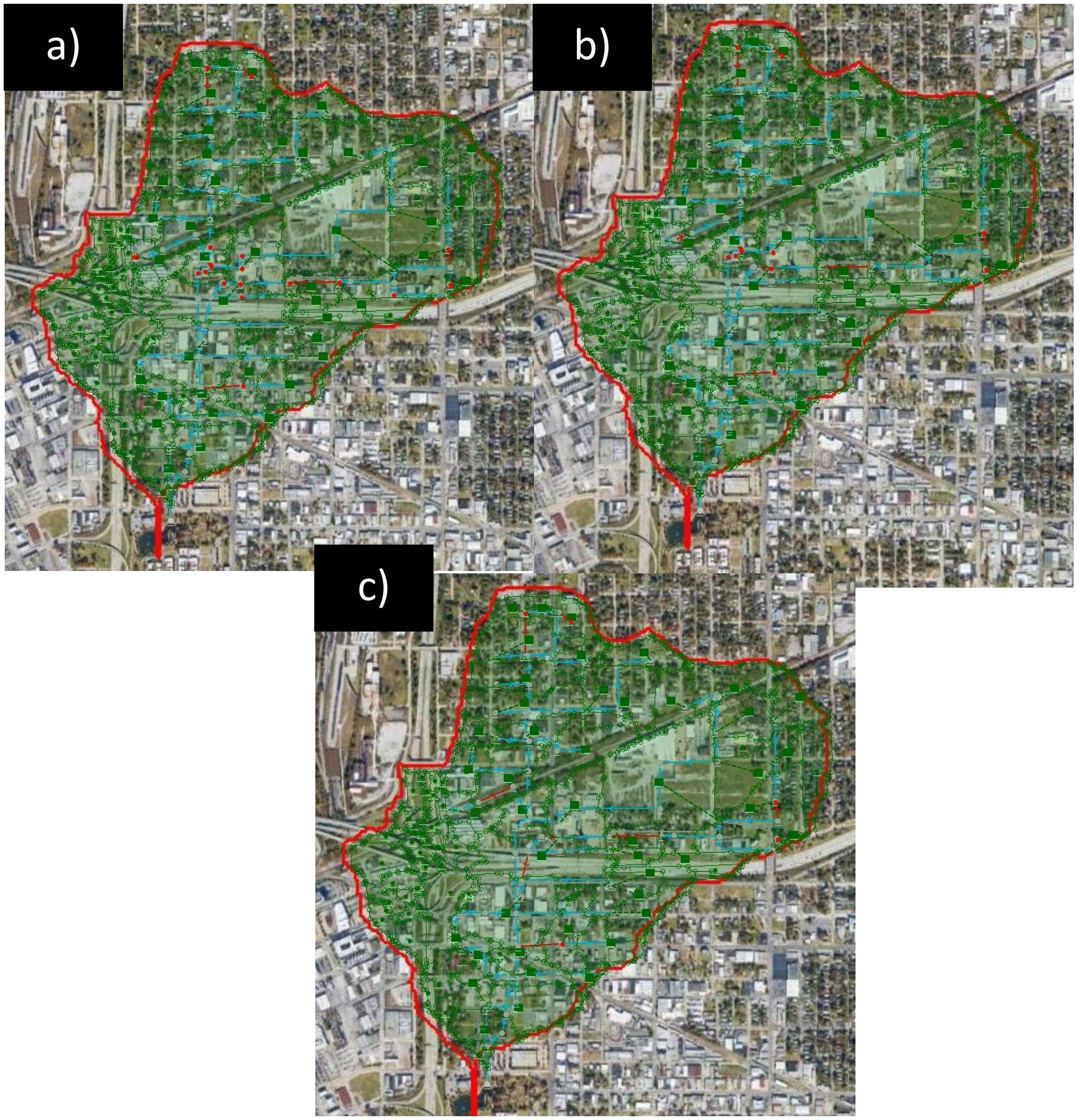


Figure 53. 10-year storm existing Pearl District for DEM resolutions. A) 30m, b) 10m, c) 1m. Areas in blue are the existing storm sewer system, areas in red represent flooding in the system (Google Earth, 2021; Innovyze, 2021).

