IDENTIFICATION OF SUITABLE LOCATIONS FOR PERMEABLE PAVEMENTS AND BIORETENTION PONDS/ RAIN GARDENS USING GIS SUITABILITY ANALYSIS FOR ENHANCED STORMWATER MANAGEMENT CAPACITY IN THE CITY OF DALLAS

by

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Abstract

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Low Impact Development (LID) Strategies have shown effectiveness in managing stormwater efficiently at its source. LID strategies can be utilized to manage storm water in coordination with conventional stormwater management infrastructure to increase efficiency and reduce flooding in case of extreme precipitation events. In this study GIS suitability analysis technique has been used to identify suitable locations for permeable pavements and bioretention ponds/ rain gardens; two of the four main LID Best Management Practices (BMPs) within the City of Dallas. The Analytical Hierarchy Process (AHP) was used to determine weights of factors for suitability Analysis. Case Studies from Bryan/College Station, Texas, USA demonstrate the effectiveness of LID BMPs in managing stormwater specifically in Texas.

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1 CHAPTER 1

INTRODUCTION:

1.1 Background:

Trinity River has a history of degradation and deterioration since 1800s due to direct discharge of untreated sewage. However since 1960s there has been a significant improvement in the water quality and biological integrity of the upper Trinity River watershed. Improvements in technology in waste water treatment plants and the federal and state regulations for conservation have been instrumental in water quality improvement (Norwine, Giardino, & Krishnamurthy, 2005). One challenge in improving water quality since 1960s has been the high growth rate of DFW area causing urbanization at a rapid rate. This has resulted in increased urban runoff with increase in impervious surface and increased municipal waste water discharges. Agricultural runoff has also affected water quality with incorporation of herbicides like atrazine in the River (USGS, 1995)(Norwine et al., 2005).

With a constantly increasing population, the consumption of water in municipal, agricultural and other areas will increase. Currently 40% of the total Texas population is dependent on the Trinity River watershed to meet their water consumption demands. The population of Texas has been projected to be 9.4 million by 2030, which is almost twice its population in 2000 (Vision North Texas, 2010). Trinity River is considered third most polluted water body in Texas. Due to industrial discharges and agricultural runoff, various pollutants and toxic substances have been added into the watershed over the years. According to a USGS study, pesticides, polycyclic aromatic hydrocarbons (PAHs) and zinc concentrations have increased considerably. In the DFW area 9 out of the 275 that are on the Public Health Service Agency for Toxic Substances and Disease Registry Priority List have been detected (USGS, 1995). The main stem of the Upper Trinity River that connects Fort Worth and Dallas has experienced increase in the nutrient concentration such as chloride and sulfate (USGS, 1995).

One of the negative effects of urbanization is the increase in the impervious cover of the land which results in huge amounts of urban runoff in case of rainfall events. According to some climate projection models the trend of extreme rainfall events is projected to increase due to climate change. This increased occurrence of extreme rainfall events will further increase the amount of runoff in urban areas causing extreme flooding as was witnessed in the record breaking rainfall in North Texas in April and May 2015("National Climate Assessment," n.d.).

A study conducted in 2013, analyzed the effect of Low Impact Development (LID) in two urbanized watersheds by comparing the runoff rate and volume before and after the implementation of LID Best Management Practices (BMPs) which include rain barrel/cisterns and permeable pavements. The results show 2-12% reduction in runoff, total phosphorus (TP) and total nitrogen (TN). The conclusion of the study notes that in order to enhance the capacity of current storm water management systems to prevent flooding, in the wake of future climate projections of extreme events, Low Impact Development (LID) strategies can be incorporated into the conventional development to manage runoff at its source. This will reduce the risk of flooding as the amount of runoff reaching the storm drains will be less with increased infiltration at the source. The LID strategies to be incorporated into traditional development will include permeable pavements and bioretention ponds/ bioswales (Ahiablame, Engel, & Chaubey, 2013).

1.2 Objective:

The objective of this paper is to identify suitable locations for permeable pavements on parking lots, and for bioretention ponds/ rain gardens on parks and open space based on four variables: 1) Soil Characteristics 2) distance from Trinity River flood plain 3) Slope and 4) Precipitation within the City of Dallas.

The target area for this study is the City of Dallas. Due to extreme rain events becoming more frequent as determined by climate projections ("National Climate Assessment," n.d.), there is a higher risk of urban flooding (Austin & Observer, n.d.). Increased impervious cover has further enhanced the threat (Lee & Heaney, 2003). Furthermore, the current drainage system on its own fails to meet the storm water management needs as was seen in the recent record breaking flooding in April and May 2015 ("President Obama declares flood disaster in Texas," n.d.). The presence of the city within the Upper Trinity River Watershed which is one of the most urbanized cities in US poses potential risk of water pollution and ground water contamination due to run off.

The reasons mentioned above led to the development of alternative storm water management practices such LID which enhance the traditional storm water management infrastructure capacity. LID strategies provide efficient and cradle to grave solutions to enhance the capacity of traditional storm water management infrastructure, in order to promote infiltration and reduce flooding (Nilsson et al., 2003). According to a study done in 2013 to indicate effectiveness of LID BMPs in reducing urban flooding, LID BMPs are most effective in reducing urban flooding during heavier and shorter term storm events. This study analysis reduction in urban flooding by implementation of three different LID BMPs; Swales, Permeable Pavements, and Green Roofs. This analysis is done for a newly established district of Shenzhen in south east China. The study finds that with all the three LID BMPs, there is a considerable reduction of flood volume and intensity for different rainfall events (Qin, Li, & Fu, 2013).

2 CHAPTER 2

LITERATURE REVIEW:

2.1 Effects of Urbanization on Storm Water:

Water pollution due to urbanization is one of the biggest challenges in water conservation planning. Urbanization and urban sprawl has considerably increased the impervious surface within a watershed resulting in degradation of water quality and deterioration of habitat. Urban sprawl has led to an increase in the rate of destruction of habitat health due to increasing impervious surfaces. It has made watershed planning and conservation very challenging (Arnold & Gibbons, 1996). The more the impervious cover, the higher the intensity of flash floods due to increased surface runoff, faster runoff concentration and increased peak flow rate. This results in economic losses, traffic disruption, health issues, and pollution (Qin et al., 2013). Planning can have a significant influence in developing strategies for preventative urbanization in order to maintain balance between pervious and impervious surfaces within a watershed. Creation of a threshold of impervious surface within the watershed can help in maintenance of that balance (Brabec, 2002). In order to prevent degradation of water quality in a watershed there should be less than 10% impervious cover (Daniels, & Daniels, 2003).

According to a study conducted in 2003, a detailed analysis of effects of imperviousness on a 58ha residential area in Boulder Colorado indicate that the Directly Connected Impervious Area (DCIA) which was 13% of the total area accounts for a major amount of the peak discharge of urban runoff. DCIA is an impervious area directly connected to a certain drainage area and therefore has a direct impact on storm water quality and quantity(Lee & Heaney, 2003).

2.2 Low Impact Development Best Management Practices:

According to US Environmental Protection Agency, "Low Impact Development (LID) is an approach to land development (or redevelopment) that works with nature to manage storm water as close to its source as possible. It employs principles such as preserving and recreating natural landscape features, minimizing effective imperviousness to create functional and appealing site drainage that treats storm water as a resource rather than as a waste product"(Coffman, France, & others, 2002; US EPA, n.d.-b).

LID has numerous best management practices (BMPs) which can be used to manage storm water on different sites with varying site conditions. The site conditions necessary to determine the most suitable types of best management practice include, soil conditions, slope, and precipitation and runoff. The four common types of LID BMPs include:

1. Bioretention Areas/ Rain Gardens
2. Permeable Pavements
3. Green Roofs

4. Rain water Harvesting

These LID BMPs reduce the impact of built environment and promotes natural movement of water within an ecosystem. It can also be used to restore hydrologic conditions of a watershed and ecosystem functions (San Antonio LID Guidance Manual, 2011). Since my objective is to find suitable locations for bioretention/rain gardens and permeable/porous pavement, I will be discussing these two in detail below:

2.2.1 *Bioretention Ponds/ Rain Gardens:*

Bioretention ponds/ rain gardens are shallow depressions in the ground landscaped to capture runoff from the surrounding areas and cause it to infiltrate into the ground (SARA, 2014). It is the most commonly used LID technique as it mimics the predevelopment hydrologic conditions, enhance biodiversity, water quality and can be incorporated into either new and existing development (Davis, Hunt, Traver, & Clar, 2009). The rain garden or bioretention system generally consists of a filtration bed, ponding area, organic or mulch layer, and plants. It functions as a soil and plant based filtration device through various physical, chemical, and biological processes (San Antonio LID Guidance Manual, 2011).

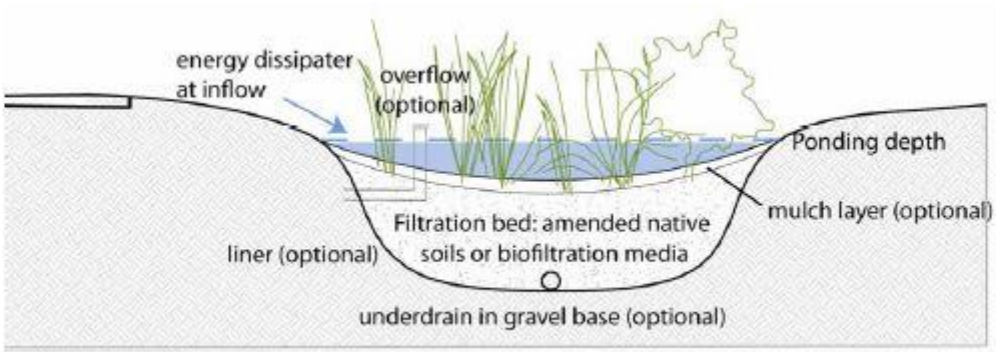

Figure 1: Bioretention Facility Concept, (San Antonio LID Guidance Manual)

There are two types of Rain Gardens/ Bioretention Systems, 1) filtration systems and 2) infiltration systems. Filtration rain gardens clean and detain storm water and prevent them from infiltration and so always have an underdrain beneath them. However, infiltration systems are designed to allow water to seep into the ground. Infiltration systems reduce much more amounts of storm water volume compared to filtration systems (San Antonio LID Guidance Manual, 2011). Both rain gardens and bioretention ponds are essentially the same. The only difference is that rain gardens have natural or only slightly modified soils, however, bioretention ponds always have engineered soils to meet the purpose (San Antonio LID Guidance Manual, 2011). For the purposes of this study, we will consider them as one BMP.

