Managing Heavy Rainfall with Green Infrastructure
An Evaluation in Pittsburgh’s Negley Run Watershed
Urban stormwater management is a growing challenge in many cities across the United States. Climate change is expected to add to this challenge by increasing the intensity or volume of rainfall from storms. In addition, there is a growing acknowledgment that these vulnerabilities are also environmental justice and equity challenges, as stormwater flooding and other negative outcomes can disproportionately affect low-income or majority-minority neighborhoods. This study applies simulation modeling and economic valuation to estimate the potential benefits and costs from the implementation of a large-scale green stormwater infrastructure system in Pittsburgh’s Negley Run watershed. This report is intended to inform local utilities, policymakers, and stakeholders engaged in stormwater and green space planning in Pittsburgh. It also adds to a growing body of literature regarding policy responses to urban flooding, sewer overflows, and environmental justice challenges in a changing climate, and it should be of interest to the national and international audience of practitioners and researchers working to address these significant challenges in cities across the globe. The report's summary provides an overview for a more general audience, while the main body of the report is more suited to technical readers.

This research was funded with grant support from the Henry L. Hillman Foundation, the Heinz Endowments, and 3 Rivers Wet Weather.

Community Health and Environmental Policy Program

RAND Social and Economic Well-Being is a division of the RAND Corporation that seeks to actively improve the health and social and economic well-being of populations and communities throughout the world. This research was conducted in the Community Health and Environmental Policy Program within RAND Social and Economic Well-Being. The program focuses on such topics as infrastructure, science and technology, community design, community health promotion, migration and population dynamics, transportation, energy, and climate and the environment, as well as other policy concerns that are influenced by the natural and built environment, technology, and community organizations and institutions that affect well-being. For more information, email chep@rand.org.
## Contents

Preface ........................................................................................................... iii  
Figures ........................................................................................................... vii  
Tables ............................................................................................................ ix  
Summary ........................................................................................................ xi  
Acknowledgments .......................................................................................... xxiii  
Abbreviations ................................................................................................. xxv  

### CHAPTER ONE  
Introduction ..................................................................................................... 1  
The Challenge of Stormwater Management in a Changing Climate ............................................... 1  
Stormwater Planning in the Pittsburgh Region ................................................................................. 2  
Managing Stormwater with a System of Green Infrastructure .............................................................. 3  
Purpose of This Report ..................................................................................................................... 5  
Pittsburgh’s Negley Run Watershed .................................................................................................. 5  
Research Questions ......................................................................................................................... 10  
Organization of This Report ......................................................................................................... 10  

### CHAPTER TWO  
Simulation Modeling and Economic Valuation Methods ................................................................. 11  
Overview of the Research Approach. ................................................................................................. 11  
Hydrology and Hydraulics Modeling ................................................................................................. 12  
Historical and Future Rainfall ........................................................................................................... 13  
Estimating Current and Future Stormwater Impacts ......................................................................... 14  
Green Stormwater Infrastructure Strategy Modeling and Costing .................................................... 15  
Estimating Strategy Benefits and Cobenefits. .................................................................................. 16  
Robust Decision Making. ................................................................................................................ 19  
Chapter Summary ......................................................................................................................... 19  

### CHAPTER THREE  
Sewer Overflows and Flooding in a Future Without Action .............................................................. 21  
Introduction ......................................................................................................................... 21  
Uncertainties Considered ................................................................................................................ 21  
Annual Time Series Analysis ........................................................................................................... 24  
Discrete Storm Analysis .................................................................................................................. 29  
Discussion and Limitations ............................................................................................................. 44  
Chapter Summary ......................................................................................................................... 46
# Figures

S.1. Pittsburgh's Negley Run Watershed and Washington Boulevard Corridor ............... xiii
S.2. Strategy Increments Evaluated in This Analysis .................................................. xv
1.1. Examples of Green Stormwater Infrastructure .................................................. 4
1.2. Negley Run Watershed Location and Scale ....................................................... 6
1.3. Negley Run Watershed and Washington Boulevard Corridor ............................ 7
1.4. Neighborhoods in the Negley Run (A-42) Watershed ....................................... 8
1.5. Negley Run Implementation Plan Concept Vision ............................................. 9
3.2. Key Components of the Negley Run Combined Sewer System ....................... 25
3.3. Recent Historical Negley Run Overflow Estimates, by Year ............................. 27
3.4. Selected Depth-Duration-Frequency Estimates Used in Discrete Storm Analysis ...... 30
3.5. Runoff by Subcatchment (MGal) from a 24-Hour, 10-Year Rainfall Event .......... 32
3.6. Change in 24-Hour, 10-Year Runoff from Historical to Average Future Climate Conditions ........................................................................................................ 33
3.7. Meadow Street Microshed Location ................................................................... 34
3.8. Meadow Street Microshed Peak One-Hour Runoff Estimates, by Rainfall Scenario .................................................................................................................. 35
3.9. Potential Street Flooding Locations from Selected Events (Historical Rainfall Scenario) ............................................................................................................... 36
3.10. Potential Street Flooding from a 1-Hour, 25-Year Modified Historical Storm ....... 39
3.11. Modeled Street Flooding from August 19, 2011, Washington Boulevard Flood ...... 40
3.12. Estimated Basement Damage for Modeled Houses from a One-Hour Storm, by Climate Scenario .................................................................................................. 43
3.13. Expected Annual Basement Damage for Modeled Houses from a 1- or 24-Hour Event, by Climate Scenario ................................................................. 44
4.1. Schematic Diagram of Cumulative Strategy Increments and Options ................ 48
4.2. U.S. Army Corps of Engineers Project Overview from Design Documentation Report ................................................................................................................. 50
4.3. Proposed Catchment Routing to Separated U.S. Army Corps of Engineers System .......................... 51
4.4. Meadow Street Microshed Conceptual Plan ..................................................... 53
4.5. Negley Run Watershed Task Force Design Charette Vision for a New Allegheny River Park Connection ........................................................................... 54
4.6. Strategy Increments 1 Through 4 ....................................................................... 56
4.7. Silver Lake Restoration Functional Concept Diagram ...................................... 57
4.8. Conceptual Diagram of Upstream Green Stormwater Infrastructure and Partial Separation Routing .............................................................................................. 58
4.9. Strategy Increments 5 Through 9 ................................................................. 59
5.1. Combined Sewer-Overflow Volume Reduction with Strategies, 2003 Typical Year Rainfall .......................................................... 66
5.2. Combined Sewer-Overflow Volume Reduction with Strategies, Recent Historical Rainfall ......................................................... 67
5.3. Combined Sewer-Overflow Reduction with Strategies, All Rainfall Scenarios ........ 68
5.4. Combined Sewer-Overflow Frequency and Duration Reduction with Strategies .......... 69
5.5. Impervious Runoff Reduction from Selected Strategies, 24-Hour, 10-Year Rainfall Event .......................................................... 71
5.6. Washington Boulevard Flood Depth Reduction from U.S. Army Corps of Engineers Conceptual Design Alternative Strategies, 24-Hour, 10-Year Synthetic Rainfall Event .... 72
5.7. Street Flooding from 2011 Washington Boulevard Flood with Selected Strategies .... 74
6.1. Multipurpose Recreational Trail with Half-Mile Buffer Area by Strategy Increment ... 79
6.2. CSO Volume and Annual Rainfall Linear Regression, FWOA and Strategy 4 ........ 84
6.3. Overflow Reduction Cost-Effectiveness with Uncertainty ......................... 86
6.4. Discounted Benefits and Costs by Strategy, 2003 Typical Year Rainfall and Nominal Assumptions .................................................. 87
6.5. Discounted Benefits and Costs by Strategy, 2013 Rainfall and Nominal Assumptions ... 88
6.6. Net Present Value by Strategy, All Scenarios ........................................ 89
6.7. Net Present Value Regret by Strategy, All Scenarios .................................. 90
6.8. Summary of Cost-Effectiveness Scenario Discovery Analysis, Strategy 9C ........ 91
### Tables

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Summary of Negley Run Watershed Stormwater Vulnerability Analysis</td>
<td>22</td>
</tr>
<tr>
<td>3.2</td>
<td>Summary of Recent Historical Negley Run Overflow Metrics for Different Periods</td>
<td>28</td>
</tr>
<tr>
<td>3.3</td>
<td>Summary of Recent Historical and Projected Future Negley Run Overflows</td>
<td>29</td>
</tr>
<tr>
<td>3.4</td>
<td>Flooding Return Period from a One-Hour Event for Selected Streets or Intersections</td>
<td>37</td>
</tr>
<tr>
<td>3.5</td>
<td>Number and Proportion of Homes Affected by Basement Flooding from a One-Hour Event</td>
<td>41</td>
</tr>
<tr>
<td>3.6</td>
<td>Homes Affected by Basement Flooding from a One-Hour Event, by Rainfall Scenario</td>
<td>42</td>
</tr>
<tr>
<td>4.1</td>
<td>Negley Run Implementation Plan Phases and Subphases</td>
<td>52</td>
</tr>
<tr>
<td>4.2</td>
<td>Summary of Modeled Strategies</td>
<td>60</td>
</tr>
<tr>
<td>4.3</td>
<td>Summary of Discounted Life-Cycle Costs by Strategy (Millions of 2019$)</td>
<td>64</td>
</tr>
<tr>
<td>5.1</td>
<td>Average Flood Depth Reduction (feet) from Strategies 1–4 for Selected Storm Events</td>
<td>73</td>
</tr>
<tr>
<td>6.1</td>
<td>Cumulative Approximate Mobility and Recreation Benefits from Cycling by Strategy Increment ($ Thousands per Year)</td>
<td>80</td>
</tr>
<tr>
<td>6.2</td>
<td>Cumulative Approximate Recreation Benefits from Pedestrian Activities by Strategy Increment ($ Thousands per Year)</td>
<td>80</td>
</tr>
<tr>
<td>6.3</td>
<td>Cumulative Approximate Air Pollution, Carbon, and Heat Island Effects from New Net Tree Plantings by Strategy Increment ($ Thousands per Year)</td>
<td>81</td>
</tr>
<tr>
<td>6.4</td>
<td>Cumulative Approximate Amenity Benefits by Strategy Increment ($ Thousands per Year)</td>
<td>82</td>
</tr>
<tr>
<td>6.5</td>
<td>Cumulative Cobenefits by Strategy Increment ($ Thousands per Year)</td>
<td>82</td>
</tr>
<tr>
<td>6.6</td>
<td>Summary of Negley Run Strategy Economic Comparisons with Uncertainty</td>
<td>83</td>
</tr>
</tbody>
</table>
Summary

Introduction

Cities across the United States are struggling to effectively manage the stormwater runoff that results from heavy rainfall. Continued population growth and urbanization, coupled with inadequate investment in old and undersized storm- and wastewater systems, have left many cities exposed to sewer overflows, flooding, and reduced water quality. In many regions, climate change adds to this challenge by increasing the volume of rainfall from storms or frequency of extreme events. In addition, there is a growing recognition that stormwater challenges are also environmental justice and equity challenges, as stormwater flooding and other negative outcomes can disproportionately affect low-income or majority-minority neighborhoods.

These challenges are especially difficult to overcome in complex and interconnected urban environments. In many cities, decisions about stormwater management are made by many different actors, including multiple government agencies, watershed and neighborhood organizations, and private landowners. Each of these actors might focus on a different goal: when considering a new investment, a utility might prioritize meeting its legal or regulatory requirements, for example, while a neighborhood organization may instead wish to reduce the frequency of street flooding or provide new amenities to local residents. As a result, local planners often make decisions in piecemeal and uncoordinated fashion, reducing the potential to invest toward shared benefits to overcome systemic challenges.

Local decisionmakers also often lack the capacity to plan when faced with future uncertainty, such as climate-influenced rainfall patterns, and instead rely on past observations alone to guide infrastructure investments that might last decades to centuries. This can lead to undersized systems and recurring stormwater problems even after significant resources have been invested. Methods for decisionmaking under uncertainty pioneered in other water management fields could help planners identify strategies that are more robust, meaning that they would perform well regardless of which future might come to pass. But these methods have not yet been mainstreamed in stormwater management and remain largely out of reach at the local level due to capacity or resource limits.

Stormwater Planning in the Pittsburgh Region

The Pittsburgh region, including the city of Pittsburgh and surrounding municipalities in Allegheny County, is a prime example of these challenges. The Pittsburgh region’s combined sewer system is inadequately sized to capture and treat most “wet weather” events, which occur frequently throughout the year. As a result, nearly every time it rains, a combined sewer
overflow occurs in at least one of the approximately 450 outfalls in the system, draining a mix of untreated wastewater and stormwater into streams and rivers.

Furthermore, high precipitation events combined with hilly topography and poor drainage can lead to flooding in many low-lying areas. Some neighborhoods regularly face rainfall flooding, which can damage homes, businesses, and municipal infrastructure, as well as block transportation routes. Basement sewer backups, basement flooding, and other water-related challenges disproportionately affect Pittsburgh’s low-income and predominantly African American neighborhoods.

The Pittsburgh region lacks an overriding authority for managing stormwater. The Allegheny County Sanitary Authority (ALCOSAN) is responsible for conveying and treating wastewater from 83 municipalities in the county, including the city of Pittsburgh. But ALCOSAN functions as a regional wastewater utility governed by federal, state, and local water-quality standards, does not build or maintain municipal storm- or wastewater infrastructure, and is not directly responsible for mitigating flooding or other stormwater impacts. The responsibility for managing these falls instead rests with the individual municipalities: In the city of Pittsburgh, this includes the Pittsburgh Water and Sewer Authority (PWSA), the local water and wastewater utility, along with other local government agencies and departments, watershed organizations, and other nongovernment stakeholders.

In 2008, ALCOSAN entered into a consent decree with the U.S. Department of Environmental Protection, Pennsylvania Department of Environmental Protection, and Allegheny County Health Department to create a plan to resolve ongoing sewer-overflow water-quality violations. A draft plan was initially developed in 2012. After years of iteration and negotiations, ALCOSAN published a final Clean Water Plan in late 2019 and subsequently received approval from the regulators for a modified consent decree.

The approximately $2 billion plan includes an expansion of the wastewater treatment plant and a series of new deep tunnels along the Ohio, Monongahela, and Allegheny Rivers to capture and store an increased volume of combined sewer flows during and after rainfall events. In response to public comment, the revised plan includes additional investment to help reduce the flow of stormwater “at the source” before it reaches the combined sewer system, which can include the employment of green infrastructure. Most investment, however, remains focused on traditional, or gray, infrastructure, such as water treatment, tunnels, pipes, and storage tanks.

Managing Stormwater with a System of Green Infrastructure

A key focus of public conversation over the Pittsburgh region’s stormwater challenges since 2012 has been on green infrastructure. Green stormwater infrastructure (GSI) uses natural elements (vegetation, soils, etc.) to capture stormwater and allow it to either infiltrate into groundwater or slowly release back into a stormwater or combined sewer system well after the storm event peak. In contrast to gray infrastructure, which is often built underground and intended for water management alone, nature-based GSI is intended to provide other co-benefits to local residents, such as new parks or green space, recreational opportunities, and improved air quality.

Western Pennsylvania’s steep topography and clay soils are often cited as barriers to more significant investment in GSI, because, respectively, these characteristics can constrain the area well suited to GSI water storage and/or limit the effectiveness of infiltration-based approaches. However, an alternate approach is to use GSI techniques as part of combined green-and-gray strategies that seek to capture and route rainfall to a centralized surface system—or daylighted
system, which includes natural features like streams, ponds, or wetlands and ultimately allows the water to flow directly to receiving waters (e.g., rivers or lakes). Where possible, this approach can in theory divert a large volume of stormwater from the combined sewer system entirely, avoiding the need to invest in expensive sewer separation while restoring some amount of natural surface flows across an urbanized watershed.

**Pittsburgh’s Negley Run Watershed**

This report addresses the challenges and opportunities outlined above for one key watershed in the city of Pittsburgh: Negley Run. Negley Run is a large watershed that drains a diverse area of Pittsburgh’s East End, including several neighborhoods that have suffered heavily from underinvestment in recent decades, such as Homewood, Larimer, and Lincoln-Lemington-Belmar. Negley Run captures more water than any other watershed in the city of Pittsburgh and is the single largest contributor of sewer-overflow volumes across the ALCOSAN service area. It also represents one of the most urgent flood-risk challenges in the city. Major rainfall events regularly lead to flash flooding along lower Washington Boulevard, a key roadway corridor that supports a high volume of commuter traffic from suburbs north of the Allegheny River (Figure S.1). In August 2011, notably, a flash flood along this corridor rapidly submerged cars during a rush-hour backup and killed four people (Balingit, 2013).

Given the range of social, economic, and environmental challenges faced in the watershed, recent local planning efforts have looked to address these problems holistically through investments in GSI. As of 2020, a working group called the Negley Run Watershed Task Force

---

**Figure S.1**

**Pittsburgh’s Negley Run Watershed and Washington Boulevard Corridor**

SOURCES: (L) Base imagery from ESRI; watershed boundary from ALCOSAN and Arcadis. (R) Mapbox.
NRWTF has regularly convened to help coordinate GSI activities across the watershed. The task force is composed of representatives from key government agencies, neighborhood organizations, environmental nonprofits, and local designers and technical experts. The RAND team has been an active participant in NRWTF since 2018, and task force members provided input and feedback throughout this research effort.

Purpose of This Report

In this report, we describe results from a research study using simulation modeling to estimate present and future risks in Negley Run from sewer overflows and flooding given future rainfall uncertainty. We then evaluate proposals for a phased series of large-scale GSI investments centered on a new daylighted system that would capture, store, and convey a large volume of rainfall to the Allegheny River. Specifically, we estimate the potential water-quality benefits and implementation costs associated with different proposed strategies and provide economic estimates of recreational, amenity, and other cobenefits to local residents. Finally, we use decisionmaking under deep uncertainty (DMDU) methods to compare total benefits to costs and explore potential trade-offs.

Although this effort focuses on one watershed, another key goal of this report is to help establish best practices for watershed-scale stormwater planning that seeks to address multiple policy objectives and explicitly accounts for future climate uncertainty. Our intention is that this study will help to inform similar efforts in other watersheds in the city of Pittsburgh, Allegheny County, and in urban areas across the nation.

This research was funded with grant support from the Henry L. Hillman Foundation, the Heinz Endowments, and 3 Rivers Wet Weather.

Research Questions

This project was guided by the following research questions:

- What are the current risks posed by heavy rainfall to the Negley Run watershed, including both sewer overflows and flooding?
- How might these risks change in futures where heavy rainfall grows more frequent or intense?
- How might a new daylighted system of GSI help to reduce sewer overflow and flood risk, and how does this vary at different levels of investment or build-out?
- What other cobenefits would proposed GSI strategies provide?
- How do the benefits and cobenefits from proposed GSI strategies compare with their costs across a range of plausible assumptions?

Strategies to Manage Stormwater in Negley Run

This research effort evaluated 17 possible stormwater management strategies for Negley Run based on the core concept of a new centralized and daylighted GSI system. These strategies would utilize both green (e.g., wetlands, streams, ponds) and gray (piped) infrastructure, store a large volume of rainfall during and after storms, and provide a new pathway for stormwater...
to flow directly to the Allegheny River along the Washington Boulevard corridor instead of flowing through the combined sewer system. They also include other amenities, such as a multi-purpose recreational trail for walking and biking. We identified these strategies using a plan and literature review, design-focused participatory workshops and stakeholder engagement, and formulation and iteration with technical experts.

Each strategy is defined by the geographic area it covers and the level of investment to be applied within that area. We identified nine cumulative *strategy increments* (1 to 9) based on geographic area, where each additional increment also includes the previously numbered increments so that the strategy builds “upward” from the bottom of the watershed into the surrounding neighborhoods. We also identified three *options* (A, B, and C) for different levels of investment to be applied within selected increments. Strategy increments 1 to 4 are derived from preliminary design work developed for PWSA for a centralized daylighted system and do not include further options. Strategy increments 5 to 9, alternately, are largely drawn from concepts developed by NRWTF and include neighborhood-scale GSI interventions. Figure S.2 shows a map with each strategy increment.

**Figure S.2**
*Strategy Increments Evaluated in This Analysis*

NOTE: RSC (regenerative stormwater conveyance) is a series of tiered riffles along Negley Run Boulevard.
One of the novel contributions of our research was to consider how a restored Silver Lake could function as a key location for storing rainfall. Silver Lake was once a body of water at the confluence of several historic streams. It was filled in after the streams were replaced with combined sewer pipes and is currently a commercial/industrial park. Returning this location to a lake would provide a sizeable basin for water retention during storms and provide a major recreational feature in an area that currently has no good park access. This restored lake, which we refer to as the Silver Lake Retention Basin (or SLRB), is a key feature for strategy increments 5 to 9.

The options included for strategy increments 5 to 9 are otherwise defined as follows:

- **Option A**: invest in additional neighborhood GSI designed to capture stormwater from 25 percent of the impervious cover (e.g., pavement, roofs, parking lots, etc.) in the selected geographic area.
- **Option B**: similar to A, except targets 50 percent of the impervious cover in the selected geographic area.
- **Option C**: similar to B, but also increases the size of SLRB to help store additional stormwater during heavy rainfall events. Only considered with strategy increments 7 to 9.

Table S.1 summarizes the strategies modeled in this analysis.

For ease of discussion in the results and analysis, we have given alternate names to three selected strategies representing varying increments of investment. Strategy 4, which includes the entirety of the centralized surface system designed to capture direct stormwater flows along Washington Boulevard and Negley Run Boulevard, is referred to as the *Central Daylighting* strategy. Strategy 7A, which includes a version of SLRB and investment in GSI to control 25 percent of impervious cover across the neighborhood of Homewood, is the *Midrange* strategy, while Strategy 9C, which represents the highest level of investment considered, is the *Max Build-Out* strategy.

### Study Results

This study builds closely on a prior pilot-scale effort focused on climate-resilient stormwater management across the Pittsburgh region (Fischbach et al., 2017). Similar to that earlier effort, this study uses simulation modeling and high-performance computing to estimate key stormwater outcomes in scenarios representing current and plausible future rainfall for the region and applies DMDU techniques to both explore the range of future climate-related uncertainty and help identify more robust strategies for stormwater management. Key research steps included:

- *develop* an updated Negley Run simulation model and estimate present and future risks with no additional infrastructure investment
- *evaluate* sewer-overflow and flood-risk reduction from watershed-scale GSI strategies for Negley Run
- *compare* the benefits, cobenefits, and costs of proposed GSI strategies.

We describe each of these steps in further detail and describe key findings from each step in the sections below.
Develop an Updated Negley Run Simulation Model and Estimate Present and Future Risks with No Additional Infrastructure Investment

We worked with Arcadis, an engineering firm, to develop a new detailed stormwater simulation model for Negley Run that includes a simplified representation of flooding along key street corridors. We used the updated model to estimate sewer overflows and flood risk across a range of historical rainfall and plausible future rainfall conditions if no additional system improvements are implemented (an FWOA). The flood-risk analysis includes street flooding and basement flooding (wet basements from rainfall or sewer line backups) in single-family homes for selected areas of the watershed.

**Key Findings**

Sewer overflow from Negley Run is higher in a range of Recent Historical rainfall patterns compared with a single Typical Year (TY). We first evaluated sewer overflows in an FWOA (no additional investment) using the same TY approach adopted for regional planning.

### Table S.1
Summary of Modeled Strategies

<table>
<thead>
<tr>
<th>Increment</th>
<th>Geographic Area</th>
<th>Option</th>
<th>Short Name</th>
<th>SLRB Size (acre-feet)</th>
<th>Impervious Cover Target (percent)</th>
<th>Area (acres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>None (&quot;future without action [FWOA]&quot;)</td>
<td>–</td>
<td>FWOA</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1</td>
<td>Diversion Channel 1 and 2</td>
<td>–</td>
<td>Channel 1/2</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>Highland and Wetland Basin</td>
<td>–</td>
<td>Basins</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>Swale and RSC</td>
<td>–</td>
<td>Swale/RSC</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>Paulson Avenue</td>
<td>–</td>
<td>Paulson (Central Daylighting)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>Silver Lake, Frankstown Avenue, Westinghouse Field</td>
<td>A</td>
<td>Frankstown-SLRB-25</td>
<td>12</td>
<td>25</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>Frankstown-SLRB-50</td>
<td>12</td>
<td>50</td>
<td>37</td>
</tr>
<tr>
<td>6</td>
<td>Kedron Street and Homewood North</td>
<td>A</td>
<td>Kedron-SLRB-25</td>
<td>12</td>
<td>25</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>Kedron-SLRB-50</td>
<td>12</td>
<td>50</td>
<td>65</td>
</tr>
<tr>
<td>7</td>
<td>Kelly Street and Homewood South</td>
<td>A</td>
<td>Kelly-SLRB-25 (Midrange)</td>
<td>12</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>Kelly-SLRB-50</td>
<td>12</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>Kelly-SLRBX-50</td>
<td>16</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td>8</td>
<td>Lincoln Avenue and Lincoln-Lemington-Belmar</td>
<td>A</td>
<td>Lincoln-SLRB-25</td>
<td>12</td>
<td>25</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>Lincoln-SLRB-50</td>
<td>12</td>
<td>50</td>
<td>189</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>Lincoln-SLRBX-50</td>
<td>16</td>
<td>50</td>
<td>189</td>
</tr>
<tr>
<td>9</td>
<td>East Hills</td>
<td>A</td>
<td>EastHills-SLRB-25</td>
<td>12</td>
<td>25</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>EastHills-SLRB-50</td>
<td>12</td>
<td>50</td>
<td>214</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>EastHills-SLRBX-50 (Max Build-Out)</td>
<td>16</td>
<td>50</td>
<td>214</td>
</tr>
</tbody>
</table>
by ALCOSAN and PWSA and estimated 865 million gallons per year of sewer overflow using this single, historically based rainfall assumption. We then compared this TY estimate to rainfall from the years 2003–2017 and determined that annual sewer overflows for the Recent Historical period are approximately 14 percent higher, on average, when compared with the TY. Using the same approach, we also estimated over 2 billion gallons of overflow from Negley Run in 2018, the wettest year on record for the Pittsburgh region as of the publication of this report. These results show that relying on TY rainfall alone likely underestimates overflow volumes under present conditions.

**Sewer overflow increases further in plausible future scenarios.** We also considered several future scenarios based on climate model projections approximately 20–25 years into the future. In the wettest future rainfall scenario considered, average annual sewer overflow is up to 26 percent higher than the TY and 10 percent higher than the 2003–2017 average.

**Negley Run already faces notable flood risk from heavy rainfall events.** The model showed sufficient flooding to close Washington Boulevard even under a storm with a 50 percent chance of occurring in a given year (a one-in-two chance, or two-year event). The results also suggest that flooding occurs regularly on streets and intersections in Homewood and surrounding neighborhoods. For the areas of Negley Run evaluated for basement flooding, we estimate that 11–18 percent of homes in the report area are at risk from either a wet basement, basement sewer backup, or both from a wide range of rainfall events with different likelihoods based on historical rainfall conditions.

**Flood risk increases with heavier rainfall from plausible future climate change.** Our modeling shows that key streets and intersections would flood more frequently when considering a projected 2020–2099 future scenario based on climate modeling. Similarly, the number of homes at risk from at least one type of basement flooding increases by 18–21 percent when comparing an average future climate scenario to historical rainfall conditions.

**Evaluate Sewer Overflow and Flood-Risk Reduction from Watershed-Scale GSI Strategies for Negley Run**

We worked with NRWTF, PWSA, other government agencies, neighborhood organizations, design teams, and engineering partners to identify 17 possible GSI strategies based on a centralized daylighted system approach for Negley Run, as described above. We then used the new simulation model to estimate the change in sewer overflow and flood risk resulting from each strategy under present and plausible future rainfall conditions.

**Key Findings**

A new centralized daylighted system and subsequent upstream investments could substantially reduce, but not eliminate, sewer overflows in Negley Run. When we evaluated each of the 17 strategies with the simulation model, we found

- the Central Daylighting strategy (Strategy 4) reduces sewer overflow by 12 to 26 percent per year (depending on the rainfall scenario)
- the Midrange strategy (Strategy 7A) reduces sewer overflow by 19 to 33 percent
- the Max Build-Out strategy (Strategy 9C) reduces sewer overflow 26 to 40 percent.

In general, the strategies reduce more sewer overflow in higher rainfall scenarios, reinforcing similar results noted in the pilot study.
A centralized daylighted system reduces flood depths along Washington Boulevard but does not fully eliminate flooding even in more frequent, lower-intensity events. With the Central Daylighting strategy, which is focused on the direct capture area, flood volume and depth along the Washington Boulevard corridor are reduced, with generally increasing flood benefit from additional increments through Strategy 4. Midrange or Max Build-Out strategies, however, do not appear to provide additional flood benefits for Washington Boulevard. Moreover, none of the strategies tested eliminate flooding at the low point of Washington Boulevard in the storm events we tested, suggesting that additional design modification or policy levers will be necessary.

Our preliminary research did not identify street or basement flood-risk reduction benefits from local GSI investments in Homewood and surrounding neighborhoods, but more investigation is needed. The initial strategies tested do not appreciably reduce the estimated frequency or extent of either street or basement flooding in the areas we modeled. However, we note that local GSI is represented in a simplified, standardized way in this analysis and is not optimized for specific local site conditions. As a result, additional research will be needed to follow up on these results and determine whether targeted project designs could provide localized risk reduction.

**Compare the Benefits, Cobenefits, and Costs of Proposed GSI Strategies**

Finally, we estimated the additional cobenefits from these strategies that might extend beyond the benefits valued for gray infrastructure projects. We combined these estimates with monetized estimates of water-quality benefits and then compared total estimates of benefits with estimated costs to evaluate sewer-overflow reduction cost-effectiveness as well as net economic benefit. The goal was to identify strategies that build resiliency against current and future rainfall conditions, search for low-regret solutions that work regardless of which future comes to pass, and highlight key trade-offs that might emerge between approaches.

**Key Findings**

Strategies that build on a daylighted surface collection system could yield highly cost-effective sewer-overflow reduction across a range of assumptions. As modeled, the Central Daylighting strategy is highly cost-effective for overflow reduction. We estimate that this strategy would cost $0.04 to $0.14 per gallon of sewer overflow reduced across a wide range of rainfall uncertainty and construction cost assumptions. This compares favorably to the average cost-effectiveness from ALCOSAN’s Clean Water Plan ($0.34 to $0.38 per gallon). Additional increments of investment beyond the Central Daylighting strategy are generally less cost-effective using this metric and show more variation across the scenarios considered. However, these additional strategies still appear be cost competitive with other local and regional investments to reduce sewer overflows under a broad range of future assumptions.

Across the strategies, scenarios with higher average annual rainfall generally lead to greater sewer overflow cost-effectiveness. Following from previous observation that the strategies have greater sewer-overflow reduction under higher annual rainfall assumptions, we found that, in general, the mid- or high-investment strategies are less cost-effective for sewer-overflow reduction than comparison benchmarks only in futures with low average annual rainfall and relatively high local GSI installation costs.