4.4.2 Soil infiltration

The variation in soil infiltration under the bioretention cells did not have as much impact as other parameters in the overall run of the models, for both areas peak flows changed at maximum 2% and flooded areas and bioretention cells remained the same in terms of red areas. Full InfoDrainage reports on the modeled bioretention cells can be found in Appendix E. The biggest difference in these runs of the model were found in the maximum average depth of water in the bioretention cell, and the half drain time of it as well, this is, the time it takes for the cell to drain half of its maximum volume during the storm. As an example, for the maximum average depth in the 25-year storm in Sunnymeade, values varied plus or minus one foot between soil types, reaching a maximum of 7.7 ft, overflowing the cell by 2.7 ft above its maximum inlet level, for the silt loam soil and a minimum of 3.5 ft for all soils. The soil with the largest half drain down time is clay, with a maximum time of 305 minutes and the lowest at 42 minutes, is sandy loam. For that same storm in Pearl District, average depth in the bioretention between the soils varied by 4 ft at the most, flooding a cell by almost 9 ft, which could be an over-estimation example, as previously seen in other sections. The half drain down time does not vary a lot and drain times are less than 10 minutes, because either the three soils drain fast enough or because the bioretention cell sand media percolates water fast back into the bigger pipes of the storm sewer system.

4.4.3 Bioretention cell media

Similarly to soil type variation, bioretention media did not have an impactful outcome on peak flow modelling results. At Sunnymeade, this could be due to the native soil being clay, the various configurations did not yield much different results as to those of the baseline model, meaning that the tight soil underneath the bioretention cells has a strong characteristic of ponding the water in the bioretention cell and not let it though the soil. For the low infiltration rate soil media (loam), the half drain time maximum is 636 minutes, in the 25-year storm, compared to the 583 minutes of the moderate infiltration rate (sandy loam media). This sandy loam media result combined with a clay soil underneath could be the cause for the higher drain time. When comparing clay soil and sandy media in the bioretention cells, drain time and maximum average depth is lower for that combination than a clay soil and sandy loam media. The fastest results, as expected, is with sandy loam soil and sand bioretention cell media. The media for Pearl District provided similar results, with no remarkable variations in peak flow reduction; the silty clay loam soil underneath the bioretention proves a good soil for quick infiltration and could work without any media at all, just using the storage layer of the bioretention.

Given the half-drain times are still under both 48 and 24 hours, soil media appropriate for plant growth in Oklahoma can be feasible on the top layer of the bioretention cells, performing the necessary infiltration tests beforehand and plant maintenance as a garden.

4.4.4 Underdrain diameters

Results for underdrain diameters showed the 0.5-in pipes of the entire system surcharge more frequently than the 2-, 4- and 6-in ones. Since the underdrains are small pipes that are only connected to the bioretention cells and not the main storm sewer system itself, it is a small change in the graphics of the model and is not picked up with a qualitative approach. The maximum outflow for both study areas go from best to worse beginning with the 6-inch underdrain in order all the way down to 0.5 inches. Although, the Sunnymeade baseline model had 2-inch orifices that connect to a 6-inch underdrain and that model performed almost as good as the one with the 6-inch underdrain and pipe.

4.4.5 Storm duration

In terms of water quality, despite the extended duration of the storm for Sunnymeade, difference in pollutant load is between 0 and 3% and for Pearl District is between 0 and 2%. These calculations were made with the data from Tables 17 through 20. Given the precipitation depth remains the same, but is only further extended one extra day, pollutants do not experience any change in concentration reduction or maximization but rather maintain the same values as the 24-hour storm with a peak flow towards the first day, instead of at the middle of the storm as observed in the hydrographs in Figure 51. The percentage of pollutant reduction also remains similar for both storms.