Bioretention systems can be used in commercial, residential, agricultural, as well as urban setting as they produce the same result in all of them. Because of this they can be used to promote infiltration, evapotranspiration, ground water recharge, reduction of peak flow volumes, as well as pollutant removal (Davis, 2008; Davis et al., 2009; Dietz, 2007; Dietz & Clausen, 2005). In various studies the capacity of bioretention ponds/ rain gardens to reduce runoff peak flow volumes range from 40% to 90% (Chapman & Horner, 2010; Davis, 2008; DeBusk & Wynn, 2011; Dietz, 2007; Line & Hunt, 2009; Roy-Poirier, Champagne, & Filion, 2010).

2.2.2 *Permeable Pavements:*

According to EPA, permeable/porous pavement is designed to temporarily store surface runoff, allowing slow infiltration into the sub soil (USEPA, 1999). Permeable Pavement is a versatile LID BMP that can be incorporated into site plans with various configurations. It can be used on parking lots, sidewalks, streets, and other impervious areas while being used for the same purpose. It allows water to infiltrate into the ground while retaining the structural and functional capacity of the original site when it replaces the impervious cover. Permeable pavement can be

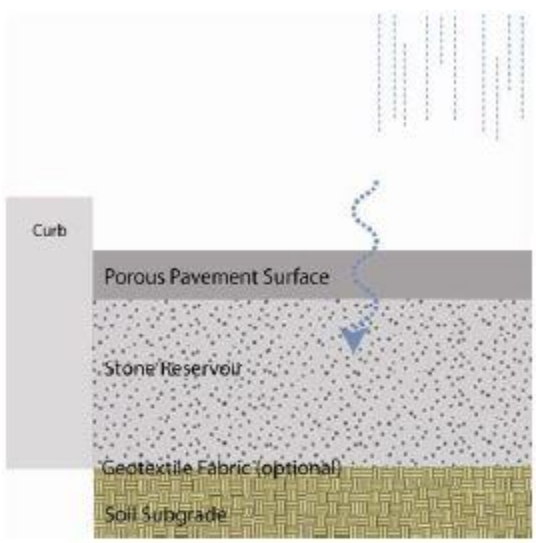

Figure 2: Permeable Pavement Concept, (San Antonio LID Guidance Manual)

used on top of the soil directly or can have an underdrain beneath the pavement to collect runoff (SARA, 2014).

Permeable pavements include porous asphalt and pervious/porous concrete, block pavers, plastic grid systems (Dietz, 2007). **Porous asphalt** is made of open graded course aggregate, bonded together with asphalt cement with adequate interconnected voids to allow water to infiltrate. **Pervious concrete** are mixtures of Portland cement, uniform, open graded course aggregate, and water. They have enough void spaces to allow fluids to seep quickly into the ground. **Block pavers** are themselves impermeable but have sufficient open spaces in the interconnections along the periphery of each block to allow water to seep into the ground. G**rid systems** are interconnected frame of pavement with wide void spaces within them. These void spaces are filled with open graded course aggregate (San Antonio LID Guidance Manual, 2011).


Figure 3: Types of Permeable Pavement. From top to bottom, clockwise; porous asphalt; pervious concrete; grid system; block pavers, (SARA, 2014)

Porous pavements cause an average runoff reduction of 50% - 93% (Ahiablame, Engel, & Chaubey, 2012). In a 2 year study in North Carolina, a permeable pavement on a parking lot captured 75% of the rainfall while the rest of 25% cased runoff (Hunt, Stephens, & Mayes, 2002). Permeable pavements can not only reduce runoff but can remove runoff generation (Bean, Hunt, & Bidelspach, 2007) even during the most intense rainfall events (Brattebo & Booth, 2003). Permeable pavement have been shown to acquire predevelopment hydrological conditions in various studies one of which showed a 93% reduction in runoff volume on two parking lots (Dreelin, Fowler, & Carroll, 2006; Fassman & Blackbourn, 2010).

2.3 Suitability Analysis:

GIS Land Suitability Analysis is one of the most commonly used techniques for identifying suitable spatial locations for various land uses based on specific requirements, preferences, or predictors (Malczewski, 2004). This technique has been used in a variety of different situations such as defining suitable habitats for animal and plant species, geological favorability, suitability of land for agricultural activities, environmental impact studies, and suitability of various public and private sector facilities (Malczewski, 2004).

The technique attribute its origin to the Overlay map technique used by landscape architects and planners in the late 19^{th} and early 20^{th} century. One of the most prominent names in developing this technique is Ian McHarg who first superimposed transparent maps of different natural and built environment factors using light to dark shading. The map that resulted provided a suitability map for each land use with light areas being more suitable and dark areas being less suitable (Malczewski, 2004).

2.3.1 Methods of GIS Land Use Suitability Analysis:

According to Hopkins (Hopkins, 1977), there are four broad categories of methods of Land-Use Suitability Analysis. The first one is Gestalt Method in which the suitability for homogenous regions is determined by field observations, aerial photographs, and topographic maps without taking into account the individual factors such as soil, land use etc. The limitation of Gestalt Method is that it is not very practical because of its tediousness and inability to account for individual factors.

The second broad category is the Mathematical Combination Method which include, ordinal combination, linear combination and non-linear combination. The method used by McHarg is considered Ordinal Combination because it identifies the greyscale for each of the factors as ordinal numbers which give an invalid mathematical operations. In order to be valid for a mathematical operation, the numbers should be at least in interval scale. The linear combination considers numbers in interval scale by incorporating weights to provide a common unit of measurement. However, this method does not provide any means of determining interdependence among factors. The non-linear combination method although does handle interdependence, but the mathematical operations because of their inability to take into account total costs are invalid.

The third category of suitability analysis is through explicit identification of regions. The two methods that are included in this category are Factor Combination Method and Cluster Analysis. Both Factor combination method and Cluster Analysis method like Gestalt method take into account homogenous regions and allow for interdependence among factors. Both methods however does not provide mean of determining rating for each of the factors.

The fourth category is Suitability by Logical Combination which include Rules of Combination method and a subset of Rules of Combination called

Hierarchical Combination Method. In this method, logical verbal rules rather than numbers are applied to a set of combination of types rather than to single combination. It allows for interdependence, however, it does not require exact mathematical expressions as in non-linear combination or to evaluate each combination separately as in factor combination.

Although Hierarchical combination method is a subset of rules of combination, it is treated separately. In the Hierarchical Combination Method, the ratings for combinations of each factors which are strongly interdependent are determined. After that the higher order combinations of the combination of the factors are rated. This sequence of hierarchical combination is repeated until a rating is achieved that include all relevant factors.

3 CHAPTER 3

METHODOLOGY:

This study will use Raster Overlay Technique in GIS to determine suitability of the various factors. All the factors will be rated based on their suitability to have a permeable pavement or bioretention pond/ rain garden for the whole city of Dallas. The weights for these factors will be determined using Analytical Hierarchy Process (AHP) developed by Thomas L. Saaty in 1980. Once the suitability of factors is determined for the whole City of Dallas, the suitable locations for the proposed LID BMPs will be identified using parking lot data for permeable pavements and parks and open space data for bioretention ponds/ rain gardens.

3.1 Study Area:

The study area for this analysis is the City of Dallas. The City of Dallas is located in the Dallas-Fort Worth (DFW) Metroplex which is one of the fastest growing metropolitan area in the United States. The current population of DFW is 7 million. This is expected to reach 9.4 million by 2030 (Vision North Texas, 2010). The City of Dallas is located within the Upper Trinity River Watershed. One of the main tributaries of Trinity River; the Elm Fork joins the main stem in the City of Dallas. The city has an area of 391sq.miles. Out of this total area 98.8sq.miles (25%) is impervious cover that excludes building structures. This impervious cover consists of athletic field courts, commercial driveways, concrete drains, concrete pads, enclosed courtyards, helipads, islands, medians, parking lots, paved roads, paved/unpaved alleys, paved/unpaved driveways, pedestrian bridges, playgrounds, public private sidewalks, railroad beds, runways, storage lots, taxiways, unpaved roads.

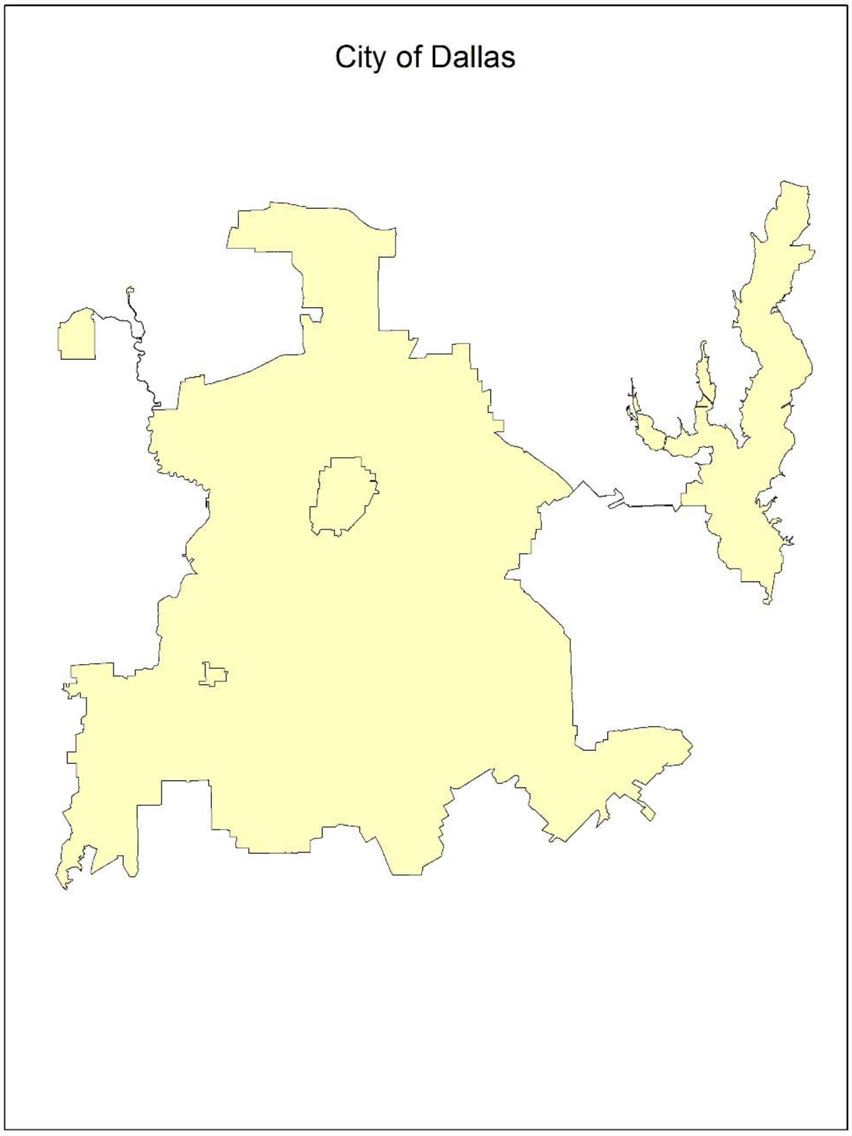

Figure 4: City of Dallas Boundary Map, (City of Dallas GIS Services)