Life-cycle cost estimates for the strategies evaluated vary based on the level of investment as well as other uncertain factors. We developed life-cycle cost estimates based on a
Managing Heavy Rainfall with Green Infrastructure

40-year planning horizon and an assumed 15-year construction time to strategy build-out while also looking across a range of cost uncertainties. Cost estimates include construction, operations and maintenance, and property compensation costs. Life-cycle cost estimates range from $15–40 million for the Central Daylighting strategy to $38–90 million for a Midrange approach. The Max Build-Out strategy is estimated to cost between $57 million and $130 million.

GSI cobenefits from the strategies we evaluated could contribute substantial value to residents when accounting for uncertainty and using conservative assumptions. Our analysis estimated a subset of GSI strategy cobenefits from recreation, bicycle commuting, pedestrian activity, tree cover, and overall amenity value. Using relatively conservative assumptions for cobenefit valuation, we nevertheless identified notable benefits associated with the proposed GSI installations. The Central Daylighting strategy is estimated to provide $1.8–$5.4 million in cobenefits per year, while either the Midrange or Max Build-Out strategies would yield $3.3–$9.7 million per year. These benefits, even though likely undervalued in the analysis, are sufficient to offset GSI strategy costs in and of themselves under many plausible futures. The results suggest that the additional services provided by GSI strategies are economically desirable over a wide range of strategy and environmental assumptions.

The net economic value of the strategies considered—taking into account life-cycle strategy costs, water-quality benefits, and cobenefits—is nearly always positive across a wide range of assumptions. Our estimates of the net economic benefit (benefits minus costs) over a 40-year planning horizon are strongly positive across nearly all strategy cost, water-quality benefit, and cobenefit assumptions. Taking into account both water-quality benefits and cobenefits, net benefit ranges from $40–144 million from the Central Daylighting strategy to $31–175 million from the Midrange strategy, with the Max Build-Out strategy yielding a somewhat lower range of $6–169 million. Figure S.3, for example, shows the economic benefit with one set of midranged scenario assumptions.

A midranged strategy could provide positive economic benefit across a wide range of assumptions. If local planners were to focus solely on cost-effective sewer-overflow reduction, the Central Daylighting strategy appears to be a robust and low-regret approach across a wide range of cost and rainfall assumptions. When taking into account a broader range of cobenefits for local residents in Homewood and surrounding neighborhoods, however, strategies that include an SLRB and additional investments in local GSI, such as the Midrange strategy, outperform the Central Daylighting strategy in the large majority of scenarios considered.

Recommendations

Negley Run GSI Design and Implementation

Invest in design and engineering efforts for the Central Daylighting strategy (Strategy 4) as a low-regret solution. Given the strategy results described above, we recommend continuing to mature designs for a centralized daylighted system and move toward engineering and construction.

Work together to expand the range of options to address street and basement flooding. We recommend that NRWTF works toward expanding the range of options available to address flooding given the mixed results from this analysis. For example, the Pennsylvania Department of Transportation, which owns and maintains Washington Boulevard as a state road, should consider roadway elevation for the low-elevation portion of the road that floods
frequently, conducted in tandem with the Central Daylighting strategy and/or other improvements. In addition, NRWTF partners working on neighborhood GSI projects should consider how these projects could be designed and sited to best address local flooding issues.

**Continue to invest in distributed local GSI projects in Negley Run neighborhoods.** The cobenefits analysis presented here shows that GSI could provide notable benefits for residents, even without taking into account potential flood-risk reduction. This suggests that continuing to invest in local GSI projects could be beneficial whether or not these projects would eventually connect in to a centralized daylighted system or provide significant sewer-overflow reduction.

**Employ an adaptive planning approach for further increments of connected GSI.** Based on this analysis, we recommend that NRWTF partner agencies adopt an adaptive approach over the next five years, proceeding with design and construction for the centralized daylighted system while preparing for possible additional investment in an SLRB and further connections to the upper watershed. Key steps could include monitoring GSI construction costs, reassessing and updating rainfall assumptions currently used for planning, and exploring the feasibility and constraints associated with a potential SLRB.

**Figure S.3**

**Benefits and Costs by Strategy, 2013 Rainfall and Nominal Assumptions**

*NOTE: This figure shows how inputs stack up under one set of scenario assumptions: 2013 rainfall and nominal (midrange) benefit and cost uncertainty assumptions for each strategy. Positive bars indicate benefits, negative bars indicate costs, and net economic benefit (net present value) can be calculated by summing across both (right column). Under these assumptions, all strategies have a positive net benefit. Results reflect a 40-year assumed planning period and a discount rate of 4 percent.*
Additional Data Collection and Research

Further refine the detailed simulation model developed for this study and integrate into regional system models to support additional sewer-overflow and flood-risk evaluation. A key step would be to integrate the detailed model back into the regional system to (1) better understand regional system interactions and (2) allow PWSA, ALCOSAN, and other partners to assess these Negley Run GSI strategies together with treatment plant expansion and other improvements identified in ALCOSAN’s Clean Water Plan.

Gather additional data to inform flood-risk assessment for Negley Run, including combined system descriptions and flow monitoring. This analysis was limited by the data available to inform model development and calibration. We recommend that PWSA and ALCOSAN develop a more complete inventory and mapping of storm inlets, inlet invert elevations, and associated pipes across the Negley Run watershed. In addition, new pipe-flow monitoring data gathered at a wider range of sample points would allow for improved calibration of the detailed model and greater confidence in simulated results compared with real-world conditions. It would also support more accurate, detailed, and complete flood-risk analysis.

Explore the use of two-dimensional surface-flow modeling to support flood-risk assessment and site-specific GSI design. This initial assessment suggested notable limitations when relying on one-dimensional (1D) analysis to evaluate GSI flood risk reduction. An improved approach would leverage two-dimensional (2D) or coupled 1D-2D flood modeling for key locations of interest, such as the Washington Boulevard corridor. In addition, coupled modeling building on this work could provide localized flood assessments at the neighborhood scale to inform GSI project siting and design.

Consider adopting an integrated, watershed-based approach for other areas of focus across the region. This study serves as a proof of concept for how an integrated, quantitative scenario-planning approach—building on advanced decisionmaking under uncertainty techniques—can help to guide a range of stormwater policy, planning, and design efforts conducted by different entities for the same watershed of focus. We believe a similar approach could benefit planners in other local or regional watersheds facing a similar range of stormwater challenges and future uncertainties.
Acknowledgments

This research benefitted from partnerships with many individuals and organizations. We gratefully acknowledge Hazem Gheith, Qiuli Lu, and Khaled Abdo with Arcadis-US for developing the updated simulation model for Negley Run. Ryan Quinn (Pittsburgh Water and Sewer Authority) and Tom Batroney (AKRF) served as key technical advisors, providing data and feedback throughout the effort. Thank you also to those that provided additional data and modeling support, including the Negley Run design teams at the U.S. Army Corps of Engineers Pittsburgh District and Tetra Tech, Lauren Cook (Eawag), Tim Prevost (ALCOSAN), and 3 Rivers Wet Weather.

We thank all members of the Negley Run Watershed Task Force who participated in regular meetings and workshops and provided feedback through this multiyear research effort. We wish to highlight the contributions of members John Stephen (Living Waters of Pittsburgh), Matt Mercurio (CivicMapper), and Gavin White and Erin Copeland (Pittsburgh Parks Conservancy) but note that this effort would not have been possible without active and thoughtful engagement with the entire task force.

Mikaela Meyer (Carnegie Mellon University) helped to assemble this report, and RAND’s Adrian Salas assisted with the final model production runs. We thank our peer reviewers, Ben Miller (RAND) and Constantine Samaras (Carnegie Mellon University), for providing feedback that substantially improved this report. We also appreciate the additional writing support, feedback, and guidance we received from RAND colleagues Chandra Garber, Debra Knopman, and Kyle Siler-Evans.

This research was funded with grant support from the Henry L. Hillman Foundation, the Heinz Endowments, and 3 Rivers Wet Weather. Thank you to Ty Gourley, Matt Barron, Mark Wolinsky, and Brian Hill for their collective support and feedback throughout this effort. We are also grateful for additional in-kind support received from the Mid-Atlantic Regional Integrated Sciences and Assessments program, funded by the National Oceanic and Atmospheric Administration. Finally, this work used the Extreme Science and Engineering Discovery Environment, which is supported by National Science Foundation grant number ACI-1548562. The Extreme Science and Engineering Discovery Environment resources utilized were provided by Bridges at the Pittsburgh Supercomputing Center through allocation TG-SES170021.
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D</td>
<td>one-dimensional</td>
</tr>
<tr>
<td>2D</td>
<td>two-dimensional</td>
</tr>
<tr>
<td>AEP</td>
<td>annual exceedance probability</td>
</tr>
<tr>
<td>ALCOSAN</td>
<td>Allegheny County Sanitary Authority</td>
</tr>
<tr>
<td>CDAR</td>
<td>Section 219 Environmental Infrastructure—Negley Run: Conceptual Design Alternative Report</td>
</tr>
<tr>
<td>cfs</td>
<td>cubic feet per second</td>
</tr>
<tr>
<td>CSO</td>
<td>combined sewer overflow</td>
</tr>
<tr>
<td>CWP</td>
<td>Clean Water Plan</td>
</tr>
<tr>
<td>DDF</td>
<td>depth-duration-frequency</td>
</tr>
<tr>
<td>DDR</td>
<td>Negley Run Section 219 Environmental Infrastructure Pittsburgh, Pennsylvania Design Documentation Report: Draft 35% Submittal</td>
</tr>
<tr>
<td>DMDU</td>
<td>decisionmaking under deep uncertainty</td>
</tr>
<tr>
<td>EAD</td>
<td>expected annual damage</td>
</tr>
<tr>
<td>FWOA</td>
<td>future without action</td>
</tr>
<tr>
<td>GSI</td>
<td>green stormwater infrastructure</td>
</tr>
<tr>
<td>H&amp;H</td>
<td>hydrology and hydraulics</td>
</tr>
<tr>
<td>HGL</td>
<td>hydraulic grade line</td>
</tr>
<tr>
<td>IWWP</td>
<td>Interim Measures Wet Weather Plan</td>
</tr>
<tr>
<td>LHS</td>
<td>Latin Hypercube Sampling</td>
</tr>
<tr>
<td>LID</td>
<td>Low Impact Development</td>
</tr>
<tr>
<td>MGal</td>
<td>million gallons</td>
</tr>
<tr>
<td>MGY</td>
<td>million gallons per year</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>NPV</td>
<td>net present value</td>
</tr>
<tr>
<td>NRIP</td>
<td>Negley Run Implementation Plan</td>
</tr>
<tr>
<td>NRWTF</td>
<td>Negley Run Watershed Task Force</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>operations and maintenance</td>
</tr>
<tr>
<td>PWSA</td>
<td>Pittsburgh Water and Sewer Authority</td>
</tr>
<tr>
<td>RDM</td>
<td>Robust Decision Making</td>
</tr>
<tr>
<td>RSC</td>
<td>regenerative stormwater conveyance</td>
</tr>
<tr>
<td>SLRB</td>
<td>Silver Lake Retention Basin</td>
</tr>
<tr>
<td>SWMM</td>
<td>EPA Storm Water Management Model</td>
</tr>
<tr>
<td>TY</td>
<td>Typical Year</td>
</tr>
<tr>
<td>UA-NR</td>
<td>Upper Allegheny–Negley Run Model</td>
</tr>
<tr>
<td>USACE</td>
<td>U.S. Army Corps of Engineers</td>
</tr>
<tr>
<td>USGCRP</td>
<td>U.S. Global Change Research Program</td>
</tr>
<tr>
<td>WWP</td>
<td>Wet Weather Plan</td>
</tr>
</tbody>
</table>
CHAPTER ONE

Introduction

The Challenge of Stormwater Management in a Changing Climate

Cities across the United States are struggling to effectively manage stormwater runoff from heavy rainfall (National Academies of Sciences and Medicine, 2019). This challenge has grown over time in response to several drivers, including impervious cover from urbanized development (roads, parking lots, roofs, etc.) that increases stormwater flow on the surface and reduces the area in which water might naturally collect, infiltrate, or flow (Dhakal and Chevalier, 2016; National Research Council, 2009b). Other challenges include undersized storm and wastewater infrastructure, originally built decades to centuries ago and not able to keep pace with population growth and urban development (ASFPM Foundation, 2019); a lack of investment in infrastructure improvements over time (ASFPM Foundation, 2019); and land use plans and zoning that do not adequately address the growth in stormwater runoff from impervious surfaces (e.g., Stone, 2004). Together, these drivers have left many cities exposed to sewer overflows, urban flooding, and reduced water quality (University of Maryland et al., 2018).

Climate change has and will exacerbate this challenge (Chester, Underwood, and Samaras, 2020; Milly et al., 2008). A growing body of literature suggests that climate warming is already increasing the intensity or volume of rainfall from storms, particularly in the northeastern United States (Fischer and Knutti, 2015; USGCRP, 2017). Climate impacts on rainfall are expected to grow with future climate change (Cheng and AghaKouchak, 2014; Salas, Obeysekera, and Vogel, 2018). The magnitude of these changes and extent to which they will be experienced over the next few decades, however, remains highly uncertain. Notably, global climate models cannot yet fully represent or capture changes in heavy rainfall with the spatial resolution or time scales necessary to inform local planning and design, and such models may not calibrate well for specific regions of focus (Cook, McGinnis, and Samaras, 2020). They also can disagree substantially on the magnitude of precipitation change over time under the same assumed future conditions (Lopez-Cantu, Prein, and Samaras, 2020). Finally, future extreme rainfall trends will depend on the choices we make as a global society regarding how soon, and to what degree, we can reduce or eliminate carbon emissions from all sectors of the economy (Min et al., 2011; USGCRP, 2017).

Despite this uncertainty, however, local storm- and wastewater utilities and other key decisionmakers must still plan for major capital investments in outdated and undersized storm- and wastewater infrastructure. And they must do so in a complex and interconnected environment where multiple key actors, including government and nongovernment entities, are working to address a range of goals simultaneously. Urban stormwater is inherently a systems problem, spanning goals related to regulatory compliance, flood risk and damage, water quality,
ecosystem services, recreational opportunities, and economic development. It is also an environmental justice and equity challenge, as stormwater flooding and other negative outcomes can disproportionately affect low-income or majority-minority neighborhoods (ASFPM Foundation, 2019). However, local planners often make these decisions in piecemeal fashion or by ignoring key uncertainties, such as changing rainfall patterns, because they are focused only on certain objectives, such as regulatory compliance, or because they lack the capacity to rigorously evaluate or compare different design approaches across multiple objectives or in different plausible futures (Fischbach et al., 2020).

**Stormwater Planning in the Pittsburgh Region**

The Pittsburgh region, including the city of Pittsburgh and surrounding municipalities in Allegheny County, is a prime example of these challenges (Heinz Endowments and the Water Center at the University of Pennsylvania, 2019). As documented in *Robust Stormwater Management in the Pittsburgh Region: A Pilot Study* (Fischbach et al., 2017; hereafter the “pilot study”), the Pittsburgh region’s combined sewer system is inadequately sized to capture and treat most “wet weather” events, which occur frequently throughout the year. As a result, nearly every time it rains, a combined sewer overflow (CSO) occurs in at least one of the approximately 450 outfalls in the system, draining a mix of untreated wastewater and stormwater into streams and rivers.

Furthermore, high precipitation events combined with hilly topography and poor drainage can lead to flooding in many low-lying areas (Elliott et al., 2020). Some neighborhoods regularly face rainfall flooding, which can damage homes, businesses, and municipal infrastructure, as well as block transportation routes. Basement sewer backups, basement flooding, and other water-related challenges disproportionately affect Pittsburgh’s low-income and predominantly African American neighborhoods (City of Pittsburgh, 2017).

The Pittsburgh region lacks an overriding authority for managing stormwater. The Allegheny County Sanitary Authority (ALCOSAN) is responsible for conveying and treating wastewater from combined and separated sewer systems across 83 municipalities in the county, including the city of Pittsburgh. But ALCOSAN functions as a regional wastewater utility governed by federal, state, and local water-quality standards; does not build or maintain municipal storm- or wastewater infrastructure; and is thus not directly responsible for mitigating flooding or other municipal stormwater impacts. The Pittsburgh Water and Sewer Authority (PWSA) delivers drinking water and provides wastewater service to customers in the city of Pittsburgh and recently expanded its efforts to more holistically invest in stormwater management through new infrastructure investments and a proposed stormwater fee (Pittsburgh Water and Sewer Authority, 2020). PWSA’s investments are limited to its service area, however, and the utility provides services to approximately 300,000 of the county’s approximately 1.2 million residents (Pittsburgh Water and Sewer Authority; U.S. Census Bureau, 2019).

In 2008, ALCOSAN entered into a consent decree with the U.S. Department of Environmental Protection, Pennsylvania Department of Environmental Protection, and Allegheny County Health Department to create a plan to resolve ongoing sewer-overflow water-quality violations by 2026 (Environmental Protection Agency Region 3, 2019). As a result, ALCOSAN initially published a draft Wet Weather Plan (WWP) for public comment in July 2012 (ALCOSAN, 2012). Subsequent to draft plan release, negotiations between the parties involved in the original consent decree continued for years, finally culminating with the
approval of a modified consent decree in 2020 (U.S. District Court for the Western District of Pennsylvania, 2020). Along with the submission of the modified consent decree, ALCOSAN released an updated regional wastewater management plan, referred to as the Clean Water Plan (CWP) (ALCOSAN, 2019c).

The approximately $2 billion CWP calls for many of the key gray infrastructure investments (e.g., water treatment plant, pipes, pumps, storage tanks) outlined in the draft plan. Specific investments include a treatment plant expansion and a series of new deep tunnel interceptors along the Ohio, Monongahela, and Allegheny Rivers to capture and store a large volume of combined sewer flows during and after rainfall events. In response to public comment, the revised plan includes additional investment to help reduce the flow of stormwater “at the source” before it reaches the combined sewer system, which can include the employment of green infrastructure (see next section). The large majority of investment ($1.6 billion), however, remains focused on gray infrastructure solutions (ALCOSAN, 2019d). Other key tenets highlighted in the updated plan are ensuring affordability to rate payers, developing flow reduction targets to be met by customer municipalities, and continued progress toward ALCOSAN taking over ownership and management of large intermunicipal sewer lines in the region (regionalization) (ALCOSAN, 2019c).

The revised plan also uses an adaptive approach: it identifies a phased Interim Measures Wet Weather Plan (IWWP) to allow for early progress on regionalization and source or flow reduction to help guide later gray infrastructure investments, reserves some resources to be targeted in later decades, and extends the timeline for plan implementation to 2036 (ALCOSAN, 2019f).

Managing Stormwater with a System of Green Infrastructure

A key focus of public conversation surrounding the Pittsburgh region’s stormwater challenges since 2012 has been on green infrastructure. Green stormwater infrastructure (GSI) specifically uses natural elements (vegetation, soils, etc.) to capture stormwater and allow it to either infiltrate into groundwater or slowly release back into a stormwater or combined sewer system well after the storm event peak (U.S. Environmental Protection Agency, undated). Examples of GSI include permeable pavement, bioswales or vegetative swales, and green roofs (Figure 1.1). In contrast to gray stormwater infrastructure, which is built for water management alone, nature-based GSI is intended to provide other cobenefits to local residents, such as new parks or green space, recreational opportunities, and improved air quality (Gaffin, Rosenzweig, and Kong, 2012). These are sometimes collectively referred to as “triple bottom line” benefits, representing social, environmental, and economic benefits (Elkington, 1997).

In recent decades, there has been a national and global push toward more holistic and integrated stormwater management, with some cities turning to large investments in GSI to manage stormwater, mitigate sewer overflows, and provide multiple cobenefits through new infrastructure investment or reinvestment. The city of Philadelphia, for example, is currently implementing a 25-year Green City, Clean Waters plan that includes over $1.6 billion in GSI investments to convert a significant fraction of the city’s impervious cover into “greened acres” (Philadelphia Water Department, 2011). In plans like this one, GSI is often represented as a large number of small, distributed nature-based projects designed to provide on-site capture and temporary storage of rainfall during storm events, with much of the benefit coming via localized infiltration into groundwater.
ALCOSAN’s original draft WWP did not consider GSI as part of its investment strategy, leading to extensive public comment and feedback from regulators, local policymakers, environmental advocates, and other stakeholders (Fischbach et al., 2017). In response, in 2015 the authority developed its “Starting at the Source” report, which evaluated the potential for GSI to be incorporated into the regional stormwater management strategy and considered additional source reduction techniques including sewer separation, infiltration reduction, and direct stream inflow removal (ALCOSAN, 2015). This analysis attempted to highlight areas with the largest potential for source reduction strategies through the lens of impact and cost-effectiveness and provided recommendations for potential projects that municipalities could undertake to support a regionally coordinated stormwater strategy. Additionally, the ALCOSAN “Starting at the Source” report explored areas in which gray infrastructure plans could be reduced in favor of an expansion of green infrastructure options. ALCOSAN subsequently established the Green Revitalization of Our Waterways grant program to help support municipal investments in source reduction, including GSI (ALCOSAN, 2019a). However, the authority’s announced Green Revitalization of Our Waterways grants to date, totaling approximately $32 million, remain a small fraction of the overall planned $2 billion CWP investment (ALCOSAN, 2019a).

The Pittsburgh region’s steep topography and clay soils are often cited as barriers to more investment in GSI, because, respectively, these characteristics can constrain the area well suited to GSI retention and/or limit the effectiveness of infiltration-based approaches (ALCOSAN, 2015). However, an alternate approach is to use GSI techniques as part of combined green-and-gray strategies that seek to capture and route stormwater to a centralized system of surface con-
veyance and storage, ultimately allowing it to flow directly to receiving waters (e.g., rivers or lakes). Where possible, this approach could in theory divert a large volume of stormwater from the combined sewer system entirely, avoiding the need to invest in expensive sewer separation while restoring some amount of natural surface flows across an urbanized watershed.

PWSA’s service area encompasses a large fraction of the region’s combined sewer system, and the utility also shares responsibility under the consent orders to reduce overflows and meet water-quality requirements. In 2016, PWSA introduced its own draft Green First program and plan to consider how the utility might use GSI first to help achieve these requirements while also reducing flood impacts and providing cobenefits to residents through a combination of gray and green projects (Mott MacDonald and Pittsburgh Water and Sewer Authority, 2016b). In this effort, PWSA identified a series of priority watersheds that make up a large fraction of the city’s CSO volumes and have the potential for GSI investment. Looking beyond infiltration-based approaches, the utility developed conceptual visions for how it could implement large-scale systems of GSI and restore some amount of natural surface flows in these watersheds. It also conducted preliminary analysis of potential plan benefits but was not able to explicitly simulate how such systems of GSI would function when implemented at the watershed scale.

**Purpose of This Report**

This report builds on the pilot study with a focused investigation on one key watershed identified in PWSA’s Green First Plan: Negley Run. Negley Run is a large watershed that drains a diverse area of Pittsburgh’s East End, including several neighborhoods that have suffered heavily from underinvestment in recent decades. It also represents one of the most urgent flood-risk challenges in the city, as heavy rainfall in the area leads to regular flooding of a key road corridor. In this report, we describe results from a research study using simulation modeling to estimate present and future risks in Negley Run from sewer overflows and flooding given future rainfall uncertainty. We then evaluate proposals for a phased series of large-scale GSI investments intended to capture, store, and convey rainfall to the Allegheny River. In addition to the stormwater benefits and strategy costs, this evaluation also includes economic estimates of recreational, amenity, and other co-benefits to local residents and compares total benefits to costs using methods for decisionmaking under deep uncertainty (DMDU).

Although this effort focuses on one watershed, another key goal of this report is to help establish best practices for watershed-scale stormwater planning that seeks to address multiple policy objectives and explicitly takes into account future climate uncertainty. Our intention is that this study will help to inform similar efforts in other watersheds in the city of Pittsburgh, Allegheny County, and in urban areas across the nation.

This research was funded with grant support from the Henry L. Hillman Foundation, the Heinz Endowments, and 3 Rivers Wet Weather.

**Pittsburgh’s Negley Run Watershed**

Building on prior analysis, this study focuses on proposals to substantially reinvest in Pittsburgh’s Negley Run watershed using a system of GSI as an alternative or augment to traditional underground pipe and storage infrastructure (gray infrastructure). This watershed—
also referred to by the technical designation “A-42 Sewershed”—is a key location of focus for both stormwater management and city resilience planning. A number of green infrastructure projects are currently in planning stages for Negley Run, and such neighborhoods as Homewood, Larimer, and Lincoln-Lemington-Belmar are priorities for city equity and resilience planning (Arcadis, 2016; City of Pittsburgh, 2017; Homewood Community Development Collaborative, Pittsburgh Department of City Planning and Urban Redevelopment Authority of Pittsburgh, 2019; Pittsburgh Water and Sewer Authority, 2016).

Geography

Negley Run (Figure 1.2) is a large (3,300 acres) and urbanized watershed at the eastern end of the city of Pittsburgh, with only 10 percent of the land area including either park or “park-like” forested locations (Mott MacDonald and Pittsburgh Water and Sewer Authority, 2016a). Washington Boulevard and Negley Run Boulevard are the primary drainage corridors (Figure 1.3), corresponding to former natural streamflow locations, and the Washington Boulevard corridor, which ends up in a valley with steep slopes on either side, leads north to

Figure 1.2
Negley Run Watershed Location and Scale

SOURCE: Authors’ analysis; base map from ALCOSAN, 2018, “Sewersheds, Outfalls, and Interceptors Located in the Conveyance and Treatment System.” Used with permission.
NOTE: Gray shading indicates areas of the system with combined sewers.

---

1 According to PWSA, “A sewer shed is the area of land where all the sewers flow to a single end point” (Pittsburgh Water and Sewer Authority, undated-a). Although this is a technically correct description of Negley Run in its current condition, a new separated stormwater connection to the river as outlined in this report would complicate that definition and in part help to restore Negley Run to its original “watershed” status. As a result, we preferentially use the term Negley Run watershed throughout this report.
a junction with the Allegheny River (Living Waters of Larimer, undated-b). The middle and upper portions of the watershed are primarily residential, with light industrial and commercial mixed in, while the lower portion includes commercial and industrial facilities, park land, and institutional and public facilities.

**Neighborhood Demographics**
Negley Run drains all or portions of 12 of Pittsburgh’s 90 neighborhoods, along with portions of the neighboring municipality of Penn Hills (Figure 1.4). Its demographics vary considerably by neighborhood: as of the 2010 U.S. Census, Homewood and East Hills had among the largest proportions of African American residents in the city (over 93 percent), with Larimer (86 percent) and Lincoln-Lemington-Belmar (79 percent) not far behind. By contrast, the populations of Highland Park and Point Breeze were 66 and 89 percent white, respectively (University Center for Social and Urban Research at University of Pittsburgh, 2011). Income disparities are similarly stark: median household income in Homewood North was about $23,000 as of the 2010 census, while it was nearly $96,000 in Point Breeze (2013 dollars) (Allegheny County/City of Pittsburgh/Western PA Regional Data Center, 2017). Homewood, Larimer, and Lincoln-Lemington-Belmar also struggle with high rates of vacant or blighted properties, with over 20 percent of homes vacant in each neighborhood (Allegheny County/City of Pittsburgh/Western PA Regional Data Center, 2017).

**Stormwater Challenges**
Negley Run captures more water than any other watershed in the city of Pittsburgh and is the single largest contributor of CSO volumes across the ALCOSAN service area. Prior analysis
estimates that the single A-42 combined sewer outfall contributes nearly 800 million gallons per year (MGY) of overflow in a Typical Year (TY), or nearly 9 percent of the systemwide total (ALCOSAN, 2019e, Sec. 4.5).

Flooding also poses important concerns across the watershed. Major rainfall events regularly lead to flash flooding along lower Washington Boulevard, a key roadway corridor that supports a large volume of commuter traffic from suburbs north of the Allegheny River. In August 2011, notably, a flash flood along this corridor rapidly submerged cars during a rush-hour backup and killed four people (Balingit, 2013). Flood gates were subsequently installed at the intersection of Washington Boulevard and Negley Run Boulevard (upstream) and Washington and Allegheny Run Boulevards (downstream), though early on the automated system was faulty and emergency police closures have been needed (Smeltz, 2018). Since early 2016, we estimate that this corridor has been closed approximately ten times due to flooding.\footnote{This information is based on our analysis of data from the Allegheny County Twitter feed, cross-checked with contemporaneous press accounts. Twitter data provided courtesy of Tom Batroney in February 2020.} In addition, upstream neighborhoods can experience street flooding on key roads or intersections, and residents report both wet basements during storm events and basement backups, where sewer lines overflow into basements and homes (Ford et al., 2018).
Participatory Planning with the Negley Run Watershed Task Force

Given the range of social, economic, and environmental challenges faced in the watershed, recent local planning efforts have looked to address these problems holistically through large-scale investment in GSI. Building from PWSA’s Green First Plan concepts, for instance, in 2017 a local design collaborative developed the Negley Run Implementation Plan (envirosocialcapital, evolveEA, and eDesign Dynamics, 2017; hereafter NRIP). This plan envisions a new separated surface connection to the Allegheny River and a phased series of investments that would eventually connect broad areas of the watershed to this newly daylighted system (Figure 1.5; envirosocialcapital, evolveEA, and eDesign Dynamics, 2017). In parallel, the Living Waters of Larimer team (now Living Waters of PGH) also convened a new working group to coordinate watershed GSI activities, called the Negley Run Watershed Task Force (NRWTF). The task force is composed of representatives from key government agencies, neighborhood organizations, environmental nonprofits, and local designers and technical experts, and has met monthly to semimonthly to help coordinate and share information over the last several years.

The RAND team has been an active participant in the NRWTF meetings since 2018, and its members provided input and feedback throughout this research effort. We discuss

Figure 1.5
Negley Run Implementation Plan Concept Vision

SOURCE: envirosocialcapital, evolveEA, and eDesign Dynamics, 2017; used with permission.
NRIP and other planning and design conducted in recent years by government agencies and local stakeholders for Negley Run in detail in Chapter Four.

**Research Questions**

This project was guided by the following research questions:

- What are the current risks posed by heavy rainfall to the Negley Run watershed, including both sewer overflows and flooding?
- How might these risks change in futures where heavy rainfall grows more frequent or intense?
- How might a new daylighted system of GSI help to reduce sewer overflow and flood risk, and how does this vary at different levels of investment or build-out?
- What other co-benefits would proposed GSI strategies provide?
- How do the benefits and co-benefits from proposed GSI strategies compare with their costs across a range of plausible assumptions?

We address each question in turn through the remainder of this report.