Table 23. Water Quality Comparison Table for Areas of Interest – Sunnymeade 2 day $4M open-lot bioretention + linear bioretention (EX: Existing system, PR: Proposed LID system, 1-YR: 1-year storm event, 5-YR: 5-year storm event, 10-YR: 10-year storm event, 25-YR: 25-year storm event, 50-YR: 50-year storm event, 100-YR: 100-year storm event)

System Comparison Table - 2-day model - Clay soil - WQ								
Historic Flooding Location		EX 1-YR	PR 1-YR	EX 5-YR	PR 5-YR	EX 10-YR	PR 10-YR
Sunnymeade & Croydon	TSS (lbs)	514.3	405.3	959.2	751.1	1151.7	899.7
	TN (lbs)	17	13.4	31.8	24.8	38.2	29.7
	TP (lbs)	2.2	1.7	4.2	3.2	5	3.9
Drakestone & Greystone	TSS (lbs)	501.5	368.7	884.1	678.8	1042.3	805.4
	TN (lbs)	15.5	11	27.2	20.3	32.1	24.1
	TP (lbs)	2.1	1.6	3.8	2.9	4.5	3.4
Elmhurst & Dorchester	TSS (lbs)	210.4	0.1	412.5	0.3	499.9	1.2
	TN (lbs)	7.8	0	15.3	0	18.5	0.1
	TP (lbs)	1.1	0	2.1	0	2.5	0

Historic Flooding Location		EX 25-YR	PR 25-YR	EX 50-YR	PR 50-YR	EX 100-YR	PR 100-YR
Sunnymeade & Croydon	TSS (lbs)	1415.9	1104.1	1632.9	1271.9	1874.1	1458.8
	TN (lbs)	47	36.5	54.2	42.1	62.2	48.3
	TP (lbs)	6.2	4.7	7.2	5.5	8.2	6.3
Drakestone & Greystone	TSS (lbs)	1256.9	982.7	1429.6	1127.5	1618.8	1287.9
	TN (lbs)	38.6	29.4	43.9	33.7	49.6	38.5
	TP (lbs)	5.4	4.1	6.1	4.7	6.9	5.4
Elmhurst & Dorchester	TSS (lbs)	620.6	3.2	719.8	2.1	830.4	2.6
	TN (lbs)	22.9	0.2	26.6	0.2	30.7	0.2
	TP (lbs)	3.2	0	3.7	0	4.2	0

Table 24. Water Quality Comparison Table for Areas of Interest – Pearl District 2 day $4M open-lot bioretention + linear bioretention (EX: Existing system, PR: Proposed LID system, 1-YR: 1-year storm event, 5-YR: 5-year storm event, 10-YR: 10-year storm event, 25-YR: 25-year storm event, 50-YR: 50-year storm event, 100-YR: 100-year storm event)

System Comparison Table - 1m model - Silty Clay Loam soil - 2 day - Water Quality							
Historic Flooding Location		EX 1-YR	PR 1-YR	EX 5-YR	PR 5-YR	EX 10-YR	PR 10-YR
E Independence & N Owasso Ave	TSS (lbs)	73.3	26.4	118.5	42.7	140.8	50.8
	TN (lbs)	3	1	4.9	1.7	5.9	2
	TP (lbs)	0.4	0.1	0.6	0.2	0.7	0.3
E Admiral Pl & N Utica Ave	TSS (lbs)	473.6	72.5	827.5	120.1	1014.7	143.8
	TN (lbs)	19.8	3	34.7	5	42.5	6
	TP (lbs)	2.6	0.4	4.5	0.7	5.5	0.8
E 3rd St and S Norfolk Ave	TSS (lbs)	365.7	85.1	610.4	132	739.3	156.3
	TN (lbs)	11.2	2.4	18.7	3.9	22.7	4.7
	TP (lbs)	1.4	0.3	2.3	0.4	2.8	0.4

