Retrofit Solutions to Reduce Urban Flooding and Related Negative Impacts

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ABSTRACT

Today's cities were not originally designed for the current density levels resulting from over six decades of an increasing global shift in population from rural areas to urban areas. This means that existing stormwater infrastructure was never intended to convey the volumes of runoff generated by the increasing paved and building surfaces. Existing case studies form the basis for this investigation into urban flooding and its impacts. The inadequacy of the stormwater infrastructures leads to urban flooding that can have devastating financial, transportation, and environmental impacts. By implementing retrofit solutions that address the variables contributing to runoff, it is possible to reduce or eliminate the problem of urban flooding without drastic redesigns of the larger stormwater infrastructure systems. Many of these potential retrofit solutions to stormwater management are low impact designs such as rain gardens, pervious pavement, and green roofs. The aim of this research is to provide guidance to those who are facing urban flooding and seeking to successfully implement retrofit solutions.

KEY WORDS: urban flooding, low impact design, runoff reduction, rain gardens, pervious pavement, green roofs, stormwater management

INTRODUCTION

Problem Introduction

When today's urban developments first began, they were not designed for the density levels that exist today. As illustrated in Figure 1 below, global levels of urban population have been continually increasing for over fifty years, and between 2006 and 2007 there was a shift in which for the first time more people lived in urban areas than rural ones (Ritchie H. & Roser M., 2018). With approximately four times more people living in urban centers currently than in 1960, that means there is also more infrastructure needed to house, transport, and service the urban population than in previous decades. In order to provide these services, spaces that were originally green have been transformed into new parking lots, roads, buildings, or other impervious surfaces.

In their *Manual on Flood Forecasting and Warning*, the World Meteorological Organization describes urban flooding as occurring "when intense rainfall within towns and cities creates rapid runoff from paved and built-up areas, exceeding the capacity of storm drainage systems" (2011, p. 1-5). As discussed in an article by Molly Oshun, overflowing of drainage systems and waterways during urban floods causes billions of dollars of damage as private property and roadways flood, yet urban flooding is understudied and less regulated compared with riverine and coastal flooding (2017).

According to a United Nations report, from 1900 to 2006, nearly 30% of all natural disasters on record were floods, and those floods account for over 18% of the total natural-disaster deaths. Nearly one-half of all people impacted by natural disasters during those years were impacted by flooding. While all of those floods were not urban flooding, it is clear from this data that flooding can have large impacts on society. As illustrated in Figure 2 below, there has been an overall net increase in the number of floods for all global regions between 1980 and 2006 (Adikari Y. et al, 2009). As urban populations increase, flooding remains a global concern and urban flooding will continue to impact a growing number of people.

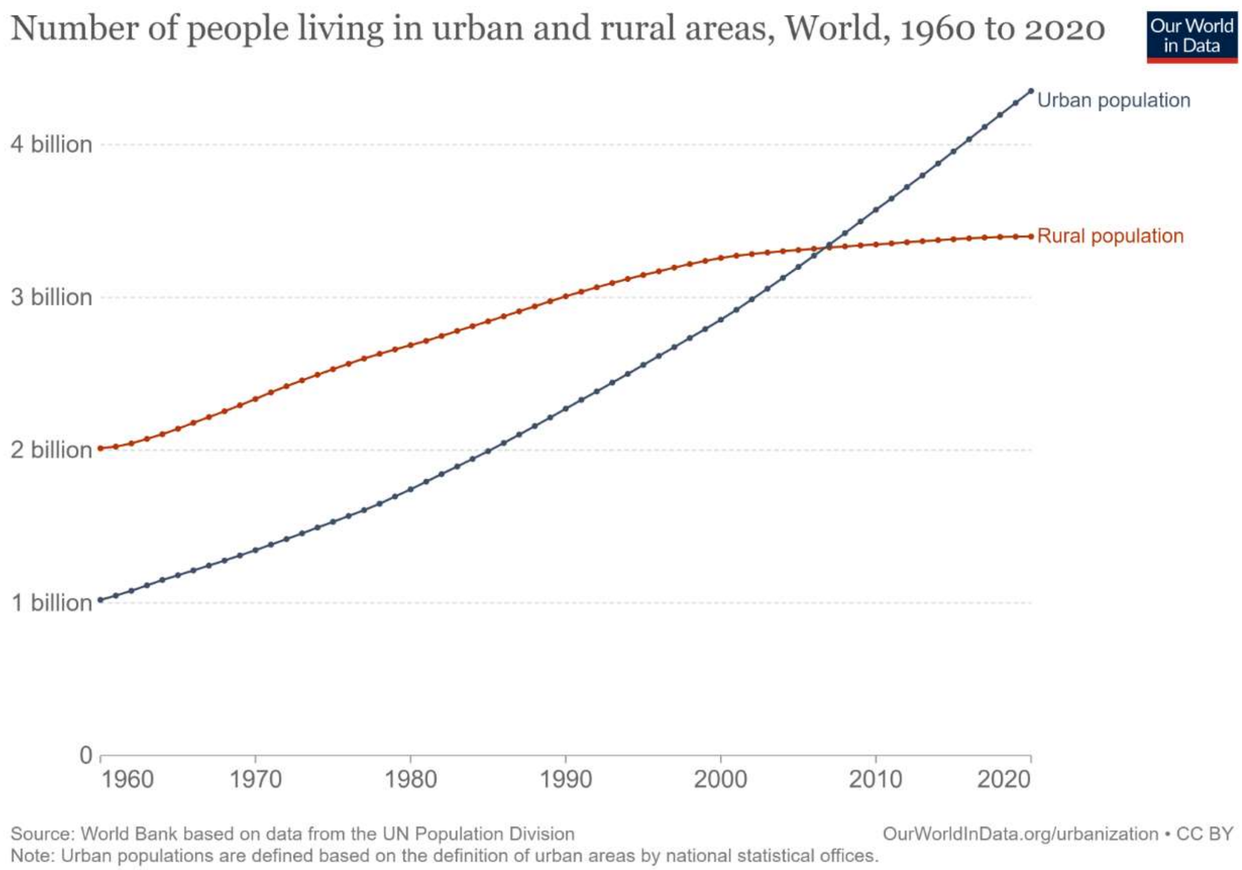

Figure 1 – Number of People Living in Urban and Rural Areas Globally (Downloaded from https://ourworldindata.org/urbanization on Oct 23, 2021)