**Organization of This Report**

This report includes seven chapters. The second chapter provides a brief overview of key research methods applied, including the simulation modeling approach and benefit and cost estimation. Chapter Three describes results from the modeling analysis with current infrastructure in place, including an investigation of growing vulnerability due to plausible future rainfall trends. In Chapter Four, we introduce the strategies evaluated to meet stormwater management goals in Negley Run and describe sources and key assumptions applied to model and estimate costs for these strategies. Chapter Five describes modeled strategy results for stormwater outcomes, such as reductions in sewer overflows or street flooding, while Chapter Six builds on this simulation modeling analysis to compare economic benefits, co-benefits, and costs from each strategy under uncertain future conditions. We conclude by summarizing key findings and recommendations for PWSA, members of NRWTF, and other stakeholders.

Also included in this report are a series of appendixes that provide additional detail on model development and validation, data sources, and methods applied. Appendix A, prepared by the Arcadis modeling team, describes the development and calibration of an updated simulation model for Negley Run. Appendix B describes additional work we performed to integrate and validate the updated model. Appendix C provides further detail on rainfall data sources, while additional methods applied to estimate sewer overflows and flood risk are detailed in Appendix D. Appendix E complements Chapter Four with additional detail on strategy modeling and cost estimation. Finally, Appendix F describes the economic methods and sources used for estimating co-benefits from green infrastructure.

This report will also be complemented by a set of forthcoming interactive visualizations, published separately, that will allow interested readers and stakeholders to explore the model results and scenario analysis in greater detail.
This study builds closely on a prior pilot-scale effort focused on climate resilient stormwater management across the Pittsburgh region (Fischbach et al., 2017). Similar to that preceding effort, this study uses simulation modeling to estimate key stormwater outcomes in scenarios representing current and plausible future rainfall for the region and applies DMDU techniques to both explore the range of future climate-related uncertainty and help identify more robust strategies for stormwater management. This effort focuses on a specific watershed of interest and adds detail to both the policy levers evaluated and performance metrics considered but otherwise builds closely on the analytical foundation of the pilot study.

As a result, in this chapter we provide a brief overview of the methods applied but with a focus on aspects where new methods or additional detail was included above and beyond the pilot study. We would encourage the reader to consult the pilot study as a companion to this report. In addition, an expanded discussion of methods and data, with considerably more detail, is provided in this document’s supporting appendixes.

This chapter begins with an overview of our research steps. We then describe the updated hydrology and hydraulics (H&H) model developed to support this effort, along with key rainfall data inputs applied. Next, we introduce the GSI strategies to be evaluated and the corresponding approach to cost estimation and summarize the methods applied to evaluate GSI cobenefits. The chapter concludes with a brief description of the Robust Decision Making (RDM) tools applied to support a comparison of GSI strategies under uncertainty.

**Overview of the Research Approach**

The pilot project, completed in 2017, used a series of linked simulation models of Pittsburgh’s combined sewer system to simulate the frequency and volume of regional sewer overflows under a wide range of scenarios and proposed infrastructure strategies. That effort leveraged high-performance computing to support large-scale scenario analysis of storm- and wastewater systems. In the analysis described in this report, we extended this analytical toolkit to evaluate a range of policy-relevant outcomes for Negley Run. Key steps included the following:

1. **Develop updated Negley Run simulation model.** We worked with Arcadis, an engineering firm, to develop a new detailed stormwater simulation model for Negley Run. This new model allowed us to consider both sewer overflows and flood risk across a range of historical rainfall and plausible future rainfall conditions.
2. **Evaluate watershed-scale GSI proposals for Negley Run.** Via NRWTF, we worked with PWSA, community organizations, design teams, and engineering partners to identify a range of proposals intended to divert, capture, or temporarily store water during rainstorms using GSI or a combination of gray and green infrastructure. We then evaluated these proposed strategies using the new simulation model to estimate CSO and flood-risk reduction benefits in different uncertain futures.

3. **Compare the benefits, cobenefits, and costs of green infrastructure.** Finally, we estimated the additional cobenefits from these strategies that might extend beyond the benefits valued for gray infrastructure projects. We combined these estimates with monetized estimates of stormwater benefits and then compared total estimates of benefits with costs to estimate sewer-overflow reduction cost-effectiveness as well as net economic benefit. The goal was to identify strategies that build resiliency against current and future rainfall conditions, search for low-regret solutions that work regardless of which future comes to pass, and highlight key trade-offs that might emerge between approaches.

### Hydrology and Hydraulics Modeling

#### Negley Run Model Development

Arcadis developed a revised H&H simulation model using the EPA Stormwater Management Model (SWMM) software platform to support this research effort (Rossman, 2015). To develop the new model, the Arcadis team began with the ALCOSAN-developed SWMM model for the Upper Allegheny region used in the pilot study (Fischbach et al., 2017). They extracted the Negley Run watershed from this model and then used additional data sets provided by PWSA or obtained from other county geographic information system sources to add new spatial and modeling detail, such as dynamic estimates of groundwater and inflow and infiltration flows. Finally, they recalibrated the model using monitored data of sewer system flows.¹

The methods applied were based on innovations developed and applied in support of stormwater planning in other cities, including Columbus, Ohio (City of Columbus Department of Public Utilities, 2015), and Buffalo, New York (UB Regional Institute at University of Buffalo, 2018). Key model updates included

- delineating runoff catchments (subcatchments) at the storm inlet level
- breaking down the delineated catchments into hydrologically independent runoff areas and groundwater sources
- modeling selected streets as open channels to help identify streets and houses with potential flooding risk.

The resulting model still relies on one-dimensional (1D) analysis to approximate surface flows and street flooding and was limited by the data available to describe the system as of early 2018 but nevertheless provides a detailed picture of stormwater flows for a large portion

---

¹ Additional data used to inform model development represent conditions in 2017–2018. There have been no major changes to the Negley Run combined sewer system since this time, but note that this modeling approach also assumes no major changes in land use between then and now. We believe this to be a reasonable assumption given subsequent monitoring of local planning and construction since that time. For more information on data sources, please see Appendix A.
of the Negley Run watershed. The new model incorporates 427 stormwater inlets, estimates stormwater runoff from 1,035 subcatchments with an average size of 3.5 acres, and includes surface flows for 849 distinct street segments.

A more detailed description of the development of this new model, which we refer to as the Negley Run (NR) model, can be found in Arcadis’s Model Investigation Report, included as Appendix A to this document.

**Upper Allegheny–Negley Run Model Integration**

A-42 interconnects with the ALCOSAN regional system and conveys dry weather flows to the ALCOSAN treatment plant but produces among the highest volumes of combined sewer overflow in the Pittsburgh region during wet weather conditions. To appropriately represent the hydraulic constraints introduced at the ALCOSAN interconnection (Metcalf & Eddy Baker/Wade-Trim, 2008), the RAND team integrated the detailed NR model back into the regional Upper Allegheny (UA) model provided by ALCOSAN that was previously used to estimate sewer overflows in Fischbach et al., 2017. We refer to the resulting model as the combined Upper Allegheny–Negley Run (UA-NR) model, which we used as the basis for the remainder of this analysis. We then conducted additional validation steps to compare UA-NR model output to monitored flow data and prior Negley Run CSO estimates developed by ALCOSAN and PWSA. Additional detail on UA-NR model integration and validation is provided in Appendix B.

**Historical and Future Rainfall**

We incorporated both annual rainfall time series and discrete storm events as inputs to the SWMM model to evaluate the performance of the combined stormwater system under different infrastructure strategies and other uncertainties.

**Annual Time Series**

The annual time series track rainfall at 15-minute intervals throughout each year. They include 16 years of historical data (2003–2018), a modified historical year (2003 Typical Year, or 2003TY) that represents the average annual historical hydrology of the region estimated by ALCOSAN, and climate-adjusted future rainfall periods. The climate-adjusted future conditions are the same downscaled rainfall projections applied in Fischbach et al., 2017, and represent a decade of the historical data (2004–2013) modified to match downscaled climate projections. Annual time series were used to evaluate volumetric sewer overflow from the entire watershed.

**Discrete Storm Events**

This analysis also considered discrete storm events in order to estimate stormwater runoff and potential flood impacts, moving beyond the sources drawn from the pilot study. The discrete

---

2 ALCOSAN selected the 2003TY for its wet weather planning based on a statistical analysis of historical rainfall conducted in 2008–2009. This entailed estimating the average annual rainfall for the region (assuming stationarity) and developing a rainfall time series to match the target rainfall volume. For more information, see ALCOSAN, “Development of the Typical Year Precipitation for the ALCOSAN Service Area,” 2009.
Managing Heavy Rainfall with Green Infrastructure

storm investigation included storm events sourced from both the historical record and synthetic storm events using standardized rainfall distributions. We modified these storms to match a wide range of historical and future climate-modified rainfall intensities derived from published depth-duration-frequency (DDF) estimates in order to evaluate metrics of stormwater runoff, street flooding, and residential basement flooding in portions of the watershed. Further information and methodological descriptions on rainfall data incorporated in the analysis are detailed in Chapter Three and Appendix C.

Estimating Current and Future Stormwater Impacts

Combined Sewer Overflows

The frequency and volume of CSOs were calculated based on the combined flow to the main outfall into the Allegheny River from annual time series simulations. Distinct overflow events were identified by applying an interevent interval (interval of time between recognized events) of 24 hours and a flow rate of 0.1 cubic feet per second (cfs) per the methods applied in ALCOSAN’s WWP (ALCOSAN, 2019e). Annual overflow event durations and frequencies (as number of events) were then calculated using these thresholds for each strategy and uncertainty condition selected for simulation.

Note that, unlike Fischbach et al., 2017, and recent investigations by ALCOSAN and PWSA, the overflow volume estimates for the Negley Run watershed estimated here do not take into account potential interactions with the remainder of the ALCOSAN regional system (e.g., Main Rivers basin, treatment plant), instead relying on UA-NR model estimates alone. This may lead to bias relative to comparable overflow estimates for A-42, though in practice these effects could be small compared with the changes introduced by the new UA-NR model itself.

Flood Impacts

We used discrete storm analysis in the UA-NR model to assess residential basement and street flooding. Residential basement flooding is caused either by water flowing from the surface or adjacent groundwater into the basement (wet basement) or from water backing up in the sewer line and overflowing a home’s sewer stack due to an elevated hydraulic pressure in the adjacent sewer main (sewer backup) from stormwater inflow to the combined system. We specifically adapted a spreadsheet tool created by Arcadis into a script that generates basement flooding results for all storm scenarios under consideration (see Appendix A).

This analysis does not include all single-family homes or streets in the watershed but is instead limited to homes along streets that were explicitly modeled by Arcadis. In general, these are streets with 18-inch or greater diameter sewer mains and where existing data were available to describe storm inlet locations and elevations.

Basement Flooding

For the sewer backup analysis, the maximum hydraulic grade line (HGL) at each house was calculated by linearly interpolating from the SWMM-reported maximum water depths at the

---

3 An HGL is defined as the surface level (elevation) of water flowing through an open channel or partially full pipe. In the case of pressurized pipes, HGL is the surface level the water would rise to in a tube connected to the pipe.
inlet and outlet nodes for the sewer conduit along which the house is located. It was assumed that the maximum depths at each node occurred simultaneously or within a negligible time difference. Houses were determined to be at risk of sewer backups if the HGL at the connection of the house lateral and sewer conduit exceeded the elevation of the basement.  

For the wet basement analysis, the same method was followed, except that the HGL at each house was calculated along the street channel from the surface inlet and outlet nodes of the street channel. Houses were determined to be at risk of wet basements from surface flooding if the HGL at the house exceeded the home’s grade elevation. This conservative assumption maintains that water would only seep into the basement along the house foundation or from first floor flooding when flood waters exceed the house’s grade, although it is also possible that elevated groundwater at a lower HGL could cause similar wet basement damage.

We further extended this analysis to calculate rough, first-order approximations of basement flood damage in dollar terms from discrete storm events or in terms of expected annual damage (EAD). This analysis was based on established methods derived from the Federal Emergency Management Agency’s Hazus Flood Model (Federal Emergency Management Agency, 2007) as well as prior research by the authors. For more information on damage estimation methods, please see Appendix D.

**Street Flooding**

For this exploratory analysis, we extended the same 1D methodology used for house flooding to estimate the frequency of street flooding at different locations within Negley Run. As noted above, these street-flooding estimates only consider a subset of streets within the watershed due to current limitations in available data describing the pipe system and stormwater inlets. This analysis further relies on a simplified representation of streets as 1D open channels in SWMM.

For this portion of the analysis, we generated a set of street points at 100-foot intervals along each street under consideration and generated flooding heights at each point for every storm scenario. Similar to the house flooding analysis, we use SWMM-reported output for all nodes to calculate both the elevation of each street point as well as the HGL at each point to determine a flood height. This method implies an assumption that streets slope at a perfectly linear rate between nodes, which likely holds true for most street segments over short distances.

See Appendix D for more information on the methods discussed in this section.

**Green Stormwater Infrastructure Strategy Modeling and Costing**

A large portion of this research effort was devoted to modeling and evaluating a progressive series of GSI strategies for Negley Run based on the Green First Plan, NRIP, and other recent work by PWSA. The methods used to identify these strategies, represent them in the UA-NR model, and develop preliminary planning level costs and implementation timelines are not

---

4 Sewer backups can also occur if the sewer lateral connected to the house is broken, collapsed, or blocked (e.g., tree root) or due to a clog in the house sewer line. These types of backups are out of the scope of this analysis.

5 This approach also underestimates potential basement flooding because it does not consider basement flooding from rain collection immediately adjacent to an external wall or flowing from a disconnected downspout. See Appendix D for further details.
discussed here but instead introduced in Chapter Four alongside a description of the resulting strategies. Additional methodological detail is also provided in Appendix E to this report.

**Estimating Strategy Benefits and Cobenefits**

A primary argument GSI projects is that they can provide benefits beyond just managing stormwater flows, but these benefits are difficult to value. Many goods and services are not traded in markets (especially nonprovisioning services) and thus are not associated with price signals from which value can be inferred. Nevertheless, economists have developed methods to estimate willingness to pay (a theoretical measure of gross benefit from the consumer side) for these nonmarket goods using alternative techniques. We briefly discuss the major methods below; for more information, the reader is referred to Champ, Boyle, and Brown, 2017.

- **Cost-based methods** do not directly estimate willingness to pay but rather use avoided costs, mitigation and restoration costs, or replacement costs to infer the value of a good or service. The logic is that if society decides (or in the case of regulation is legally required) to provide a nonmarket good or service, the relatively known costs of providing it in a “business as usual” sense is an estimate of the minimum value of that good or service. When applying this value to a new project, it is assumed that the marginal/average value of the service is at least as much as the known cost figure.

- The **hedonic property method** is a revealed-preference technique based on the theory that property values should reflect the amenities surrounding a property, such as recreational opportunities and aesthetics. The method uses statistical models to estimate the (marginal) values associated with an amenity or disamenity, and these values are used as estimates of the value of the service. These can be converted to a flow measure using an appropriate discount rate. The values obtained for this method are specific to the property owners.

- The **travel cost method** is a revealed-preference technique generally appropriate for recreational and other trip-based values. It assumes that the demand for recreation is inversely related to the costs to travel to a site and uses statistical models, travel time, and measures of the value of time to estimate the value of a recreational trip to a participant.

- **Stated preference** methods, such as contingent valuation and choice experiments, use survey data to estimate willingness to pay. Using an experimental design, researchers use discrete choice questions (in which a respondent makes a choice over some menu of alternatives) and statistical models to estimate how much income a respondent would be willing to give up to obtain some level of a good or service and remain at the same level of satisfaction. Unlike other methods, nonuse values (values stemming from the mere existence of a good or service or the option to use it in the future) can be estimated using stated preference techniques.

- **Benefit (or value) transfer** methods use values from previous research in a new context to value nonmarket goods and services. This can be as simple as taking one value from a study that is similar in context and using it in another or as complex as a metaregression that statistically models the results of research from many contexts, accounting for differences across studies. In the latter case, the statistical model is used to obtain appropriate values for a new study.
In an ideal world, community-specific studies of all values of interest for a project or program would be used in the decisionmaking process to reflect the specific preferences of stakeholders and the attributes of the project or program. In reality, this is infeasible. As such, researchers and decisionmakers must make trade-offs between potential errors in value estimation and feasibly documenting the likely magnitudes of the benefits and costs of a project or program.

We use a mix of methods to estimate benefits and cobenefits in this report. Given an inability to collect primary data due to time and budgetary constraints, we rely entirely on secondary data. Stormwater management benefits are calculated using cost avoidance, while flooding benefits are calculated using depth-damage relationships (essentially a functional benefit transfer technique). Both are driven by the hydraulics modeling results, which serve as an input into both benefit categories.

For cobenefits, we generally use a benefit transfer approach, at times in conjunction with models that appear in the literature and are appropriate for estimating quantity changes. In cases where such models are unavailable (e.g., we do not have access to a transportation model suitable for estimating changed travel times as a result of street flooding), we rely on conservative assumptions that likely underestimate the particular benefit. Still, readers should interpret these results with caution.

We briefly discuss the methods used to estimate benefits and costs in the sections that follow. Additional details are provided in Appendix F.

**Sewer Overflow Reduction Benefits**

This analysis considers both CSO reduction and other cobenefits in economic terms. To compare this research with recent water-quality plans developed by ALCOSAN and PWSA in response to legal mandates from regulators, CSO reduction is compared with capital costs directly to estimate cost-effectiveness in terms of cost per gallon of overflow reduced ($/gal). This provides a common basis for comparing the cost-efficiency of the strategies in this report to other water-quality capital investments planned for the region in response to the consent order.

In addition, we also seek to estimate the potential benefits from CSO reduction (water-quality improvement) directly in dollar terms, representing the social benefit that results from cleaner waterways. This allows us to sum water-quality benefits and other cobenefits for a more complete benefit-cost comparison. For this portion of the analysis, we flip the analysis around and instead use the cost-effectiveness estimated from ALCOSAN’s final and approved Clean Water Plan for regionwide CSO mitigation to serve as a proxy for potential water-quality benefits in Negley Run. This approach assumes that the capital investment planned for other local CSO mitigation projects is a reasonable proxy for the social value of CSO reduction and improved water quality and that each dollar spent on the Negley Run strategies evaluated here would help to avoid a dollar spent on CSO reduction elsewhere in the system in the near or long term.

This approach is called the cost avoidance approach in the literature and is an example of a cost-based valuation method. It does not directly estimate willingness to pay but rather uses avoided costs, mitigation and restoration costs, or replacement costs to infer the value of a good or service. The logic is that if society decides to provide a nonmarket good or service, the relatively known cost of providing it is an estimate of the minimum value of that good or service. For more information, the reader is referred to Champ et al., 2017, and Champ, Boyle, and Brown, 2017.
**Additional Cobenefits**

While our framing of the problem considers CSO reduction as the primary benefit of the green infrastructure solutions, the nature of these solutions suggests a suite of potential cobenefits that traditionally engineered solutions (gray infrastructure) will not provide. In particular, the design strategies (see Chapter Four) include a recreational trail, tree planting, and development of green open space that may provide additional amenities to city residents. We briefly discuss valuation methods for these elements below; for more detail and appropriate citations, see Appendix F.

**Recreation Benefits and Benefits to Bicycle Commuters**

We generally follow the methodology outlined in National Cooperative Highway Research Program, 2006, to estimate the number of bicycle commuters and new recreational cyclists and use a conservative 1:1 ratio of pedestrians to new cyclists as in Intertwine Partner Agency and Alta Planning and Design, 2011, to estimate the number of pedestrians. This approach combines information on the share of bicycle transportation shares from the U.S. Census’s American Community Survey with an estimate of the population around a new facility and several empirical relationships from regression models to estimate the subpopulations expected to benefit from a new bicycle facility in urban environments. Once this estimate is obtained and extrapolated to a calendar year, average values are multiplied by the physical quantities to convert the estimates to a monetary benefit. The National Cooperative Highway Research Program provides empirical formulas that give a range of estimates for new (induced) cyclists as a result of the new facility.

**Benefits from Tree Planting**

An increased number of trees in an urban environment can lead to benefits from average temperature reduction due to increased canopy (typically termed the *urban heat island effect*), which results in less energy (and thus costs) used in cooling buildings. In addition, trees can sequester carbon that is valued as a global public good, as well as providing additional air-quality benefits that are more localized. We use the basic calculations documented in a 2015 study (Davey Resource Group, 2015)6 of the benefits of Pittsburgh street trees using the program i-Tree, which is a tree valuation software package based on research from the U.S. Forest Service.7

**Amenity Values**

In addition to the benefits already discussed, residents of Pittsburgh may be willing to pay for perceived aesthetic improvements, or amenity values, as a result of the installation of green infrastructure (assuming they view “greening” as a good). One means of measuring this value is through the hedonic property method, which assumes that aesthetic services, along with other use values, are capitalized into the value of properties affected by those services. As such, while any statistical increase in property values attributable to proximity to green infrastructure will include amenity benefits, it will also include the capitalized values of all other ecosystem services that accrue to the owner.

---

6 The study also used i-Tree to estimate stormwater benefits and aesthetic/property value benefits, but they were not used in this report because we estimate such benefits separately.

7 Note that trees can also theoretically contribute to habitat, biodiversity, and runoff capture. Given the urban environment in Pittsburgh, we suggest that the first two will be relatively minor and thus value them at zero, while the third is captured by the stormwater modeling exercise.
Given the potential for double counting, as well as the uncertainty involved and the fact that we separately estimate recreational benefits, we assume that green infrastructure and the associated open space it creates are not negatively valued, focus on houses within a quarter-mile buffer around the trail, and assume that these values lie between 0 and 2.5 percent of average property values in the watershed. This is generally on the low end of the range of capitalized values of open space in the literature (typically 2–8 percent), but this range likely includes services other than amenity values.

Robust Decision Making

Finally, this study builds on the RDM approach previously described in the pilot study. RDM is a general analytical method intended to help identify policies or strategies that are robust against future uncertainty, meaning that they will perform well regardless of which future comes to pass (Groves and Lempert, 2007; Lempert, 2019; Lempert, Popper, and Bankes, 2003). Robust strategies are often adaptive, meaning that they specifically lay out different decision pathways and signposts that would trigger a jump from one path to another (Haasnoot et al., 2013; Kwakkel, Haasnoot, and Walker, 2015). RDM is one of a series of quantitative decision analysis methods that leverage exploratory modeling (Bankes, 1993), quantitative scenario analysis, and iterative learning to support DMDU. There is a large and rapidly growing literature that describes these methods, and interested readers are referred to the recently published DMDU textbook Marchau et al., 2019, for an in-depth discussion of various complementary approaches, as well as recent case study applications.

In practice, this report applies a handful of well-established DMDU techniques also described in the pilot study and is not intended to break new methodological ground. We introduce these techniques when needed in Chapters Three and Six. However, we note that, to date, there are relatively few examples of DMDU applied to urban stormwater planning challenges, with Fischbach et al., 2017 (the pilot study) and Groves et al., 2018, serving as notable exceptions. In part, this is likely due to the overall challenge of H&H simulation modeling for stormwater systems. These models require substantial effort and supporting data to build and calibrate and can be very computationally intensive to run, creating important barriers to employing DMDU techniques. Nevertheless, the need for these approaches to inform climate-resilient stormwater management is evident, and we hope that this study serves as a stepping-stone to broader applications.

Chapter Summary

This chapter provided an overview of the modeling tools and analytical techniques employed in this research effort. We introduced a new H&H model for the Negley Run watershed, described approaches for estimating sewer overflows and flood risk under present and plausible future conditions, and summarized economic and decision analysis methods employed to estimate benefits and compare strategies under uncertainty. We also noted where these methods are expanded on in supporting appendices as well as the broader literature. In the next chapter, we employ the simulation model to investigate policy-relevant stormwater outcomes for Negley Run under current conditions and in a future without action (FWOA).
Chapter Three

Sewer Overflows and Flooding in a Future Without Action

Introduction

The Negley Run watershed faces a range of stormwater management challenges under present conditions, and as noted in Chapter One future climate change could exacerbate these challenges. In this chapter, we explore recent rainfall trends and use simulation modeling to estimate their effects on the Negley Run watershed. We also expand this analysis to consider how vulnerability might grow or change with future climate uncertainty. The analysis here assumes that no further investments in stormwater mitigation are made in Negley Run, thus providing a FWOA baseline against which proposed strategies can be compared.

We first introduce and discuss the rainfall uncertainties considered in this chapter and throughout the remainder of the report. We then present results from the SWMM modeling analysis for key outcomes of interest for Negley Run: CSOs, stormwater runoff from impervious surfaces, and rainfall flooding. Estimated present and future flood impacts include street flooding, potential wet basements, and basement sewer backups for selected areas of the watershed. The methods for each portion of the analysis are summarized in Chapter Two of this report, with additional detail provided in the supporting appendixes.

Table 3.1 summarizes the components of the analysis in this chapter using the “XLRM” framework (Lempert, Popper, and Bankes, 2003). “X” stands for uncertain factors that may affect the ability to achieve planning goals; “L” is short for policy levers, the actions that policymakers or utilities can implement toward one or more goals; “R” represents the relationships between these elements used to estimate outcomes, often contained in simulation models; and “M” summarizes the performance metrics used to evaluate outcomes of interest and measure progress toward goals. In this portion of the analysis, no additional policy levers are considered beyond current system conditions, which we refer to as an FWOA (future without action). In the next chapter, we introduce a series of incremental strategies to evaluate that build on this framework.

Uncertainties Considered

Current and Projected Rainfall in Pittsburgh

This analysis focuses on uncertainty associated with recent rainfall trends as well as how future climate change might influence heavy rainfall patterns in Pittsburgh and Western Pennsylvania.
As introduced in Chapter Two, this entailed using recent downscaled estimates of precipitation for Pittsburgh (Cook, Anderson, and Samaras, 2017; Cook, McGinnis, and Samaras, 2020; Fischbach et al., 2017) and incorporating them into the updated SWMM model for a large-scale simulation analysis. We evaluated this in two ways: (1) using annual time series data, at a 15-minute time step, to estimate combined sewer overflows for each past or projected future year; and (2) using estimates of heavy rainfall volumes from discrete storms of different durations or annual recurrence frequencies, drawn from DDF curves, to estimate runoff and potential flood impacts.

Fischbach et al., 2017, compares Recent Historical rainfall to past rainfall statistics dating to midcentury. Other recent investigations have also explored recent rainfall at the regional or national level and detected an increase in average annual rainfall, with notable increases in rainfall volume from the most extreme events (Asadieh and Krakauer, 2015; Donat et al., 2016; USGCRP, 2017).

In preparation for our analysis, we compared estimates of regional extreme rainfall recurrence in the National Oceanic and Atmospheric Administration’s (NOAA) Atlas 14 database (Bonnin et al., 2006) to a 16-year observed record of rainfall derived from a local high-resolution radar-adjusted rainfall database (3 Rivers Wet Weather, 2019) for a representative point at the center of the Negley Run watershed. Specifically, we estimated the approximate number of storms that meet or exceed a certain rainfall volume we would expect to observe during a 16-year period based on the median Atlas 14 DDF estimates, ranging from the 2-year (50 percent annual exceedance probability) to the 100-year (1 percent annual exceedance probability).
ability) event. For instance, Atlas 14 estimates the median 2-year, 24-hour rainfall event to be 2.3 inches, so we would expect to observe approximately eight rainfall events of at least this amount, on average, over the 16-year time span. We then compared these estimates to the actual number of events meeting or exceeding the Atlas 14 thresholds based on radar-adjusted observed data in Negley Run.

Figure 3.1 shows this comparison for 24-hour (1-day) rainfall events. Each column shows the estimated and actual count of events exceeding the Atlas 14 rainfall volume threshold, which is shown in the column header. Returning to the example, we expected approximately 8 24-hour events where at least 2.3 inches of rain fell, but over this period we observe 18 events meeting or exceeding this threshold. For the 5-year event, we would expect just over three 24-hour storms of at least 2.9 inches but observed 10 events of this size or greater.

This comparison shows that the count of extreme 24-hour rainfall events observed in Negley Run during this period is consistently greater than the median Atlas 14 projections would suggest at all frequencies. We see similar patterns when comparing events with 1-, 3-, 6-, and 12-hour durations, and the pattern holds when looking at Atlas 14 ninetieth-percentile estimates instead (not shown). Figure 3.1 is suggestive of a climate signal in Pittsburgh from these extreme events when compared with the Atlas 14 regional estimates and supports the recent literature finding an increase in the frequency of extreme rainfall events in Pennsylvania and across the Northeast region (USGCRP, 2017).

This brief analysis is preliminary and necessarily limited, however. For instance, 16 years is a relatively short period to establish any long-term pattern—by comparison, NOAA uses 30-year periods to estimate climate normals. In addition, the observations may be influenced

---

**Figure 3.1**

*Observed Versus Estimated 24-Hour Rainfall Events in Negley Run (2003–2018)*

<table>
<thead>
<tr>
<th>Expected return interval/depth (inches)</th>
<th>Total count</th>
<th>Expected count</th>
<th>Total minus expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-year</td>
<td>18</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>5-year</td>
<td>10</td>
<td>6.8</td>
<td>3.2</td>
</tr>
<tr>
<td>10-year</td>
<td>10</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>25-year</td>
<td>3</td>
<td>4.4</td>
<td>1.4</td>
</tr>
<tr>
<td>50-year</td>
<td>2</td>
<td>2.4</td>
<td>0.2</td>
</tr>
<tr>
<td>100-year</td>
<td>2</td>
<td>0.6</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**NOTE:** This figure compares the total count of events of at least a given depth (inches) for the selected duration at the centroid of the Negley Run watershed, compared with the expected number of events of that depth and duration based on median NOAA Atlas 14 estimates for Pittsburgh.
by a range of year-to-year variations, including post-tropical-storm events that sometimes reach Western Pennsylvania, that may not otherwise be connected to climate warming. Finally, NOAA’s estimates bring together observations from many rain gauges across the region, which might differ from extreme rainfall observed at any location, such as Negley Run. However, the results certainly support the need to explore and plan for precipitation events beyond the design thresholds commonly used from Atlas 14.1

**Initial Moisture Deficit**

For the FWOA analysis focused on discrete storm events, we also considered uncertainty associated with prior rainfall conditions. SWMM generally assumes that the soil is dry at the beginning of a simulation, but soils saturated with water from earlier rainfall events—which reduces the capacity to adsorb additional water into the soil—can increase surface stormwater runoff in the early stages of a heavy rainfall event (Rossman and Huber, 2016). To account for this, we evaluated discrete storms under two scenario conditions: (1) a default dry condition, where the assumption is that no rain fell preceding the event, and (2) a saturated soils condition, where we assume that a given storm occurs after a prior rainfall event and that soil capacity to hold additional water is limited. The methods used for the saturated soils assumption in SWMM are described in Appendix C.

**Annual Time Series Analysis**

The Negley Run watershed drains to two large sewer mains over 100 inches in diameter that run northward in parallel toward the Allegheny River below Washington Boulevard. These pipes intersect with an ALCOSAN regional interceptor via a set of smaller pipes and gates, allowing wastewater to flow into the ALCOSAN system under dry conditions. During most rainfall events, however, system capacity is quickly exceeded, and this infrastructure instead diverts combined rainfall and sewer flows farther along Washington Boulevard, joins into a single pipe, and releases sewer overflows from a single outfall located slightly westward along the Allegheny River.2 Figure 3.2 provides a schematic representation of the main components of the combined sewer system in Negley Run.