3.2 Factors for Suitability Analysis:

The Factors that determine suitability of LID BMPs would include environmental factors that influence runoff generation, runoff volume, and runoff rate as well as factors that affect water quality when the runoff flow into a natural water body, and factors that promote flooding in low areas where runoff accumulates. This would include slope of the surface. As runoff generated from the impervious cover moves from higher elevation to lower elevation, the more the impervious cover, the more is the runoff volume and the greater the slope, the higher the flow rate of runoff.

Another factor that determines suitability of LID BMPs is soil types based on their hydrological characteristics. Out of the numerous soil types, each one is divided into four categories based on their infiltration capacity called soil hydrological characteristics.

The third factor that affect the suitability of LID BMPs is distance from the flood plain. The Trinity River flood plain is the area that is vulnerable to flooding in case of extreme rainfall event that generate huge volumes of runoff. The flood plain being lower in elevation captures all the runoff at a very rapid rate and being unable to dispose water at the same rate results in accumulation of the water and therefore causes flooding. The presence of impervious cover within the flood plain further pronounces the effect of flooding. LID strategies can enhance the runoff infiltration capacity within the floodplain area with high percentage of impervious areas.

Precipitation is another variable that influences runoff generation as more the amount of precipitation, the more the runoff generated.

This study will attempt to find suitable locations for LID BMPs in the City of Dallas based on these four factors:

1. Slope
2. Soil hydrological characteristics
3. Floodplain
4. Annual precipitation

3.3 Data Collection:

In order to conduct suitability analysis in GIS, the GIS data was collected through various sources. The following table provides the sources from where the GIS data for each factor was obtained:

Datasets	**Sources**
City Boundary	City of Dallas
Soil Data	USDA NRCS Geospatial Gateway
Elevation Data: 2ft Contour	City of Dallas
Current Floodplain	City of Dallas
Average Annual Precipitation	USDA NRCS Geospatial Gateway

Impervious Cover	City of Dallas
Parks and Open Space	City of Dallas

Table 1: GIS Datasets and Sources

For all the data processing, the raster cell size was fixed to 25. The elevation data obtained was 2ft contour map for the Dallas County. This map was used to create digital elevation model (DEM) with a cell size of 25 using raster interpolation in data management tools. GIS data for all the factors was clipped using Clip tool from Geoprocessing toolbar to provide data for only the City of Dallas using the City of Dallas Boundary data.

3.4 Reclassification:

After GIS data for all the factors were obtained, they were reclassified based on their suitability for LID BMPs within the city of Dallas. The reclassification of all factors for both permeable pavements and bioretention ponds/ rain gardens was the same as both the LID BMPs have similar requirements of suitability for each factor (SARA, 2014). The reclassification scale was chosen as -2 to 5, 5 being the most suitable and -2 being the most suitable. The negative values were also included in the scale to discourage the LID BMPs in certain scenarios where the value of the factor is way above the permitted range. The ratings were given based on literature and author's subjective opinion.

3.4.1 *Slope:*

The data for slope was obtained by the DEM created using 2ft contour map for the Dallas County. The DEM was converted into slope map using Slope from the Spatial Analyst tools in arc toolbox. The slope was obtained in percent rise. According to San Antonio River Authority LID Technical Guidance Manual, the ideal slope for both permeable pavements and bioretention ponds/ rain gardens is < 2%. Due to this reason slope between 0% - 3% was given the maximum rating of 5 followed by decreased rating with increased slope. The slope of 16% or greater was given a negative rating of -1 as practically it is impossible to build permeable pavements and bioretention ponds/ rain gardens on a slope as high as 15%. The reason for this is that greater slope causes the runoff to flow at very high rate and rate of infiltration is extremely low, therefore the cost of developing an LID BMP is not justified at higher slopes. The following table provides the rating for suitability of LID BMPs for each category of slope in the City of Dallas:

Slope (%age)	**Suitability Rating for LID BMPs**
0% - 3%	5
4% - 7%	3
8% - 11%	2
12% - 15%	1
16% and greater	-1

Table 2: Suitability Rating for Slope

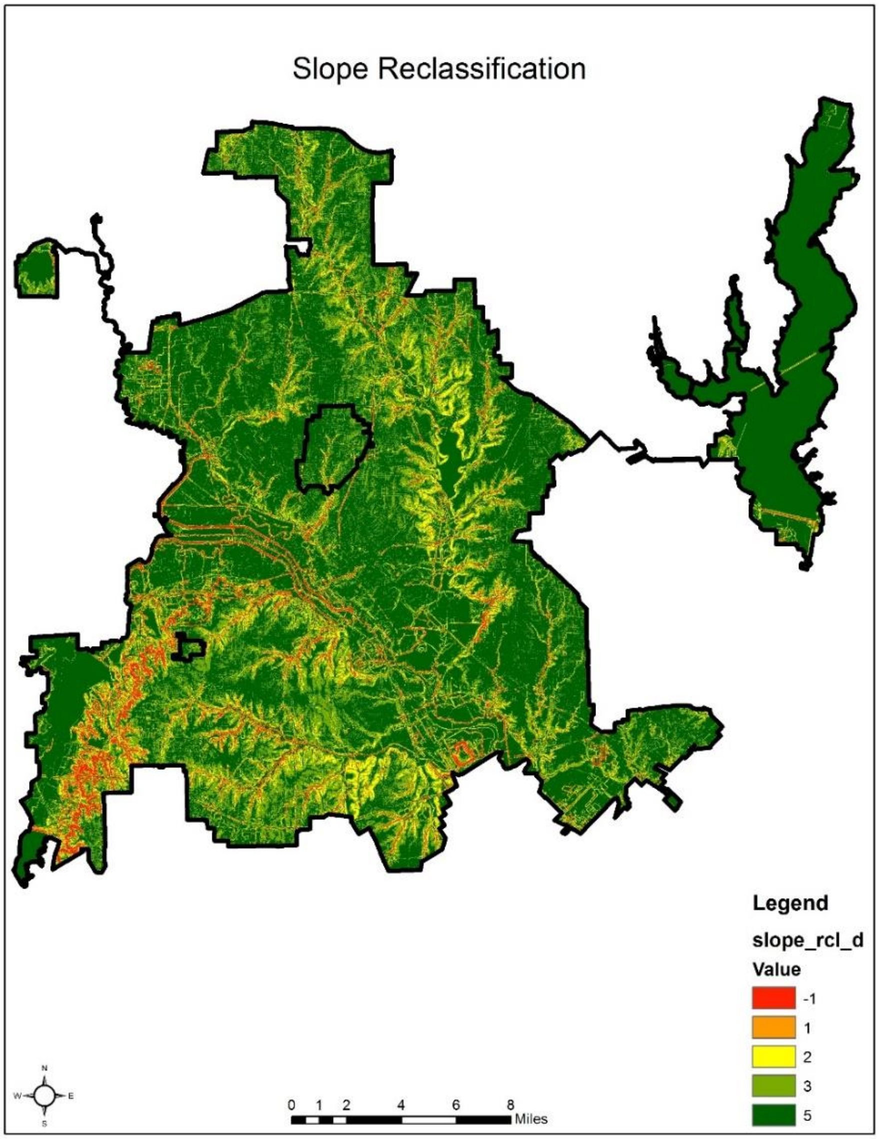

Figure 5: Slope Reclassification

3.4.2 *Soil Hydrologic Characteristics:*

Soil data was obtained from United States Department of Agriculture (USDA) National Resource Conservation Service (NRCS) Geospatial Gateway for the Dallas County. The NRCS divides each soil type into four Hydrologic Soil Group (HSG) on the basis of soil potential for runoff. These are the four HSGs

- **Soil Group A**: sand, loamy sand, or sandy loam, which have low runoff potential and high infiltration rates even when thoroughly wetted.
- **Soil Group B**: silt loam or loam, which have a moderate infiltration rate when thoroughly wetted.
- **Soil Group C**: sandy clay loam, which has low infiltration rates when thoroughly wetted.
- **Soil Group D**: clay loam, silty clay loam, sandy clay, silty clay, or clay, which have very low infiltration rates when thoroughly wetted.