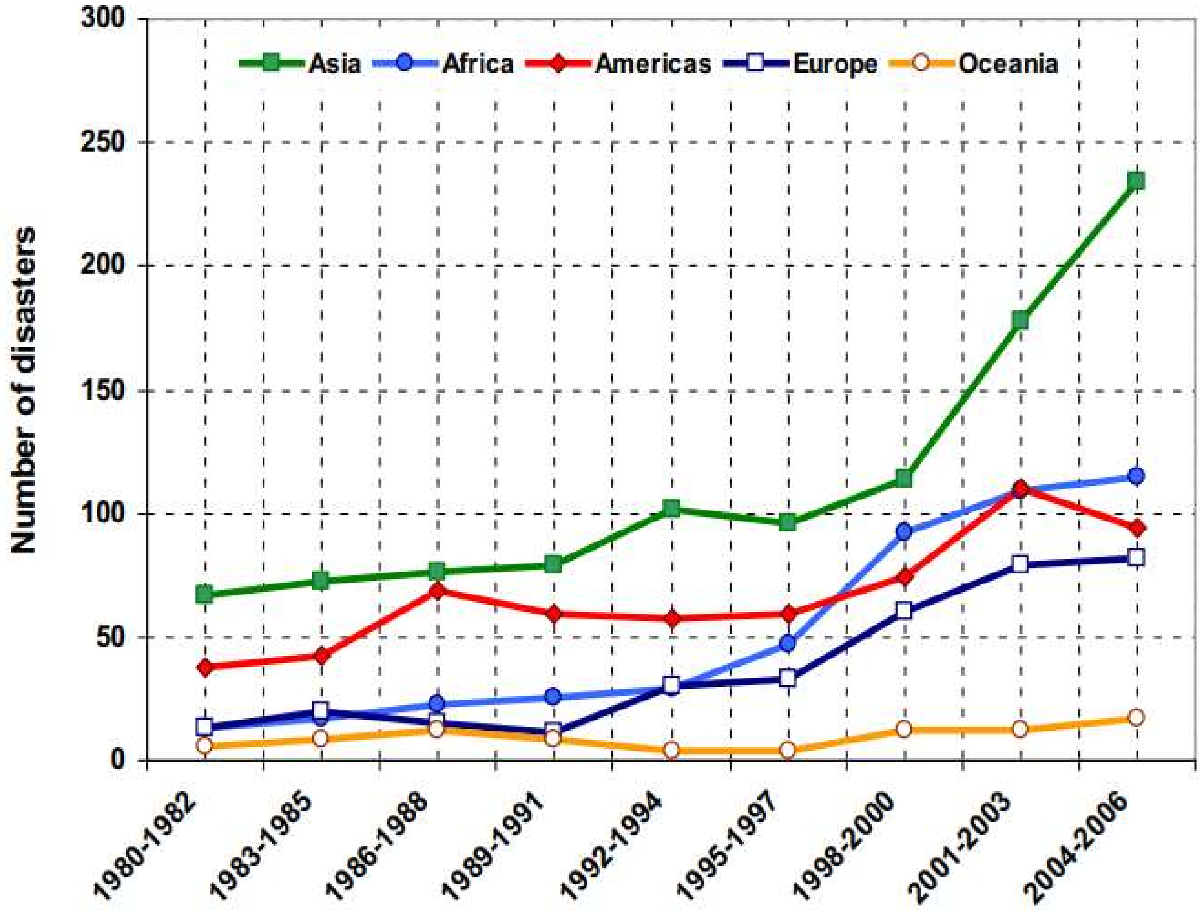

Figure 2 – Flood Events on Record by Region from 1980 to 2006 (Adikari Y. *et al*, 2009)

Justification, Scope, and Limitations

As mentioned above, many urban areas were not designed with the current density of impervious surfaces anticipated. Often, existing guides for stormwater infrastructure are centered around new development. While those guides are helpful for their intended purpose, they aren't always directly translatable to addressing existing built environments. For example, it is often impractical or impossible to increase existing storm sewer sizes to handle the increased flow volumes to the size that would be recommended by a design guide. Existing developments may not have room to install the size of detention ponds that would be recommended or required by a design standard. For this reason, it is necessary to also have guidance available for implementing retrofit solutions.

Since stormwater can have such tangible impacts on the environment, there are many case studies, products, and potential solutions for addressing urban flooding. For this reason, it is feasible to center the integrated project report around this topic and compile the information in a way that makes it accessible and applicable. The intended scope of the project is to serve as an introductory document covering the need for a solution, potential solutions, and the factors impacting the implementation of solutions. The potential solutions given will be covered in a more general way within the report, and the references cited in the report will allow the reader to do more in-depth investigation once they have identified their options.

Given the complexity of the factors contributing to the management of stormwater, this integrated project report will have limitations on what is included. For example, there are whole textbooks covering individual variables within stormwater design such as soil type. The report is not intended to be a single-source detailed guide including every possible problem and solution within the topic. Rather, this report contains an overview of the approach to solving urban stormwater management problems.

OBJECTIVES AND RESEARCH QUESTIONS

General Objective and Research Questions

The general objective of this integrated project report is be to provide a compilation of information related to retrofit solutions for urban stormwater. The goal is that this information can serve as a launching point for the assessment of stormwater management needs in existing urban areas and potential solutions framed around existing case studies. Several questions will be addressed by the content of this report: where are retrofit stormwater solutions needed, what are potential solutions, and how should the solutions be implemented and regulated? Figure 3 below shows a summary of the proposed research questions and their limitations.

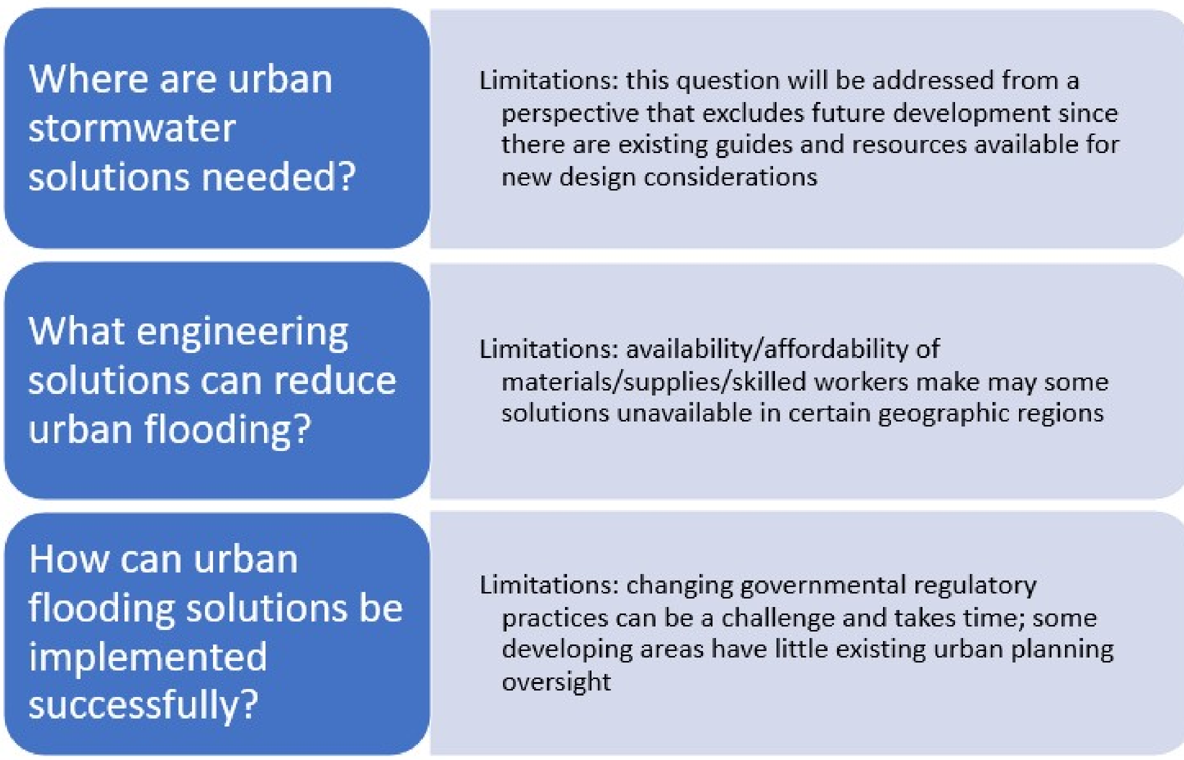

Figure 3 – Research Questions

Intermediate Objectives and Project Timeline

Meeting the project objectives requires the compilation of data in several areas. Case studies from previously implemented stormwater projects will be assessed from an engineering standpoint for their applicability, successes, and limitations. In addition to the engineering perspective, case studies will also be analyzed from a financial and regulatory standpoint in cases for which those aspects are included in the study documentation. In order to compile options for retrofit solutions for urban stormwater, a few visual guides will be provided with information on possible solutions, such as rain gardens and green roofs.