We used SWMM to represent water and pipe flows in this system and estimate both Recent Historical and projected future combined sewer overflows from Negley Run. For Recent Historical conditions, we evaluated sewer overflows annually from 2003 through 2018, as well as the modified 2003TY to allow for comparison with prior PWSA and ALCOSAN analysis. For projected future conditions, we adopted the same downscaled rainfall projections applied in Fischbach et al., 2017, representing a decade of rainfall conditions approximately 20–30 years into the future (2038–2047). These sequences represent rainfall patterns from 2004 through 2013, but with the rainfall intensity modified to match two different downscaled climate model projections.

Both sets of projections—termed “Higher Intensity Rainfall” and “Higher Total Rainfall,” respectively, in Fischbach et al., 2017—represent plausible futures where precipitation volumes increase, on average and at the extremes, compared with recent history. These projec-

---

1 This is further reinforced by the infrequency of Atlas 14 updates, a concern noted in prior work (see Fischbach et al., 2020, for example).

2 The identifier for this outfall is MH122E001-OF in PWSA and ALCOSAN reporting and documentation.
Overflows were estimated according to the methods described in Chapter Two and Appendix D. We include three key metrics: annual overflow volume, annual hours in overflow, and a count of discrete overflow events per year.

**Comparison with Prior Typical Year Estimates**
We first compared UA-NR model results against prior ALCOSAN and PWSA estimates of CSOs from Negley Run for the 2003TY rainfall year under existing infrastructure conditions.

---

3 See Fischbach et al., 2017, and Cook, Anderson, and Samaras, 2017, for further details and climate model hindcasting comparisons. See Fischbach et al., 2017, and Cook, Anderson, and Samaras, 2017, for further details and climate model hindcasting comparisons. Note also that default soil moisture conditions were assumed at the start of each rainfall year, because soil moisture will vary dynamically in SWMM during the time series analysis.
As a reminder, the local utilities currently continue to rely on 2003 TY rainfall estimates alone to inform system planning and design. ALCOSAN previously estimated 777 MGY of overflow from the A-42 outfall for 2003 TY rainfall with existing infrastructure to inform CWP development, while PWSA’s estimate in the Green First Plan was slightly higher (783 MGY) (ALCOSAN, 2019e; Pittsburgh Water and Sewer Authority, 2016, Table 2-1). We estimate 865 MGY of overflow volume for these same conditions using the UA-NR model, 10–11 percent higher than the ALCOSAN and PWSA estimates. Given the number of changes implemented in this model relative to the regional models and subsequent model recalibration, the difference in estimates is to be expected.

We also applied similar methods as ALCOSAN to estimate overflow duration and frequency at the A-42 outfall based on model output (see Appendix B). Using the UA-NR model, we estimated that the Negley Run combined sewer system would spend 1,522 hours in overflow during 2003 TY rainfall conditions, with approximately 85 distinct overflow events. ALCOSAN’s prior estimates during CWP development were 1,085 hours in overflow and 66 distinct events, respectively, so the UA-NR results are notably higher for both metrics.

We discuss key modeling changes that might lead to these differences in Appendix B, but the most significant factors are likely to be the following:

- This model has been rebuilt and recalibrated for the Negley Run watershed and uses SWMM functionality not included in previous efforts (e.g., groundwater module). This could shift the timing of when wet weather flows reach the combined system.
- Both the ALCOSAN and PWSA estimates take into account interactions with the regional system, while UA-NR estimates are focused on this basin alone to reduce computational demand and run time. This lack of integration could underestimate the amount of capacity available in the ALCOSAN interceptor so that some small rainfall events are being “counted” as overflows instead of flowing primarily to the regional system and treatment plant.

Nevertheless, after making these comparisons, we determined that UA-NR would be suitable to use in support of this planning-level exploratory analysis. We note, however, that further work is needed to align UA-NR results with utility estimates and real-world conditions, ideally through recalibration using new flow metering.

**Recent Historical Combined Sewer Overflows**

Figure 3.3 shows our modeled CSO estimates for each rainfall year from 2003 through 2017. The vertical axis indicates the annual volume of overflow (in MGY), the horizontal axis shows the duration of overflow (in hours), and point size is scaled by the frequency of discrete overflow events (number of events). This figure shows that volume and duration of overflow are generally correlated, though with notable variation between years. Frequency of events varies across a narrower range and shows a somewhat weaker (though still observable) correlation with overflow volume. Results from the 2003 TY are highlighted with solid reference lines, while the dashed line instead shows a 15-year average of results from 2003 through 2017.

Recent Historical CSOs are summarized in Table 3.2 for all three metrics. We include an average value for just the 10-year period 2004–2013, to allow for direct comparison to Fischbach et al., 2017, as well as to the future climate projections that are constructed from this same 10-year period. We also separately summarize results for an expanded range of years
Figure 3.3
Recent Historical Negley Run Overflow Estimates, by Year

NOTE: Figure shows RAND modeled overflow estimates. Dotted line indicates the average results from all years shown. Figure shows results separately for both 2003 and 2003TY because the latter removes some rainfall events to better match long-term historical statistics (see ALCOSAN, 2009, for more information).

(2003–2017) to create a 15-year average that incorporates more recent rainfall. The final rainfall year in our analysis, 2018, is the wettest year on record for Pittsburgh as of the publication of this report, and the estimated CSO outcomes from this year are so large that we excluded it from the summary and consider it separately.

Table 3.2 indicates that the average overflow volume from 2004 through 2013 (968 MGY) is about 12 percent higher than the results from the 2003TY using the updated UA-NR SWMM model (865 MGY), while the tenth- to ninetieth-percentile range (692–1,174 MGY) indicates substantial year-to-year variation. This summary period also shows a similar average frequency of overflow events compared with the 2003TY, though the duration of hours in overflow is somewhat higher on average (1,653 hours, or about 19 percent of the year). When considering the broader 15-year summary from 2003 through 2017 and including more recent years, in comparison, all three metrics are somewhat higher on average than those estimated using the 2003TY alone.

The 2018 rainfall year, however, shows an entirely different rainfall paradigm. Average rainfall across the radar-adjusted rainfall inputs is over 66 inches, leading to over 20 inches
of average surface runoff in SWMM. Both statistics are more than double those found in the 2003TY, and this leads to a total estimated CSO volume of 2,177 MGY, over 150 percent higher than prior estimates based on the 2003TY. As the wettest year on record as of the publication of this report, 2018 remains an outlier but is nevertheless important to consider in a what-if analysis to understand how the current system and proposed strategies might perform under very extreme rainfall conditions.

**Projected Future Combined Sewer Overflows**

Results from the projected future scenarios are summarized in Table 3.3. This table retains the Recent Historical results from Table 3.2 and includes columns indicating the percent difference from the 2003TY for each metric and summary period.

Overall, the Higher Intensity Rainfall scenario shows both CSO volume and duration increases similar to Recent Historical estimates. The Higher Total Rainfall scenario, however, yields a notably greater increase in overflow volume (26 percent) and hours in overflow (20 percent). Frequency is largely unchanged, but this result is expected given the downscaling approach.4

---

4 The downscaled climate projections include the same events as the period 2004–2013, though the intensity of each event has been modified to match climate model projections using the delta change method. As a result, the frequency of overflow events should be very close to that observed for the 10-year 2004–2013 period, with minor variation due to the statistical thresholds used to indicate the beginning and end of each overflow event.

---

### Table 3.2

<table>
<thead>
<tr>
<th>Rainfall Period</th>
<th>Average Annual Rainfall (inches)</th>
<th>Average Annual Overflow Volume (MGY)</th>
<th>Average Annual Overflow Duration (hours)</th>
<th>Average Annual Overflow Frequency (events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003TY</td>
<td>36.8</td>
<td>865</td>
<td>1,522</td>
<td>85</td>
</tr>
<tr>
<td>Recent Historical (2004–2013)</td>
<td>40.0 (33.4–44.8)</td>
<td>968 (692–1,174)</td>
<td>1,653 (1,208–1,897)</td>
<td>84 (76–94)</td>
</tr>
<tr>
<td>Recent Historical (2003–2017)</td>
<td>41.0 (34.3–46.6)</td>
<td>986 (688–1,158)</td>
<td>1,663 (1,266–1,863)</td>
<td>87 (76–100)</td>
</tr>
<tr>
<td>Wettest year on record (2018)</td>
<td>66.2</td>
<td>2,177</td>
<td>3,338</td>
<td>80</td>
</tr>
</tbody>
</table>

NOTE: Results in parentheses show the tenth- to ninetieth-percentile range across the years included in each Recent Historical summary. Annual rainfall represents an average across all 3 Rivers Wet Weather radar-adjusted pixels used in the UA-NR model simulation. For comparison, ALCOSAN estimates 777 MGY from outfall MH122E001-OF (ALCOSAN, 2019e) for the 2003TY, but using a different model, SWMM version, and experimental design. PWSA similarly estimated 783 MGY for A-42 in the Green First Plan under existing conditions (Pittsburgh Water and Sewer Authority, 2016, Table 2-1).
In general, these scenario comparisons reinforce similar conclusions as the pilot study. Looking at a 10- or 15-year average representing Recent Historical conditions leads to 12–14 percent higher CSO estimates in Negley Run compared with the 2003TY alone, with corresponding increases in overflow duration. The magnitude of change could increase further in plausible future climate conditions, most notably the Higher Total Rainfall scenario.

Discrete Storm Analysis

Depth-Duration-Frequency Estimates

In addition to annual time series, we also evaluated a large set of discrete extreme rainfall events using SWMM. The rainfall amounts considered derive from NOAA Atlas 14 (Bonnin et al., 2006) as well as recent estimates of historical and climate projected extreme rainfall in Pittsburgh (Cook, McGinnis, and Samaras, 2020). The future projected DDF curves were the best available for Pittsburgh at the time of this research. Note, however, that the underlying data only incorporate a subset of available climate models and downscaling methods and thus may not fully capture the range of future precipitation uncertainty (Lopez-Cantu, Prein, and Samaras, 2020). Except for Atlas 14, all DDF volumes are estimated for the rain gauge located in the Highland Park neighborhood, just outside of the Negley Run watershed.5

Figure 3.4 summarizes the rainfall depths used in the discrete storm analysis, by source, for the 1-hour and 24-hour rainfall event. Rainfall depth (inches) is shown on the vertical axis, while the return periods considered (2-year to 1,000-year) are shown on the horizontal axis.6

Table 3.3
Summary of Recent Historical and Projected Future Negley Run Overflows

<table>
<thead>
<tr>
<th>Rainfall Period/Scenario</th>
<th>Average Annual Rainfall (inches)</th>
<th>Average Annual Volume (MGY)</th>
<th>Difference from 2003TY (percent)</th>
<th>Average Annual Duration (hours)</th>
<th>Difference from 2003TY (percent)</th>
<th>Average Annual Frequency (count)</th>
<th>Difference from 2003TY (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003TY</td>
<td>36.8</td>
<td>865</td>
<td>n/a</td>
<td>1,522</td>
<td>n/a</td>
<td>85</td>
<td>n/a</td>
</tr>
<tr>
<td>Recent Historical (2004–2013)</td>
<td>40.0</td>
<td>968</td>
<td>12</td>
<td>1,653</td>
<td>9</td>
<td>84</td>
<td>–1</td>
</tr>
<tr>
<td>Recent Historical (2003–2017)</td>
<td>41.0</td>
<td>986</td>
<td>14</td>
<td>1,663</td>
<td>9</td>
<td>87</td>
<td>2</td>
</tr>
<tr>
<td>Wettest year on record (2018)</td>
<td>66.2</td>
<td>2,177</td>
<td>152</td>
<td>3,338</td>
<td>119</td>
<td>80</td>
<td>–6</td>
</tr>
<tr>
<td>Higher Intensity Rainfall (2038–2047)</td>
<td>40.2</td>
<td>969</td>
<td>12</td>
<td>1,698</td>
<td>12</td>
<td>82</td>
<td>–4</td>
</tr>
<tr>
<td>Higher Total Rainfall (2038–2047)</td>
<td>43.3</td>
<td>1,089</td>
<td>26</td>
<td>1,823</td>
<td>20</td>
<td>83</td>
<td>–3</td>
</tr>
</tbody>
</table>

NOTE: Percent difference is relative to the 2003TY estimate. Annual rainfall represents an average across all 3 Rivers Wet Weather radar-adjusted pixels used in the UA-NR model simulation.

5 DDF estimates for the Highland Park gauge were provided to the authors by Dr. Lauren Cook. These include estimates of the 500- and 1,000-year return periods, which were previously unpublished.

6 DDF curves estimate the likelihood of recurrence for storms of different durations and volumes. Specifically, they estimate the annual exceedance probability (AEP) for a given volume of rainfall over an event duration, which can be interpreted as the probability of seeing at least that much rainfall during such an event in a given year. The “return period” is a common way of describing the AEP: for instance, a 10-year return period indicates a 1-in-10 chance in each year of seeing at least a certain rainfall, or 10-percent AEP.
In the FWOA analysis, we also estimated results for 3-, 6-, and 12-hour events, but results in this report are focused on the 1- and 24-hour event for clarity in response to specific design and planning requests received during conversations with NRWTF. Additional FWOA results will be made available separately through forthcoming web-based data visualizations.

This summary comparison yields several notable insights. First, although the median rainfall estimates from the regional Atlas 14 and gauge-specific historical estimates are similar, the range of uncertainty is much wider from the single gauge estimate, especially for less frequent, more intense events. For example, both Atlas 14 and Cook, McGinnis, and Samaras, 2020; Bonnin et al., 2006.

NOTE: Red line indicates the median (fiftieth-percentile) estimate, while the gray shading shows the tenth-to-ninetieth-percentile range. Horizontal axis shown in logarithmic scale. Figure developed by authors.
Sewer Overflows and Flooding in a Future Without Action

ras estimate the median 24-hour, 100-year rainfall at 4.9 inches, but the tenth- to ninetieth-percentile range from Cook, McGinnis, and Samaras (3.5 to 7.2 inches) is much wider than Atlas 14 (4.5 to 5.2 inches). This is to be expected based on differences in methodology, but it is nevertheless important because it shows that the return frequency of heavy rainfall at a given location like Highland Park might differ substantially from official estimates developed as regional summaries, even when relying on historical observations alone.

Second, the projections of future rainfall show the potential impact of climate change on heavy rainfall depth and recurrence. Comparing historical and projected results for Highland Park, for example, we see that 2 inches of rainfall from a 1-hour event has a 50-year return period (2-percent AEP) based on historical observations. However, an average across three downscaled model projections (Average Future) shows this event frequency increasing to approximately a 10-year return period (10-percent AEP) by the end of the century. Looking at it another way, the median 50-year event depth increases from 2 inches (Historical) to 2.7 inches (Average Future) when projecting possible future changes.

Finally, the climate impact from the projected DDF curves is increasingly evident for larger, less-frequent events. This general pattern is consistent with the findings from the National Climate Assessment for precipitation across the Northeast (USGCRP, 2017), but here we see how this translates to a specific location in Pittsburgh. Note, however, that the range of uncertainty grows increasingly larger for the Average Future results moving into the extremes: for instance, the Average Future estimate for the 24-hour, 100-year event could be from 4.5 to 10.1 inches when looking across the tenth- to ninetieth-percentile range. Specific depth results from all events, percentiles, and scenarios considered in this analysis are provided for reference in Appendix C to this report.

**Stormwater Runoff Results**

**Watershed Results by Subcatchment**

Drawing on the sources described above, we estimated the volume of stormwater runoff from impervious surfaces for all subcatchments in Negley Run for each frequency, duration, percentile value, and scenario (historical or projected future). For example, Figure 3.5 shows the impervious runoff volume by subcatchment from a 24-hour, 10-year storm based on the Cook, McGinnis, and Samaras, 2020, median historical estimate at the Highland Park gauge. These results show that total impervious runoff varies with subcatchment size, as expected. Total runoff is generally 0–0.5 MGal for the roughly city-block scale subcatchments located in the Homewood neighborhood, though we note some variation here attributable to different amounts of impervious area (roofs, driveways, alleys, etc.) in each location.

Figure 3.6 shows how this 24-hour, 10-year total runoff would change when looking at Average Future climate conditions instead. The estimated rainfall volume increases from 3.2 to 3.9 inches for this event, yielding runoff volume increases 30–40 percent for most subcatchments. Selected locations, typically very small subcatchments, show greater increases in percentage terms. The degree of change varies by storm duration and frequency, but we see notable increases in runoff volumes and peak runoff across the range of events considered (not

---

7 As a reminder, we did not consider land use change in this analysis, so these estimates assume that future land use stays the same as present-day conditions.
These additional runoff results will be made available through a forthcoming web visualization tool.

**Detailed Example: Meadow Street Microshed**

Location-specific runoff results from this simulation analysis can be used to inform the planning and design of neighborhood- or microshed-scale GSI. Members of NRWTF have developed concept-level designs for a microshed centered on Meadow Street in the Larimer neighborhood.
Sewer Overflows and Flooding in a Future Without Action

(Pittsburgh Parks Conservancy and Larimer Consensus Group, 2019), for example, and asked for input on the appropriate peak runoff values to help develop sizing assumptions for the onsite green infrastructure storage. This area is defined somewhat differently in the UA-NR model compared with the NRWTF boundaries (Figure 3.7)—the corresponding UA-NR subcatchment is larger (27.2 acres vs. 16.6 acres) and extends farther to the south and west, so they are not necessarily directly comparable at this stage. But this area is nevertheless a useful example to highlight the application of these results to microshed-scale design and planning.

Focusing on a 1-hour peak rainfall period, we estimate total impervious runoff from the 1-hour, 10-year median historical (1.5 inch) event for the Meadow Street area at 0.5 MGal Runoff peaks at 15 cfs during this simulated 1-hour event. These results increase to 0.8 MGal of total runoff in the median Average Future scenario, with a peak of 28 cfs. Note that this

Figure 3.6
Change in 24-Hour, 10-Year Runoff from Historical to Average Future Climate Conditions

SOURCE: © 2020 Mapbox © OpenStreetMap.
NOTES: Median rainfall volume is 3.9 inches from the Cook, McGinnis, and Samaras, 2020, Average Future DDF estimate compared with the historical DDF at the Highland Park gauge. Figure shows the change in runoff results (in percent) from impervious surfaces only assuming default (dry) soil moisture conditions and applying a synthetic hydrograph at each subcatchment. Unshaded subcatchments within the study area indicate locations with no impervious surfaces. Land use is assumed to remain the same as present-day conditions.
assumes dry conditions prior to the storm: with saturated soils, alternately, the peak values from a 1-hour, 10-year rainfall increase to 25 cfs (Historical rainfall scenario) or 39 cfs (Average Future scenario), respectively.

Figure 3.8 compares the 1-hour peak runoff results for the Meadow Street subcatchment from the 2- to the 100-year event for the Historical, Atlas 14, and Average Future scenarios assuming dry starting conditions. Shaded regions show how these results vary across the tenth- to ninetieth-percentile event range to provide a more complete picture of the range of uncertainty. This comparison reinforces that the peak 1-hour runoff increases more sharply in the Average Future projection at higher return periods but with a correspondingly greater range of uncertainty. As a result, engineering design and capture targets for this location may need to account for these broader ranges to ensure reliable performance during future rainfall peaks.

Street Flooding

We next used the discrete storm analysis framework to estimate the frequency of street flooding at different locations within Negley Run. As noted in Chapter Two, these street flooding estimates only consider a subset of streets within the watershed due to current limitations in available data describing the pipe system and stormwater inlets. This analysis relies on a simplified representation of streets as 1D open channels in SWMM; though suitable for preliminary analysis, there are notable limitations to this approach, and results should be interpreted with caution (see Appendix D for further discussion).

Given these limitations, we use the 1D flood results to highlight street locations potentially exposed to flooding during rainfall events of different duration and frequency rather than provide more systematic maps of flood depth. We use a flood depth threshold of just under one foot to identify streets where peak flooding might impede traffic flows or temporarily close streets or intersections.9

---

9 This disruption threshold is based on Pregnolato et al., 2017, who identify 30 centimeters (0.98 feet) as the “maximum threshold for safe driving, stopping, and steering (without loss of control)” after a systematic review of the recent literature.
Figure 3.8
Meadow Street Microshed Peak One-Hour Runoff Estimates, by Rainfall Scenario

NOTE: Median peak runoff (cfs) from each scenario under default (dry) soil moisture conditions, with the tenth to the ninetieth percentile displayed as shaded regions.

Street Flood Recurrence from Synthetic Rainfall Events

Figure 3.9 shows a sampling of street flooding maps from the discrete storm analysis using this approach for four events of varying duration and intensity (Historical rainfall scenario, dry starting conditions). Gray lines show the extent of the street flood analysis in the UA-NR model as currently constructed, while blue points highlight locations where peak flood depths might exceed the safe driving threshold. Beginning with the 1-hour, 2-year event (1 inch, upper left pane), flood depths exceed this threshold only at the lowest point along lower Washington Boulevard. The extent of flooding increases with the 1-hour, 10-year event (1.5 inches, upper right pane), with a greater portion of lower Washington affected along with the intersection of Washington Boulevard and Highland Drive, Washington and Negley Run Boulevards, and selected intersections farther up the watershed in Homewood (e.g., the intersection of Kelley Street and Sterrett Street). The bottom row shows greater rainfall volumes from 24-hour events (2.1 and 3.2 inches, respectively, from the 2- and 10-year events). The 24-hour, 2-year event yields more rainfall but over a longer period, and thus the extent of flooded streets is similar to (or slightly less than) that from the 1-hour, 10-year event. By contrast, the 24-hour, 10-year event shows the potential for widespread street flooding, with extensive flooding along Washington Boulevard and numerous locations in Homewood, Belmar, and East Hills potentially affected.

Similar results from all modeled storms are not shown here but will be made available through a forthcoming interactive web tool.
Looking across the range of discrete storms, we can summarize the potential frequency of street flood impacts for various modeled locations in Negley Run by identifying the return period at which flooding first exceeds the street flood thresholds under different scenarios. Table 3.4 provides this summary for a range of modeled streets or intersections under both historical and climate-projected scenario conditions (one-hour event, median rainfall estimates). The one-hour event is shown because this provides the most concise estimate of a concentrated rainfall peak at which flooding could occur.

These results show how different rainfall scenario assumptions affect the potential frequency of street flooding. Lower Washington Boulevard exceeds the depth threshold with a minimum of a 50-percent chance every year (2-year return interval) under both current and
projected future conditions (top row). By contrast, model results show the intersection of Kelly Street and Sterrett Street flooding at the 25-year return period (4-percent AEP) under historical conditions but at the 5-year return period (20-percent AEP) under the projected future conditions.

**Historical Exemplar Storms**

The results from the analysis above may overstate the extent of flooding because they rely on an assumption that the same amount of rain is falling everywhere across the watershed simultaneously and according to the same pattern of rainfall over time. This approach is useful for understanding localized runoff or developing consistent flood statistics. However, real storms

---

**Table 3.4**  
*Flooding Return Period from a One-Hour Event for Selected Streets or Intersections*

<table>
<thead>
<tr>
<th>Street Location</th>
<th>Key Streets or Intersections</th>
<th>Historical (Highland Park)</th>
<th>NOAA Atlas 14</th>
<th>Average Future (2020–2099)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Washington Boulevard Corridor</strong></td>
<td>Lower Washington Boulevard</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Washington and Highland</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Washington and Negley Run</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Upper Washington Boulevard</td>
<td></td>
<td></td>
<td>500</td>
</tr>
<tr>
<td><strong>Homewood/Belmar/ East Hills</strong></td>
<td>Bennett and Dallas</td>
<td>500</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Bennett Street (Dallas to Murtland)</td>
<td>100</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Fleury Way (Sterrett to Collier)</td>
<td>500</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Frankstown (Sterrett to Collier)</td>
<td>500</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Frankstown and Collier</td>
<td>500</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Hamilton and Albion</td>
<td>25</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Hermitage and Murtland</td>
<td>50</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Kelly and Homewood</td>
<td>500</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Kelly and Sterrett</td>
<td>25</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Kelly Street (Dallas to Murtland)</td>
<td>100</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Kelly Street (Homewood to Sterrett)</td>
<td>500</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Kelly Street (Sterrett to Collier)</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Paulson Avenue</td>
<td></td>
<td>1,000</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>Tioga and Rosedale</td>
<td>500</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Tioga Street (Brushton to Rosedale)</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

**NOTE:** Assumes median rainfall estimate from each source and default (dry) soil moisture conditions; flood depth threshold: 0.98 feet.

---

10 Note that we did not model events more frequent than the two-year return period, such as the one-year or one-month event. These more frequent estimates are available from Atlas 14, but not the other rainfall source used in this analysis.
may cause greater or less flooding in certain parts of the system as they move across an area or produce intense rainfall peaks. In general terms, we might expect to see less of a basinwide impact from a real storm relative to the synthetic storms, but this will vary by event.

For this analysis, in addition to synthetic storms, we also evaluated a range of *historical analogue* storms that derive from the 3 Rivers Wet Weather historical radar-adjusted rainfall data set. The methods used to derive and adjust these storms to represent rainfall volumes from the DDF curves are described in Appendix C. Here we highlight the results from several historical exemplar events as a complement to the results above.

**June 17, 2009 (1-Hour, 25-Year Event)**

The rainstorm that occurred on June 17, 2009, was a brief (1-hour) event that yielded approximately 1.5 inches of rain in the middle of Negley Run. In our analysis, we scaled this storm up to match the DDF statistics for a 1-hour, 25-year event. We kept the same storm pattern each time but used scaling factors to create historical exemplar storms that produced approximately 1.8 inches or 2.4 inches for the Historical and Average Future scenarios, respectively. Figure 3.10 shows the results from the scaled-up June 17 storm, with the scenarios compared in the columns. The rows show how street flooding results vary across the two initial moisture deficit scenarios, with the top row showing default (dry) starting conditions and the bottom row reflecting saturated soils prior to the event.

Starting in the upper left pane, we see that this scaled-up historical 1.8-inch event yields only minor street flooding along Washington Boulevard and at selected intersections in Homewood. The lower left pane shows the same short duration event but occurring on top of already saturated soils instead of dry conditions. Under these conditions, the simulation shows more extensive flooding and notable impacts along Washington Boulevard, enough to necessitate a road closure.

The same 1-hour, 25-year storm scaled to match the climate-altered Average Future (2.4 inches) shows more extensive street flooding under both dry (upper right pane) and saturated (lower left pane) starting conditions.

However, other historical events considered in the analysis do not necessarily show extensive flooding even with similar or greater rainfall volumes than those discussed above. A key factor is whether there is a sharp peak of rainfall during the event. In general terms, storms with more gradual or steady rainfall over the course of the event are less likely to cause street flooding even with the same overall volume, because street drains are sized to handle only a certain volume of rainfall over time.11

**2011 Washington Boulevard Flood**

Another event of interest for planning and design is the August 19, 2011, storm. Over 3 inches of rain fell across the Negley Run watershed over an approximately 8- to 9-hour period in this storm, with a peak of 1.4 inches over 15 minutes that occurred during afternoon rush hour around 4:15 p.m. Due to the typical rush-hour traffic backup that occurs on northbound Washington Boulevard, this storm led to the tragic death of four people who were trapped when floodwaters rose suddenly to a peak of over 8 feet around their idled cars (Balingit, 2013). Subsequent to this event, flood gates were installed at both ends of lower Washington Boulevard (from Negley Run Boulevard to Allegheny River Parkway) to help prevent cars from entering the most dangerous stretch during heavy rainfall events (WTAE Pittsburgh, 2011).

---

11 Street drains may also become clogged, further reducing their capacity during intense rainfall periods.
This storm, with a volume of 3.3 inches, would be considered a 24-hour, 10-year (10-percent AEP) event per the statistical estimates from the Historical or Atlas 14 scenarios. The storm increases in likelihood to a 5-year (20-percent AEP) event when instead looking at the climate-altered Average Future scenario. If we instead consider it as a 12-hour event, the likelihood numbers are somewhat lower (25-year Historical, 10-year Average Future), but the same basic pattern holds. Figure 3.11 shows the extent of street flooding from this historical event as represented in the UA-NR 1D flood modeling.

**Basement Flooding**

Another common effect of heavy rainfall in Pittsburgh is residential basement flooding, caused either by water flowing from the surface or adjacent groundwater into the basement (wet basement) or from water backing up in the sewer line and overflowing a home’s sewer stack due
to an elevated hydraulic pressure in the adjacent sewer main (sewer backup) from stormwater inflow to the combined system. Combinations of these effects, such as a leaking or broken sewer line allowing rainfall-driven groundwater to back up into the home, are also possible, especially in older homes (Ford et al., 2018). Basement flooding can lead to foundation or other structural damage, damage to contents, and adverse health impacts from mold growth (Garrett et al., 1998; Ladson and Tilleard, 2013; Zock et al., 2002).

As introduced in Chapter Two, and with the methods described in further detail in Appendices A and D, we used a simplified approach to identify where and how frequently homes might be affected by wet basements or sewer backups in Negley Run. This analysis does not include all homes in the watershed but is instead limited to the homes along the streets noted in the previous section. In total, we were able to estimate potential wet basements for 930 homes.

12 This analysis focused on single-family homes with basements. We estimate a total of 9,099 such homes across Negley Run based on tax assessor data.
Sewer Overflows and Flooding in a Future Without Action

in Negley Run\(^{13}\) and potential sewer backups for 346 homes. The homes we were able to model are primarily located in the neighborhoods of Homewood, Belmar, and East Hills.