Historic Flooding Location		EX 25-YR	PR 25-YR	EX 50-YR	PR 50-YR	EX 100-YR	PR 100-YR
E Independence & N Owasso Ave	TSS (lbs)	162.3	58.7	179.3	64.9	197.9	71.7
	TN (lbs)	6.8	2.3	7.5	2.5	8.2	2.8
	TP (lbs)	0.9	0.3	0.9	0.3	1	0.4
E Admiral Pl & N Utica Ave	TSS (lbs)	1202.1	167.1	1351.9	185.3	1520.3	205.4
	TN (lbs)	50.4	7	56.7	7.8	63.7	8.6
	TP (lbs)	6.5	0.9	7.3	1	8.2	1.1
E 3rd St and S Norfolk Ave	TSS (lbs)	867.9	180.2	970.5	199	1085.5	219.1
	TN (lbs)	26.7	5.3	29.8	5.8	33.4	6.4
	TP (lbs)	3.3	0.6	3.7	0.7	4.2	0.7

Figure 54 shows an example for the 10-year storm on Sunnymeade with different storm durations. The peak flow happens around the same minutes for all runs on both models between minutes 720 and 760, despite being a 1 or a 2 day. It is possible that a bigger difference would be shown shall the model be shorter than 24 hours or larger than 48.

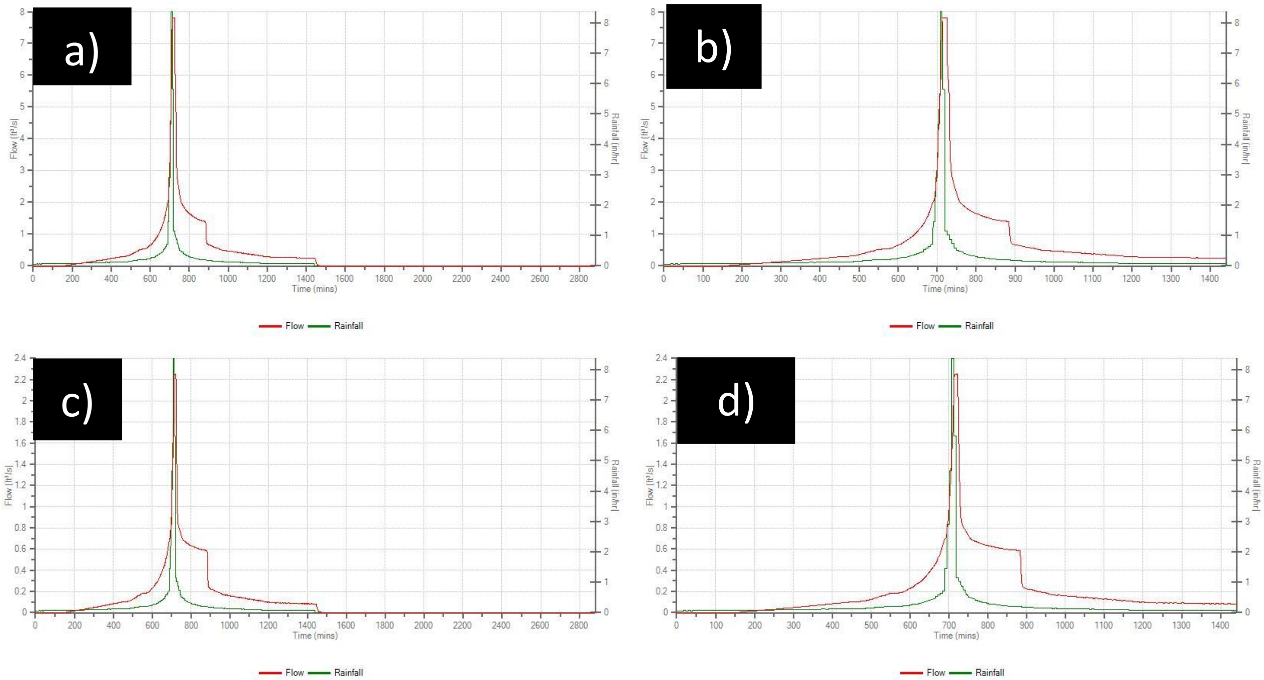


Figure 54. 10-year storm bioretention cell on Sunnymeade. A) Existing 2-day, b) Existing 1-day, c) LID 2-day and d) LID 1-day

4.5 Cost estimate

Cost estimations for the maximum applied LID models are shown for both study areas in Tables 25 and 26. These cost estimates reflect the higher-performance proposed LID models: for Sunnymeade: open-lot BRC, LBC and PC gutter and streets, for Pearl District: open-lot BRC and LBC. These priced BMPs are a result of the optimization and modelling results and show that optimization results can be a high-cost estimation of what can be applied to the watersheds, specifically mentioning Sunnymeade, since optimization yielded this BMP combination would be $18M. The total cost for Sunnymeade with all LID included is $5,308,109 and for Pearl District is $1,364,881.