Figure 4 below shows the Gantt chart for the integrated project. The tasks are organized by the intermediate assignments, *tareas activas*, that were completed as part of the project process. The final item, the *tarea núcleo*, is this report.

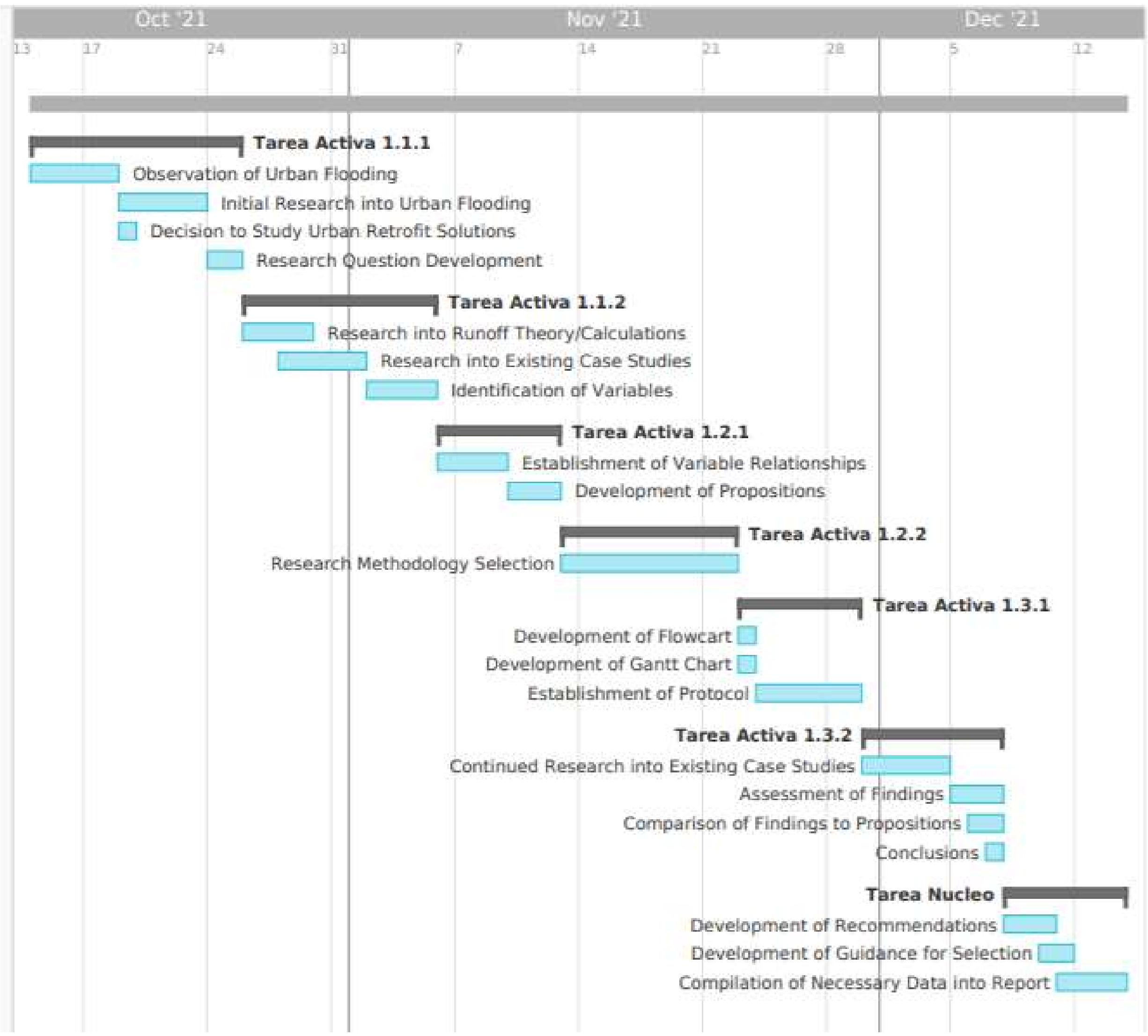

Figure 4 – Integrated Project Gantt Chart (created using the Free Edition of "teamgantt" available at https://www.teamgantt.com/)

THEORETICAL FOUNDATION

SCS Runoff Calculation Method

In 1986 the USDA released their Technical Release 55, typically abbreviated TR-55, which covers a methodological approached to stormwater calculations in small, urban watersheds. Due to the scope of TR-55's content, the methodology provides guidance for making estimates and reasonable assumptions based on available data. Unlike riverine flood analysis, urban watersheds often do not have well-documented or long-term flow data. TR-55's methodology takes into account several variables that contribute to the final calculated flows. The method discussed in TR-55 allows designers to calculate flows for various storms and different times within those storms. The input variables include rainfall, runoff, time, and storage effects. Each of these variables is covered in additional detail below.

For rainfall, TR-55 divides the United States into four areas with associated rainfall-time distributions. The distributions were developed based on the intensities of typical regional storms using available duration-frequency data. In addition to these rainfall distributions, rainfall depths for most of the country are shown with lines over a map of the entire country with each state and county outlined. Depth data is given for 24-hour storm periods for the following storms: 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year. The areas of the Western United States not included in TR-55 and the most current available data for anywhere in the US can be found in the National Oceanic and Atmospheric Administration (NOAA) Precipitation Frequency Estimates. Many municipalities will have a design manual with the specific rainfall data and design storms they want engineers to use in their calculations to ensure consistency.

Runoff is calculated using the SCS curve numbers in the TR-55 methodology. The primary factors that contribute to the curve number are the hydrologic properties of the soil and the type of ground cover. There are four hydrologic soil groups that represent different ranges of infiltration rates. Type A soils infiltrate the most water and Type D infiltrate the least. "Most urban areas are only partially covered by impervious surfaces: the soil remains an important factor in runoff estimates" (USDA, 1986, p. 2-1). The types of cover in TR-55 range from desert shrub to parking lots. With the hydrologic soil group and cover type, TR-55's tables can be used to determine the curve number.

The main time factor in TR-55 is the time of concentration. Time of concentration is defined as "the time for runoff to travel from the hydraulically most distant point of the watershed to a point of interest within the watershed" (UDSA, 1986, p. 3-1). The hydraulically most distant point means the point from which it takes the longest for the flow to reach the point of interest. Several factors contribute to the travel times of water within a watershed: surface roughness, channel shape, flow patterns, and slope. Due to the influence of these factors, the time of concentration is not necessarily the longest physical path that water will travel. For example, a physically shorter path over thick grass can be a slower path of travel than a longer distance over a smoothly paved surface.

Storage has an impact on when peak discharges occur at a point of interest downstream of the storage. An example of traditional storage would be a detention pond. This happens because for storage to occur, the outflow from the storage must be at a slower rate than peak inflow to the storage. TR-55 has equations and graphs to assist designers with calculating the effects of storage. As with most methodologies, there are also various software options available that use the TR-55 methodology so that the designer does not have to do the calculations by hand.

Identifying Variables

Variables Related to Stormwater Flow

The determination of where urban flooding is occurring is typically a matter of observation or reporting by affected parties. In order to determine contributing conditions where stormwater solutions are needed, it is necessary to quantify the flow at key points of interest. For urban retrofit projects, these calculations take into account existing developed conditions and design storm rainfalls based on historic rainfall data. As discussed above, there are a variety of variables related to stormwater calculations.