**Number and Proportion of Houses Affected**

Table 3.5 summarizes the number and proportion of homes within the modeled area potentially affected by each type of basement flooding from a 1-hour event for the 2- to 1,000-year return periods (Historical rainfall scenario). This table separately lists modeled wet basements, “extra” homes we sought to consider for wet basement impacts beyond the immediately modeled streets (see Appendix D), and modeled sewer backups. It also includes an estimate of the total homes potentially affected.\(^{14}\)

Results show that 19–26 percent of homes included in the modeled area could be affected by wet basements depending on the severity of the 1-hour peak storm event. Expanding the area considered beyond the immediately modeled streets adds another 73 to 84 homes, a relatively small proportion (5–6 percent) of the homes added. The number and proportion of homes potentially experiencing sewer backups shows greater variation by event severity: 4 percent of modeled homes might experience a backup from a 2-year (50-percent AEP) event, but 51 percent would from a 1,000-year event. In total, we estimate 11–18 percent of homes in the study area would be affected by at least one mode of basement flooding from a 2- to 1,000-year median rainfall event from the Historical rainfall scenario. Although we do not have a reliable set of past observed data to confirm these modeled estimates, the prevalence of wet basements and basement

<table>
<thead>
<tr>
<th>Return Period</th>
<th>Wet Basement</th>
<th>Percent Modeled Homes</th>
<th>Added Wet Basement</th>
<th>Percent Added Homes</th>
<th>Sewer Backup</th>
<th>Percent Modeled Homes</th>
<th>Total Affected Homes</th>
<th>Percent Modeled Homes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>173</td>
<td>19</td>
<td>73</td>
<td>5</td>
<td>13</td>
<td>4</td>
<td>251</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>178</td>
<td>19</td>
<td>73</td>
<td>5</td>
<td>28</td>
<td>8</td>
<td>259</td>
<td>11</td>
</tr>
<tr>
<td>10</td>
<td>190</td>
<td>20</td>
<td>73</td>
<td>5</td>
<td>51</td>
<td>15</td>
<td>286</td>
<td>12</td>
</tr>
<tr>
<td>25</td>
<td>198</td>
<td>21</td>
<td>76</td>
<td>6</td>
<td>90</td>
<td>26</td>
<td>329</td>
<td>14</td>
</tr>
<tr>
<td>50</td>
<td>200</td>
<td>22</td>
<td>80</td>
<td>6</td>
<td>115</td>
<td>33</td>
<td>355</td>
<td>15</td>
</tr>
<tr>
<td>100</td>
<td>209</td>
<td>22</td>
<td>80</td>
<td>6</td>
<td>143</td>
<td>41</td>
<td>374</td>
<td>16</td>
</tr>
<tr>
<td>500</td>
<td>234</td>
<td>25</td>
<td>85</td>
<td>6</td>
<td>173</td>
<td>50</td>
<td>420</td>
<td>18</td>
</tr>
<tr>
<td>1,000</td>
<td>244</td>
<td>26</td>
<td>84</td>
<td>6</td>
<td>177</td>
<td>51</td>
<td>433</td>
<td>18</td>
</tr>
<tr>
<td>Total Modeled Homes</td>
<td>930</td>
<td>100</td>
<td>1,373</td>
<td>100</td>
<td>346</td>
<td>100</td>
<td>2,367</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 3.5**

Number and Proportion of Homes Affected by Basement Flooding from a One-Hour Event

NOTE: Median rainfall estimates from the Historical rainfall scenario assuming default (dry) soil moisture, applying the synthetic rainfall approach. The sum of modeled homes in the first three columns is greater than the total in the rightmost column because 282 homes were evaluated in both the wet basement and sewer backup analysis.

\(^{13}\) The extended analysis we attempted looking at upstream subcatchments (“Added Wet Basement”) added an additional 1,373 homes, but relatively few were added to the flood total.

\(^{14}\) Note that this total is less than the sum of the individual columns because some homes can be affected by multiple modes of flooding simultaneously.
backups emerging from the modeled analysis is consistent with our expectation based on community meetings as well as resident-reported issues identified in a recent survey of Negley Run neighborhoods (Ford et al., 2018).

Expanding this analysis to consider other rainfall scenarios, Table 3.6 shows the total count and proportion of homes affected in the analysis when instead applying Atlas 14 or Average Future rainfall assumptions for a 1-hour event. These results indicate that at or beyond the 5-year return period Atlas 14 scenario assumptions result in about 7‒10 percent more homes affected, while Average Future climate assumptions yield 18‒20 percent more homes. Additional results from this scenario analysis will be available through a forthcoming data visualization tool.15

### Preliminary Basement Damage Estimates

We extended this analysis to also consider how basement flooding might translate to property damage. This entailed making simplifying assumptions, as described in Appendix D, and the results should be considered first-order approximations only. Furthermore, the damage estimates included here only include homes located on or near the streets included in the UA-NR model and therefore represent only a subset of the potential damage from rainfall that could occur when considering neighborhoods across the entire watershed.

Figure 3.12 shows estimated basement damage by return period and climate scenario from a 1-hour storm (fiftieth percentile, dry starting conditions). Here, we include outcomes from the three distinct climate model projections along with the model ensemble average (Average Future) to better illustrate the spread across climate models. Damage estimates combine all modes of basement flooding described above and range from approximate $450,000

---

15 Results mapped by structure are omitted from this analysis due to the preliminary, simplified nature of the modeling approach and to ensure that the research does not result in any adverse impacts on individual property owners or residents.
from a 2-year event to $900,000–$1 million from a 1,000-year event, depending on scenario. Results at the ninetieth percentile (not shown) or assuming wet starting conditions do not vary greatly from these median estimates, with similar damage ranges observed though with somewhat higher probabilities of recurrence. In general, the estimate based on the Historical rainfall scenario yields the lowest damage estimates across the range of storm frequencies, followed by Atlas 14 projections. The downscaled climate projections are consistently higher than the estimates based on historical rainfall alone across the range of return periods.

Basement damage can also be estimated by averaging across storms of different frequencies. EAD, sometimes referred to as average annual loss, can be thought of as the average damage per year expected from rainfall events of all types. Any given year might produce basement flood damage much greater or less than this estimate, but EAD is intended to give insight on the long-term average over many years. We used standard methods and additional simplifying assumptions to estimate EAD for basements in houses modeled in the study (see Appendix D), summarizing across the entire range of modeled rainfall events. Figure 3.13 shows EAD estimates for the 1- and 24-hour event for selected climate scenarios.

These results indicate EAD results of about $450,000–$550,000 from a 1-hour event and $525,000–$625,000 from a 24-hour event for the homes included in the modeling analysis under Historical or Atlas 14 estimated rainfall conditions. This can be interpreted to mean that heavy rainfall causes about half a million dollars in basement damage, on average, every year.
Looking instead at projected future conditions from the Average Future scenario, the tenth- to ninetieth-percentile range increases to $550,000‒$580,000 (1-hour event) and $600,000‒$720,000 (24-hour event), or a change of 8‒16 percent compared with the Historical rainfall scenario estimate. The damage increases are relatively modest when considering the average across storms, but this could be due to the limited and incomplete nature of the flooding investigations. We further discuss this in the remaining sections of this chapter.

**Discussion and Limitations**

The various modeling results described above generally reflect the extensive risks posed by heavy rainfall in Negley Run in terms of both sewer overflows and flooding. These risks are already evident under present conditions as represented in the UA-NR model. Our exploration of a limited number of future climate-influenced rainfall scenarios suggests that these risks could continue to grow with future climate change, though the challenge of the present—and uncertainty surrounding the future projections—do not yet suggest obvious courses of action to mitigate these risks, such as climate-informed design targets for PWSA or other local plan-
ners. Instead, we anticipate that the results from this analysis will be used to inform ongoing deliberations among NRWTF, engineering design by PWSA and its partners, and local GSI planning at the neighborhood scale.

We conclude the chapter by noting limitations evident in the current analysis and identifying additional steps that could help fill current gaps.

Limitations of the Sewer-Overflow Analysis

CSO estimates from the UA-NR model do not yet account for interactions with the broader regional system. As previously noted, this could lead to upward bias in the CSO estimates, because regional balancing could show additional capacity in the ALCOSAN interceptor to accept wet weather flows not observed in the UA-NR model alone. In addition, we do not yet account for how Negley Run results would change with broader improvements to the regional system, including treatment plant expansion of the construction of deep tunnel interceptors as called for in the CWP. Future work could integrate the UA-NR model back into the regional system to consider these effects jointly.

The UA-NR model is limited by available observed flow data to inform calibration. The detailed model applied here was built and recalibrated with limited observed flow data for calendar year 2008 gathered in large sewer mains. New flow-monitoring data gathered at a wider range of sample points would allow for improved calibration of the detailed model and greater confidence in simulated results compared with real-world conditions. It would also support more accurate and detailed flood analysis, as noted below.

Limitations of the Flood-Risk Analysis

The 1D approach to flood analysis is preliminary and approximate. This analysis leveraged the existing 1D modeling capabilities in the SWMM model to allow for detailed evaluation across the watershed at relatively low computational cost (see Appendix D). It provides initial insight into the potential locations exposed to street and basement flooding. However, this analysis does not fully represent dynamic two-dimensional (2D) surface flows during rainfall events, either in streets or elsewhere across the watershed, and thus provides an incomplete picture of potential flood locations or peak water depths. An improved approach would leverage coupled 1D-2D flood modeling—also referred to as dual drainage models—for key locations of interest, such as the Washington Boulevard corridor. In addition, coupled modeling building on this work could provide localized flood assessments at the neighborhood scale to inform GSI project siting and design.

The flood-risk assessment only considers a subset of potential flood hazards. The street and basement flood analysis does not consider additional hazards that might occur with extreme rainfall, including landslides or more substantial structural damage from standing or flowing water on the surface resulting from a low-probability, high-consequence event (e.g., a 100-year or 500-year event). We also do not consider damage to nonresidential structures, such as the commercial and industrial properties along Upper Washington Boulevard, or multifamily buildings. Finally, the basement flood analysis does not include house-specific issues that may lead to flooding, such as a broken sewer lateral, clogged sewer line, or rain collection adjacent to an external wall or flowing from a disconnected downspout. As a result, this analysis likely underestimates flood effects and associated damage for the area directly modeled.
The UA-NR flood analysis was constrained by available data regarding the storm sewer system. Flood-modeling capabilities were also limited by data available to inform model development, which constrained our estimates to only a subset of the watershed. A complete inventory and mapping of storm inlets, inlet invert elevations, and associated pipes across the watershed, along with additional flow monitoring, would allow for a more complete assessment of flood risk using either 1D or coupled 1D-2D (dual drainage) assessment.

Chapter Summary
This chapter described our evaluation of sewer overflows and flooding in the Negley Run watershed using the updated UA-NR model under past, present, and plausible future rainfall conditions assuming no new investments in the system (FWOA). We described the rainfall uncertainties considered in this chapter and throughout the remainder of the report. We then presented estimates for several key outcomes of interest, including CSOs, stormwater runoff from impervious surfaces, and rainfall flooding for selected street and neighborhood locations. In the next chapter, we introduce the GSI-based strategies considered in this effort and then evaluate them using the same modeling framework in Chapter Five.
CHAPTER FOUR
Strategies to Manage Stormwater in Negley Run

Introduction

The previous chapters characterized both the current and potential FWOA impacts to overflows and flooding in the Negley Run watershed. This area of Pittsburgh—encompassing several neighborhoods, including, but not limited to, East Hills, East Liberty, Highland Park, Homewood, Larimer, Lincoln-Lemington-Belmar, and Point Breeze—has been the focus of an extensive amount of planning, by both community advocates and government agencies and authorities. These range from local, neighborhood-scale interventions focused primarily on beautification and stormwater infiltration to watershed-scale GSI implementations that endeavor to achieve partial separation through connected conveyance mechanisms. We also consider how these projects would include associated access and maintenance infrastructure with potential cobenefits, such as a multipurpose recreational trail that could be built in several phases, linking the Allegheny River to the existing Highland Park velodrome and areas farther up Washington Boulevard.

This chapter assesses a variety of these project “levers” for inclusion in a set of potential watershed-scale strategies. For the purposes of our study, we assume both local- and watershed-scale projects will be built and coordinated to control impervious areas in accordance with planning objectives. To do so, we use a Low Impact Development (LID) module native to SWMM to apply GSI to modeled subcatchments. In addition to the planning-scale cost estimate of GSI options, we calculate the costs for a potential configuration of the conveyance network at a density and structure similar to other proposed pilot projects. We do not include, however, additional storage or detention performance associated with the conveyance infrastructure that may subsequently connect local interventions.

Our methods of preliminary analysis included plan and literature reviews, design-focused participatory workshops and stakeholder engagement, and formulation and iteration with technical experts. Following this review, we identified nine cumulative strategy increments (1 to 9) based on geographic area and three options (A, B, and C) for different levels of investment to be applied within selected increments. Strategy increments 1 to 4 are derived from preliminary design work developed by the U.S. Army Corps of Engineers (USACE) and PWSA, and do not include further options. Strategy increments 5 to 9, alternately, are largely drawn from concepts developed by the NRWTF.

Strategy increments 5 and 6 each have two options (A and B, representing impervious cover control targets of 25 or 50 percent of area, respectively), while strategy increments 7 to 9 have three options each (A, B, and C, which builds on B but increases the size of centralized storage beyond current rainfall standards for climate resilience).
Each strategy increment (e.g., 7) and option, if applicable (e.g., B), constitutes a strategy (in this case, 7B). The strategy increments are cumulative in numerical order. For example, strategy increment 7 assumes that all elements of 6 and below have been completed. Similarly, strategy option B assumes that the level of impervious cover control has been applied consistently across the prior strategy increments (e.g., 7B assumes that 6B and 5B have already been implemented as well). Figure 4.1 provides a schematic diagram of the process, which refers to the mapped areas described later in Figure 4.6 and Figure 4.9.

**Literature Review to Inform Strategy Development**

This section provides a summary of the key documents and other processes we reviewed, including, but not limited to, the following:

- **Section 219 Environmental Infrastructure—Negley Run: Conceptual Design Alternative Report** (hereafter CDAR) from April 2018, in partnership with PWSA (presented by Stantec/Tetra Tech Joint Venture) (Stantec/Tetra Tech JV, 2018)
- **Negley Run Section 219 Environmental Infrastructure Pittsburgh, Pennsylvania Design Documentation Report: Draft 35 percent Submittal** (hereafter DDR) from May 2019, in partnership with PWSA (prepared by Tetra Tech JV) (Tetra Tech, 2019)
- **NRIP** from 2017 by envirosocialcapital, evolveEA, and eDesign Dynamics (envirosocialcapital, evolveEA, and eDesign Dynamics, 2017)
- **A-42 Negley Run Sewershed: Meadow Street Microshed Concept Plan** from June 2019 for the Pittsburgh Parks Conservancy presented by Larimer Consensus Group (Pittsburgh Parks Conservancy and Larimer Consensus Group, 2019)
• The Green First Plan: A City-Wide Green Infrastructure Assessment, a draft report for PWSA from 2016 (Pittsburgh Water and Sewer Authority, 2016).

U.S. Army Corps of Engineers Conceptual Design Alternatives and Design Documentation

In response to flooding and long-standing stormwater challenges described in previous chapters, USACE launched a study of the Negley Run watershed, which would transform the combined drainage into a separated, largely daylighted system. Authorized by the USACE Pittsburgh District in December 2015, the proposed project in partnership with PWSA consists of several concepts and phases within a 75-acre valley from “Negley Run Boulevard from East Liberty Boulevard on the south to the intersection of Washington Boulevard and continuing north along Washington Boulevard to the intersection with Allegheny River Boulevard” (Tetra Tech, 2019). CDAR explored the conceptual design, functional aspects, project phasing, and cost of

• Concept 1: a series of tiered riffles (regenerative stormwater conveyance [RSC] system) along the upper portion of Negley Run Boulevard
• Concept 2: a vegetated swale along the lower portion of Negley Run Boulevard, ending in a wetland basin
• Concept 3: several detention basins along Washington Boulevard connected by open channels as well as traditional piped infrastructure.

CDAR also established typical performance parameters for the separated system drawn from NOAA Atlas 14 rainfall estimates. Specifically, the combined green and gray infrastructure was sized to detain up to the 24-hour, 10-year design-storm (3.3-inch) volume within its basins.

The subsequent DDR converted each of these concepts into a phased project with infrastructure associated with a contributing area to the separated systems (Figure 4.2), reversing numbering to start from the slopes surrounding the lower portion of the watershed:

• CDAR Concept 3/DDR Phase 1: Diversion Channel 1 and 2
• CDAR Concept 2/DDR Phase 2: Highland and Wetland Basin
• CDAR Concept 1/DDR Phase 3: Vegetated Swale and RSC.

However, the DDR 35-percent design scope was limited to just Concept 3/Phase 1 (Figure 4.2, black outline). Due to this limited scope, PWSA advised us to instead use the series of detailed plan drawings and longitudinal sections found in Appendix G of CDAR to assess the area, length, and construction methodologies of key features. In addition, CDAR included detailed costing information with quantity takeoffs and unit prices that we used for our subsequent cost analysis (see Appendix D).

In contrast, the DDR proposed how separated sewer catchments might route to the Diversion Channel and berm, Highland Basin, Wetland Basin, Swale, and RSC areas shown in Figure 4.3. This mapping informed subsequent modeling efforts to assess performance during various design storm events and annual rainfall scenarios.

---

1 Daylighting is the process of removing, exposing, and/or restoring piped stormwater infrastructure to improve conveyance, ecological function, or other aesthetic goals that typically consists of former streams buried by past development and engineering practices.
Given the relatively advanced nature of these plans and public and peer review to date, we directly translated their parameters into the UA-NR model as our first three strategies: strategy increments 1, 2, and 3, corresponding to Phase 1, 2, and 3, respectively. We also include an additional contributing area along Paulson Avenue, at the request of PWSA, as strategy increment 4.²

² Ryan Quinn (PWSA), personal communication with the authors, January 30, 2020.
NRIP was our other source of primary strategy formulation. In addition to diagramming major design and functional planning concepts (parcels for acquisition, paved area for removal, and buildings for demolition), it provides estimates for percent impervious cover of the contributing area, costs, stormwater volumes either retained and removed or detained and released, and relative soft cost intensity for design, engagement, and process. Table 4.1 details the four phases of NRIP, each with separate subphases (and some additional contextual notes). Our final set of strategy increments 5 to 9 largely tracks the geography and trajectory of Phases 3 and 4 laid out in NRIP, with some minor modifications where we

- consolidated a limited portion of Phase 3A with all of Phase 3B and 3C
- included GSI upgrades with neighborhood greening efforts
- aligned portions of Phases 4A and 4B as well as Phases 4E and 4F with sewer infrastructural networks rather than the above-ground street grid urban fabric.

These changes were to simplify our modeling efforts or more closely resemble contemporary processes (for example, the Homewood Comprehensive Plan [Homewood Community Development Collaborative, Pittsburgh Department of City Planning and Urban Redevelopment Authority of Pittsburgh, 2019]). Due to the logistical complexity of land acquisition, structure
demolition, and renaturalized construction, we did not include the full scope of Phase 3A or any of Phase 3D in our strategies.

**Other Strategy Sources**

Over the potential lifetime of green infrastructure performance, we anticipate a substantial amount of neighborhood change. For example, the Larimer/East Liberty Choice Neighborhoods Initiative was recently awarded $30 million from the U.S. Department of Housing and Urban Development to build new housing units and a neighborhood park, Liberty Green at Larimer Park (Urban Redevelopment Authority of Pittsburgh, undated). This revitalization would not have been possible without the economic and community development work of the Living Waters of Larimer, a project of the Larimer Consensus Group and the Kingsley Association (Living Waters of Larimer, undated-a). The Living Waters of Larimer efforts also led to the creation of the River Roots project, an art exhibit integrated with rainwater infrastructure (Urban Redevelopment Authority of Pittsburgh, 2019).

Beyond the USACE and NRIP processes, several additional local-scale urban planning projects and proposals informed our strategy formulation. For example, the Meadow Street Microshed Concept Plan is a focused, community-based planning effort focused on a portion of the Larimer and East Liberty neighborhoods (Pittsburgh Parks Conservancy and Larimer Consensus Group, 2019). Developed for the Pittsburgh Parks Conservancy and presented by...
Larimer Consensus Group, the plan envisions collecting stormwater from across this microshed by installing GSI including green alleys, tree pits, and bioretention cells to a series of streets and intersections. These systems are intended to work together to control the impervious runoff from the microshed delineated by the red line in Figure 4.4. Given similar neighborhood composition and configuration elsewhere in the study area, particularly in Homewood, the detailed parameters for GSI developed for this effort supported our identification of policy levers for subsequent strategies, as well as the costing analysis. Additional planning processes for Homewood and other neighborhoods are described in Appendix E.

**Design-Focused Participatory Workshops and Stakeholder Engagement**

**Negley Run Watershed Task Force Convenings**

A key component of the RDM methodology is deep and iterative engagement with stakeholders—sometimes referred to as “deliberation with analysis” (National Research Council, 2009a). The RAND research team was a regular participant and contributor to NRWTTF meetings, which occurred throughout the project effort on a monthly to quarterly basis. For example, NRWTTF
convened a design charrette in August 2018 with more than 30 participants to develop an integrated concept vision for Lower Washington Boulevard (Pittsburgh Parks Conservancy and Pittsburgh Water and Sewer Authority, 2018). Breakout groups deliberated a range of policy levers, including detention ponds, roadway elevation, bike paths, or a new park connection to the Allegheny River, and then assembled these concepts into strategies that emphasized cobenefits and a holistic “one water” systems approach (Figure 4.5). In addition, participants noted some potential issues of concern for future analysis, such as sediment generated by the neighboring steep slopes. The consensus vision developed in this effort formed the basis for a follow-on workshop in November 2018.

**RAND-Convened Strategy Workshops**

RAND convened two in-person and remotely connected participatory workshops at our Oakland office with NRWTF to assess important consensus concepts, facilitate strategy development, review preliminary results, and set the agenda for subsequent research efforts. These occurred in November 2018 and November 2019, respectively. Attendees included NRWTF participants from government agencies, nonprofits, neighborhood organizations, and design firms, including representatives from ALCOSAN, PWSA, evolveEA, Sierra Club, 3 Rivers Wet Weather, Pittsburgh Parks Conservancy, Lincoln-Lemington Consensus Group, Point Breeze North Development Corporation, and other interested professionals, residents, and students. The methods and results of these workshops are described in more detail in Appendix E.

**Figure 4.5**

Negley Run Watershed Task Force Design Charette Vision for a New Allegheny River Park Connection

Iterative Design and Technical Engagement
Throughout the strategy and model development phases, the RAND team coordinated PWSA, USACE, and Tetra Tech (as a part of the USACE team). We shared a draft version of the Arcadis-developed Negley Run model to help support Tetra Tech’s lower watershed modeling, and Tetra Tech provided versions of their design concepts represented in 1D SWMM to inform our strategy modeling. We also corresponded occasionally to clarify operational assumptions and design decisions in CDAR. PWSA was regularly briefed on preliminary findings and provided technical guidance on SWMM parameters and modeling best practices. The PWSA team’s detailed feedback throughout informed our strategy formulation, key parameters, and understanding of results.

Strategy Formulation and Modeling Assumptions

U.S. Army Corps of Engineers Conceptual Design
As described in previous sections, our strategies derive in large part from the USACE CDAR as well as NRIP. In addition, we used technical and costing information for levers from PWSA’s Green First Plan (Pittsburgh Water and Sewer Authority, 2016) and the Meadow Street microshed proposal (Pittsburgh Parks Conservancy and Larimer Consensus Group, 2019). As a base case, Strategy 0 refers to the FWOA discussed in Chapter Three.

Our workshops with NRWTF and additional consultation with PWSA suggested that grouping strategies by geography was the most useful approach, as it could contribute to phasing for subsequent implementation planning. This approach allowed for the direct translation of the CDAR Concept 3 (Diversion Channel 1 and 2), CDAR Concept 2 (Highland and Wetland Basin), and CDAR Concept 1 (Swale and RSC) into Strategies 1, 2, and 3 (reflecting the phasing of DDR). We also included a multipurpose recreational trail as discussed in the NRWTF workshops. Following guidance from PWSA, we then added an additional separated contributing area along Paulson Avenue east of Washington Boulevard to the USACE design, which was designated Strategy 4. These areas within the lower Negley Run watershed are diagrammed in Figure 4.6.

Silver Lake Retention Basin
One of the novel contributions of our research was to characterize the form and function of a stormwater detention facility at a restored Silver Lake. Silver Lake was once a body of water at the confluence of several historic streams that was filled in after the streams were buried and replaced with piped conveyance infrastructure; it is currently a commercial/industrial park. We hereafter refer to this as the Silver Lake Retention Basin, or SLRB. The former lake area, which sits below Westinghouse Field, is approximately five acres with eight feet of grade change. Given its current use as a set of privately owned self-storage warehouses and prior industrial uses, we did not assume any excavation in order to provide the range of potential storage volumes. We also did not assess the feasibility of this transformation nor undertake any engineering analysis, but a public agency would need to do so if such a path were to be pursued (see Appendix E).

PWSA’s Green First Plan used a 1.5-inch rainfall over the contributing impervious drainage area for GSI sizing (approximately equivalent to the NOAA Atlas 14 estimate for a 10-year, 1-hour event). We followed this approach for all GSI in the upper watershed and then scaled
SLRB so that the total instantaneous storage volume spanning both local GSI and SLRB approximates the 10-year, 24-hour event (3.2 inches of rainfall) at the largest increment of strategy build-out. This resulting total is consistent with the design assumptions made for the USACE CDAR system.

We assumed that a restored SLRB would have some amount of constant water depth (nominally 1 foot on average), a 72-hour underdrain (reaching a peak discharge rate of 2.8 cfs) that flows to the separated Wetland Basin envisioned in CDAR, 12 acre-feet of storage to hold the managed impervious area of 214 upstream impervious acres, and a 10-year, 1-hour overflow that rejoins into the combined system at the head of Washington Boulevard.

In selected strategies, we also tested an expanded version of this restored basin (SLRBX) that includes an additional 4 acre-feet of storage capacity to match a plausible climate-induced increase in the 10-year, 1-hour storm event to 2 inches, as shown in the Average Future discrete rainfall scenario in Chapter Three. As mentioned in the previous section, the 2 acres of water
area set within a 5-acre amenity area is not a dissimilar condition from that at Panther Hollow Lake (see Figure 4.7).

SLRB or SLRBX would have either a surface conveyance or subsurface piped infrastructure connecting it down Washington Boulevard to the USACE Wetland Basin associated with Strategy 3. We did not design or assess the feasibility of this link, as it requires access to if not purchase of private property, but we did include a construction cost estimate. This is a critical link for both the separated system and potential community cobenefits. Again, we did not design or assess the feasibility of a multimodal bike and pedestrian path, but we did offer a construction cost estimate as the SLRB or SLRBX recreational amenity area would act as a new access point in Homewood to the broader network of trails extending to the velodrome, Highland Park, and the Allegheny River.

**Neighborhood Green Stormwater Infrastructure Connected to the Silver Lake Retention Basin**

Next, we consider how areas of the upper watershed could be managed through a microshed approach, including both localized GSI and further connection to SLRB. Each upper watershed strategy is intended to treat either 25 or 50 percent of the catchment’s impervious cover. For example, the first strategy increment that includes SLRB also incorporates a contributing area of separated infrastructure and either local GSI or broader neighborhood greening along Frankstown Avenue, as envisioned in NRIP. The 25-percent impervious management option is termed Strategy 5A, whereas the 50-percent control option is Strategy 5B.

Though neighborhood greening could take many forms, we model this as a series of discrete bioretention cells using SWMM’s LID module that allows for the introduction of 2D or 3D GSI into a 1D model (see Appendix E for details). In practice, it would likely be a mix of levers, such as complete streets, tree pits, or other techniques. Each of the modeled cells are sized to capture and retain a 1.5-inch design storm from contributing impervious areas such as parking lots and streets, with the stormwater either infiltrating or draining down over a period

---

3 Complete streets “are designed and operated to enable safe access for all users, including pedestrians, bicyclists, motorists, and transit riders of all ages and abilities. . . . There is no singular design prescription for Complete Streets; each one is unique and responds to its community context. A complete street may include: sidewalks, bike lanes (or wide paved shoulders), special bus lanes, comfortable and accessible public transportation stops, frequent and safe crossing opportunities, median islands, accessible pedestrian signals, curb extensions, narrower travel lanes, roundabouts, and more” (Smart Growth America, undated). Many cities also include smart technologies, alternative allocations of space, and newer approaches to stormwater management within the right-of-way improvements.
of 72 hours. Should the amount of runoff exceed the storage capacity, the bioretention cells flow either into the next impervious subcatchment or the combined system.

The underdrains from each of these subcatchment-based LID units are routed directly to SLRB. For simplicity, we do not explicitly model the conveyance infrastructure, but it is assumed to be costed at the same intensity (flow volume) and density (along streets) as the Meadow Street microshed proposal. Given the uncertainty of whether this would be open channel versus piped infrastructure and other constraints, we conservatively did not assume any storage volume or peak attenuation associated with conveyance. This was also the case for the SLRB to USACE system connection along Washington Boulevard (Figure 4.8).

The conveyance systems from Kedron, Hermitage, and Kelly Streets (strategy increments 6 and 7) necessitate access to the Silver Lake site. We envision that whether these would be underground pipes or surface connections, the street-level passages could be park-like improvements with associated bike and pedestrian infrastructure. While we did not design or assess the feasibility of these potential amenities, we did offer construction cost estimates as they would generate cobenefits of drawing the recreational and commuter network deeper into their associated neighborhoods.

The East Hills extension is a novel strategic consideration to this report not previously considered in NRIP. The UA-NR model structure afforded additional resolution in this area, and we wanted to examine how attenuating runoff near the intersection of Oakwood and Bennett Streets with Frankstown Avenue might affect overall function. Strategy 9C represents the maximum possible build-out for the proposed system of GSI, which includes the East Hills extension, local GSI to address 50 percent of the impervious area, and an expanded SLRBX.

All of strategy increments 6 through 9 will require conveyance from the separated GSI system to SLRB or SLRBX. Again, we did not design or assess the feasibility of surface conveyance or subsurface piped infrastructure but included it in our construction cost estimate. Though we assume that some of this stormwater utility work will be associated with such

Figure 4.8
Conceptual Diagram of Upstream Green Stormwater Infrastructure and Partial Separation Routing

NOTE: Conceptual diagram applies to strategy increments 5 through 9.
improvements as renovated bike lanes and pedestrian sidewalks, perhaps amounting to such neighborhood amenities as complete streets, not knowing their location or incremental value to existing conditions, we did not include such transformations in our cobenefits analysis.

The remaining strategy increments (see Figure 4.9 and Table 4.2) are as follows:

- **Kedron and Hermitage Streets**: Strategies 6A and 6B (25/50-percent impervious cover target)
- **Kelly Street**: Strategies 7A, 7B, and 7C (same logic as above; 7C implements SLRBX, the climate-resilient version of Silver Lake detention)
- **Lincoln Avenue**: Strategies 8A, 8B, and 8C
- **East Hills**: Strategies 9A, 9B, and 9C.