These prices are local Oklahoma City bid estimates and can work out for initial phases of LID implementation for flood reduction in Oklahoma. Details on bids are shown in Appendix F.

Table 25. Cost Estimate for proposed LID system in Sunnymeade

Sunnymeade Total Cost Summary Table		
143	100 ft Linear BRCs	$ 3,593,648.59
1	BRC at Sunnymeade & Croydon	$ 652,954.22
1	BRC at Guilchester Park	$ 291,517.08
1	PCG street on N Wellington Ave	$ 410,692.17
31	100 ft PCG	$ 359,297.73
	Total Cost	**$ 5,308,109.79**
	With 25% Contingency	**$ 6,635,137.23**

Table 26. Cost Estimate for proposed LID system in Pearl District

Sunnymeade Total Cost Summary Table		
51	100 ft Linear BRCs	$ 907,943.93
2	Open lot BRC	$ 183,961.45
	Total Cost	**$ 1,091,905.37**
	With 25% Contingency	**$ 1,364,881.72**

Chapter 5: Conclusions and Recommendations

The main objective of this study was to reduce localized peak flow in Oklahoma City and Tulsa neighborhoods, using stormwater models that showed flood-prone and storm sewer surcharge areas and were designed and analyzed to place LID techniques such as bioretention cells and pervious concrete for stormwater management. LID implementation has become part of the urban stormwater management in the United States, because of its cost-effectiveness and capabilities to maximize ecosystem services by mimicking a site's pre-development hydrologic conditions with non-invasive infrastructure. Modeling these stormwater controls provides useful information for designing, planning, and implementing infrastructures that alleviate surcharged storm sewer systems and flood highly urbanized areas. The methods developed in this research contributed to accurate hydrologic and hydraulic modeling for existing drainage systems in densely populated watersheds, thanks to proper land use and hydrologic calculations, optimization procedures and site visits. The results showed that bioretention cell and pervious concrete implementation have high potential for peak flow reduction in urbanized areas as well as in improving water quality and enhancing landscape architecture.

5.1 Conclusions

Noteworthy conclusions from the modeling exercise and consequent results are listed below:

- Considering the limited available green space in most urban areas, such as Tulsa and Oklahoma City, right-of-way linear bioretention cells prove to be a highly effective, non-invasive method for peak flow reduction and water quality improvement.
- The coupling of open-lot bioretention with pervious concrete gutters did not achieve high peak flow or pollutant reduction rates, given the scale of the Sunnymeade watershed, this

limited amount of applied LID technique did not have a significant impact on the watershed as opposed to linear bioretention cells.

- In Sunnymeade, the baseline open-lot bioretention and linear bioretention proved to be nearly as effective as the all-in open-lot, linear bioretention, pervious concrete gutter and streets, differing by a maximum of 8% in areas of interest.
- The updated optimization procedure by McMaine (2017), proved to be a highly efficient tool for planning purposes to provide a pre-modeling analysis on the most feasible, suitable and cost-effective techniques to suit each study area. This process, coupled with modelling, requires multiple iterations to reach the most cost-effective solution, that is also able to meet the goals of the research at multiple phases.
- Given the costs of high-resolution survey data and the computational cost of running such fine resolution models, publicly available data, when adjusted correctly to buildings, streets, pipelines, etc., is an efficient model input when evaluating large watersheds.
- On the contrary, for accurate results on the storm sewer system to evaluate, survey data should be as detailed as possible, accounting for correct pipe slopes, sizes and invert elevations.
- In Sunnymeade peak flow is reduced from the 100-year storm event to as low as the 25-year storm event, yielding a 30% flow reduction in one of the most flooded areas on the northwest area of the neighborhood. On the southwest area, where there is more pervious area, and the maximum runoff reduction percentages are obtained, the flow is reduced by 92%.
- In Pearl District, flow reduction ranges from 57% to almost 80%, reducing the peak flow from the 100-year storm event, down to < 1-year in the best of cases.