With a focus on the SCS method, the variables are flow, rainfall, runoff factor, time, path of travel, drainage area, and storage effects. The runoff factor can be further broken down into soil type and cover or land use. Rainfall, cover type, soil, length of travel, storage, and area are the independent variables. Designers do not have control over the rainfall, but the rest can be manipulated to varying extents. The independent variables influence the dependent variables: flow and time of concentration. The tables below show the relationships between the variables based on the SCS calculations as described in TR-55. A designation of "Direct" means that if the independent variable increases, the dependent variable increases. Likewise, if the independent variable decreases, so does the dependent variable when there is a direct relationship. The opposite is true of the "Indirect" correlations: if the independent variable increases or decreases, the dependent variable does the opposite. It should also be noted that the time of concentration and peak flow have an indirect relationship; the faster the runoff reaches the point of interest (lower time of concentration), the higher the peak flow will be.

Table 1 – Relationship Between Independent Variables and Peak Flow

Independent Variable	Relationship to Peak Flow
Rainfall Amount	Direct
Cover Porosity	Indirect
Soil Porosity	Indirect
Storage Amount	Indirect
Drainage Area	Direct

Table 2 – Relationship Between Independent Variables and Time of Concentration

Independent Variable	Relationship to T_C
Length of Travel	Direct
Cover Roughness	Direct
Storage Amount	Indirect

In addition to knowing the relationships between the variables, it is important to look at the ability of these variables to be manipulated. In the context of finding retrofit solutions to urban flooding, it is important to know both the amount of flow to be dealt with and what contributing factors (independent variables) can be modified. Table 3 below shows the manipulability of the independent variables related to SCS flow calculations.

Table 3 – Manipulability of Independent Variables – Flow

Independent Variable	Ability to Manipulate	Notes
Rainfall Amount	no	weather cannot be changed
Cover Porosity	yes	even fully urbanized cover can be changed
Soil Porosity	yes & no	changeable for small areas but not whole watersheds
Length of Travel	yes	flow can be rerouted or given obstacles to go around
Storage Amount	yes	storage can be decreased or increased
Drainage Area	yes	sub-areas within the overall watershed can be changed

Variables Related to Impacts of Unmitigated Urban Flooding

Unlike stormwater flow calculations, the variables contributing to the impacts of unmitigated urban flooding can be difficult to define due to the complexity. The following table shows a list of some of the variables involved in urban flood impacts.

Table 4 – Variables in Urban Flood Impacts

Independent Variables	Dependent Variables
Location/Elevation of Utility Structures	Cost of Repair
Depth of Flooding	Disruption of Travel
Location of Flooding	Increased Flow at Sewer Treatment
Volume of Flooding	Contamination
Location of Building Structures	
Level of Floodproofing of Structures	
Current/Former Land Use at Location of Flooding	
Cost of Material and Labor	

The location and elevation of utility structures are important for two primary reasons: floodwater may enter into the structures or erode the soil that supports them. According to FEMA, "a large portion of flood damage is incurred by components of building utility systems" (1999, p. 1-2). If flooding is deeper than the local sanitary sewer structures, rainwater runoff can enter the structures and impact the volumes reaching the treatment plant; if the flooding is severe enough, raw sewage may come up out of the structures in what is known as a wet-weather sanitary sewer overflow (Ogidan, O., & Giacomoni, M., 2016). Land use is an independent variable because the type and quantity of pollutants that can be transported by stormwaters depends on what is or was happening on the land (Euripidou, E., & Murray, V., 2004). For example, a parking lot typically has oil and other leaked chemicals from vehicles on its surface, and a former industrial site could have industry-related pollutants still in the soil even after the site ceases industrial operations. Land use also influences whether or not urban flooding impacts transportation. Flooding of parking lots, roadways, sidewalks, trails, and stops or stations can all directly create interruptions to transportation of goods and/or individuals within the urban network. Material and labor prices come into play when flood damage needs to be repaired.

As with the stormwater calculations, only some of the independent variables can realistically be manipulated for an existing urban area. While it may be physically possible to move existing buildings or large utility structures such as manholes, it is not feasible in most existing cases. Table 5 below identifies which independent variables can reasonably be manipulated.

Table 5 – Manipulability of Independent Variables – Flood Impact

Independent Variables	Reasonably Manipulated?
Location/Elevation of Utility Structures	Sometimes
Depth of Flooding	Yes
Location of Flooding	Yes
Volume of Flooding	Yes
Location of Building Structures	No
Level of Floodproofing of Structures	Sometimes
Current/Former Land Use at Location of Flooding	No
Cost of Materials and Labor	No

As shown in the table above, the variables most feasibly controlled regarding flooding impacts are the depth, location, and volume of flooding. This means that ultimately, to minimize the effects of urban flooding, the variables shown as manipulatable in Table 3 are key. The prioritization of where to implement changes depends on the severity of impacts to the dependent variables shown in Table 4.

<u>Variables Related to Solution Implementation</u>

In order for implementations to be successful, more than engineering is needed. In the reality of urban developments, there are a variety of stakeholders. Each of these stakeholders will have their own motivations, resources, and level of investment in the situation. Table 6 below includes a list of some of these stakeholders with regards to flood mitigation in the urban environment along with an approximate level of interest and influence for each.

Table 6 – Stakeholders in Urban Flooding Solutions

Stakeholders	Level of Interest	Level of Influence
Local Government	moderate to high	high
Impacted Businesses	high	low to moderate
Impacted Utility Providers	high	moderate to high
Impacted Users of Infrastructure (roads, sidewalks, ec)	moderate	low
Impacted Homeowners	high	low
External Engineering/Environmental Groups	moderate to high	low to moderate
State/Federal Government	low to moderate	moderate to high

The reasons for the interest in urban flooding solutions typically differs from group to group. For example, businesses and homeowners are likely to have an interest because of the financial or physical damage to their property. Utility providers may have an interest in reducing the risk to their employees and equipment involved in making repairs to flood damaged structures in addition to a financial interest. Road and sidewalk users usually don't have a strong financial interest as much as a convenience interest since they may have to be rerouted around flooded areas. For external environmental interest groups, their level interest could vary based on the environmental impacts of flooding at given locations. Local government has an interest from both infrastructure and economic positions. State and Federal government entities are often invested only in flooding that has a large-scale impact. For example, situations relating to federally designated floodplain in the United States will trigger federal interest.

As with levels of interest, levels of influence are also based on a variety of factors. Those with the ability to change legislation hold high levels of influence. Groups or agencies that develop design codes have influence on how problems are addressed. Businesses, groups, or individuals with strong economic influence can help bring issues to the forefront of discussions. For example, a large business that attracts people to the area will likely have more direct access to decision-makers than the owner of a small single-family home. Another source of influence is the relationship to public health; this could include providers of potable water, water treatment, hospitals etc. Table 7 below summarizes some of the independent variables that impact the interest and influence levels.

Table 7 – Independent Variable Related to Levels of Interest and Influence

Independent Variables - Interest	Independent Variables - Influence
Damage to Property	Legislative Power
Risk to People	Regulation or Code Development/Adoption
Restriction of Physical Access	Economic Influence
Environmental Impacts (pollution, erosion, etc)	Proximity to Leaders in Government
Reduction of Property Value	Public Health Impact
Changes to Regional or National Floodplain	

There is another set of variables related to stakeholders and the successful implementation of stormwater solutions in the urban environment. These variables are related to resources. Different stakeholders have different resources based on their relationship to the situation. Table 8 below shows some of the variables related to the implementation of urban stormwater solutions. Table 9 shows a general relationship between the stakeholders and the implementation variables.