*Figure 4.9
Strategy Increments 5 Through 9*
<table>
<thead>
<tr>
<th>Increment</th>
<th>Geographic Area</th>
<th>Option</th>
<th>Short Name</th>
<th>SLRB Size (acre-feet)</th>
<th>Impervious Cover Managed</th>
<th>Area (acre)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>None</td>
<td>–</td>
<td>FWOA</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>CDAR Phase 1</td>
</tr>
<tr>
<td>1</td>
<td>Diversion Channel 1 and 2</td>
<td>–</td>
<td>Channel 1/2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>CDAR Phase 2</td>
</tr>
<tr>
<td>2</td>
<td>Highland and Wetland Basin</td>
<td>–</td>
<td>Basins</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>CDAR Phase 2</td>
</tr>
<tr>
<td>3</td>
<td>Swale and RSC</td>
<td>–</td>
<td>Swale/RSC</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>CDAR Phase 3</td>
</tr>
<tr>
<td>4</td>
<td>Paulson Avenue</td>
<td>–</td>
<td>Paulson (Central Daylighting)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>PWSA request</td>
</tr>
<tr>
<td>5</td>
<td>Silver Lake, Frankstown Avenue, Westinghouse Field</td>
<td>A</td>
<td>Frankstown-SLRB-25</td>
<td>12</td>
<td>25</td>
<td>18</td>
<td>NRIP Phase 3BC and 4AB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>Frankstown-SLRB-50</td>
<td>12</td>
<td>50</td>
<td>37</td>
<td>NRIP Phase 3BC and 4AB</td>
</tr>
<tr>
<td>6</td>
<td>Kedron Street and Homewood North</td>
<td>A</td>
<td>Kedron-SLRB-25</td>
<td>12</td>
<td>25</td>
<td>32</td>
<td>NRIP Phase 4ABEF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>Kedron-SLRB-50</td>
<td>12</td>
<td>50</td>
<td>65</td>
<td>NRIP Phase 4ABEF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>Kedron-SLRBX-50</td>
<td>16</td>
<td>50</td>
<td>150</td>
<td>NRIP Phase 4ABEF</td>
</tr>
<tr>
<td>7</td>
<td>Kelly Street and Homewood South</td>
<td>A</td>
<td>Kelly-SLRB-25 (Midrange)</td>
<td>12</td>
<td>25</td>
<td>75</td>
<td>NRIP Phase 4CD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>Kelly-SLRB-50</td>
<td>12</td>
<td>50</td>
<td>150</td>
<td>NRIP Phase 4CD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>Kelly-SLRBX-50</td>
<td>16</td>
<td>50</td>
<td>150</td>
<td>NRIP Phase 4CD</td>
</tr>
<tr>
<td>8</td>
<td>Lincoln Avenue and Lincoln-Lemington-Belmar</td>
<td>A</td>
<td>Lincoln-SLRB-25</td>
<td>12</td>
<td>25</td>
<td>95</td>
<td>NRIP Phase 4EF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>Lincoln-SLRB-50</td>
<td>12</td>
<td>50</td>
<td>189</td>
<td>NRIP Phase 4EF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>Lincoln-SLRBX-50</td>
<td>16</td>
<td>50</td>
<td>189</td>
<td>NRIP Phase 4EF</td>
</tr>
<tr>
<td>9</td>
<td>East Hills</td>
<td>A</td>
<td>EastHills-SLRB-25</td>
<td>12</td>
<td>25</td>
<td>107</td>
<td>NRIP Phase 4EF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>EastHills-SLRB-50</td>
<td>12</td>
<td>50</td>
<td>214</td>
<td>NRIP Phase 4EF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>EastHills-SLRBX-50 (Max Build-out)</td>
<td>16</td>
<td>50</td>
<td>214</td>
<td>NRIP Phase 4EF</td>
</tr>
</tbody>
</table>
For ease of discussion in the results and analysis through the remainder of the report, we have given alternate names to three selected strategies representing varying increments of investment. Strategy 4, which includes the centralized surface system as envisioned in the USACE CDAR design together with an extension up Paulson Avenue, is referred to as the *Central Daylighting* strategy. Strategy 7A, which includes a version of SLRB and investment in GSI to control 25 percent of impervious cover through the Kelly Street increment, is the *Midrange* strategy, while Strategy 9C, which represents the highest level of investment considered, is the *Max Build-Out* strategy. These alternate names are also noted in Table 4.2.

**Planning-Level Strategy Construction Costs**

Planning-level costs were developed as part of the CDAR effort, and following guidance from PWSA, we adopted cost ranges for Strategies 1, 2, and 3 directly from CDAR. Given the substantial uncertainty associated with the potential implementation of our strategies, for the additional strategies we took several approaches to generating preliminary cost estimates. The first was a bottom-up construction cost estimate that drew on assemblies and unit takeoffs from the USACE CDAR. This applied to Strategy 4, SLRB/SLR BX, and upper watershed conveyance infrastructure. The second approach was to draw a range of costs relative to impervious acres managed by GSI from several sources, primarily the Meadow Street microshed report (Pittsburgh Parks Conservancy and Larimer Consensus Group, 2019) but also from ALCOSAN’s *Starting at the Source* (ALCOSAN, 2015) and PWSA’s *Green First Plan* (Mott MacDonald and Pittsburgh Water and Sewer Authority, 2016b). Separately, we also used two different approaches to estimate the potential cost of compensation for private landowners at the proposed Silver Lake detention basin site. The sections below provide an overview of our costing methodology, which is further developed in Appendix E.

**U.S. Army Corps of Engineers Conceptual Design Alternative Report Estimating Methodology for Built Infrastructure**

The Stantec/Tetra Tech Joint Venture compiled a bottom-up construction cost estimate for the USACE CDAR. Concept 3 (DDR Phase 1) was estimated as $8.7 million with a -30-percent/+50-percent uncertainty range, reflective of an AACE Class 4 estimate (AACE International, 2005). All three concepts together were estimated to cost $13.4 million. The subsequent Tetra Tech estimate for the DDR submission was somewhat lower for CDAR Concept 3; however, we chose not to use it given the lower level of consistent details and potential project scope changes. The CDAR costing assumptions allowed us to generate spreadsheets to estimate a connection for Paulson Avenue in Strategy 4, as well as the build-out and connections for Silver Lake (see Appendix E for details). Per CDAR, a construction contingency of 52.5 percent was applied to the bottom-up estimates throughout.

**Estimating Neighborhood Green Stormwater Infrastructure by Impervious Acres Managed**

For the neighborhood greening and GSI strategies in the upper watershed, we principally relied on the Pittsburgh Park Conservancy’s work for the Meadow Street microshed (Pittsburgh Parks Conservancy and Larimer Consensus Group, 2019). Though we used the construction costs of individual GSI typologies of bioretention, tree pits, and so on for our own nominal estimates of neighborhood greening and conveyance units, we also bracketed the potential cost range using...
low and high estimates per acre of impervious area controlled. Several projects and authorities in the Pittsburgh region have established rules of thumb for treatment and conveyance per impervious acre, ranging from $220,000 for the Meadow Street microshed (Pittsburgh Parks Conservancy and Larimer Consensus Group, 2019), to $260,000 from ALCOSAN’s retrofit estimate (ALCOSAN, 2015), to a low and high range of $324,000 to $432,000 from PWSA’s Green First Plan (Mott MacDonald and Pittsburgh Water and Sewer Authority, 2016b).

Appendix E details our cumulative construction cost methodology and Chapter Six analyzes the full range of cost uncertainties. For comparison purposes, given that we anticipate both operational and cost efficiencies associated with such a large-scale deployment of GSI, our bottom-up estimated midrange (nominal) cost to treat an acre of impervious area was equivalent to $255,000 for 214 acres in the Max Build-Out strategy (Strategy 9C). The location of GSI projects—whether in the right-of-way, on private property, or centralized on publicly owned land—is beyond the scope of our assessment, but may substantially affect costs.

**Estimating Compensation for Private Landowner at Proposed Silver Lake Site**

We also estimated compensation for either the purchase or eminent domain acquisition of the self-storage businesses at Silver Lake. This cost was estimated at $3.8 million in NRIP. Appendix E details our two bounding methodologies in full, but extrapolating its 2016 sale value at a 30-percent market increase would result in a low estimate of $4.4 million. This compares to a high estimate based on a $12-per-square-foot net annual income and 10-percent capitalization rate common to industrial properties in the area. Assuming an assembled, buildable site of substantial density, this could reach up to $22 million. This is a substantial source of uncertainty and would have a notable impact on the overall cost-efficiency of proposed GSI in Homewood and beyond.

**Planning-Level Operations and Maintenance Costs**

The potential operations and maintenance (O&M) costs of GSI can vary widely depending on its type (bioretention cell vs. detention basin, for example) and intensity of required activity (aesthetic improvement vs. reconstruction). Unfortunately, the USACE CDAR does not address O&M, and DDR says that it will be developed later as part of a separate plan. Similarly, ALCOSAN’s *Starting at the Source* does not offer guidance. Our further review of the literature found three potential methods: (1) percentage of construction cost by type of GSI, (2) percentage of construction cost by type of anticipated maintenance activity, and (3) cost per impervious acre treated.

The first method assumes annual maintenance costs are typically a percentage of construction costs. EPA guidance suggests that these may range from 1 percent for detention basins to 7 percent for swales and bioretention cells (U.S. Environmental Protection Agency, 1999). Other localities skew even higher—for example, King County, Washington, suggests that annual O&M costs may represent 15–20 percent of a stream restoration project’s total construction cost. An alternative approach suggests that regular aesthetic maintenance might amount to 5 percent of installation costs. In contrast, moderate repair (replacement of shrubs or trees, unclogging, etc.) typically costs 10–15 percent, while a major repair (regrading or erosion repair and sediment removal) might reach as high as 35–50 percent (Knutson, 2015; Price, Holladay, and Wainger, 2019).
The PWSA Green First Plan estimates that O&M for GSI costs approximately $4,400 per impervious acre treated (in 2016 dollars), which adjusted for inflation would be $4,700 (in 2019 dollars). PWSA’s work is ongoing at the time of publication, and our brief literature review suggests a broad potential range of total annual routine maintenance, with a green roof varying between approximately $3,000 and $5,000 per acre of impervious area managed, whereas tree infiltration trenches range between approximately $2,000 and $3,400, and bioretention cells ranges from approximately $1,200 to 2,000 (Water Environment Federation, 2015).

Ultimately, we used both the percentage and cost-per-impervious-acre methods given the affinity to how we calculated construction costs. For Strategies 1 through 4 and SLRB/SLRBX, we estimated the annual O&M cost as a percentage of the construction costs based on our bottom-up estimation methodology. To capture the uncertainty, we estimated O&M as costing 2–8 percent of the associated construction cost per year, with a nominal estimate of 6 percent. This broad range accounts for the possibility of damaging high-discharge events, especially in future scenarios.

In contrast, we took PWSA’s Green First Plan guidance of $4,700 in annual O&M costs per impervious acre managed as our nominal case and high estimate for the upper watershed GSI. Recognizing that this estimate may not fully match our anticipated GSI typologies for bio-retention cell and tree infiltration trenches, we established a lower bound estimate of $2,350 per impervious acre in keeping with national best practices (Water Environment Federation, 2015).

**Planning-Level Implementation Assumptions**

To generate life-cycle costs for the strategies, we made several assumptions about the time to complete each phase, planning horizon, and discount rate. First, we estimated that the build-out for this system would take approximately 15 years. We used the USACE CDAR process to guide our anticipated timeline. After a five-year planning effort, CDAR projected that it would take five to six years to complete all concepts under consideration (Strategies 1 through 4) (Stantec/Tetra Tech JV, 2018). Similarly, a five-year planning effort starting in 2020 could establish a five-year construction process for Silver Lake and one of the neighborhood-scale GSI installations (strategy increments 5 and 6). Last, the other upper watershed strategies could be deployed in years 10 to 15. There may be some additional cost savings to be realized through constructing the entire chosen set of strategy increments at once or via various contracting vehicles, but given the currently planned phased approach, we did not assess this source of potential cost uncertainty further.

PWSA previously noted that GSI installations would need to be recapitalized at the mid-point of their 50-year planning horizon (Pittsburgh Water and Sewer Authority, 2016). Following this assumption, we assumed a 25-year effective period of performance for GSI (therefore our maintenance and reinvestment timeline), leading to an overall 40-year planning horizon when accounting for strategy build-out time. This extends our analysis to 2060, over a decade beyond ALCOSAN’s required build-out for the Clean Water Plan.

We assume the construction costs to be incurred in a linear fashion over each five-year increment, applying a discount rate of 4 percent (see Chapter Six). Potential cobenefits and O&M costs begin accruing on completion of each five-year construction cycle. As capital sources are variable and uncertain, especially over this time scale, we followed other planning guidance and did not assume any additional financing costs (Environmental Finance Center at
Furthermore, we note that, at current rates, financing costs are negligible compared with the construction contingency. With construction cost equivalent to capital cost for this analysis, Table 4.3 summarizes our low, nominal, and high estimates of capital, O&M, and life-cycle costs for each strategy.

<table>
<thead>
<tr>
<th>ID</th>
<th>Strategy</th>
<th>Capital Cost</th>
<th></th>
<th>O&amp;M Cost</th>
<th></th>
<th>Life-Cycle Cost</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>Nom</td>
<td>High</td>
<td>Low</td>
<td>Nom</td>
<td>High</td>
</tr>
<tr>
<td>1</td>
<td>Channel 1/2</td>
<td>5.7</td>
<td>8.1</td>
<td>12.1</td>
<td>2.8</td>
<td>8.5</td>
<td>11.3</td>
</tr>
<tr>
<td>2</td>
<td>Basins</td>
<td>6.9</td>
<td>9.9</td>
<td>14.8</td>
<td>3.5</td>
<td>10.4</td>
<td>13.8</td>
</tr>
<tr>
<td>3</td>
<td>Swale/RSC</td>
<td>8.7</td>
<td>12.4</td>
<td>18.6</td>
<td>4.3</td>
<td>13.0</td>
<td>17.3</td>
</tr>
<tr>
<td>4</td>
<td>Paulson</td>
<td>9.7</td>
<td>13.9</td>
<td>20.9</td>
<td>4.7</td>
<td>14.1</td>
<td>18.8</td>
</tr>
<tr>
<td>5A</td>
<td>Frankstown-SLRB-25</td>
<td>20.4</td>
<td>27.7</td>
<td>39.7</td>
<td>6.9</td>
<td>20.2</td>
<td>26.2</td>
</tr>
<tr>
<td>5B</td>
<td>Frankstown-SLRB-50</td>
<td>21.9</td>
<td>29.8</td>
<td>42.8</td>
<td>7.4</td>
<td>21.3</td>
<td>27.7</td>
</tr>
<tr>
<td>6A</td>
<td>Kedron-SLRB-25</td>
<td>24.0</td>
<td>32.7</td>
<td>47.3</td>
<td>7.3</td>
<td>21.0</td>
<td>27.4</td>
</tr>
<tr>
<td>6B</td>
<td>Kedron-SLRB-50</td>
<td>26.4</td>
<td>36.2</td>
<td>52.5</td>
<td>8.3</td>
<td>22.9</td>
<td>29.3</td>
</tr>
<tr>
<td>7A</td>
<td>Kelly-SLRB-25</td>
<td>30.1</td>
<td>41.4</td>
<td>60.3</td>
<td>8.3</td>
<td>22.9</td>
<td>29.3</td>
</tr>
<tr>
<td>7B</td>
<td>Kelly-SLRB-50</td>
<td>35.6</td>
<td>49.3</td>
<td>72.1</td>
<td>10.1</td>
<td>26.6</td>
<td>33.0</td>
</tr>
<tr>
<td>7C</td>
<td>Kelly-SLRBX-50</td>
<td>38.0</td>
<td>52.7</td>
<td>77.2</td>
<td>10.9</td>
<td>29.1</td>
<td>36.3</td>
</tr>
<tr>
<td>8A</td>
<td>Lincoln-SLRB-25</td>
<td>37.6</td>
<td>52.1</td>
<td>76.3</td>
<td>8.7</td>
<td>23.7</td>
<td>30.1</td>
</tr>
<tr>
<td>8B</td>
<td>Lincoln-SLRB-50</td>
<td>39.1</td>
<td>54.4</td>
<td>79.7</td>
<td>11.0</td>
<td>28.3</td>
<td>34.7</td>
</tr>
<tr>
<td>8C</td>
<td>Lincoln-SLRBX-50</td>
<td>41.5</td>
<td>57.8</td>
<td>84.8</td>
<td>11.8</td>
<td>30.8</td>
<td>38.0</td>
</tr>
<tr>
<td>9A</td>
<td>EastHills-SLRB-25</td>
<td>40.6</td>
<td>56.4</td>
<td>82.8</td>
<td>8.9</td>
<td>24.3</td>
<td>30.6</td>
</tr>
<tr>
<td>9B</td>
<td>EastHills-SLRB-50</td>
<td>41.8</td>
<td>58.2</td>
<td>85.5</td>
<td>11.5</td>
<td>29.4</td>
<td>35.8</td>
</tr>
<tr>
<td>9C</td>
<td>EastHills-SLRBX-50</td>
<td>44.2</td>
<td>61.6</td>
<td>90.6</td>
<td>12.3</td>
<td>31.8</td>
<td>39.1</td>
</tr>
</tbody>
</table>

NOTE: The Central Daylighting (Strategy 4), Midrange (Strategy 7A), and Max Build-Out (Strategy 9C) strategies are highlighted in bold for reference. As a reminder, the strategy increments are cumulative in numerical order, meaning that each successive numbered increment also includes the previous numbered increments.

Sacramento State, 2019; McGarity et al., 2015; U.S. Environmental Protection Agency, 2017). Furthermore, we note that, at current rates, financing costs are negligible compared with the construction contingency. With construction cost equivalent to capital cost for this analysis, Table 4.3 summarizes our low, nominal, and high estimates of capital, O&M, and life-cycle costs for each strategy.

Chapter Summary

This chapter detailed the process used for identification and development of GSI strategies explored in this analysis. We summarized the main literature sources informing the analysis, including the USACE processes, NRIP, and local-level planning initiatives. We also included an explanation of the stakeholder engagement process through design-focused participatory planning gatherings to illustrate the iterative nature of strategy formulation. Final GSI strategies modeled and performance assumptions are outlined, along with their relation to ongoing current planning efforts in the Negley Run watershed. Sources for estimating GSI costs and assumptions used for the cost-benefit analysis are also noted. We examine performance results of the strategies discussed above in Chapters Five and Six.
In the previous chapter, we described a series of iterative building strategies intended to capture and divert a substantial volume of stormwater across the Negley Run watershed while also providing other benefits to city residents. This chapter describes the results from the simulation modeling analysis with these strategies implemented. Specifically, we focus here on modeled flow results, including combined sewer overflows, impervious runoff, and flooding. Chapter Six builds on this modeling evaluation with economic analysis, including estimates of strategy cobenefits and a comparison of overall monetized benefits and costs under uncertainty.

This chapter mirrors the structure of Chapter Three, comparing with-strategy and FWOA results for overall stormwater and sewer system flows, CSOs, runoff, and flooding in turn. Throughout this analysis, we applied the same basic modeling approach and structure described previously, though some of the modeling experiments were constrained to stay within available computing resources. We modified the UA-NR model to represent each of the 17 strategies described in Chapter Five and ran this model using both annual time series and discrete storms to consider performance across multiple metrics and a range of plausible conditions.

Additional results from the with-strategy analysis not presented in this chapter will be made available through forthcoming web-accessible interactive data visualization tools.

Sewer-Overflow Reduction

A key question regarding the proposed system of green infrastructure for Negley Run is to what degree such a system could reduce the volume and frequency of CSOs under present and future conditions. Prior evaluations of sewer-overflow reduction strategies focused on Negley Run were limited in scope: PWSA’s Green First Plan (Pittsburgh Water and Sewer Authority, 2016), for example, applied a high-level infiltration-based analysis to represent GSI in the watershed under 2003TY rainfall conditions only. The more detailed visioning and design work that followed, including NRIP (envirosocialcapital, evolveEA and eDesign Dynamics, 2017) and USACE CDAR (Stantec/Tetra Tech JV, 2018) and 35-percent DDR efforts (Tetra Tech, 2019), used runoff or flow capture as metrics and did not directly estimate overflows.

In this section, we summarize the rainfall flow capture and sewer-overflow reduction from the 17 proposed strategies across a range of years and rainfall scenarios. Due to computing resource
limitations, we limited the with-strategy experimental design to three rainfall years from each of the scenarios discussed in Chapter Three (Recent Historical, Higher Intensity Rainfall, Higher Total Rainfall), while also including the 2003TY and 2018 (current wettest year on record). This yielded a total of 11 years simulated in the UA-NR model for each of the 17 strategies, or 187 additional simulation-years in total. Appendix B describes this design in further detail.

Combined Sewer Overflows

We estimated sewer overflows from the A-42 outfall with each strategy in place and compared these to FWOA overflows.

2003 Typical Year Combined Sewer-Overflow Volumes

Figure 5.1 shows a summary of the results from each strategy using 2003TY rainfall. Beginning from a without action baseline of 865 MGal, the incremental strategies tested reduce annual overflows from between 23 and 223 MGal (3–26 percent).

The Central Daylighting strategy (Strategy 4), which includes full build-out of the USACE CDAR design including all directly contributing areas, reduces CSO volumes by 107 MGal (12 percent), while the extension to SLRB and incremental addition of neighborhood GSI jumps notably at the Kelly Street addition (168–192 MGal reduced, or 19–22 percent). The

---

1 We were unable to utilize the Pittsburgh Supercomputing Center’s high-performance computing resources as intended for the strategy analysis due to COVID-19. The Pittsburgh Supercomputing Center prioritized a large segment of its computing resources for epidemiological modeling in support of pandemic response. As a result, we reduced some dimensions of the simulation analysis, such as the number of simulation years evaluated, in order to finish the experiments using the Amazon Web Services platform. See Appendix B for more information on the experimental design.
additional Lincoln or East Hills extensions further reduce overflows, and we observe modest performance differences between the options to use GSI to manage 25 versus 50 percent of the impervious area in the targeted neighborhoods. The results show little improvement in CSO reduction from the option to create an expanded Silver Lake (Strategies 7C, 8C, or 9C).

By comparison, the strategy options evaluated in PWSA’s Green First Plan, which included GSI in Negley Run along with other systemwide improvements, such as treatment plant expansion, showed a similar range of overflow reduction at the A-42 outfall, ranging from approximately 207 to 263 MGY for the 2003TY (Pittsburgh Water and Sewer Authority, 2016, Sec 3 Appendix C). However, the strategies evaluated by PWSA envisioned investment in distributed local GSI across a much broader area of Negley Run to achieve these outcomes, with either 485 or 614 impervious acres managed, respectively (Pittsburgh Water and Sewer Authority, 2016, Table 2-5, p. 2–11). The strategies in this analysis, by contrast, use a centralized approach and are thus much less reliant on distributed projects. Strategies 7A and 7B, for example, seek to manage either 75 or 150 impervious acres with local projects, while the Max Build-Out strategy (Strategy 9C) would target a total of 214 impervious acres. This suggests that the interconnected system evaluated here could more efficiently yield overflow reduction. We will consider this in terms of cost-efficiency in the next chapter.

Recent Historical Overflow Volumes

Looking beyond the 2003TY, we find that all strategies considered yield a considerably greater volume and higher proportion of CSO reduction in other rainfall scenarios considered. Figure 5.2

Figure 5.2
Combined Sewer-Overflow Volume Reduction with Strategies, Recent Historical Rainfall

NOTE: Results represent an average across three simulation years (2009, 2011, and 2013).
shows the same CSO comparison as Figure 5.1, but using the Recent Historical rainfall scenario instead. In this scenario, CSO reduction ranges from 174 to 398 MGY across the strategies considered, or 17‒40 percent of overflows reduced. The relative performance between strategies shows a similar pattern as in Figure 5.1 above, but with overall better performance under these rainfall conditions.

This is not simply due to a difference in rainfall volumes. Although the 2003TY is drier on average than the Recent Historical scenario (see Chapter Three), the average annual overflow from the subset of years modeled with strategy is similar, and even the lowest rainfall year included in the analysis (2009, annual rainfall volume 33.5 inches) shows more CSO reduction than the 2003TY (36.8 inches). Instead, the particular pattern of storms included in the 2003TY seems to be the primary driver of these more modest outcomes and might in general be leading to more pessimistic assessments of stormwater management options for Negley Run.

**Combined Sewer-Overflow Volume Reduction for All Years Modeled**

Figure 5.3 summarizes the volume of CSO reduction from all strategies in all rainfall scenarios, including the future scenarios. 2018 is shown separately as well to demonstrate CSO

**Figure 5.3**

Combined Sewer-Overflow Reduction with Strategies, All Rainfall Scenarios

NOTE: Recent Historical results represent an average across three simulation years (2009, 2011, and 2013). Higher Intensity and Higher Total Rainfall scenario results similarly average three projected future years (2043, 2045, and 2047). This subset of years was chosen to span the range of CSO volumes observed in the FWOA analysis, with a similar overall average. For more information, see Appendix B.
reduction under an extreme rainfall case. This comparison further illustrates that 2003TY results are pessimistic about strategy performance compared with alternate representations of average annual rainfall. In fact, performance differences between the current and future rainfall scenarios are much smaller in magnitude than between Recent Historical and the 2003TY. At the other end of the range, in the record wettest year, the strategies reduce CSO volumes by 244 MGal (Strategy 1) to 643 MGal (Max Build-Out, or Strategy 9C), or 11‒30 percent of the 2.2 billion gallons estimated FWOA volume.

**Combined Sewer-Overflow Frequency and Duration Reduction**

In addition to volume reduction, PWSA and ALCOSAN are also seeking to reduce the annual duration and frequency of overflow events to meet water-quality requirements. We used the UA-NR model to estimate the change in duration and frequency to help inform this effort. Figure 5.4 provides a scatterplot summary of the change in frequency and duration using 2003TY rainfall alongside Recent Historical and two future rainfall scenarios. The horizontal axis indicates the reduction in overflow frequency (count of events), while the vertical axis shows the change in duration (hours in overflow).

In general, we see a similar pattern in performance in terms of frequency and duration as with volume. Reductions are more modest assuming 2003TY rainfall, while the other scenarios
considered show greater levels of both frequency and duration reduction. For instance, Strategy 3 yields 1 fewer overflow event and a reduction of 63 hours in overflow in the 2003TY compared with without action conditions (85 events, 1,522 hours in overflow). The same strategy shows an average of 11 fewer overflow events and a reduction of 236 hours in overflow assuming Recent Historical rainfall instead.²

Strategy performance in terms of frequency and duration is similar in the Higher Intensity and Higher Total Rainfall scenarios as well, with reductions of approximately 7–15 events and 200–300 hours depending on scenario. Strategies with SLRB and more substantial investments in local GSI, starting with the Midrange strategy (Strategy 7A), show a jump in performance relative to strategies focused primarily on the USACE CDAR region. Overall, the modeled results suggest that iterations of the proposed stormwater system could also notably reduce the time and frequency in overflow for A-42, with a high fraction flowing instead through the new stormwater-only pathway to the Allegheny River.

Runoff Capture from Local Green Stormwater Infrastructure

We next evaluated strategy performance using discrete storm analysis, building on the approach described in Chapter Three. To conserve computing resources, we focused on 1-hour and 24-hour duration events when comparing strategies but otherwise retained the same rainfall and soil moisture uncertainties considered in the FWOA analysis.

An initial step was to estimate the extent to which local GSI in Homewood and East Hills could reduce the flow of impervious runoff into the combined sewer system. This analysis necessarily focused only on strategy increments 5 through 9, as Strategies 1 through 4 do not include these investments. Figure 5.5 shows an example of the estimated impervious runoff reduction by modeled subcatchment from selected strategies for a 24-hour, 10-year event (3.2 inches, Historical rainfall scenario). The top row shows strategies with a 25-percent impervious area target, while the bottom shows the same strategies but with a 50-percent target instead.

For this event duration and rainfall depth, modeled results show impervious runoff reduction from local GSI ranging from approximately 5 to 25 percent (top row, 25-percent strategies) or 5 to 50 percent (bottom row, 50-percent strategies) depending on location and subcatchment size.

Similar runoff results can be made available for all 1-hour and 24-hour simulated storms in the forthcoming interactive data visualizations. We expect these to be of value for follow-on local planning and design work by PWSA, ALCOSAN, and other NRWTF members but do not further detail them in this report.

² For comparison, average FWOA A-42 overflow frequency in the Recent Historical scenario is approximately 89 events using the three years simulated for this portion of the analysis, with an annual duration of 1,704 hours. These averages are close to those presented in Table 3.3 for all Recent Historical rainfall years (85 events and 1,522 hours, respectively).
Flood-Risk Reduction

Returning to the analysis of flood risk using the 1D UA-NR model, we found a mixed picture of results, suggesting that additional analysis and design will be needed to address flooding concerns across Negley Run.

Street Flooding

In general, the discrete storm modeling results show that the system represented in the USACE CDAR report could reduce flood depths along the Washington Boulevard corridor during major rainstorms. Figure 5.6 shows an example of flood depth reduction from a 24-hour, 10-year event (3.2 inches, Historical rainfall scenario) from Strategies 1 through 3, representing the main components of the CDAR system. Beginning with the Channel 1/2 and river
outlet (Strategy 10, left pane), we see modest depth reductions along Lower Washington and at the intersection of Highland Drive. Including the Highland and Wetland Basins (Strategy 2, middle pane) increases both the extent and amount of depth reduction, while the additional benefit from the Swale/RSC along Negley Run Boulevard (Strategy 3, right pane) is modest and focused at the intersection of Washington and Negley Run.

Similar street depth reduction in this corridor can be observed from these strategies for events of different durations, frequencies, and depths. Table 5.1 shows the average depth reduction for selected stretches of roadway for selected storms, comparing Historical (left) and Average Future (right) estimated DDF values. Average depth reduction ranges from 0.1 to 0.9 for Lower Washington Boulevard, where the low point in the watershed is located. Though notable, in all of these events this area still floods above the approximately 1-foot flood depth threshold identified in Chapter Three, meaning that the road would still need to be closed. Moving farther south, depth reduction is generally greater at the intersection of Washington and Highland Drive, especially with the introduction of the detention basins in this area (starting with Strategy 2). Strategies 3 and 4 show additional minor improvement for the intersection of Washington and Negley Run in these events, but most of the benefit appears to come from the first two strategy increments.
Table 5.1
Average Flood Depth Reduction (feet) from Strategies 1–4 for Selected Storm Events

<table>
<thead>
<tr>
<th>Location ID</th>
<th>Strategy Name</th>
<th>1-hour Historical (Highland Park)</th>
<th>24-hour Historical (Highland Park)</th>
<th>1-hour Average Future (2020–2099)</th>
<th>24-hour Average Future (2020–2099)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Washington Boulevard 1</td>
<td>Channel 1/2</td>
<td>-0.1</td>
<td>-0.2</td>
<td>-0.3</td>
<td>-0.3</td>
</tr>
<tr>
<td>2</td>
<td>Basins</td>
<td>-0.4</td>
<td>-0.5</td>
<td>-0.8</td>
<td>-0.9</td>
</tr>
<tr>
<td>3</td>
<td>Swale/RSC</td>
<td>-0.4</td>
<td>-0.5</td>
<td>-0.8</td>
<td>-0.9</td>
</tr>
<tr>
<td>4</td>
<td>Paulson</td>
<td>-0.4</td>
<td>-0.6</td>
<td>-0.8</td>
<td>-0.9</td>
</tr>
<tr>
<td>Washington and Highland Boulevard 1</td>
<td>Channel 1/2</td>
<td>0.0</td>
<td>-0.1</td>
<td>-0.2</td>
<td>-0.1</td>
</tr>
<tr>
<td>2</td>
<td>Basins</td>
<td>-0.3</td>
<td>-0.9</td>
<td>-1.8</td>
<td>-2.1</td>
</tr>
<tr>
<td>3</td>
<td>Swale/RSC</td>
<td>-0.3</td>
<td>-0.9</td>
<td>-1.8</td>
<td>-2.1</td>
</tr>
<tr>
<td>4</td>
<td>Paulson</td>
<td>-0.3</td>
<td>-0.9</td>
<td>-1.8</td>
<td>-2.2</td>
</tr>
<tr>
<td>Washington and Negley Run Boulevard 1</td>
<td>Channel 1/2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>Basins</td>
<td>-0.2</td>
<td>-0.3</td>
<td>-0.2</td>
<td>-0.7</td>
</tr>
<tr>
<td>3</td>
<td>Swale/RSC</td>
<td>-0.3</td>
<td>-0.4</td>
<td>-0.4</td>
<td>-0.8</td>
</tr>
<tr>
<td>4</td>
<td>Paulson</td>
<td>-0.3</td>
<td>-0.4</td>
<td>-0.4</td>
<td>-0.9</td>
</tr>
</tbody>
</table>

NOTE: Average reduction in 1D flood depth (ft) in the modeled street channels assuming default (dry) soil moisture conditions and using the synthetic rainfall event approach.