According to SARA LID Technical Guidance Manual, Soil A and B are ideal for LID BMPs because of their high and moderate infiltration rate. Soil C and D are considered less suitable and need engineered soils for LID implementation which increases the cost of implementation. The soil data was first classified into these four categories. Each of these four soil categories was then reclassified into suitability ratings as given below:

Hydrologic Soil Group	Suitability Rating for LID BMPs
Soil Group A	5
Soil Group B	4
Soil Group C	2
Soil Group D	1

Table 3: Suitability Rating for Soil

The following map illustrates the reclassification of soil in the City of Dallas:

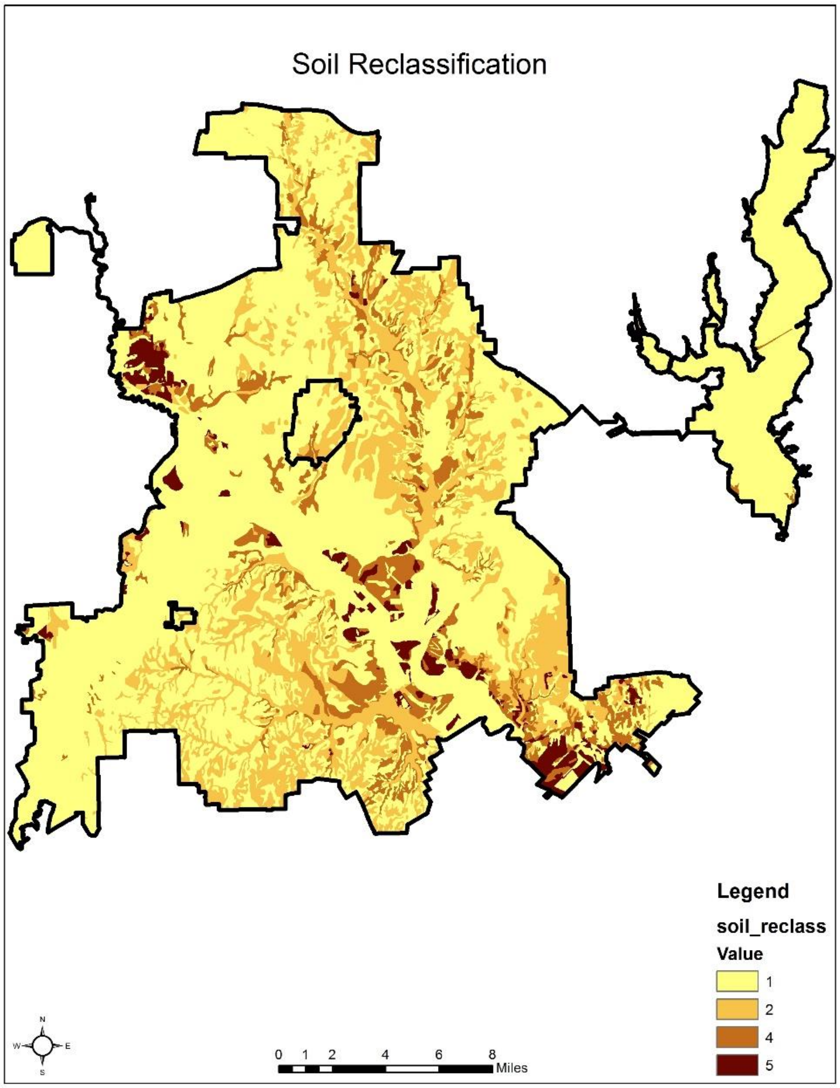

Figure 6: Soil Reclassification

3.4.3 Proximity to Floodplain:

Floodplain data was obtained from the City of Dallas GIS Services Website. In order to consider potential areas for LID BMPs according to distance from the floodplain, Euclidean Distance was used to create a buffer of successive 0.5 mile buffer rings up to greater than 2 mile radius. The current floodplain data included the following flood zones which are categorized by FEMA as either high risk, and moderate or minimal risk (“Flood Zone Definitions,” n.d.) within the City of Dallas:

- **Zone A:** Areas subject to inundation by 1%-annual-chance flood event (100-year floodplain). Because detailed hydraulic analysis is have not been performed, no Base Flood Elevations (BFEs) or flood depths are shown.
- **Zone AE:** Areas subject to inundation by 1%-annual-chance flood event (100-year floodplain) determined by detailed methods.
- **Zone X:** These are moderate and minimal risk areas present within or outside of the 1%-annual-chance flood event or 0.2% annual chance flood event.
- **0.2% Annual Chance Flood Hazard:** This is the 500-year floodplain not categorized as either minimal or moderate risk areas.

According to the San Antonio LID Guidance Manual, the floodplain should not have any development. However, the city of Dallas has considerable amount of impervious cover within the floodplain. In order to mitigate the effects of impervious cover within the floodplain, LID BMPs can be implemented. Due to this reason the areas closer to the current floodplain are considered more suitable for LID BMPs because of their ability to infiltrate runoff and prevent flooding in case of flood event, thereby mitigating the effects of flooding. The following suitability rating was assigned on the basis of proximity to floodplain:

Distance from the Floodplain (miles)	Suitability Rating for LID BMPs
0.5	5
1	4
1.5	3
2	2

Table 4: Suitability Rating for Distance from Floodplain

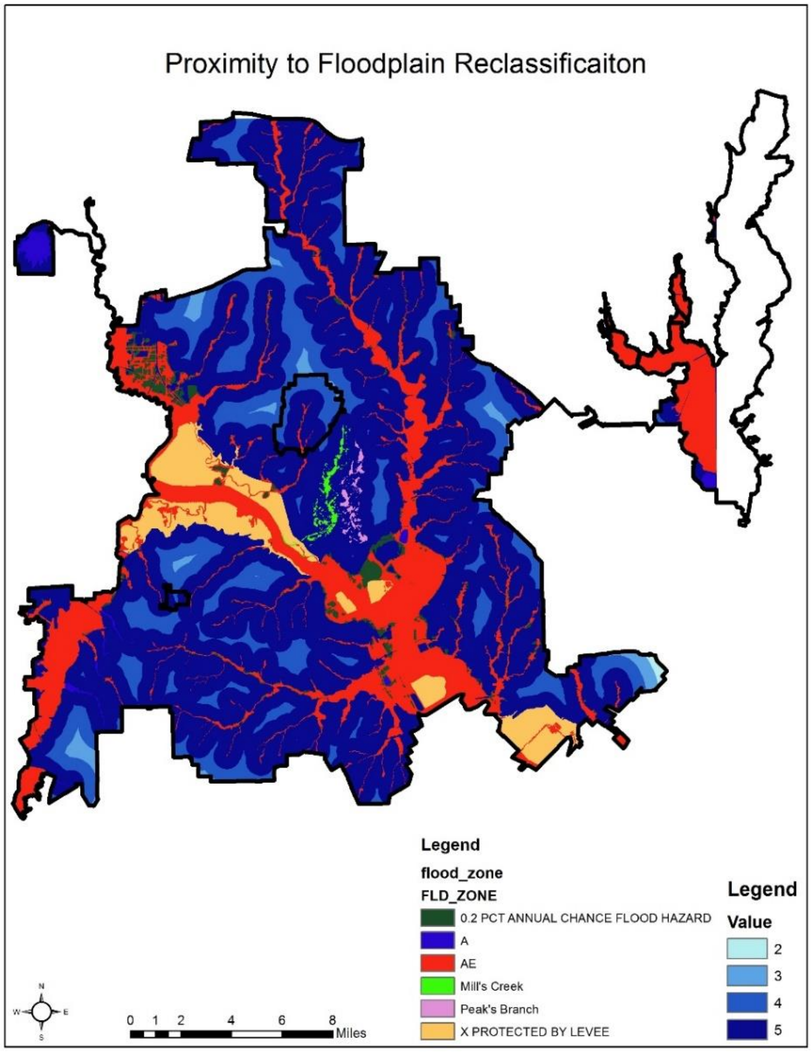

Figure 7: Proximity to Floodplain Reclassification

3.4.4 *Average Annual Precipitation:*

Average Annual Precipitation data was obtained for the State of Texas from USDA NRCS Geospatial Gateway from which the data for Dallas was extracted using clip from Geospatial toolbar in ArcGIS. The precipitation data showed five annual average precipitation measures in the City of Dallas, however, there isn't much of variation. From east Dallas to west Dallas, the precipitation changes from 37 inches per year to 41 inches per year. The precipitation plays a significant role in the generation of runoff. Due to increased projected extreme precipitation events like the one in April and May 2015, the runoff volume and peak flow rate will increase. Due to this reason the higher the annual average precipitation the more suitable it is for LID BMPs in order to mitigate runoff generation and promote infiltration to prevent flooding. The following suitability ratings were assigned to the five precipitation measures:

Annual Average Precipitation (inches)	Suitability Ratings for LID BMPs
37	1
38	2
39	3
40	4
41	5

Table 5: Suitability Rating for Annual Precipitation

3.5 Weighting:

The weighting of the factors was carried out using the Analytical Hierarchy Process (AHP) Developed by Thomas L. Saaty (Saaty, 1980). This method is based on pair-wise comparison of the factors which are considered for suitability. A matrix is used for pair-wise comparison of each factor with itself and the rest of the factors to determine the relative importance of each factor. In this process the sum

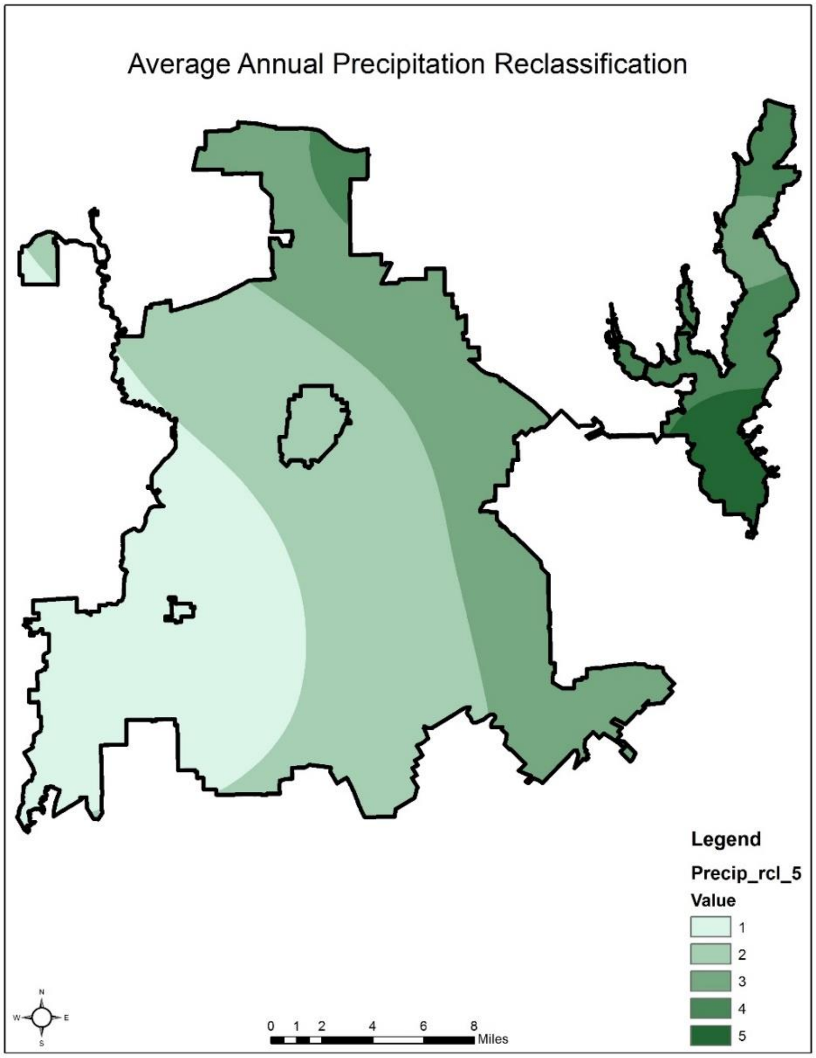

Figure 8: Average Annual Precipitation Reclassificaiton

of the weights for all the factors should be 1. The rank order for all the factors are determined based on their relative importance to each other. Once the rank is determined, all the factors are given scores in the pair-wise comparison matrix according to the following scale given by Saaty (Saaty, 2008).