Table 8 – Independent Variables Related to Implementation

Independent Variables - Implementation
Engineering Knowledge/Guidance
Finances
Space (land area, roof area, etc)
Time
Maintenance Equipment

Table 9 – Stakeholder Relationships to Implementation Variables

Stakeholders	Independent Variables - Implementation				
	Knowledge	Finances	Space	Time	Maint Equip
Local Government	probable	probable	possible	probable	probable
Impacted Businesses	improbable	possible	possible	possible	improbable
Impacted Utility Providers	possible	probable	improbable	improbable	possible
Impacted Users of Infrastructure	improbable	improbable	improbable	possible	possible
Impacted Homeowners	improbable	improbable	probable	probable	possible
External Environmental Groups	probable	possible	improbable	possible	improbable
State/Federal Government	probable	probable	improbable	improbable	possible

One difference between the variables related to stakeholders and those discussed in the previous sections is that they are not easily directly manipulated. Engineering knowledge can be gained by those that don't have it, but only to a certain point without formal education. In this case, instead of manipulating the variables, it is the way that they are combined that becomes important. For example, an individual cannot easily change the level of economic influence they have in order to raise their influence regarding solutions for urban flooding.

PROPOSITIONS

Proposition 1

The first proposition for the integrated project is "urban flooding can be reduced or eliminated by the implementation of localized solutions that impact one or more of the independent variables in the SCS methodology." This is linked to the following research question: what engineering solutions can reduce urban flooding? As mentioned previously, the upgrade of existing infrastructure to meet current design codes or recommendations is often infeasible. For example, it is often unreasonable to proposed the upgrade of city-wide storm sewer systems to handle the additional flows resulting from full urbanization. For that reason, the project focuses on less invasive solutions such as the rain gardens, pervious pavement, and green roofs.

Proposition 2

The second proposition for the integrated project is, "Proper mitigation of urban flooding can reduce negative financial, transportation, and environmental impacts caused by floods." This proposition is linked to the following research question: where are urban stormwater solutions needed? The location where the implementation of solutions should be prioritized depends on the severity of the observed and/or calculated impact(s).

Proposition 3

The third proposition for the integrated project is "successful implementation of solutions to urban flooding is tied to combining the input and resources of stakeholders with both high interest and high influence." This proposition is linked to the following research question: how can urban flooding solutions be implemented successfully? The third proposition centers around creating groups that involve parties with high interest, high influence, and the necessary resources for successful implementation including maintenance.

METHODOLOGY

Scope

Since each of the three propositions is related to relationships between independent and dependent variables, the scope of the proposed integrated project is primarily explanatory. Though each proposition is related to how different variables correlate, the research is focused more on the “how” than the “why” of each relationship. Proposition One is connected to the relationship between urban flooding runoff and the independent variables of the SCS methodology. Proposition Two is connected to the relationship between reducing urban flooding and the independent variables of financial, transportation, and environmental impacts. Proposition Three is based on the relationship between successful implementation of solutions and the independent variables of stakeholder interest and influence.

Type of Study

The type of study will be qualitative since the propositions do not include specific numerical predictions. Proposition One is related to the reduction of urban flooding, but this reduction is not quantified. Proposition Two is related to the reduction of negative impacts by reducing flooding, but this reduction is not quantified either. Proposition Three is related to the successful implementation of solutions, and no quantifier is given for what constitutes success. Even though the proposed study is qualitative, it will primarily be centered around existing quantitative research.

Approach

The approach of the integrated project is based on the use of existing case studies. Since the research is qualitative and not dealing with a group of subjects over time nor assessing subjects at a snapshot in time, it is neither longitudinal nor cross-sectional. Due to time constraints, a new case study or experiment is infeasible.

Sample Profile

The integrated research project is centered around retrofit solutions to urban flooding. Therefore, the primary focus of the research for Propositions One and Two is areas that are already urbanized and solutions that are feasibly implemented in that context. The case studies have to fit within those criteria in order to be fully applicable. Some of the case studies have been applied theoretically using stormwater modeling software to a real-world location, and some of the case studies have been implemented in-situ. By using a combination of theoretical applications and actual applications, the relationships between the variables can be more clearly identified as well as corroborate that the theoretical assumptions are reasonable. Proposition Three will look at case studies which include implementation in the urban context and contain information regarding stakeholder involvement.

Measurement Instrument

As mentioned in the previous section, one of the principle means for obtaining evidence will be the use of previously documented case studies. Another source is documentation related to the theory of stormwater runoff calculations with the SCS methodology being the central focus. The launching point for the integrated project was the direct observation of some of the consequences of inadequate urban stormwater management, but this will not be a primary measurement instrument for the evaluation of the propositions. Although a majority of the measurement instruments are classified as documentation, the nature of the literature on the theory and the case studies allows for a triangulation of the evidence collected.

Summary of the Research Methodology

The following figure summarizes the overall methodology of the project.

Scope

- Explanatory

Type of Study

- Qualitative

Approach

- Existing Case Studies

Sample Profile

- Urban Context
- Retrofit Flooding Solutions
- Existing Case Studies - Theoretical and Implemented

Measurement Instrument

- Documented Case Studies
- Published Theory Texts

Figure 5 – Summary of the Project Methodology

RESULTS

Proposition 1

In order to analyze this proposition, it is necessary to look at case studies in which one or more of the independent variables were manipulated to see if these changes led to reduced or eliminated flooding. The following studies show which variables were manipulated and what changes resulted.

Study 1: Green Roofs in Eindhoven, The Netherlands (Costa S. et al, 2021)

In this study, two different green roof scenarios were modeled in Eindhoven. In one, green roofs were added to all flat roofs with an individual area under 2,000 square meters. In the other, they modeled the implementation of green roofs on half of the flat industrial roofs in Eindhoven. The first scenario resulted in an implementation of 393 hectares, and the second scenario resulted in an implementation of 105 hectares. By changing traditional roof cover to green roofs, the team manipulated the following variables within the footprint of the implementation: cover porosity, soil porosity, and storage amount. Each of the variables was increased which, per the SCS method, leads to a decrease in peak runoff volumes. The following table shows the percent decrease in flooded area and flooded volumes. As shown, the manipulation of the variables led to decreased flooding for the modeled 5, 10, and 100-year storms.

Table 10 – Green Roof Reduction in Flooding from the Base Scenario - calculated from the data reported by Costa S. et all (2021)

Scenario	% Decrease in Flooded Area			% Decrease in Volume		
	T=5 Years	*T=10 Years*	*T=100 Years*	*T=5 Years*	*T=10 Years*	*T=100 Years*
1st	32.15	22.54	17.30	36.94	27.54	22.07
2nd	7.77	5.87	5.15	8.92	7.19	5.72

Study 2: Pervious Pavement in Kansas (Yan-wei Sun et al, 2011)

In this study, the effects of pervious pavement were modeled in comparison with both the undeveloped and developed conditions of the site. The site that was investigated has an area of 17,000 square meters with a developed impervious area of 86%. Pervious pavement was modeled to replace the 8,700 square meters of parking surface. By modeling pervious pavement in place of traditional pavement, the study manipulated the following SCS variables: cover porosity, soil porosity, and storage amount. The soil porosity is changed within the footprint of the pervious pavement by the addition of a gravel base material under the pavement. The following table shows the results of the modeled scenarios. As demonstrated by the values in the table, for the given site conditions, the pervious pavement condition has less stormwater runoff than the undeveloped condition. This means that the manipulation of the SCS variables as modeled would drastically reduce if not eliminate localized flooding.