- Despite seeing flooding in the bioretention cells for the LID models, all the cells meet the requirement of draining in less than 24 hours to decrease mosquito habitat presence.
- Publicly available topographic data at 1-m in Sunnymeade, yields similar results as to those of the 1-ft model, with differences between 0.03% and 6% in flow values. The 10-m data also performed well, with a range of 1-10% of difference to the 1-ft model and the 30-m data with a range of 2-23% of difference, which may be attributed to the bigger pixel size of these resolutions, which accounts for a higher area within the influence of each pixel and therefore influences the velocity of surface runoff and peak flow
- Coarse resolution data tends to lower runoff quantities and overestimation of flood prone locations given its larger pixel size and lack of detail mainly regarding the direction and accumulation of rainwater in the urban systems.
- Moderate infiltration bioretention cell media is a feasible option for peak flow reduction. This media not only contributes to storm sewer system relief but sustains plant growth for better landscaping and added value.
- The InfoDrainage model is not highly susceptible to specific variable data, such as underdrain diameter, soil infiltration or media amendments for large watersheds, these input variations had minimal impact in overall modeling results.

5.2 Recommendations

Flooding is one of the most common and devastating natural disasters that exist, which added to extreme precipitation and land use changes, are the main triggers for this issue. Intensified rainfall exacerbated by climate change has caused nearly $75 billion in flood damage in the U.S. in the past three decades (CNBC, 2021). For these reasons there needs to be more innovative stormwater management implementation in the U.S., such as large-scale construction of green infrastructures or LID techniques.

Recommendations for appropriate modeling and consequent accurate results include performing a current storm sewer system survey, with access to manholes and other points of interest. Cost-estimation needs to be performed as detailed and earlier in the process as possible, since it is a defining factor in the stormwater controls to be implemented in the watersheds, and constant price fluctuations lead to optimization changes, which lead to changes in modeling and its results.

Further, more-detailed modeling may include changing not only the infiltration rate underneath the bioretention cells, but also change the watersheds soil group based on site-performed infiltration tests with real storms, and consequent change in curve number and initial abstraction values, to take a deeper look into certain areas, which may lead into more bioretention cell friendly soils, that may also contribute to save money on not having to spend in the engineered media, unless absolutely necessary.

This project is pioneer in the state of Oklahoma in terms of implementing LID for flood reduction, since most of these infrastructures are usually aimed for water quality improvement purposes. The process and results presented here are evidence of the capacity and potential that green infrastructures have in reducing runoff volume, which are not only comparable to grey infrastructure (pond) implementation capacities but also add and contribute positively to a site's landscape, habitat, water quality improvement and water quantity reduction, without the need to acquire big extensions of land or perform big constructions. Based on the efficient results here obtained, LID implementation (especially bioretention cell) is highly recommended for the state of Oklahoma for stormwater management.

5.3 Lessons learned

From this project, the main lesson learned, is how to manage time properly and schedule things with time and accuracy. Model building is a tedious process and requires the handling of many inputs and variables that an engineer must have clear to perform the hydrologic calculations correctly so that the hydraulic and 2D hydrologic models reflect what happens or will happen in the real world. Added to the pre-processes of model building, it is also important to know the model one is to work with as good as possible, this entails attending workshops, asking superiors, experts, doing online research and reading manuals on how to properly handle the model, its most valuable capacities and qualities. It's valuable to know how to transform calculations into a watershed with miles of pipes and manholes, that on massive storm events, as one sees in Oklahoma especially during the spring, floods and needs the help of an engineer who knows how, where and why water needs to be managed to mitigate and prevent further damage to the system, the infrastructure, and most importantly, people's lives.

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