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
2	Weak or Slight	
3	Moderate importance	Experience and judgement slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is demonstrated very strongly over another, its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
1.1 – 1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be

		too noticeable, yet they can still indicate the relative importance of the activities

Table 6: Pair-wise Comparison Matrix Scale, (Saaty 2008)

In order to identify proper ranks of each of the factors, surveys were conducted among LID professionals, researchers, and students. Based on the number of responses for the relative importance of each factor, the rank of relative importance of each factor was assigned. The individual surveys and a summary of survey analysis is given in the appendix. The weights for both permeable pavements and bioretention ponds/ rain gardens are calculated separately due to the difference in ranking given to each factor in both the LID BMPs in the surveys.

3.5.1 *Weighting for Permeable Pavement:*

The following pair-wise comparison matrix was developed on the basis of the ranks determined from the surveys for permeable pavements:

	Slope	**Soil Hydrologic Characteristics**	**Annual Precipitation**	**Proximity to Floodplain**
Slope	1	3	0.33	1
Soil Hydrologic Characteristics	0.33	1	0.20	0.33
Annual Precipitation	3	5	1	3
Proximity to Floodplain	1	3	0.33	1

Table 7: Pair-wise Comparison Matrix for Permeable Pavement

Annual Precipitation was ranked the highest followed by proximity to floodplain and slope which had the equal ranking. The last ranking was assigned to soil hydrologic characteristics. A normalized matrix was obtained for the ranking given in the pair-wise comparison by dividing each column cell by the sum of that column. The total of each normalized column came out as 1. All the normalized values in rows were averaged to attain the weights for each factor. The Consistency Measure was determined by multiplying the factor ranks for every other factor with the average of normalized ranks for all factors and dividing by the normalized factor average.

	Slope	**Soil**	**Annual Precipitation**	**Proximity to Floodplain**	**Total**	**Average (Weights)**	**Consistency Measure**
Slope	0.19	0.25	0.18	0.19	0.80	0.200893	4.039506
Soil	0.06	0.08	0.11	0.06	0.32	0.078869	4.015094
Annual Precipitation	0.56	0.42	0.54	0.56	2.08	0.519345	4.080229
Proximity to Floodplain	0.19	0.25	0.18	0.19	0.80	0.200893	4.039506
Total	1.00	1.00	1.00	1.00		1	

Table 8: Normalized Matrix for Permeable Pavement

Once the consistency measure was determined, the Consistency Index (CI) was calculated using the following formula where *n* is the order to the matrix:

$$CI = \frac{Average - n}{n - 1}$$

$$CI = 0.014528$$

Using the Random index given by Saaty (Saaty, 1980) which was *RI = 0.9*, the Consistency Ratio (CI) was determined using the following formula:

$$CR = \frac{CI}{RI}$$

$$CR = 0.016142$$

As the CR was less than 0.1 the weights determined using AHP are acceptable. The following table provide weights for each factor for the suitability analysis of permeable pavements:

Factors	**Weights**
Slope	20%
Soil	8%
Annual Precipitation	52%
Proximity to Floodplain	20%

Table 9: Weights for Permeable Pavement

Using the weights determined above, a suitability map was created in using the Weighted Sum tool in Spatial Analyst. The red shade represents high suitability whereas the green shade represents low suitability. The west of the City of Dallas has the highest suitability as the annual precipitation is highest in the west part of the city. Also the areas with slope greater than 15% are less suitable.

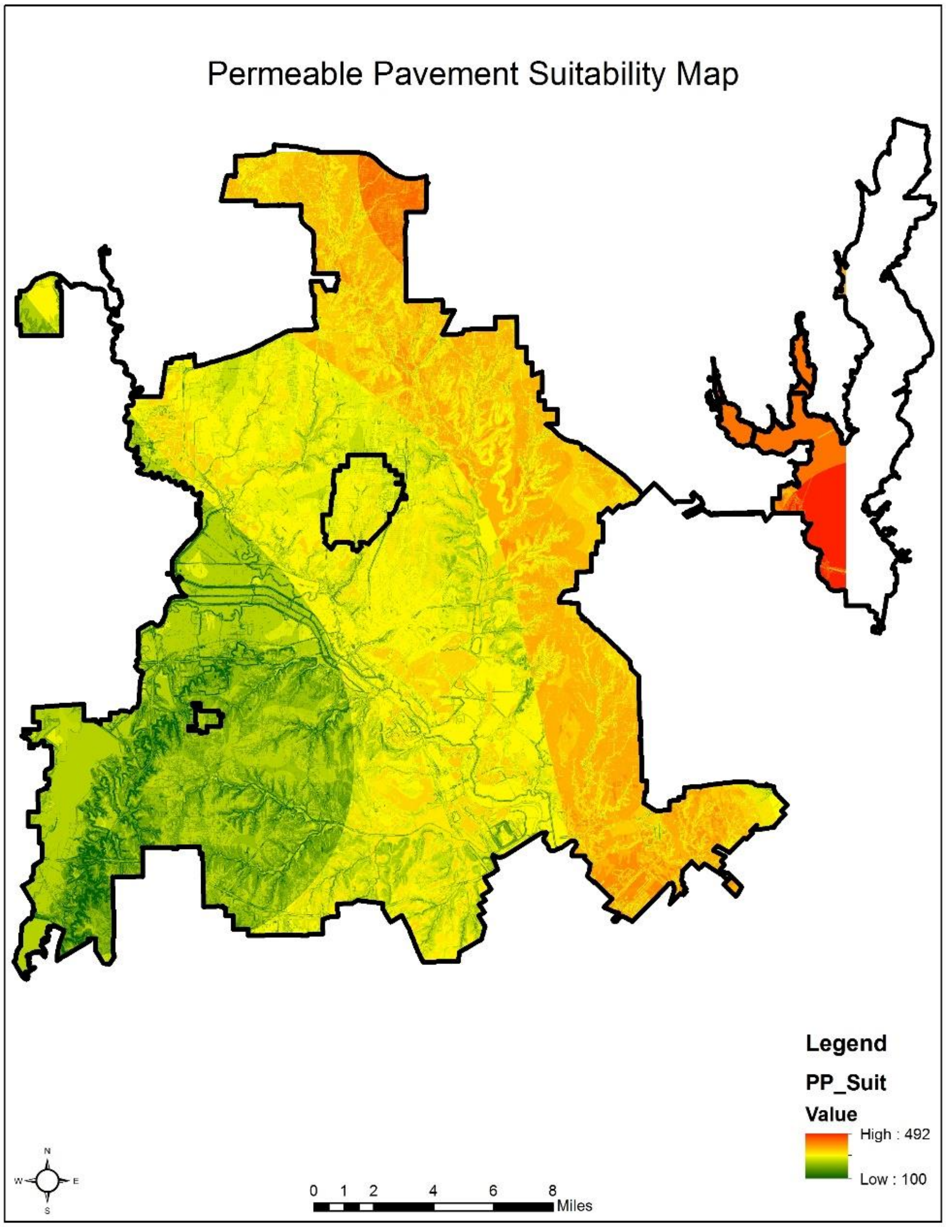

Figure 9:Permeable Pavement Suitability Map

3.5.2 Weighting for Bioretention Ponds/Rain Gardens:

For bioretention ponds/rain gardens, following pair-wise comparison matrix was developed on the basis of the ranks determined from the surveys:

	Slope	**Soil**	**Annual Precipitatio n**	**Proximity to Floodplain**
Slope	1	3.00	0.33	0.33
Soil	0.333	1	0.20	0.20
Annual Precipitatio n	3.000	5.000	1	1.00
Proximity to Floodplain	3.000	5.000	1.000	1
Total	7.333333	14.00	2.53	2.53

Table 10: Pair-wise Comparison Matrix for Bioretention Ponds/ Rain Gardens

Annual Precipitation and proximity to floodplain were ranked the highest for bioretention ponds/ rain gardens followed by slope and soil hydrologic characteristics. A normalized matrix was obtained for the ranking given in the pair-wise comparison by dividing each column cell by the sum of that column. The total of each normalized column came out as 1. All the normalized values in rows were averaged to attain the weights for each factor. The Consistency Measure was determined by multiplying the factor ranks for every other factor with the average of normalized ranks for all factors and dividing by the normalized factor average.