Table 11 – Peak Flows and Runoff Volumes for Three Scenarios – data from Yan-wei Sun et al (2011)

Scenario	**Peak Flow (m^3/s)**			**Runoff Volume (m^3)**		
	T=2 Years	*T=10 Years*	*T=100 Years*	*T=2 Years*	*T=10 Years*	*T=100 Years*
Undeveloped	0.290	0.062	0.141	326.5	474.3	1191.2
Dev - no control	0.251	0.428	0.722	3512.0	1873.0	2887.0
Pervious Pavement	0.007	0.018	0.037	21.1	50.30	508.6

Study 3: Rain Gardens Across the United States (Jennings A.A., 2016)

This study is another theoretical study that uses actual location-specific data. 35 sites for which there was sufficient historic rainfall data were selected for the modeling of a rain garden. The same rain garden was modeled in each location, and the rain garden was modeled to collect flow from half of a residential roof based on the average roof size of a home in the United States. The manipulated SCS variables may vary slightly depending on the existing conditions at each site, but in general they are: cover porosity, soil porosity, length of travel, and storage amount. Whether the cover and soil porosities are changed or nor would depend on the typical soil profile and cover in each geographic location. The following table summarizes the reduction in runoff at each modeled site. As shown by the data in the table, the runoff for the drainage leaving the half of the roof was reduced by between 51% and nearly 100% depending on the location. These reductions reflect a decrease in runoff and therefore in flooding at all 35 locations across the States.

Table 12 – Runoff Reduction using a Rain Garden – data from Jennings (2016)

Location	Total Precipitation over Time Period (m)	Total Runoff Reduction (%)
Spokane, Washington	1.35	99.78
Arco, Idaho	0.90	97.83
Lander, Wyoming	0.90	96.61
Cortez, Colorado	1.15	95.86
Las Cruses, New Mexico	0.54	91.67
St. Mary, Montana	2.19	90.80
Merced, California	0.53	90.21
Gaylord, Michigan	3.06	89.01
Whitman, Nebraska	1.12	88.10
Ithica, New York	2.87	87.78
Baker, Nevada	1.03	87.10
Goodwell, Oklahoma	1.03	84.99
Wolf Point, Montana	1.29	84.29
Aberdeen South Dakota	1.33	83.85
Corvallis, Oregon	3.05	83.10
Coshocton, Ohio	3.11	82.38
Goodridge, Minnesota	1.73	79.49
Old Town, Maine	3.48	79.04
Champaign, Illinois	2.70	77.74
Yuma, Arizona	0.31	76.45
Charlottesville, Virginia	3.39	74.86
Des Moines, Iowa	2.49	74.34
Blackville, South Carolina	3.48	73.63
Manhattan, Kansas	2.06	72.96
Crossville, Tennessee	4.59	72.32
Kingston, Rhode Island	3.59	70.69
Santa Barbra, California	0.90	69.81
Batesville, Arkansas	3.15	68.48
Bronte, Texas	1.54	66.31
Edinburg, Texas	1.58	65.29
Sebring, Florida	4.03	64.14
Selma, Alabama	4.15	63.83
Redding, California	2.82	59.75
Lafayette, Louisiana	4.66	56.98
Quinault, Washington	11.75	51.33

Study 4: Rain Garden Field Implementation in Burnsville, Minnesota (Barr Engineering Group, 2006)

In this study, rain gardens were implemented in-situ for a residential watershed in Burnsville, Minnesota. A control watershed and implementation watershed were chosen so that the runoff volumes could be measured and compared. Before the rain gardens were implemented, the runoff from both sites was measured during a storm event to ensure the control and study showed comparable results. The SCS variables manipulated were cover porosity, length of travel, and storage amount. The cover porosity was changed by directing flow from the street (impervious) into the garden (pervious) by the use of curb cuts. The following figure shows the reduction in runoff from the watershed compared to the control. Overall, there was a measured reduction in runoff of around 90% which shows that the manipulation of the variables greatly reduced the flood potential.

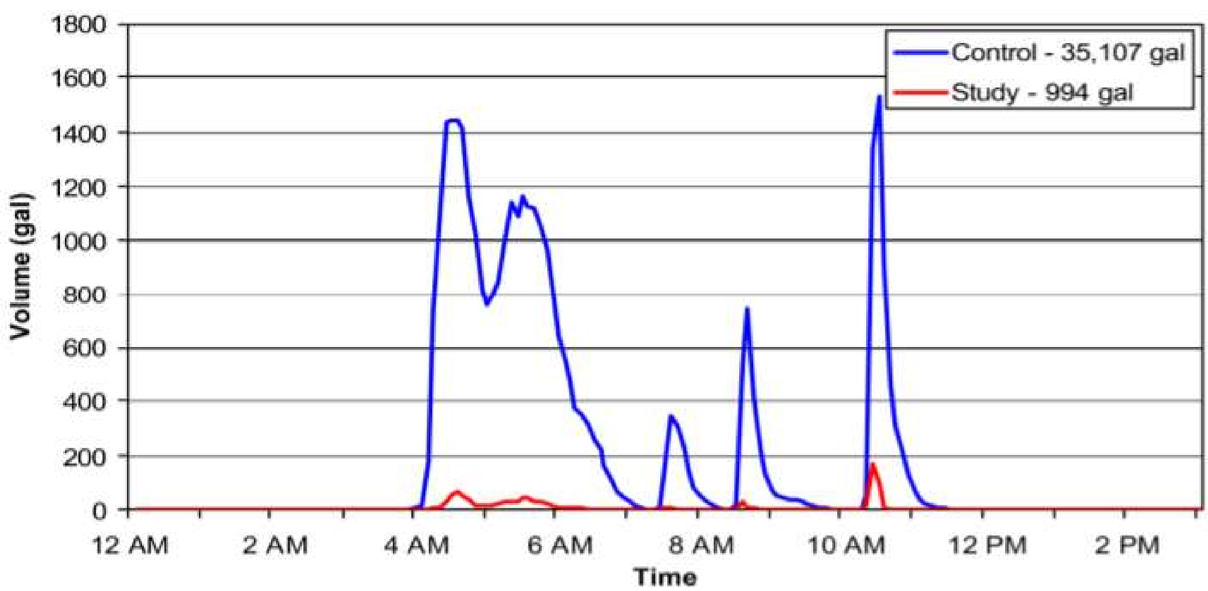

Figure 6 – Post-Construction Runoff Data from 0.71” Rainfall on May 29, 2004 (Barr Engineering Group, 2006)

Comparison of Studies 3 and 4: Rain Gardens

The data in studies 3 and 4, when compared with each other, strengthen the results. Study 3 by Jennings was implemented using theoretical stormwater modeling following industry standards. Study 4 by Barr Engineering Group was physically implemented in the field. The site of the Barr study is nearly equidistant from two of the Jennings sites as shown by Figure 7 below. Site 1 at the bottom left of the image is Aberdeen, South Dakota. Site 2 to the bottom right is the Barr Study. Site 3 at the top is Goodridge, Minnesota. As shown by the Jennings data, the Minnesota site showed a reduction of approximately 80% theoretically and the South Dakota site showed nearly an 84% reduction theoretically. The Barr study showed around a 90% reduction in runoff for the field study. Comparing the data from the theoretical case study sites and the applied case study, it supports that the assumptions made in the theoretical study are reasonable.