The results above are based on the synthetic storm approach, which, as noted in Chapter Three, might overstate the extent and depth of street flooding compared with observed rainfall events. As a result, we also evaluated a small number of historical storm events with the strategies in place, either with observed historical rainfall or with rainfall intensity increased to correspond with future projected DDF volumes (see Appendix C). Figure 5.7 returns to one such storm, the 2011 Washington Boulevard flood, and shows modeled results with Strategies 2 and 3 in place.

Compared with the without action results (left pane), including the CDAR system up to the Highland and Wetland Basins (Strategy 2, middle pane) reduces the street area exposed to concerning depths of flooding, especially near the intersection and in a portion of Lower Washington Boulevard. Connecting in the Swale/RSC along Negley Run Boulevard (Strategy 3) further reduces the extent of flooding from this event between Negley Run Boulevard and Highland Drive and reduces the footprint of flooding greater than one foot in the lower area. However, model results still show notable flooding at the low point in the system in this strong storm with the proposed CDAR system implemented.

Results presented above focus on Strategies 1 through 4, representing the extent of the direct capture region identified by PWSA for the USACE CDAR effort. The UA-NR discrete storm modeling showed essentially no additional benefit in terms of street flood mitigation in the Washington Boulevard corridor from strategies incorporating SLRB and with additional investments in local GSI in Homewood in the East Hills (strategy increments 5 through 9).

For modeled streets in Homewood, we note minor improvements in certain intersections (e.g., Hamilton and Albion, Kelly and Murtland, Tioga and Rosedale) from strategies that
include the Kelly Street increment or beyond and seek to address 50 percent of the impervious area (i.e., strategy options B or C: therefore, Strategies 7B, 7C, 8B, 8C, 9B, and 9C). The improvements (not shown) are modest, however, and we discuss in the final section of this chapter how this analysis leaves open key questions to address regarding how to mitigate localized flood impacts in Negley Run neighborhoods.

**Basement Flooding**

Following the street flood analysis above, the modeled strategy results show little to no benefit with respect to basement flooding in Homewood, Lincoln-Lemington-Belmar, or East Hills. The number of homes affected and estimated basement damage remain basically unchanged in the model results with strategies in place. This is true for both 1-hour and 24-hour events and when looking across the range of return intervals. Although the model results previously discussed showed runoff capture from local GSI, this does not translate to a reduced number of homes exposed to flood conditions during extreme rainfall events in our modeling. Nor do we appear to observe sufficient additional capacity introduced into the existing combined sewer system during rainfall peaks, even with the maximum strategy in place, to prevent basement sewer backups.

However, in this case we note that an absence of evidence does not necessarily mean that GSI projects would not provide risk-reduction benefits at the block- or house-level scale. Instead, we believe that the lack of benefit noted in the modeling results could be due instead to the limitations of this planning-level 1D flood analysis. We discuss these limitations and potential research next steps in the following section.
Discussion and Limitations

Overall, the simulated strategy results presented in this chapter showed a mixed picture of benefits related to sewer overflows and flooding. CSO reduction benefits are notable and consistent across the range of strategies and rainfall scenarios considered and compare favorably to past estimates from PWSA’s Green First Plan. Strategies 1 through 4, focused on the direct capture area, yield flood volume and depth reduction along the Washington Boulevard corridor as intended, with increasing flood benefit from additional strategy increments.

Strategy increments 5 through 9, which focus instead on the indirect capture area in the upper watershed, do not appear to provide additional flood benefits for Washington Boulevard. They also do not appreciably reduce the estimated frequency or extent of either street or basement flooding in modeled areas of Homewood, Belmar, or East Hills. Moreover, none of the strategies tested eliminate flooding on lower Washington Boulevard when looking at the 1D results, even from a one-hour, two-year event. This suggests that additional refinement of the CDAR design and/or additional policy levers will be needed, which we will return to in the concluding chapter of this report.

We conclude the chapter with a brief discussion of limitations and next steps. The same model limitations observed in Chapter Three apply to this analysis, but we note several additional limitations from the modeled comparison of strategies.

Limitations of the Sewer-Overflow Analysis

This analysis does not yet consider combined benefits with regional system improvements or progress toward wet weather flow capture targets. Building on the Chapter Three discussion, because the UA-NR model is not yet integrated with the regional system, we cannot yet estimate how these strategies would perform together with regional system improvements, such as the treatment plant expansion. Due to the lack of integration between the UA-NR and regional models, we also elected not to report progress toward ALCOSAN and PWSA’s target goal of capturing 85 percent of wet weather flows at this stage of research. Next steps would entail using the UA-NR model together with other key modules (e.g., PWSA’s regional model or ALCOSAN’s Main Rivers and Regional Balance Model; see the pilot study) to consider the strategies and rainfall scenarios presented here together with other regional improvements, up to and including the entire CWP.

Limitations of the Flood-Risk Analysis

The 1D planning-level approach may lack sufficient detail to identify flood benefits in the upper watershed. As noted in Chapter Three, the simplified 1D analysis does not capture how actual overland flow occurs during rainstorms or could be correspondingly redirected or captured with GSI installations in place. In addition, local GSI is represented in this analysis in a simplified, standardized way using the SWMM LID module in the UA-NR model and is not optimized for specific local site conditions.

As a result, additional research will be needed to follow up on these results and determine whether specific project designs could provide localized risk reduction. Because the initial high-level findings were indeterminate, follow-on work could entail applying 2D or coupled 1D-2D modeling to estimate flooding for specific site locations and then using these results to develop focused GSI designs intended to redirect surface floodwaters away from
key streets, intersections, or structure locations. We hope that the UA-NR model could serve as a detailed 1D basis for these efforts, but they would nevertheless likely necessitate further model refinement and 2D analysis to more conclusively determine the potential for risk reduction from local GSI.

Chapter Summary

This chapter presented scenario results from the UA-NR model with the proposed Negley Run strategies in place. We discussed sewer-overflow and flood-risk results, in turn, with strategies in place for a subset of the rainfall years and scenarios introduced in Chapter Three, and generally found strongly positive CSO reduction and a mixed picture with respect to flood risk. We build on this modeling analysis in Chapter Six, first presenting results from the cobenefits analysis and then comparing benefits with strategy costs in the final RDM analysis.
A central argument for using GSI to manage stormwater rather than traditional gray infrastructure alone is the potential for these investments to provide additional social, environmental, and economic (“triple bottom line”) benefits to residents. In this chapter, we build on the prior assessment of stormwater flow reduction from the modeled strategies to also consider additional cobenefits, represented as monetized values according to the methods described in Chapter Two. We first present the economic cobenefits estimated for each strategy in different categories considered. We then bring these estimates together with traditional stormwater benefits and strategy cost estimates to complete a benefit-cost comparison by strategy. Recognizing the great degree of uncertainty still present in both benefit and cost assessments, this comparison is conducted across a range of uncertainty using DMDU methods and building on the approach detailed in Fischbach et al., 2017. The chapter concludes with a discussion of key findings from the comprehensive strategy assessment.

**Economic Cobenefits from Green Infrastructure**

The results give the baseline cobenefit values by strategy prior to any uncertainty analysis. As noted in Chapter Two, there are three major categories of cobenefits analyzed here: recreational benefits and benefits accruing to bicycle commuters as a result of new nonmotorized transportation infrastructure, benefits from the planting of trees (including urban heat island effects, carbon sequestration, and localized air pollution effects), and amenity values accruing to property owners as a result of increased green space. These categories are consistent with past literature on GSI (see, e.g., Stratus Consulting, 2009), though we do not include economic impact measures, such as jobs and poverty reduction. As noted in Chapter Two and Appendix F, we have used reasonably conservative assumptions in the estimation of cobenefits, focusing on those ecosystem services for which estimates or methods are reasonably clear and transparent.

---

1 We also prepared to estimate potential benefits from avoided commuting time due to a reduction in flooding outcomes along Washington Blvd; however, as the modeling results indicated only marginal benefits and the approach required rather heroic assumptions (in the absence of a transportation model), we do not include these estimates herein. See Appendix F for more details.

2 Economists make a distinction between economic impacts, which measure flows of economic activity through an economy, and overall welfare, which measures essentially consumer and producer surplus from the provision or trade of goods and services. Our approach herein is consistent with the latter.
That said, there are likely some additional benefits to the GSI approach that are not reflected in the analysis. For example, additional nontree vegetation that provides additional provisioning, regulation, habitat, or nonrecreation and nonaesthetic cultural services are not included in the estimates below (see De Groot et al., 2012, for more discussion of the subservices within each category). While likely nonzero, our prior is that these benefits are likely of relatively small magnitude.

Another example is the potential of Pittsburgh/Allegheny County residents other than property owners near the new amenities to be willing to pay for GSI for aesthetic or other nonrecreational reasons. Nonuse values such as these are incredibly site and population specific and can only be measured using stated preference methods. As such, they are generally not well suited for estimation via benefit transfer methodologies and thus are excluded here. Our prior, based on experience with valuing other environmental amenities, is that mean willingness to pay for partial greening of the Negley Run watershed among all residents is likely positive, though we have very little information as to the exact magnitude. As such, the exclusion of nonuse benefits to residents of the city or county likely biases our estimates of the cobenefits downward.

**Recreation and Commuting Benefits**

Recreation and new bicycle commuter benefits are calculated according to the methods described in Chapter Two and Appendix F. The primary driver of these benefits are the estimates of (new) cycling and pedestrian behavior induced by proximity to a new amenity—in this case, a multipurpose recreational trail. Figure 6.1 shows single-family houses contained within a half-mile buffer from the potential trail by strategy increment. While there also may be some substitution from preexisting users to the new facility, which likely implies either lower cost of access for an equivalent recreational experience or a higher-quality experience (thus increasing benefits), we did not have a model suitable to estimate this behavior, and thus we set these values equal to zero. The ramifications of this decision are to likely bias the recreational benefits (conditional on the induced demand model being correct) downward.

Table 6.1 reports cumulative estimated mobility benefits (from the estimated share of cycling commuters) and cycling recreational benefits by strategy in cumulative thousands of dollars per year, based on current housing patterns and planned location of the new multipurpose trail. Commuting time is assumed valued at the average wage, while the use value of cycling time is assumed to be ten dollars per hour. Low, nominal, and high estimates are provided for recreational cycling benefits based on varying levels of new induced demand resulting from proximity to the new trail.

As seen in the table, benefits are nondeclining as the scale of GSI increases (i.e., as the increment increases). This is as expected, as trail length generally increases with scale, at least up to strategy increment 7 (after which the length of the multipurpose trail is fixed). Mobility benefits range from $38,000 per year for the smallest solution (Channel 1/2) to $1.8 million per year for the Kelly, Lincoln, and East Hills strategies. Nominal-level recreational cycling benefits are of similar magnitude despite the larger number of participants, ranging from $24,000 per year for the Channel 1/2 strategy to $1.3 million per year for the three largest strategies. At the high end, cycling recreational benefits total just over $4 million per year.

In the absence of additional information, we assume a 1:1 ratio of noncycling to cycling use of the trail, with a slightly smaller value of $8.95 per use. Results are reported in Table 6.2 and are about 90 percent of the recreational cycling values reported in Table 6.1.
Benefits from Tree Planting

As seen in Table 6.3, tree planting results in reduced air pollution, carbon sequestration, and reduced energy use (urban heat island) as a result of biological processes and canopy shade, especially with respect to “green streets.” Typically, these benefits are estimated based on a tree count, though in reality the benefits likely vary somewhat with species and tree age. For this study, each new net total tree is valued at $17.73 per year, with 76 percent of this value attributable to local air pollution benefits and an additional 17 percent to local energy use benefits due to shade. The remaining benefits associated with carbon sequestration are not entirely locally appropriable, as carbon sequestration is a global public good.
### Table 6.1
Cumulative Approximate Mobility and Recreation Benefits from Cycling by Strategy Increment ($ Thousands per Year)

<table>
<thead>
<tr>
<th>Increment</th>
<th>Strategy</th>
<th>Mobility Benefit (in $)</th>
<th>Low</th>
<th>Nominal</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Channel 1/2</td>
<td>38</td>
<td>14</td>
<td>24</td>
<td>78</td>
</tr>
<tr>
<td>2</td>
<td>Basins</td>
<td>320</td>
<td>125</td>
<td>213</td>
<td>682</td>
</tr>
<tr>
<td>3</td>
<td>Swale/RSC</td>
<td>991</td>
<td>405</td>
<td>692</td>
<td>2,212</td>
</tr>
<tr>
<td>4</td>
<td>Paulson</td>
<td>991</td>
<td>405</td>
<td>692</td>
<td>2,212</td>
</tr>
<tr>
<td>5</td>
<td>Frankstown</td>
<td>1,494</td>
<td>617</td>
<td>1,054</td>
<td>3,371</td>
</tr>
<tr>
<td>6</td>
<td>Kedron</td>
<td>1,612</td>
<td>673</td>
<td>1,149</td>
<td>3,674</td>
</tr>
<tr>
<td>7</td>
<td>Kelly</td>
<td>1,779</td>
<td>742</td>
<td>1,267</td>
<td>4,054</td>
</tr>
<tr>
<td>8</td>
<td>Lincoln</td>
<td>1,779</td>
<td>742</td>
<td>1,267</td>
<td>4,054</td>
</tr>
<tr>
<td>9</td>
<td>East Hills</td>
<td>1,779</td>
<td>742</td>
<td>1,267</td>
<td>4,054</td>
</tr>
</tbody>
</table>

**NOTE:** Value of time for mobility benefit is assumed to be average wage ($24.07/hour). Recreation benefit from new recreational cyclists only, valued at $10 per hour cycling, assuming a 40-minute trip and 20 minutes, preparation and clean-up. Results are identical for all strategy options by increment (e.g., strategy increment 5 refers to Strategies 5A and 5B).

### Table 6.2
Cumulative Approximate Recreation Benefits from Pedestrian Activities by Strategy Increment ($ Thousands per Year)

<table>
<thead>
<tr>
<th>Increment</th>
<th>Strategy</th>
<th>Noncycle Recreation (in $)</th>
<th>Low</th>
<th>Nominal</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Channel 1/2</td>
<td>13</td>
<td>22</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Basins</td>
<td>112</td>
<td>191</td>
<td>610</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Swale/RSC</td>
<td>363</td>
<td>619</td>
<td>1,980</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Paulson</td>
<td>363</td>
<td>619</td>
<td>1,980</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Frankstown</td>
<td>552</td>
<td>943</td>
<td>3,017</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Kedron</td>
<td>602</td>
<td>1,028</td>
<td>3,288</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Kelly</td>
<td>664</td>
<td>1,134</td>
<td>3,628</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Lincoln</td>
<td>664</td>
<td>1,134</td>
<td>3,628</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>East Hills</td>
<td>664</td>
<td>1,134</td>
<td>3,628</td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** Assumes 1:1 ratio of new pedestrian to new cyclist. Daily use benefit assumed to be $8.95 per use. Results are identical for all strategy options by increment (e.g., strategy increment 5 refers to Strategies 5A and 5B).

The table shows that benefits from trees are generally smaller than those associated with recreational benefits but are generally increasing in the scale of the GSI strategy. Note that the Basins and Swale/RSC strategies are associated with an identical number of new net trees, and hence the benefits are identical. The range of values is $1,100 per year for the 60 new net trees associated with the Channel 1/2 strategy to nearly $72,000 per year for the larger East Hills strategy, which is assumed to add just over 4,000 net new trees.
Amenity Values

The final major category of cobenefits are the amenity benefits associated with the improved aesthetic and related benefits of GSI greening. To estimate these benefits, we rely on the theory that these benefits are capitalized into the value of homes in proximity of the new green space, suggesting that amenity benefits are driven by the property count around an appropriate buffer (in this case, approximately a quarter of a mile). While research suggests benefits in the single-digit percentage range (see Appendix F) with a “rule of thumb” of about a 5-percent increase in home values near vegetated open space, we opt to present a range of 1‒2.5 percent of the mean-valued home ($134,000) to account for potential double counting of recreational or other estimated benefits not necessarily related to amenity values.

Results are reported in Table 6.4, with the capitalized values converted to annual values using an infinite time horizon and 3-percent discount rate. Benefits range from zero for the smallest scale GSI strategy to $222,000 per year for the Kedron, Kelly, Lincoln, and East Hills increments. Readers are reminded that amenity or other nonuse benefits for households outside the buffer region (i.e., residents in other parts of the city) are not included in these estimates, thus resulting in a conservative figure.

Finally, we conclude this section by providing a summary of the range of all cobenefits listed above, including low, nominal, and high estimates for the discussion that follows. Table 6.5 shows the sum across cumulative approximate annual cobenefits listed above.

---

3 At the scale of the Kedron strategy, the buffer includes all properties in the database used to calculate such benefits. As such, the value of Strategies 6X–9X may be biased toward zero due to a lack of inclusion of possibly affected properties not included in the database but located within the buffer.
Table 6.4
Cumulative Approximate Amenity Benefits by Strategy Increment ($ Thousands per Year)

<table>
<thead>
<tr>
<th>Increment</th>
<th>Strategy</th>
<th>Property Count</th>
<th>1 percent Annual Benefit (in $)</th>
<th>2.5 percent Annual Benefit (in $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Channel 1/2</td>
<td>0</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>Basins</td>
<td>170</td>
<td>6.8</td>
<td>17.1</td>
</tr>
<tr>
<td>3</td>
<td>Swale/RSC</td>
<td>1,006</td>
<td>40.5</td>
<td>101.2</td>
</tr>
<tr>
<td>4</td>
<td>Paulson</td>
<td>1,692</td>
<td>68.1</td>
<td>170.1</td>
</tr>
<tr>
<td>5</td>
<td>Frankstown</td>
<td>2,004</td>
<td>80.6</td>
<td>201.5</td>
</tr>
<tr>
<td>6</td>
<td>Kedron</td>
<td>2,206</td>
<td>88.7</td>
<td>221.8</td>
</tr>
<tr>
<td>7</td>
<td>Kelly</td>
<td>2,206</td>
<td>88.7</td>
<td>221.8</td>
</tr>
<tr>
<td>8</td>
<td>Lincoln</td>
<td>2,206</td>
<td>88.7</td>
<td>221.8</td>
</tr>
<tr>
<td>9</td>
<td>East Hills</td>
<td>2,206</td>
<td>88.7</td>
<td>221.8</td>
</tr>
</tbody>
</table>

NOTE: Assumes properties affected are in a quarter-mile buffer around trail associated with scenario. The 1 percent and 2.5 percent capitalized values are converted to annual values using a 3 percent discount rate. Average home value is assumed to be $134,071. Results are identical for all strategy options by increment (e.g., strategy increment 5 refers to Strategies 5A and 5B).

Table 6.5
Cumulative Cobenefits by Strategy Increment ($ Thousands per Year)

<table>
<thead>
<tr>
<th>Increment</th>
<th>Strategy</th>
<th>Low</th>
<th>Nominal</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Channel 1/2</td>
<td>66</td>
<td>86</td>
<td>187</td>
</tr>
<tr>
<td>2</td>
<td>Basins</td>
<td>565</td>
<td>732</td>
<td>1,630</td>
</tr>
<tr>
<td>3</td>
<td>Swale/RSC</td>
<td>1,800</td>
<td>2,344</td>
<td>5,286</td>
</tr>
<tr>
<td>4</td>
<td>Paulson</td>
<td>1,829</td>
<td>2,372</td>
<td>5,356</td>
</tr>
<tr>
<td>5</td>
<td>Frankstown</td>
<td>2,762</td>
<td>3,590</td>
<td>8,102</td>
</tr>
<tr>
<td>6</td>
<td>Kedron</td>
<td>3,002</td>
<td>3,905</td>
<td>8,823</td>
</tr>
<tr>
<td>7</td>
<td>Kelly</td>
<td>3,316</td>
<td>4,311</td>
<td>9,724</td>
</tr>
<tr>
<td>8</td>
<td>Lincoln</td>
<td>3,330</td>
<td>4,326</td>
<td>9,738</td>
</tr>
<tr>
<td>9</td>
<td>East Hills</td>
<td>3,346</td>
<td>4,341</td>
<td>9,754</td>
</tr>
</tbody>
</table>

NOTE: The lower estimate of amenity benefits is used for the nominal assumption in this table and for the benefit-cost comparisons in the next section. Results for the Central Daylighting strategy (increment 4), Midrange (increment 7), and Max Build-Out (increment 9) strategies are highlighted in bold. Summed values may not match prior tabular results due to rounding.

Comparing Benefits and Costs with Deep Uncertainty

The final portion of this analysis compares stormwater and water-quality benefits, other cobenefits, and strategy life-cycle costs to estimate cost-effectiveness and overall net economic benefits under uncertainty. We return to the XLRM framework to summarize the key components of this analysis (Table 6.6), building on the strategy descriptions and analysis described in previous chapters.
Uncertain Factors and Experimental Design

Annual Rainfall Uncertainty

Because the hydrologic results presented in the preceding chapter did not reveal any economic benefit from flood-risk reduction, this portion of the investigation focuses on the annual time series modeling of CSO reduction only. This chapter uses the same simulated rainfall years and scenarios as in Chapter Five to represent CSOs. However, to generalize the uncertainty analysis, we noted that the simulated CSO outcomes described in Chapter Five show a highly linear correlation with annual rainfall volume, which in turn allows for interpolation. Figure 6.2, for example, shows the estimated annual A-42 CSO volumes (y-axis) for the subset of years included in the with-strategy analysis plotted against annual rainfall depth (x-axis) for Strategy 0 (FWOA) and the Central Daylighting strategy (Strategy 4). The results show a close correlation between CSO volume and annual rainfall for each strategy. As a result, for the uncertain strategy comparisons, we used simple linear regression to fit annual overflow volume as a function of annual rainfall volume and interpolated additional plausible CSO outcomes across a range of assumptions about long-term average annual rainfall volume (35 to 45 inches). Each strategy was modeled separately, and this regression approach was updated accordingly, so the interpolation is a function of rainfall volume only.

Table 6.6
Summary of Negley Run Strategy Economic Comparisons with Uncertainty

<table>
<thead>
<tr>
<th>Uncertain Factors (X)</th>
<th>Policy Levers and Strategies (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual rainfall</td>
<td>USACE CDAR increment</td>
</tr>
<tr>
<td>• 2003TY</td>
<td>Channel 1/2</td>
</tr>
<tr>
<td>• 2003–2017 rainfall</td>
<td>Highland and Wetland Basin</td>
</tr>
<tr>
<td>• Future average annual rainfall (35–45 inches/year)</td>
<td>Swale/RSC</td>
</tr>
<tr>
<td>• Paulson Avenue</td>
<td></td>
</tr>
<tr>
<td>GSI benefits</td>
<td>SLRB</td>
</tr>
<tr>
<td>• Water-quality benefits</td>
<td>SLRB: 12 acre-feet</td>
</tr>
<tr>
<td>• Recreation benefits (cycling)</td>
<td>SLRBX: 16 acre-feet</td>
</tr>
<tr>
<td>• Recreation benefits (pedestrian)</td>
<td>Local GSI increment: Homewood and East Hills</td>
</tr>
<tr>
<td>• Amenity benefits</td>
<td></td>
</tr>
<tr>
<td>Strategy costs</td>
<td></td>
</tr>
<tr>
<td>• USACE CDAR capital cost</td>
<td>Frankstown Avenue</td>
</tr>
<tr>
<td>• SLRB capital cost</td>
<td>Kedron Street</td>
</tr>
<tr>
<td>• Silver Lake compensartion cost</td>
<td>Kelly Street</td>
</tr>
<tr>
<td>• Local GSI capital cost</td>
<td>Lincoln Avenue</td>
</tr>
<tr>
<td>• Annual O&amp;M cost</td>
<td>East Hills extension</td>
</tr>
<tr>
<td>Local GSI impervious area managed</td>
<td></td>
</tr>
<tr>
<td>• 25 percent</td>
<td></td>
</tr>
<tr>
<td>• 50 percent</td>
<td></td>
</tr>
</tbody>
</table>

Model Relationships (R) | Performance Metrics (M) Associated with Goals
--- | ---
UA-NR SWMM model | CSO reduction capital cost-effectiveness ($/gal.)
Climate rainfall downscaling | Discounted economic benefit (2019$)
Ecosystem services cobenefit estimation | Discounted life-cycle strategy cost (2019$)
Cost estimation | Net present value (NPV) (2019$)

Scope of Comparative Analysis

Uncertain Factors and Experimental Design

Annual Rainfall Uncertainty

Because the hydrologic results presented in the preceding chapter did not reveal any economic benefit from flood-risk reduction, this portion of the investigation focuses on the annual time series modeling of CSO reduction only. This chapter uses the same simulated rainfall years and scenarios as in Chapter Five to represent CSOs. However, to generalize the uncertainty analysis, we noted that the simulated CSO outcomes described in Chapter Five show a highly linear correlation with annual rainfall volume, which in turn allows for interpolation. Figure 6.2, for example, shows the estimated annual A-42 CSO volumes (y-axis) for the subset of years included in the with-strategy analysis plotted against annual rainfall depth (x-axis) for Strategy 0 (FWOA) and the Central Daylighting strategy (Strategy 4). The results show a close correlation between CSO volume and annual rainfall for each strategy. As a result, for the uncertain strategy comparisons, we used simple linear regression to fit annual overflow volume as a function of annual rainfall volume and interpolated additional plausible CSO outcomes across a range of assumptions about long-term average annual rainfall volume (35 to 45 inches). Each strategy was modeled separately, and this regression approach was updated accordingly, so the interpolation is a function of rainfall volume only.
Green Stormwater Infrastructure Strategy Benefits

This analysis compares CSO reduction benefits with costs in two ways. First, to compare our results with recent legally mandated water-quality plans developed by ALCOSAN and PWSA to achieve Clean Water Act compliance, we directly compare the volume of CSO reduction to capital costs to estimate cost-effectiveness in terms of cost per gallon of overflow reduced ($/gal.). In addition, in order to estimate the potential benefits from CSO reduction in dollar terms, we instead use the cost-effectiveness estimated from ALCOSAN’s final and approved Clean Water Plan for regionwide CSO mitigation as a proxy for water-quality benefits in Negley Run (cost-avoidance approach; see Chapter Two).

To implement this approach, we used the average cost-effectiveness ($/gal.) from the updated ALCOSAN Clean Water Plan. The full CWP is estimated at $0.38/gal. (2019 dollars) (ALCOSAN, 2019b), while the IWWP to be implemented first is estimated at $0.34/gal. (ALCOSAN, 2019f).\(^4\) This latter value also matches the high end of the cost-effectiveness

\(^4\) Values from the CWP are dominated by the capital cost of additional water treatment, storage and conveyance infrastructure, and other gray infrastructure investments targeted solely at sewer-overflow reduction and water-quality improvement. These investments are assumed to provide no additional cobenefits so that values reflect the potential benefit from water-quality improvement without double counting.
estimated in PWSAs Green First Plan (updated to 2019 dollars) (Pittsburgh Water and Sewer Authority, 2016, Table ES-5). As a result, we estimated the economic benefit from the Negley Run strategies as a one-time water-quality benefit of $0.34/gal–$0.38/gal. multiplied by the estimated gallons of overflow reduction from each strategy or strategy increment.

For the other cobenefits, we considered the entire range of uncertainty from recreation and amenity values presented earlier in this chapter.

**Strategy Costs**
We also considered strategy performance across the full range of cost uncertainty described in Chapter Four and Appendix E. This includes uncertainty associated with the USACE CDAR system, SLRB capital cost, SLRB land compensation cost, local GSI capital cost, and long-term average O&M cost for the GSI system. See Chapter Four, Table 4.3 for a summary of the range of life-cycle project costs considered in this analysis.

**Final Scenario Ensemble**
Bringing all of these uncertain factors together, we used Latin Hypercube Sampling (LHS)⁵ to generate an efficient sample across ten uncertain factors, as listed in Table 6.6. We used a sample of 1,000 points, added 2 more to represent all inputs set to their lowest and highest values, and finally included 2 “nominal” sample points that use default assumptions for benefit and cost uncertainties and include the exact modeled CSO volumes using either the 2003TY or 2013 rainfall.⁶ This led to a total of 1,004 uncertain futures that we use to compare strategies through the remainder of this report.

**Economic Performance Metrics**
For each strategy and in each scenario, we estimated two key outcomes:

- **CSO reduction cost-effectiveness**: a comparison of the estimated overflow reduction from each strategy to the undiscounted capital cost, represented as $/gal.
- **NPV**: the discounted sum of monetized benefits minus discounted life-cycle costs for each strategy.

**Strategy Comparison Results**

**Combined Sewer-Overflow Reduction Cost-Effectiveness**
We first compare results in terms of the cost-effectiveness of these investments toward the legally mandated overflow reduction goals. Figure 6.3 summarizes the cost-effectiveness of each strategy estimated using the uncertainty approach outlined above. The range of outcomes across 1,004 uncertain futures is represented using box plots, with orange or blue points highlighted to show the nominal cost assumptions with modeled 2003TY or 2013 rainfall year results, respectively.

These uncertain comparisons show that investing in the USACE CDAR strategy increments (Strategies 1 through 4) could be highly cost-effective for CSO compliance across a wide range of assumptions. With the exception of the 2003TY result for Strategy 1 (noted in

---

⁵ LHS is a statistical sampling method that helps to ensure that the entire distribution of each parameter is sampled consistently; it is often used to develop efficient samples for DMDU modeling research. We developed this sample using the LHS package in the R statistical software, applying the Columnwise Pair algorithm to help develop an optimal design (The Comprehensive R Archive Network, undated).

⁶ For the Recent Historical rainfall scenario, 2013 rainfall serves as a proxy.
Chapter Five), the scenario range for these strategies falls well below the ALCOSAN reference values. The optimistic end of the range is as low as $0.03/gal., while the highest values from Strategies 2 through 4 (corresponding to lower average annual rainfall and high CDAR capital costs) are still at or below $0.15/gal. This provides notable evidence to support PWSA proceeding with additional design increments for the lower portion of the watershed as part of a CSO compliance strategy, as these investments appear to compete very favorably with other proposed CSO interventions based on this modeling effort.