	Slope	Soil	Annual Precipitation	Proximity to Floodplain	Total	Average (Weights)	CI
Slope	0.14	0.21	0.13	0.13	0.61	0.153452	4.032665
Soil	0.05	0.07	0.08	0.08	0.27	0.068694	4.009287
Annual Precipitation	0.41	0.36	0.39	0.39	1.56	0.388927	4.066784
Proximity to Floodplain	0.41	0.36	0.39	0.39	1.56	0.388927	4.066784
Total	1.00	1.00	1.00	1.00		1	

Table 11: Normalized Matrix for Bioretention Ponds/ Rain Gardens

Once the consistency measure was determined, the Consistency Index (CI) was calculated using the following formula where *n* is the order to the matrix:

$$CI = \frac{Average - n}{n - 1}$$

$$CI = 0.014627$$

Using the Random index given by Saaty (Saaty, 1980) which was *RI = 0.9*, the Consistency Ratio (CI) was determined using the following formula:

$$CR = \frac{CI}{RI}$$

$$CR = 0.016252$$

As the CR was less than 0.1 the weights determined using AHP are acceptable. The following table provide weights for each factor for the suitability analysis of permeable pavements:

Factors	Weights
Slope	15%

Soil	7%
Annual Precipitation	39%
Proximity to Floodplain	39%

Table 12: Weights for Bioretention Ponds/ Rain Gardens

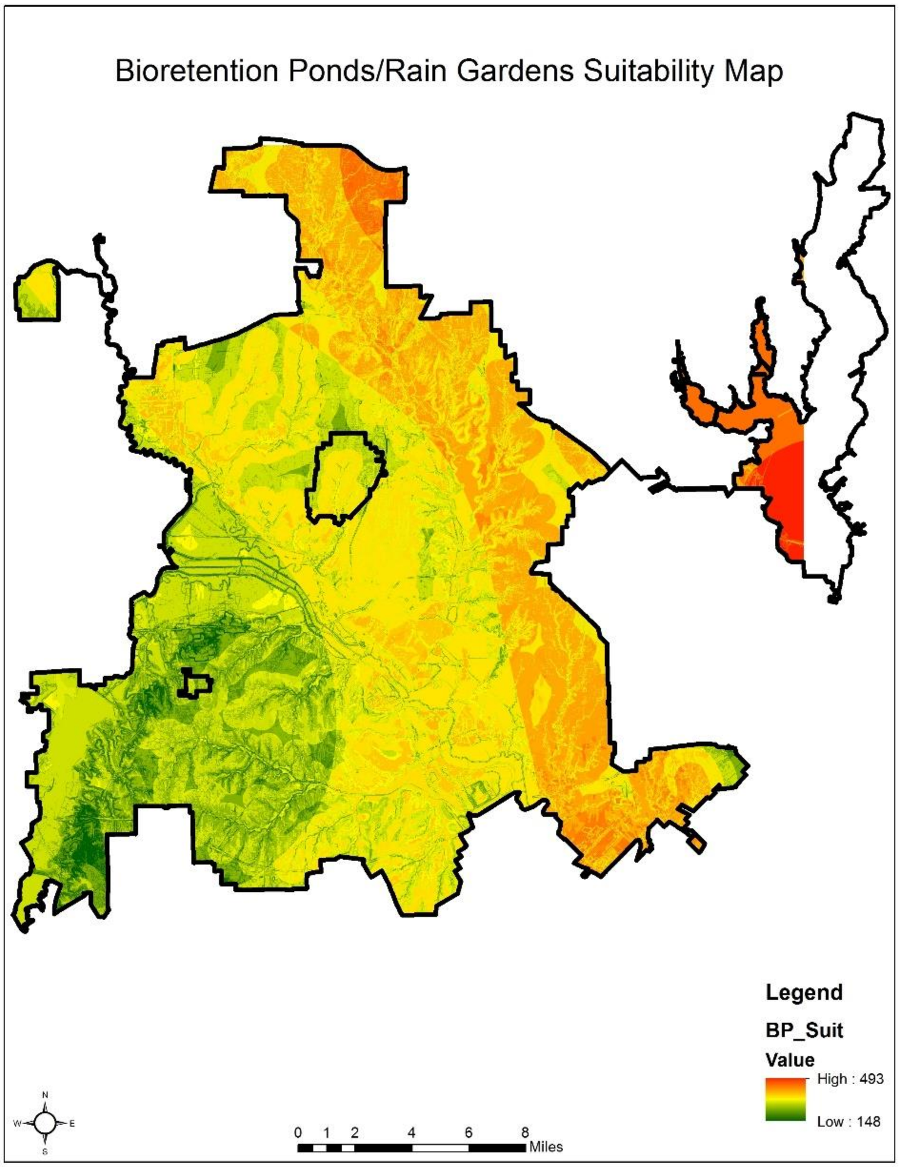

Figure 10: Bioretention Pond/ Rain Garden Suitability Map

Using the weights given determined above, a suitability map was created in using the Weighted Sum tool in Spatial Analyst. The shade of red represents high suitability whereas the shade of green represent low suitability. This suitability map for bioretention ponds/ rain gardens also show higher suitability in west Dallas where the annual precipitation is higher than east Dallas. Also areas closer to the floodplain tend to show more suitable locations for bioretention ponds/ rain gardens than areas further away from the floodplain.

4 CHAPTER 4

RESULTS:

Permeable pavement have been used most commonly and successfully in parking lots. Due to this reason, this study proposes to retrofit existing parking lots

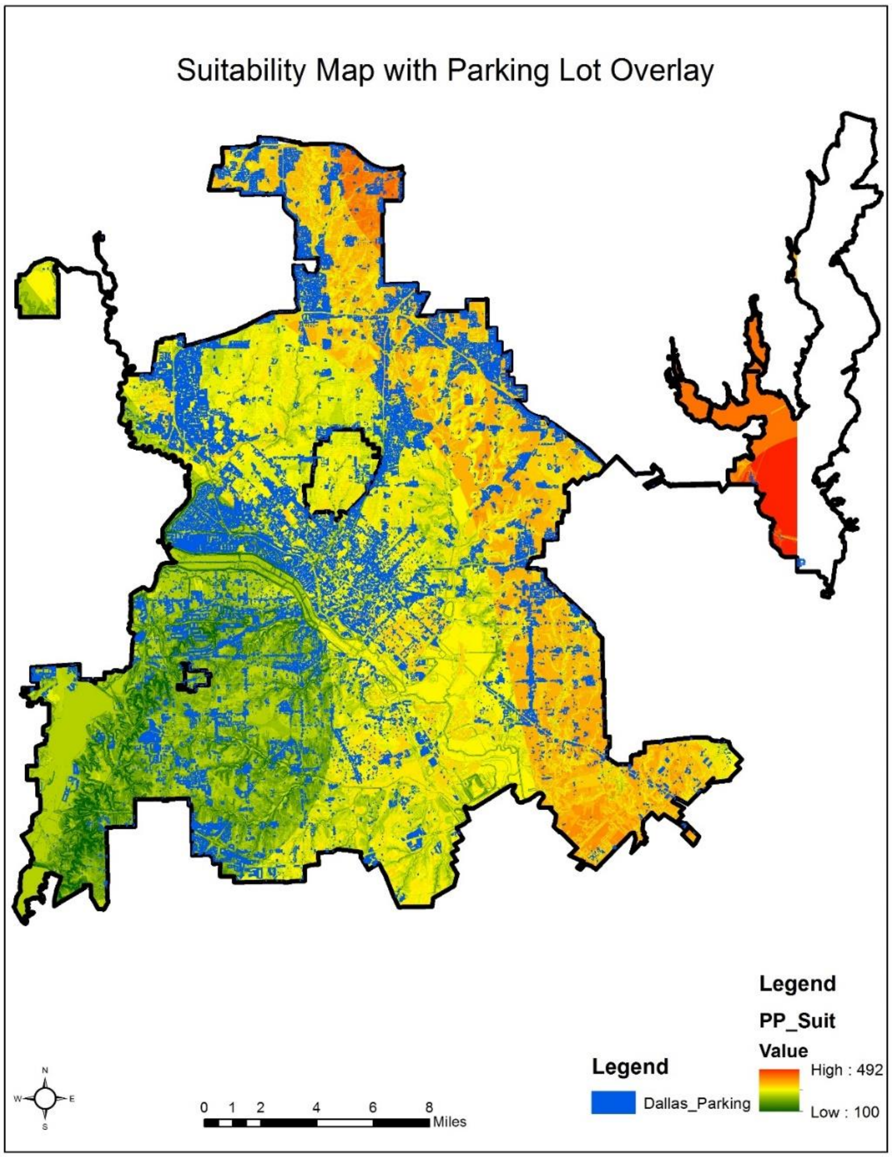

Figure 11: Suitability Map with Parking Lot Overlay

in the City of Dallas to permeable pavements, based on the suitability of the permeable pavements to each specific location.

Out of the 98.87sq.miles of impervious cover excluding building structures, 3.17sq.miles is parking lots which makes up about 3.2% of the total impervious cover. The map above shows that there are considerable number of parking lots in the west of Dallas which are in the high permeable pavement suitability areas.

Similarly bioretention ponds/ rain gardens can be installed in parks and open spaces within the City of Dallas. Parks comprise 26.385 sq. miles (6.74%) of the City of Dallas. They can be utilized as a source of reducing runoff rate and volume in case of extreme flood events by installation of rain gardens/ bioretention ponds within them, and can greatly increase the infiltration capacity of the land area thereby mitigating extreme flood events. The following map below shows the overlay of parks within the City of Dallas over suitability map for bioretention ponds/ rain gardens:

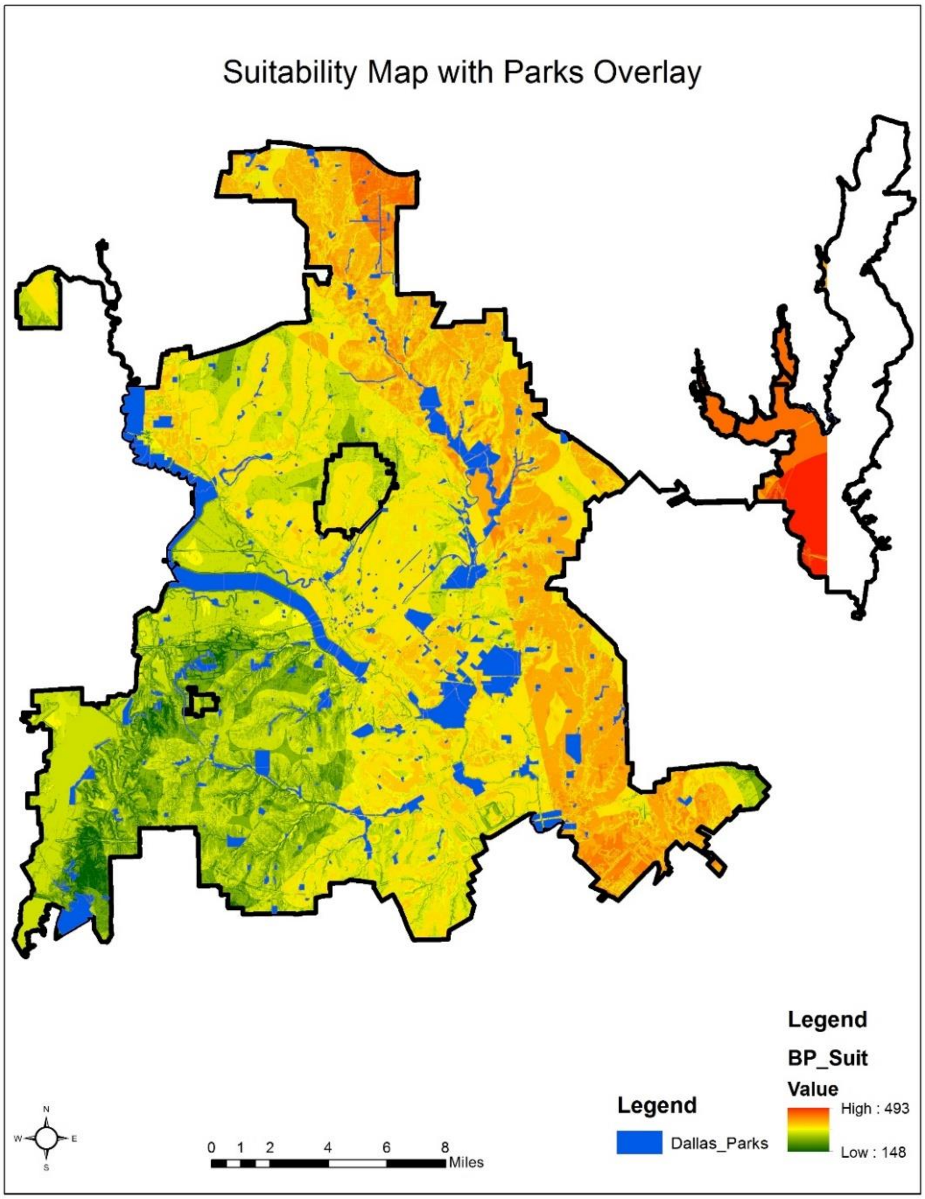

Figure 12: Suitability Map with Parks Overlay

5 CHAPTER 5

CASE STUDY: BIORETENTION FOR STORMWATER MANAGEMENT IN TEXAS; BRYAN/ COLLEGE STATION, TEXAS:

Most of the case studies for Low impact development are from states other than Texas due to which it is hard to assess whether LID BMPs would be effective in Texas with different climatic conditions, soil composition, and vegetation or not. Despite its popularity, the LID strategies such as bioretention is not included in any of Texas Department of Transportation (TxDOT) stormwater management guidelines. TxDOT is in charge of managing 1.1 million acres of rights of way in Texas. In consideration of the regulation by National Pollution Discharge Elimination System (NPDES), the State of Texas has set up a new state stormwater permit system that requires all small scale construction (1 acre minimum) to acquire the MS4 permit. The MS4 permit requires municipalities to include a plan of or implement BMPs to reduce pollutant runoff from municipal operations (Texas A&M Transportation institute, 2013).

In 2007 some researchers from Texas A&M University, College Station conducted pilot and field experiments to measure the performance of bioretention cells within the climatic, soil and vegetation conditions of Texas. The purpose of this project was to demonstrate the effectiveness of bioretention to be used by TxDOT as stormwater management strategy. The researchers first conducted pilot studies using 5 bioretention cells on the Texas A&M University Riverside Campus followed by a field experiment to demonstrate its applicability on real world scenario. This was a 4 year project (2008 -2012) with a total budget of almost $463,000. Out of this 95% was for research while 5% ($9,000) was used to construct the facility. Out of this $9,000, $1,900 was used for labor, $3,300 for equipment, and $3,900 for materials for this 640sq.ft facility.

5.1 Pilot Study:

For the Pilot Study, 5 bioretention cells were constructed using metal garbage dumpsters having the dimensions of 6ft long, 6ft wide, and 4ft deep. The bottom of the cell was lined with a perforated PVC pipe to collect the outflow. On top of the pipe was placed an 8 inch layer of gravel followed by 4 inch layer of pea gravel, and 2ft depth of compost amended soil. In four of the five cells, the soil was topped with native vegetation such as Bermudagrass, while the fifth one was left without vegetation to be used as a control.

The results of the pilot study showed the peak flow rate of effluent was significantly reduced compared to the peak flow rate of influents. The control cell demonstrated more detention time and so more pollution removal compared to vegetated ones. The reason being vegetation increases infiltration and thereby provides less time for pollutants to be adsorbed to the soil and broken down. However, all the five cells demonstrated reduced metal, Nitrogen (N) and Phosphorus (P), and Total Suspended Solid (TSS) concentrations.

5.2 Field Experiment:

In order to conduct the field experiment, the site selected was in Bryan, Texas close to a gas station where SH 21 meets the service road (SH 6 frontage). The site selection was based on cost, proximity, adequate pollution load, site specific conditions providing a ponding area and drainage area. The surrounding land use was suburban highway. The main users of the gas station parking was 18 wheelers.

The bioretention facility created was 670 ft^2 with rounded edges for a drainage area of 67200 ft^2 (approximately 2 acres) designed to store a mean 3 hour storm event (0.77 inch). The construction of the bioretention facility was similar to the pilot cells with PVC pipe at the bottom to collect effluents followed by 8 inches of gravel, 4 inches of pea gravel, 18 inches of soil media and vegetation. The researchers used two types of bioretention facilities in the field experiment; 1) with internal water storage (IWS) and 2) without internal water storage (non-IWS). The IWS as created by installing another pipe on top of the underdrain pipe that created a depth of 0.5 meters for internal water storage.

The results of the experiment were obtained over a period of about 1.5 year. Because of drought in 2011, TxDOT extended the project for a year to assess the exact performance of bioretention facility. The results for IWS were obtained in Spring 2012 and for non-IWS in August 2012. Both IWS and non-IWS show significantly reduced peak flow rates and increased detention times for filtration of pollutants. The IWS facility was comparatively more affective than non-IWS facility. The non-IWS facility removed moderate amounts of metals, N and P, and TSS whereas IWS facility removed nearly all TSS, more amounts of N and P than non-IWS, and significant amounts of metals. The maintenance of the cell was minimal except for occasional irrigation in case of drought.

6 CHAPTER 6

CONCLUSION:

In the wake of fast urban growth of DFW Metroplex the City of Dallas can be a pioneer in promoting green infrastructure by incorporating LID practices into the current stormwater management infrastructure. LID practices for stormwater management not only has significance in reducing impacts of floods due to extreme precipitation events, it also causes ground water recharge, and filters runoff pollutants. Two main hindrances in the implementation of LID strategies are considered to be the cost of implementation and maintenance as well as state and municipal government policies that do not encourage LID BMPs.

Recently numerous studies have been published that indicate the cost of implementation of and maintenance of LID is less than the cost of installation of conventional stormwater systems especially if the ecosystem services such as groundwater recharge, pollutant filtration, and reduction in flooding are also considered. However, the cost is largely dependent upon the site specific conditions. According to an EPA report in which 17 Low Impact Development case studies were compared for their cost with conventional stormwater management system, most of them showed reduced costs of LID compared to conventional stormwater management systems. However, some studies still showed higher costs of LID compared to conventional LID strategies (US EPA, n.d.-a).

Many of the state and municipal governments also do not promote LID through public policy. The case study presented above mentions the lack of LID strategies in TxDOT guidelines for stormwater management on public right of ways. One of the reasons could be the inadequate information regarding the performance of LID strategies in varying climatic, hydrological, soil, and ecological conditions. Further research needs to be done regarding performance of LID strategies in making them more adaptable to varying site conditions and in reducing costs through innovation and efficient use of materials and resources.

APPENDIX

ADDITIONAL ATTACHMENTS

Survey:

Suitability Analysis for Low Impact Development

Suitability Analysis for Permeable Pavement and Bioretention Ponds in the City of Dallas

GIS Suitability Analysis is a method of identifying suitable locations for different land uses based on factors affecting that land use. The factors can include soil composition, slope, etc. I am working on finding suitable parking lot locations for permeable pavement and suitable locations in parks and open space for bioretention ponds in the city of Dallas. This suitability Analysis is based on four factors: Slope, Soil Hydrologic Characteristics, Annual Precipitation, and proximity to Flood Plain. For each of these variables. In order to determine the relative importance of each particular variable at one particular location, I need expert opinion on which variable has more weight compared to all the others at each location. My study focuses on reducing runoff volume to prevent flooding. The purpose of my study is to present a proactive strategy to enhance the capacity of current storm water management system in case of extreme flooding similar to the flooding during April and May this year in Dallas. Please fill out this survey to give your opinion on the the strength of each variable compared to all the other variables. Thank you!