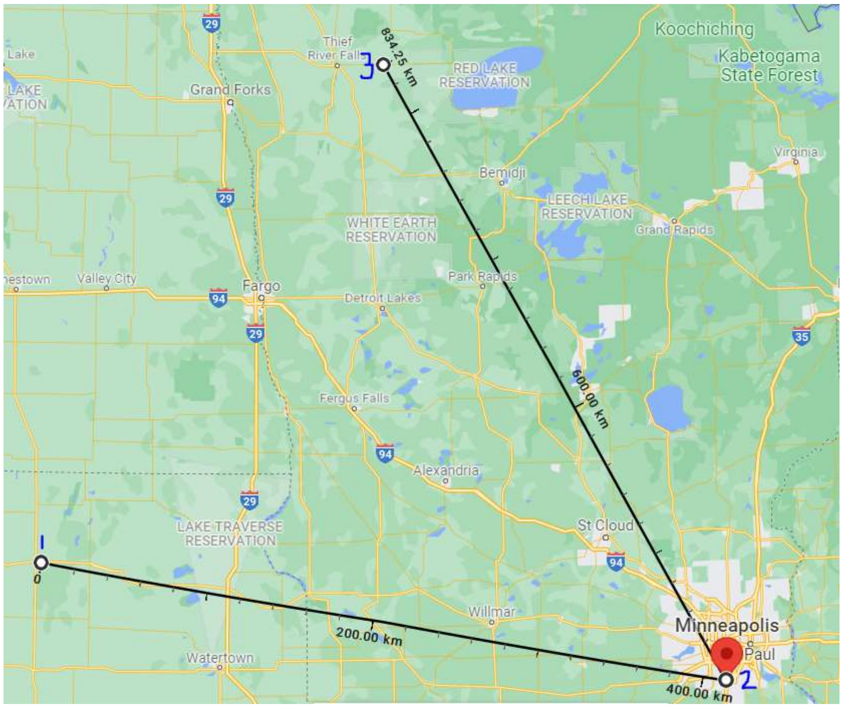

Figure 7 – Locations of Case Study Sites: 1 - Aberdeen, SD; 2 – Burnsville, MN; 3 – Goodridge, MN (Source: Google Maps)

Proposition 2

In order to assess the validity of the proposition, it is necessary to show that there are negative financial, transportation, and environmental impacts that can result from urban flooding. The following sources show the links between flooding and negative impacts on finances, transportation, and the environment. In addition to the general information cited in the variables section regarding the impacts of urban flooding, the following specific cases give additional evidence to the impact.

Case 1: Tulsa Flood (Canfield K., 2021)

In early 2019, The city of Tulsa, Oklahoma in the United States experienced flooding. The flooding was a combination of urban flooding and riverine flooding from the Arkansas River. The total cost of the damages incurred by the city of Tulsa was listed at $12.3 million. The wastewater and stormwater systems account for over 50% of those damages. Another portion of the damage was at a previous landfill site in which the erosion from the flooding exposed the landfill and allowed trash to be released into the environment. One of the impacts to transportation was in a location were the creek bank expanded and destabilized the roadway.

Case 2: Study of Cook County, IL (The Center for Neighborhood Technology, 2014)

Cook County, IL ranks second in population for the counties in the United States. 5,231,351 residents were on record at the time of the study which was more than 40% of the population of the state. Approximately 42% of the county is impervious surface, and most of the residential property has basements. Per the research in the study, in a 5-year period, urban flooding insurance claims that were paid totaled over $773 million with an average claim of more than $4,000. The following graph shows the results of a survey on the dollar expenses due to urban flooding experienced by residents, and the values in the table are an average of the responses.

Figure 8 – Average Estimated Dollar Expenses Due to Flooding in Cook County, IL (CNT, 2014)

Case 3: Ellicott City, MD 2018 Flash Flooding (CBS News, 2018)

The city of Ellicott, MD in the United States experienced a large urban flooding event in 2018 due to heavy rains falling in the area. The streets were filled with rushing water flowing with such force that cars were swept away, and one pedestrian was also carried away in the flood waters. The photo below shows the urban flood water rushing down Main Street. The flooding also caused a sewer main to break a couple miles from downtown, and around 500,000 gallons of raw sewage were spilled before the leak could be stopped.

Figure 9 – Main Street in Ellicott City on May 27, 2018 (CBS News, 2018a)

Proposition 3

According to Proposition Three, an implementation is more likely to be successful if it combines the resources of stakeholders with high interest and influence. For example, a homeowner in an area impacted by urban flooding will most likely have a high interest and time, but they are unlikely to have the necessary engineering knowledge or finances to fully address the issue. On the other hand, the state or federal government is more likely to have access to funding, and engineers with connections to the government or external environmental groups are most likely to have the engineering knowledge needed to address the flooding. The following cases look at scenarios in which a group of stakeholders with a variety of interest and influence levels came together to address urban flooding.

Case 1: Cook County, IL Community Approach (Oshun M., 2017)

This case study takes place in the same county of Illinois in the United States that was discussed above, but this case took place a few years later. In this case, the county government hired the research organization from the previous study, CNT, to implement an initiative for stormwater management called RainReady. This initiative approaches the issue of urban flooding with an emphasis on community planning. They developed four areas of focus for a community approach to reducing flooding: increasing community understanding of stormwater risks, collectively identifying solutions to prioritize, communicating a clear implementation plan to local leadership, and beginning implementation on high priority areas while continuing additional planning. The project team spent 15 months developing a specific plan of action for the focus area to help residents. The planning team used community-reported flooding to find areas impacted by urban flooding that may have gone undetected by a purely engineering approach using stormwater modeling or insurance and government reports. In order to try to maximize the success of the project, RainReady had a member dedicated to being in charge of local community outreach to improve communication between the government and residents. The residents were also provided guidance for some actions steps they could take to reduce their flood risks upfront before the full implementation would take place. The Army Corps of Engineers was also brought into the project to help adapt a new method for assessing the watersheds.

The RainReady Plans outline implementation steps to lead to decreased urban flooding with a focus on green infrastructure. These plans are designed to have a wider impact and be more cost effective than traditional, large engineered solutions to flooding. The plans also include changes at both the level of individual properties and public land which fits in with the goal to increase collaboration between homeowners, government, and other area partners.

Case 2: Retrofit Rain Gardens in Burnsville, Minnesota (Barr Engineering Group, 2006)

This study was also discussed above, but with an emphasis on the engineering aspect of the rain garden effectiveness. In this section, the focus is on the stakeholders involved. The watersheds involved in the study are in existing neighborhoods. The rain gardens were retrofit into a neighborhood that was originally constructed in the 1980s. As part of the project, individual designs were created for each individual residence that was participating in the project, and the team emphasized education for homeowners and easy maintenance. Each homeowner got to participate in the creation of the planting designs for their rain garden. The contractors on the project did the initial installation including sod removal, excavations, backfilling, and the installation of the edging. The homeowners did the planting, and the contractors came back to do the finishing work with mulch and sod. According to the study report, the raingardens were maintained well by the homeowners which indicated that the rain gardens were viewed as an amenity by most of the participants. This is important because poor maintenance can reduce the ability of the rain garden to function as designed.

CONCLUSIONS

Proposition 1

As shown in each of the studies above, both theoretically implemented and physically implemented, by manipulating the independent variables from the SCS methodology, the peak flow and total runoff volumes were reduced. In some cases, the reduction was greater than 90%. No cases were encountered for which the flow increased where a decrease would be expected by the SCS methodology. When runoff amounts are reduced, there is less water leaving the site and contributing to localized flooding. This means that in light of the data from the case studies, Proposition One is confirmed as true.

Proposition 2

From the general data and case-specific data above, it is clear that urban flooding causes financial, transportation, and environmental impacts. This means that by reducing urban flooding, the consequences of urban flooding would also be reduced. Therefore, Proposition Two can be confirmed.

Proposition 3

While the cases discussed above show the benefits of the type of approach suggested in Proposition Three, no studies were found that offer a comparison between this type of approach and an approach to implement retrofit solutions that does not combine stakeholders with varying interest and influence. Therefore, the conclusion for this proposition is that it is not disproven, but additional studies would be required in order to conclude that Proposition Three is valid.

Assessment of Research Conclusions

Proposition One - *Validated*

- urban flooding can be reduced or eliminated by the implementation of localized solutions that impact one or more of the independent variables in the SCS methodology

Proposition Two - *Validated*

- proper mitigation of urban flooding can reduce negative financial, transportation, and environmental impacts caused by floods

Proposition Three - *Supported but Inconclusive*

- successful implementation of solutions to urban flooding is tied to combining the input and resources of stakeholders with both high interest and high influence

Figure 10 – Propositions and Conclusions

The general objective of the integrated project was to provide a compilation of information related to retrofit solutions for urban stormwater. With the research included above to assess each of the three propositions, this objective has been met. Each of the three propositions was related to one of the three originally posed research questions. By addressing the three propositions, the research questions have also been addressed. Even though Proposition Three was not conclusive, the completed research regarding the propositions still helps answer the third research question: how can urban flooding solutions be implemented successfully?

From the analysis of the propositions, it becomes clear that urban flooding is an important topic in today's cities. Damage to property, persons, and the environment can and does occur as a result of urban flooding. With the research included in this report, a foundation is given to see where urban flooding needs to be addressed, potential solutions for addressing it, and suggestions on the involvement of various stakeholders in the implementation. The following section contains additional guidance regarding some of the retrofit solutions that can be considered by designers and planners for addressing urban flooding.

RECOMMENDATIONS AND RESOURCES

The use of the following resources should be based on the propositions and their conclusions. Based on Proposition One, options are needed that allow the manipulation of the SCS variables in an urban context. Based on Proposition Two, the upfront investment of these solutions should not be considered in isolation; since flooding has negative impacts, these solutions can reduce the risk of repeated future costs. Even though Proposition Three did not have a definitive conclusion, it is still recommended that the selection of solutions take into account the various stakeholders and their related interest, influence, and resources.

When looking into possible solutions, there are several factors for designers and planners to take into consideration. There are physical factors: space available, soil types, structural capacity of the existing structures, etc. One important environmental factor is the potential for pollution if a proper solution and location are not selected. There are also financial factors to take into consideration including how the improvements will be funded (local government funds, grants, private funds, etc.) for both the installation and maintenance as well as any money that could be saved by reducing flood damage. There are factors related to the construction including what materials are available locally and if skilled workers are required for the installation. Finally, there are social factors that can come into play including how the implementation is received by the owners and/or users of the property. A thoughtful selection takes into account all of these factors.

Some of the following resources have been developed by compiling information from multiple sources. Individual citations are indicated with numbered footnotes. In addition to the resources on the following pages, the EPA's page on Low Impact Development contains additional resources pertaining to breaking down barriers to implementation which are briefly summarized in the figure below (2021b).

Table 13 – Low Impact Development Solution Options by Location

Location	Rain Gardens	Bioswale	Stormwater Planter	Infiltration Trench	Permeable Pavement	Green Roofs	Rainwater Collection	Downspout Disconnection
Transportation[1]								
Arterial	x	x		x	x			
Collector	x	x	x	x	x			
Local Roads	x	x	x	x	x			
Alleys				x	x			
Parking Lots	x	x	x	x	x			
Buildings[2]							x	x
Steep Roof						x	x	x
Flat or Low Slope								
Site[2]	x	x	x	x	x			

1 - Environmental Protection Agency, 2021a

2 - Guillette A., 2016

Table 14 – Low Impact Development Solution Impacts on Water (data from Guillette A., 2016)

LID Option	Peak Flow Control	Volume Reduction	Water Quality Improvement	Water Conservation
Rain Garden	x	x	x	
Bioswale	x	x	x	
Stormwater Planter	x		x	
Infiltration Trench	x	x	x	
Permeable Pavement	x	x	x	
Green Roof	x		x	
Rainwater Collection	x	x		x
Downspout Disconnection	x	x	x	

Table 15 – Low Impact Development Solution Descriptions

LID Option	Description	Advantages	Approximate Cost (USD)	Maintenance
Rain Garden	Depressed area with plants and soils designed to increase infiltration[1]	can be large or small, good for retrofit, increased aesthetics, habitat for wildlife[1]	$3-$4 per sf for residential, $10-$40 per sf for commerical[2]	routine maintenance of landscaping[2]
Bioswale	vegetated conveyance channel with filtration media[1]	treats and conveys, can replace hardscaping at the edges of roadways, slows flow[1]	$0.25 - $0.50 per sf[2]	routine maintenance of vegetation by mowing, removing weeds, etc.[2]
Stormwater Planter	Landscape areas that receive water and either infiltrate or convey water to an underdrain[1]	increased aesthetics, widely applicable in high-density urban areas[1]	$6,000 over 0.25 acres of impervious surface plus $1,500 per unit[2]	checking for clogging of filter media and toxic material accumulation[2]
Infilltration Trench	Linear trench filled with rock and sand wrapped in a geotextile, underdrains optional[1]	allows for smaller downstream controls such as inlets and pipes, limited space needed for install[1]	$40 per sf [3]	remove sediments, mowing, check for continued ponding after storms[1]
Permeable Pavement	pavement that permits infiltration through void spaces, underdrains optional[1]	reduces ice hazards for drivers and pedestrians[1], easily retrofitted[2]	varies, usually higher than traditional paving[2]	routine surface sweeping, annual vacuuming of sediment[2]
Green Roof	Rooftop with a special soil layer and vegetation[2]	increased roof life[4], energy cost savings[4], no ground space needed for implementation	$10 - $200 per sf depending on how extensive it is[4]	similar to any other landscaping
Rainwater Collection	collection of rainwater from structures into barrels or cisterns[2]	can be used at varying scales for things like personal garden watering, large fountains, air conditioning, etc.[2]	$120 for barrels and varies for cisterns based on size and if they are above or below grade[2]	Draining after storms, debris removal[2]
Downspout Disconnection	Downspouts drain onto to pervious areas instead of going straight into sewers[2]	increased infiltration, less storm sewer needed	no cost	removal of debris

1 - Environmental Protection Agency, 2021a

2 - Guillette A., 2016

3- University of New Hampshire Stormwater Center, 2017

4 - First American Roofing, 2021

#1 Community Resources

- LID increases infiltration which reduces runoff
- LID has environmental and economic upsides
- LID can be implemented at any stage of development

#2 LID Terminology

- Green Infrastructure
- Sustainable Stormwater Management
- Smart Growth

#3 Economic Savings

- Money saved by reducing paving and curbs and traditional stormwater infrastructure
- Increased home values
- In a study of 17 LID cases througout the US, total cost savings were between 15 and 80 percent

#4 Aesthetics

- Add habitat for insects
- Adds more of a park feel
- Reduces urban heat

#5 Effectiveness

- Studies show reduction in pollutants
- Studies show reduction on runoff

#6 Maintenance

- LID can reduce lifecycle costs
- Maintenance can be a team effort between the municipality and the community

#7 Incentives

- Stormwater credits or reduced fees
- Rebates or Financing
- Awards

#8 Soil Contraints

- Options are available for clay soils
- Designs should take into account the soil conditions

#9 Slopes

- Design changes can be made to accomodate LID on sloped sites
- Studies show successful implementation

#10 Heavy Rainfall

- LID can be designed to allow for intense rainfall events beyond the normal capacity of the LID
- Overflow devices and bypasses can be used

#11 Small Spaces

- LID can be effective even at a small scale
- Multiple small solutions can be used together for a large impact

#12 Local Codes

- Codes need to be updated so that phrasing gives designers an option for LID without needing exceptions
- Education of stakeholders is an important part of making LID accessible and attractive to developers

Figure 11 – Summary of EPA Barrier Buster Fact Sheets (2021b)

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