1. What is your opinion on the importance of each particular variable compared to other variables for suitability of Permeable Pavement in the City of Dallas

	Extremely important	Fairly Important	Moderately Important	Slightly Important	Not important
Slope					
Soil Hydrologic Characteristics					
Annual Precipitation					
Proximity to Flood Plain					

2. What is your opinion on the importance of each particular variable compared to other variables for suitability of Bioretention Ponds in the City of Dallas

	Extremely Important	Fairly Important	Moderately Important	Slightly Important	Not Important
Slope					
Soil Hydrologic Charactertics					
Annual Precipitation					
Proximity to Flood Plain					

Done

Powered by SurveyMonkey

Survey Question 1 Response Summary:

Q1

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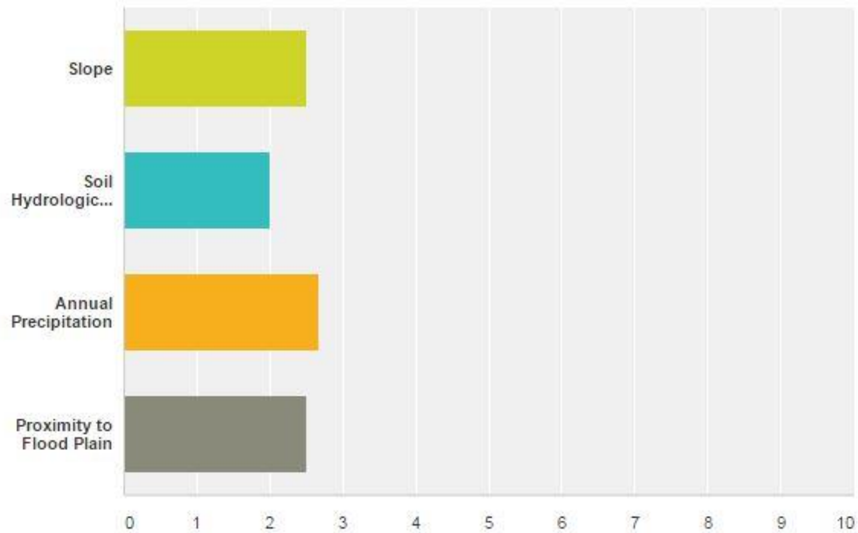
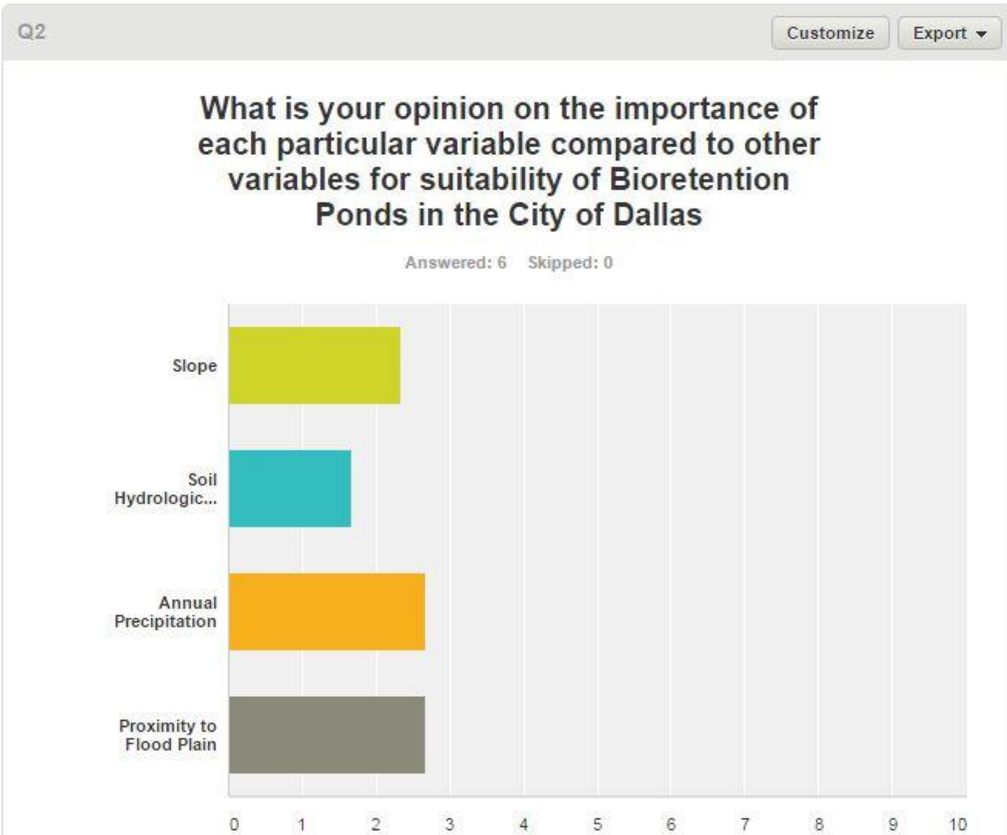
What is your opinion on the importance of each particular variable compared to other variables for suitability of Permeable Pavement in the City of Dallas

Answered: 6 Skipped: 0



	Extremely important	Fairly Important	Moderately Important	Slightly Important	Not important	Total	Weighted Average
Slope	16.67% 1	33.33% 2	33.33% 2	16.67% 1	0.00% 0	6	2.50
Soil Hydrologic Characteristics	33.33% 2	50.00% 3	0.00% 0	16.67% 1	0.00% 0	6	2.00
Annual Precipitation	33.33% 2	16.67% 1	16.67% 1	16.67% 1	16.67% 1	6	2.67
Proximity to Flood Plain	16.67% 1	50.00% 3	16.67% 1	0.00% 0	16.67% 1	6	2.50

Survey Question 2 Response Summary:



	Extremely Important	Fairly Important	Moderately Important	Slightly Important	Not Important	Total	Weighted Average
Slope	0.00% 0	83.33% 5	0.00% 0	16.67% 1	0.00% 0	6	2.33
Soil Hydrologic Charactertics	66.67% 4	0.00% 0	33.33% 2	0.00% 0	0.00% 0	6	1.67
Annual Precipitation	33.33% 2	16.67% 1	16.67% 1	16.67% 1	16.67% 1	6	2.67
Proximity to Flood Plain	16.67% 1	33.33% 2	33.33% 2	0.00% 0	16.67% 1	6	2.67

Individual Survey Responses:

#1

COMPLETE

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PAGE 1: Suitability Analysis for Permeable Pavement and Bioretention Ponds in the City of Dallas

Q1: **What is your opinion on the importance of each particular variable compared to other variables for suitability of Permeable Pavement in the City of Dallas**

Slope	Fairly Important
Soil Hydrologic Characteristics	Extremely important
Annual Precipitation	Extremely important
Proximity to Flood Plain	Moderately Important

Q2: **What is your opinion on the importance of each particular variable compared to other variables for suitability of Bioretention Ponds in the City of Dallas**

Slope	Fairly Important
Soil Hydrologic Charactertics	Extremely Important
Annual Precipitation	Extremely Important
Proximity to Flood Plain	Moderately Important

#2

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PAGE 1: Suitability Analysis for Permeable Pavement and Bioretention Ponds in the City of Dallas

Q1: **What is your opinion on the importance of each particular variable compared to other variables for suitability of Permeable Pavement in the City of Dallas**

Slope	Slightly Important
Soil Hydrologic Characteristics	Slightly Important
Annual Precipitation	Not important
Proximity to Flood Plain	Not important

Q2: **What is your opinion on the importance of each particular variable compared to other variables for suitability of Bioretention Ponds in the City of Dallas**

Slope	Slightly Important
Soil Hydrologic Charactertics	Moderately Important
Annual Precipitation	Not Important
Proximity to Flood Plain	Not Important

#3

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PAGE 1: Suitability Analysis for Permeable Pavement and Bioretention Ponds in the City of Dallas

Q1: **What is your opinion on the importance of each particular variable compared to other variables for suitability of Permeable Pavement in the City of Dallas**

Slope	Moderately Important
Soil Hydrologic Characteristics	Fairly Important
Annual Precipitation	Extremely important
Proximity to Flood Plain	Fairly Important

Q2: **What is your opinion on the importance of each particular variable compared to other variables for suitability of Bioretention Ponds in the City of Dallas**

Slope	Fairly Important
Soil Hydrologic Charactertics	Moderately Important
Annual Precipitation	Fairly Important
Proximity to Flood Plain	Extremely Important

#4

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PAGE 1: Suitability Analysis for Permeable Pavement and Bioretention Ponds in the City of Dallas

Q1: **What is your opinion on the importance of each particular variable compared to other variables for suitability of Permeable Pavement in the City of Dallas**

Slope	Extremely important
Soil Hydrologic Characteristics	Fairly Important
Annual Precipitation	Fairly Important
Proximity to Flood Plain	Extremely important

Q2: **What is your opinion on the importance of each particular variable compared to other variables for suitability of Bioretention Ponds in the City of Dallas**

Slope	Fairly Important
Soil Hydrologic Charactertics	Extremely Important
Annual Precipitation	Extremely Important
Proximity to Flood Plain	Fairly Important

#5

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PAGE 1: Suitability Analysis for Permeable Pavement and Bioretention Ponds in the City of Dallas

Q1: **What is your opinion on the importance of each particular variable compared to other variables for suitability of Permeable Pavement in the City of Dallas**

Slope	Moderately Important
Soil Hydrologic Characteristics	Extremely important
Annual Precipitation	Moderately Important
Proximity to Flood Plain	Fairly Important

Q2: **What is your opinion on the importance of each particular variable compared to other variables for suitability of Bioretention Ponds in the City of Dallas**

Slope	Fairly Important
Soil Hydrologic Charactertics	Extremely Important
Annual Precipitation	Moderately Important
Proximity to Flood Plain	Moderately Important

#6

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Q1: **What is your opinion on the importance of each particular variable compared to other variables for suitability of Permeable Pavement in the City of Dallas**

Slope	Fairly Important
Soil Hydrologic Characteristics	Fairly Important
Annual Precipitation	Slightly Important
Proximity to Flood Plain	Fairly Important

Q2: **What is your opinion on the importance of each particular variable compared to other variables for suitability of Bioretention Ponds in the City of Dallas**

Slope	Fairly Important
Soil Hydrologic Charactertics	Extremely Important
Annual Precipitation	Slightly Important
Proximity to Flood Plain	Fairly Important

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BIOGRAPHICAL INFORMATION

Muzaib Riaz's Degrees and Certificates include Bachelors of Science in Environmental Science form Forman Christian College University Lahore, Pakistan. He also has a Graduate Certificate in Geographical Information System from The University of Texas at Arlington, College of Architecture Planning and Public Affairs. Write a paragraph here about your academic career, research interests, degrees earned, projects worked on, and/or future plans.

Muzaib has also worked as a Community Development Intern with the City of Carrollton, Texas from October 2014 to June 2015. At the City of Carollton, his job was to execute ongoing administration, monitoring, and reporting for the Neighborhood Enhancement Matching Grant projects and/or programs as required by funding sources and applicable regulations with supervision from staff. Ensure compliance with grant requirements. Maintain, reconcile, and manage program reporting, analyze activities and data to identify and correct inaccuracies, and to ensure compliance with program funds. Prepare reports for our management and our governing board, the Neighborhood Advisory Commission (NAC).