The cost-effectiveness performance of strategy increments 5 through 9, which all include a SLRB and various geographies of local GSI treatment area options, is generally less favorable than that of Strategies 1 through 4 and also shows more variation across the ensemble of scenarios. However, these strategies still appear to be cost competitive with other investments to reduce CSOs under a broad range of future assumptions. A large fraction of futures from the remaining strategies shows cost-effectiveness comparable or better than the ALCOSAN IWWP or CWP projects, but the question remains as to whether the additional benefits introduced by these investments can outweigh the less efficient performance using this metric. We
will return to this question, as well as a further investigation of key drivers of cost-effectiveness performance, after summarizing net economic benefits with NPV.

**Net Economic Benefit**

Net economic benefit from the strategies evaluated in this analysis depends on four key inputs discounted according to the implementation schedule described in Chapter Four over a planning period of 40 years: capital costs, O&M costs, overflow benefits (avoided costs), and cobenefits. Figure 6.4 shows how these four inputs stack up under one set of assumptions: 2003TY rainfall and nominal (midrange) benefit and cost uncertainty assumptions for each strategy. Positive bars indicate benefits, negative bars indicate costs, and NPV can be calculated by summing across both (right column). For example, in the 2003TY scenario, net present cost for the Central Daylighting strategy (Strategy 4) is estimated at $28 million ($14 million + $14 million), while net present benefit would be $68 million ($30 million + $38 million). This translates to an NPV estimate of $40 million, or a benefit-cost ratio of approximately 2.4.

---

For these comparisons, we applied a discount rate of 4 percent, which is close to the interest rate of 3.93 percent reported by PWSA as an average across its outstanding debt as of 2019 (Pittsburgh Water and Sewer Authority, undated-b). We also explored results from the 2020 federal discount rate of 2.75 percent (Bureau of Reclamation, 2019), as well as a 6-percent rate as applied in prior ALCOSAN and PWSA life-cycle cost analysis (ALCOSAN, 2019b; Pittsburgh Water and Sewer Authority, 2016) but elected to report the midrange estimate given the positive net benefits observed across all rate assumptions.
With the 2003TY and other nominal assumptions, the results show that discounted benefit always exceeds discounted cost, and NPV is positive for all but Strategy 1. In addition, even if cobenefits alone are compared against life-cycle costs, Strategies 3, 4, 5A, and 5B, as well as 6A, nevertheless show positive net benefits under these assumptions. Readers are reminded that the cobenefits calculations are likely conservative and biased downward as well.

Figure 6.5 shows the same comparison and assumptions but using 2013 rainfall instead as a proxy for Recent Historical rainfall (see Figure 6.2).

Figure 6.6 expands on this comparison to show NPV results for the full range of uncertainty using box plot summaries. Once again, orange and blue points highlight nominal assumptions for reference, corresponding to the results shown in Figure 6.4 and Figure 6.5 above. This figure shows that NPV over a 40-year planning period is strongly positive across nearly all scenario assumptions, with only a handful of strategies yielding net negative outcomes in selected conditions. Notably, no combination of assumptions leads to negative NPV for Strategies 2, 3, 4, 5A and 5B, 6A and 6B, 7A–7C, and 8A, and the net benefit ranges from $20 million to over $100 million for many plausible futures. Figure 6.6 also shows that the nominal assumptions introduced earlier are generally more pessimistic in terms of NPV but nevertheless nearly always yield positive net benefit when accounting for all inputs.

Additionally, discounted net benefits are positive across a wide range of scenario conditions even if we exclude avoided costs associated with CSO overflows and “count” cobenefits only. This is especially notable because the cobenefits estimated here do not include any flood-risk reduction due to limitations with the analysis approach and could be undervalued. If these

Figure 6.5
Discounted Benefits and Costs by Strategy, 2013 Rainfall and Nominal Assumptions

<table>
<thead>
<tr>
<th>ID and strategy name</th>
<th>Costs ($)</th>
<th>Benefits ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Channel 1/2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Basins</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Swale/RSC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Paulson</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5A Frankstown-SLRB-25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5B Frankstown-SLRB-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6A Kedron-SLRB-25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6B Kedron-SLRB-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7A Kelly-SLRB-25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7B Kelly-SLRB-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7C Kelly-SLRB-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8A Lincoln-SLRB-25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8B Lincoln-SLRB-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8C Lincoln-SLRB-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9A EastHills-SLRB-25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9B EastHills-SLRB-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9C EastHills-SLRB-50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
strategies were also to provide economic flood-risk reduction or other benefits, as expected, this would further increase the NPV estimates presented here.

**Strategy Regret and Trade-Offs**

Because the NPV results are largely positive across all strategies, another way to consider the difference between strategies is by converting NPV estimates to NPV “regret” (Lempert, Popper, and Bankes, 2003; Savage, 1954). This metric seeks to evaluate strategy performance in each uncertain future, identifying the highest performing strategy for each possible set of assumptions and then measuring how far from that “ideal” outcome a given strategy might perform. A low-regret strategy, using this approach, is one that performs close to the best possible outcome across many or most scenarios.

Figure 6.7 shows a comparison of the NPV from each Negley Run strategy considered, rescaled using this regret-based approach. This reframing helps to distinguish between strategy performance across the scenario ensemble. NPV regret starts relatively high at Strategy 1,

---

8 More specifically, in each uncertain scenario, the best performing strategy among those compared is assigned a regret value of zero, and regret for each remaining strategy is measured as the distance between its performance and the performance of the best possible strategy in that scenario. This is then recalculated for each of the 1,004 uncertain scenarios in the analysis. Strategies that yield low regret across the full range of scenarios can be considered more robust to the uncertainties considered.
Managing Heavy Rainfall with Green Infrastructure

declines with additional increments of investment up to Strategies 6A, 6B, or 7A, and then begins to increase again with the Lincoln Avenue or East Hills extension increments.

This figure, combined with the cost-effectiveness results in Figure 6.3, helps to illustrate the trade-offs between strategies and a potential path forward for PWSA and other NRWTF planners and stakeholders. If planners were focused on cost-effective sewer-overflow reduction alone, the Central Daylighting strategy (Strategy 4) appears to be a robust and low-regret approach across a wide range of cost and rainfall assumptions. When taking into account a broader range of cobenefits for local residents in Homewood and surrounding neighborhoods, however, strategies that include an SLRB and several increments of local GSI appear to outperform the CIDAR design alone. Specifically, a Midrange strategy (Strategy 6A or 7A) appears to do the best job of minimizing NPV regret across the range of uncertain futures considered. In other words, the cobenefits analysis would tend to push toward higher levels of investment in GSI up to these strategies, and they represent potentially robust options when taking into account multiple cobenefits and a broad range of uncertainty.

Scenario Discovery for Poor Cost-Effectiveness Performance

The question remains, however, as to how NRWTF stakeholders might make the decision to push for an SLRB and significant further investments in local GSI in Homewood. Per Figure 6.3, there might be concern that these additional increments would yield comparatively
poor CSO cost-effectiveness, even if their overall net economic benefits remain positive. As a next step, we chose the Max Build-Out strategy (Strategy 9C) and used “scenario discovery” methods to help identify a subset of uncertain drivers that often or always lead to poor or unacceptable cost-effectiveness performance for this strategy (Bryant and Lempert, 2010; Lempert and Groves, 2010). Much of this analysis was conducted with interactive visualization, but we were also guided by the extension of these methods described in Dalal et al., 2013.

Paring down from the ten original dimensions of uncertainty included in this analysis, interactive scenario discovery revealed that two key drivers—average annual rainfall and average cost of local GSI per impervious acre—were most often associated with cost-effectiveness performance higher than the $0.34/gal. ALCOSAN IWWP reference point. Figure 6.8 shows

Figure 6.8
Summary of Cost-Effectiveness Scenario Discovery Analysis, Strategy 9C

![Graph showing the relationship between average annual rainfall and GSI cost per impervious acre treated.](image)

NOTE: Each point represents one mapping of assumptions to consequence, and points are not assumed to be equally likely. Some points may overlap. The vulnerable region identified is shaded gray and corresponds to the following linear relationship (in thousands): GSI-cost-per-acre = 29.75 × average rainfall + 785. The gray shaded region captures 81 percent of the futures with cost-effectiveness higher than $0.34/gal. (coverage), while 81 percent of futures with these characteristics yield above-threshold cost-effectiveness (density).
a summary the scenario discovery results for the Max Build-Out strategy (Strategy 9C). Each point on the plot indicates one of the 1,004 uncertain futures in the scenario ensemble. Points shaded in purple highlight futures of concern, where cost-effectiveness is higher than $0.34/gal., while gray points yield acceptable cost-effectiveness below this threshold. Gray shading indicates the region identified as vulnerable, while points falling into this region are shown as filled.

This analysis shows that a combination of annual rainfall and GSI cost per acre can best help to identify cases with poor cost-effectiveness performance. If average annual rainfall is closer to the 2003TY estimate (36.8 inches for the UA-NR modeled region; see Table 3.2), for example, a GSI cost per impervious acre above approximately $300,000 could lead to above-threshold cost-effectiveness. Alternately, if average annual rainfall in the near future more closely resembles the 2003–2017 Recent Historical (41 inches) or Higher Total Rainfall (43 inches) estimates, the Max Build-Out strategy does not lead to higher than expected cost-effectiveness irrespective of GSI costs.

Interestingly, this analysis identifies several of the same key uncertain drivers as Fischbach et al., 2017, which focused on the entire ALCOSAN regional system. We arrive at a similar conclusion here, which is that the proposed GSI strategies are increasingly cost-effective in higher rainfall futures, and concern about high GSI implementation costs might decline as future rainfall increases.

Toward an Adaptive Planning Approach
The strategy comparisons above suggest a path forward for PWSA, USACE, ALCOSAN, other local agencies, and the NRWTF to incorporate adaptivity into Negley Run GSI planning. Specifically, these results provide support to move forward with design and engineering for the Central Daylighting strategy (Strategy 4) as a low-regret option for near-term CSO reduction, building on existing work. In parallel, over the next five years, the utilities, agencies, and local NRWTF partners could take the following steps to help prepare for possible additional investment in an SLRB and further connections to the upper watershed:

- Progress forward with site-specific and microshed GSI plans, with the goal of bringing enough pilot sites online to gain a more accurate understanding of real-world GSI construction costs for sites in Negley Run. These could also be better optimized for localized flood control using 2D simulation, as discussed in Chapter Five, and designed so that they could eventually drain toward the SLRB if constructed.
- Monitor the “signpost” of average annual rainfall, and regularly reassess these values and expectations based on new climate projections that might emerge.
- Further explore the feasibility of an SLRB and its associated connection to the CDAR system, with a focus on the private property considerations and other potential constraints.

This approach would push forward the decision as to whether to proceed beyond the Central Daylighting strategy and would help to provide near-term benefits to residents from the local GSI projects whether or not they ultimately connect into the central daylighted system. If the results from these assessments suggest favorable conditions to proceed (i.e., lower GSI costs, increasing average rainfall, addressable constraints), relevant agencies and partners could decide to move forward at that stage. If not, the partnering organizations could proceed
forward with Strategy 4 as is and instead focus on local infiltration-based GSI for further investment.

Discussion and Limitations

The analysis above suggests that the GSI strategies considered here are generally associated with at least competitive (and, at most, desirable) economic outcomes over a fairly wide range of future environmental conditions (rainfall) and economic estimates (estimates of the benefits and costs of the strategies), especially when major categories of cobenefits are included in the analysis. Cost-effectiveness (in terms of $/gal.) for the strategies, which focuses only on CSO outcomes and essentially ignores cobenefits, is generally lower than the ALCOSAN IWWP and CWP benchmarks for the 2013 rainfall pattern with nominal economic assumptions (see Figure 6.2), and the same economic assumptions result in positive NPVs (which include cobenefits) for all but one strategy using 2003TY and 2013 rainfall scenarios.9

That said, the degree of desirability from either a pure economic (NPV) or regret standpoint depends in large part on which individual future is ultimately realized. For example, while cost-effectiveness is favorable for all strategies under the 2013 rainfall scenario relative to the benchmarks, this is not the case for the larger-scale GSI scenarios using 2003TY rainfall levels (again assuming nominal economic assumptions). Furthermore, the uncertainty analysis over both environmental and economic parameters shows that deviations from nominal assumptions or changes in environmental conditions (or both) can lead to relative cost ineffectiveness when focused on CSO outcomes. The addition of cobenefits associated with the GSI strategies, however, mitigates this risk substantially, but not completely, in that estimated NPV is positive for most of the strategies over most of the set of futures (see Figure 6.4). In general, a drier future or underestimate of the costs of GSI implementation tend to favor lower increments of investment, and regret tends to be smallest (and robustness largest) for the moderate-scale strategies 5A and 5B (Frankstown), 6A and 6B (Kedron), and 7A (Kelly-SLRB-25).

While this analysis has attempted to take into account major sources of uncertainty and is conservative in the assumptions made about the overall level of (co)benefits from GSI outcomes, there are still several limitations to the analysis. First, calculations of cost-effectiveness and NPV generally do not incorporate considerations of risk preferences into the quantitative analysis. That is to say, when faced with uncertain futures, a risk-averse decisionmaker may prefer a solution with a lower variance in outcomes and a lower mean of that (good) outcome to a riskier solution with a higher mean but higher variance. Functionally, in the context of Negley Run, if the GSI strategies are associated with more uncertainty than a more traditional gray infrastructure solution, the cost-effectiveness and NPV analysis above could overstate the true (risk-adjusted) desirability of the strategies.

Second, while the uncertainty analysis incorporated variation in the key economic parameters related to the overall level of annualized benefits as well as environmental conditions, the specific timing of costs and benefits, as well as the discount rate, were not included as part of the experimental design.10 This is an important consideration for long-lived infrastructure

9 The exception is the Channel 1/2 scenario for 2003 TY (see Figure 6.4).

10 Note, however, that variation in the overall discounted capital and O&M costs as reported in Chapter Four do capture some of this variance.
projects in which costs are generally front-loaded and benefits accrue generally later in the time horizon. Cost and schedule overruns in construction of any of the GSI solutions would tend to increase the present value construction costs and decrease the present value of benefits over a fixed time horizon. An increase in the discount rate would similarly tend to inflate present value costs and decrease present value benefits, all else equal.

Finally, as with all modeling exercises, there are explicit and implicit assumptions that can affect the overall quantitative estimates of cost-effectiveness, NPV, and regret. In addition to the aforementioned timing and discount rate considerations, we note the following:

- In general, the cobenefits categories included in the analysis are likely only a subset of the probable real-world benefits; that is, it is likely that cobenefits are underestimated. In particular, the modeling showed little change in the estimates of basement flood damage, but this may be due more to modeling limitations than real-world effects. Similarly, while there is some evidence of reduced flooding along Washington Boulevard, it was not sufficient to monetize any benefit as the effect on road closures would be minimized. Finally, certain other provisioning, regulating, and cultural ecosystem service categories, as well as more social aspects such as “community cohesion,” may be affected by the GSI strategies but were not monetized due to a lack of data. Combined, this suggests that the benefits of GSI strategies are understated.
- While the uncertainty analysis is intended to provide information on strategy outcomes over a wide range of likely economic and environmental conditions, there is no guarantee that all potential outcomes are included in the analysis. In particular, “tail” (or extremely unlikely) outcomes may be excluded, and if these are associated with relatively disproportionate negative outcomes coupled with risk aversion, the analysis may overstate the potential benefits of GSI strategies.
- Opportunity costs associated with construction activities or negative outcomes associated with GSI strategies (e.g., an increase in pest populations or poor design resulting in disamenities to residents) were not included in the analysis. To the extent that these types of outcomes would be associated with adoption of a strategy, the costs of said strategy would be understated.
- Distributional aspects of the benefits and costs over the affected population were not addressed in the analysis. To the extent that benefits and costs are appropriated by different subpopulations, the conclusions inferred from aggregate outcomes may not be reflective of every subpopulation of interest.
- All results are conditional on the parameterization of the SWMM model detailed in Chapter Two and Appendix B, the storm/rainfall scenarios detailed in Chapters Two and Three and Appendix C, the strategy assumptions made in Chapter Four and Appendix E, and the benefit transfer methodology chosen and parameterized as documented in Chapter Two and Appendix F.

**Chapter Summary**

The benefit-cost analysis presented in this chapter suggests that the GSI strategies developed for the Negley Run watershed are generally economically viable but not universally so over the range of economic and environmental futures considered. In particular, the overall desirability
of the solutions—from a CSO-decreasing cost-effectiveness perspective, an NPV perspective, or a robustness perspective—depends critically on the inclusion of cobenefits associated with green infrastructure, the costs associated with GSI construction per acre, and the overall level of rainfall.

The cost-effectiveness analysis compared the GSI strategies to benchmark CSO costs per gallon based on ALCOSAN IWWP and CWP reference points. This analysis eliminated the consideration of additional cobenefits with GSI solutions. Depending on the realized future, there is good evidence that the smaller-scale strategies (especially Strategies 2 through 4) are more cost-effective than the benchmarks but mixed evidence that larger-scale efforts are competitive according to this metric (see Figure 6.2). Indeed, when using 2003TY rainfall data and nominal economic assumptions, most of the GSI strategies are associated with a negative NPV when only the water-quality benefits are considered (see Figure 6.3, water-quality benefits only).

The incorporation of cobenefits, however, generally tends to reverse this conclusion (see Figure 6.4 and Figure 6.5). For 2003TY and 2013 rainfall patterns, coupled with nominal economic assumptions, only Strategy 1 (Channels 1/2) for 2003TY rainfall fails to have a benefit-cost ratio less than 1, while the moderate to larger-scale strategies tend to have positive NPVs in the $20‒$60 million range. This result is fairly robust to uncertainty over environmental and economic futures, with only the larger-scale strategies (beginning with Strategy 8B and 8C, Lincoln and SLRB or SLRBX-50) admitting a relatively small subset of futures for which NPV is negative. Coupled with the fact that the cobenefits are likely undervalued in the analysis, these results suggest that the additional services provided by GSI strategies are likely not only economically desirable for an assumed deterministic future but are so over a wide range of strategy and environmental assumptions.

Finally, in terms of risk, the moderate-sized GSI strategies considered here tended to be associated with lower levels of regret (i.e., deviations from the optional strategy if the future were known; see Figure 6.5). As such, if decisionmakers were relatively risk-averse with respect to the costs of GSI strategies as well as system performance over environmental uncertainty, a preferred implementation strategy may be to implement a moderate-sized solution, evaluate that solution and update key assumptions regarding benefits and cost, and then make decisions as to possible expansion. The results presented in this chapter suggest that such an adaptive strategy would most likely easily pass a benefit-cost test before implementation while minimizing the possible downside risks.
Overview

In the final chapter of this report, we provide a summary of key findings from the modeling investigation and strategy comparison. We first discuss findings related to sewer-overflow reduction, then turn to flooding, and finally present our comparison of strategies. Based on these findings, we then suggest recommended next steps for stormwater planning in Negley Run for planning agencies and stakeholder partners in NRWTF. The recommendations provided here are directed toward all task force members, but we expect them to be of particular interest to local, state, and federal government participants including PWSA, ALCOSAN, City of Pittsburgh Department of City Planning and Urban Redevelopment Authority, Pennsylvania Department of Transportation, and USACE.

To help illustrate the range of results across the 17 strategies evaluated, we again use the shorthand defined in Chapter Four to refer to 3 bracketing strategies through the remainder of this chapter. Strategy 4, which includes the centralized surface system as envisioned in the USACE CDAR design together with an extension up Paulson Avenue, is referred to as the Central Daylighting strategy. Strategy 7A, which includes a version of the SLRB and investment in GSI to control 25 percent of impervious cover through the Kelly Street increment, is the Midrange strategy, while Strategy 9C is the Max Build-Out strategy.

Key Findings

Sewer Overflows

CSO volumes from Negley Run are higher when using Recent Historical rainfall than in a TY and increase further in plausible future scenarios.

We estimate 865 MGY of CSO volume using the 2003TY adjusted rainfall year adopted for regional storm- and wastewater planning by ALCOSAN and PWSA and assuming no additional investments in the combined sewer system. This estimate is in line with but somewhat higher than prior past estimates. Our estimates are approximately 14 percent higher (986 MGY) when instead averaging model results from a 15-year sequence of Recent Historical rainfall (2003–2018). This increases further to 26 percent (1,089 MGY) in a Higher Total Rainfall future rainfall scenario. Using this modeling approach, we estimated over 2,177 MGY in 2018, the wettest year on record for the Pittsburgh region as of 2020. These results show that relying on TY rainfall alone will lead to underestimates of CSO under present-day or plausible future conditions.
A new separated connection to the Allegheny River and subsequent upstream investments could substantially reduce, but not eliminate, sewer overflows in Negley Run.

Assuming 2003TY rainfall, the Central Daylighting strategy reduces CSO volumes by 107 MGY (12 percent), while the Midrange strategy yields 168 MGY (19 percent) and Max Build-Out yields 223 MGY (26 percent) of overflow reduction per year. Using Recent Historical assumptions instead, both the volume and percent of overflow reduction from all strategies increase—for instance, the Midrange strategy CSO reduction under these assumptions is 330 MGY, or 33 percent of the total annual volume. In general, the strategies produce more CSO reduction in higher rainfall scenarios, reinforcing similar results noted in the pilot study.

Strategies that build on a separated surface collection system could yield highly cost-effective CSO reduction across a range of assumptions.

The Central Daylighting strategy is highly cost-effective for overflow reduction, with results ranging from $0.04/gal. to $0.14/gal. across a wide range of rainfall uncertainty and construction cost assumptions. Additional increments of investment up to and beyond the Midrange strategy ($0.13/gal. to $0.35/gal.) are generally less cost-effective using this metric and show more variation across the ensemble of scenarios. However, these strategies still appear to be cost competitive with other local and regional investments to reduce CSOs under a broad range of future assumptions.

Scenarios with higher average annual rainfall lead to greater cost-effectiveness from the strategies we evaluated.

This finding follows from the observation above that the strategies yield greater CSO reduction under higher annual rainfall assumptions. In general, we found that the mid- or high-investment strategies are less cost-effective only in futures with low average annual rainfall and relatively high local GSI installation costs.

Flooding

1D flood modeling provides some capacity to evaluate flooding from storms of different duration and frequency.

As a proof of concept, the 1D flood modeling approach used in this effort provided some value in considering potential risks from heavy rainfall in terms of street or basement flooding. The relatively low computational cost allowed us to simulate thousands of different events and compare across several key dimensions of rainfall uncertainty and provided the capacity to evaluate risk reduction along the key Washington Boulevard corridor. However, the 1D planning-level approach lacked sufficient resolution to tailor local GSI projects for flood risk reduction or identify potential flood benefits in the upper watershed.

Negley Run already faces notable flood risk from heavy rainfall events.

We found that street flooding is a common occurrence in Negley Run, with the model showing sufficient flooding to close Washington Boulevard even under a 2-year, 1-hour synthetic rainfall event. The results also suggest that flooding occurs regularly on streets and intersections in Homewood and surrounding neighborhoods. For the subset of Negley Run evaluated for basement flooding, we estimate that 11–18 percent of homes in the study area are at risk from either a wet basement, basement sewer backup, or both from a 2- to 1,000-year rainfall event based on Historical rainfall conditions.
Flood risk increases with heavier rainfall from plausible future climate change.
Our modeling shows that key streets and intersections would flood more frequently when considering a projected 2020–2099 Average Future scenario based on climate modeling. Similarly, the number of homes at risk from at least one type of basement flooding increases by 18–21 percent when comparing the Average Future scenario to Historical rainfall conditions.

Strategies for a separated surface collection system focused on lower Negley Run reduce flood depths on Washington Boulevard but do not eliminate flooding even in relatively higher-frequency, lower-intensity events.
The Central Daylighting strategy, focused on the direct capture area, yields flood volume and depth reduction along the Washington Boulevard corridor as intended, with generally increasing flood benefit from additional strategy increments. Midrange or Max Build-Out strategies, however, do not appear to provide additional flood benefits for Washington Boulevard. Moreover, none of the strategies tested eliminate flooding at the low point of Washington Boulevard in the storm events we tested, suggesting that additional design modification or policy levers will be necessary.

Our preliminary research did not identify additional street or basement flood-risk reduction benefits from local GSI investments in Homewood and surrounding neighborhoods, but more investigation is needed.
The initial strategies tested do not appreciably reduce the estimated frequency or extent of either street or basement flooding in modeled areas of Homewood, Belmar, or East Hills. However, we note that local GSI is represented in this analysis in a simplified, standardized way using the SWMM LID module in the UA-NR model and is not optimized for specific local site conditions. As a result, additional research will be needed to follow up on these results and determine whether specific project designs could provide localized risk reduction.

Green Stormwater Infrastructure Strategy Costs and Benefits
Life-cycle cost estimates for the strategies evaluated vary based on the level of investment as well as other uncertain factors.
We developed life-cycle cost estimates based on a 40-year planning horizon and assumed 15-year construction time to strategy build-out while also looking across a range of cost uncertainties. Cost estimates include construction, O&M, and property compensation costs, and construction costs were developed using a bottom-up approach. Life-cycle cost estimates range from $15–$40 million for the Central Daylighting strategy to $38–90 million for a Midrange approach. The Max Build-Out strategy is estimated to cost between $57 and $130 million.

GSI cobenefits from the strategies we evaluated could contribute substantial value to residents when accounting for uncertainty and using conservative assumptions.
Our analysis estimated a subset of GSI strategy cobenefits from recreation, bicycle commuting, pedestrian activity, tree cover, and overall amenity value. Using relatively conservative assumptions, we nevertheless identified notable benefits associated with the proposed GSI installations. The Central Daylighting strategy is estimated to provide $1.8–$5.4 million in cobenefits per year, while the Midrange and Max Build-Out strategies would yield $3.3–$9.7 per year. These benefits, even though likely undervalued in the analysis, are sufficient to offset GSI strategy costs in and of themselves under many plausible futures. The results suggest that
the additional services provided by GSI strategies are economically desirable over a wide range of strategy and environmental assumptions.

The net economic value of the strategies considered—taking into account life-cycle strategy costs, water-quality benefits, and cobenefits—is nearly always positive across a wide range of assumptions.

NPV estimates over a 40-year planning horizon are strongly positive across nearly all scenario assumptions. Taking into account both avoided infrastructure costs and cobenefits, NPV ranges from $40‒$144 million from the Central Daylighting strategy to $31‒$175 million from the Midrange strategy, with the Max Build-Out strategy yielding a somewhat lower range of $6‒$169 million.

A midranged strategy could provide positive economic benefit across a wide range of assumptions.

If local planners focus on cost-effective sewer overflow reduction alone, the Central Daylighting strategy appears to be a robust and low-regret approach across a wide range of cost and rainfall assumptions. When considering NPV and taking into account a broader range of cobenefits for local residents in Homewood and surrounding neighborhoods, however, strategies that include an SLRB and several increments of local GSI outperform the Central Daylighting strategy in the large majority of scenarios considered. Specifically, the Midrange strategy appears to do the best job of minimizing NPV regret across the range of uncertain futures considered.

The strategies considered for Negley Run support an adaptive planning approach.

The strategies we considered include several possible pathways for investment, with the opportunity to stop or change course in light of new information. As a result, they lend themselves to an adaptive approach where PWSA or other partners could continue to invest up to the Central Daylighting strategy while also monitoring pilot GSI performance and taking steps to help prepare for possible additional investment in an SLRB and further connections to the upper watershed. If the results from these assessments suggest favorable conditions to proceed, PWSA and its NRWTF partners could decide to invest in further strategy increments at that stage.

Recommendations

Negley Run Green Stormwater Infrastructure Design and Implementation

Invest in design and engineering efforts for the Central Daylighting strategy (Strategy 4) as a low-regret solution.

The results from the cost-effectiveness and economic benefits analysis show that the centralized daylighted system along Washington and Negley Run Boulevards envisioned in the USACE CDAR could achieve CSO reduction while providing cobenefits to residents and allowing for additional increments of investment at later stages. As a result, we recommend continuing to mature these designs and move toward engineering and construction.

Work together to expand the range of options to address street and basement flooding.

Our analysis suggests that the policy levers considered in this analysis may not be sufficient to eliminate regular flooding along Washington Boulevard or address localized flood issues in Negley Run neighborhoods. We therefore recommend that NRWTF work toward expanding
the range of options available to address flooding. For example, the Pennsylvania Department of Transportation, which owns and maintains Washington Boulevard as a state road, should consider roadway elevation for the low-elevation portion of the road that floods frequently, conducted in tandem with other improvements as outlined in CDAR and other visioning efforts. Combined with the Central Daylighting strategy, road elevation would likely help to resolve the persistent flooding noted in this analysis at this low point. In addition, NRWTF partners working on neighborhood GSI or microshed projects should consider how these projects could be designed and sited to best address local flooding issues.

**Continue to invest in distributed local GSI projects in Negley Run neighborhoods.**

The cobenefits analysis presented here shows that GSI could provide notable benefits for residents, even without taking into account potential flood-risk reduction. This suggests that continuing to invest in local GSI projects could be beneficial whether or not these projects would eventually connect in to a centralized daylighted system or provide extensive sewer-overflow reduction. Furthermore, these projects would allow NRWTF partners to learn more about local GSI construction and O&M costs, helping to inform future decisions about whether to expand local GSI investment.

**Employ an adaptive planning approach for SLRB or further increments of connected GSI.**

As discussed in Chapter Six, over the next five years, we recommend that NRWTF partner agencies adopt an adaptive approach, preparing for possible additional investment in an SLRB and further connections to the upper watershed while design and construction for the centralized daylighted system proceeds ahead. Key steps could include monitoring GSI construction costs, reassessing and updating TY rainfall values currently used for planning, and exploring the feasibility and constraints associated with a potential SLRB.

**Additional Data Collection and Research**

**Further refine the detailed simulation model developed for this study and integrate into regional system models to support additional sewer-overflow and flood-risk evaluation.**

A key step would be to integrate the UA-NR model back into the regional system to (1) better understand regional system interactions and (2) allow PWSA, ALCOSAN, and other partners to assess these Negley Run GSI strategies together with treatment plant expansion and other improvements identified in the CWP.

**Gather additional data to inform flood-risk assessment for Negley Run, including combined system descriptions and flow monitoring.**

This analysis was limited by the data available to inform model development and calibration. We recommend that PWSA and ALCOSAN develop a more complete inventory and mapping of storm inlets, inlet invert elevations, and associated pipes across the Negley Run watershed. In addition, new pipe flow-monitoring data gathered at a wider range of sample points would allow for improved calibration of the detailed model and greater confidence in simulated results compared with real-world conditions. It would also support more accurate, detailed, and complete flood-risk analysis.

**Explore the use of 2D modeling to support flood-risk assessment and site-specific GSI design.**

This initial assessment suggested notable limitations when relying on 1D analysis to evaluate GSI flood-risk reduction. An improved approach would leverage 2D or coupled 1D-2D (dual
drainage) modeling for key locations of interest, such as the Washington Boulevard corridor. In addition, coupled modeling building on this work could provide localized flood assessments at the neighborhood scale to inform GSI project siting and design.

**Consider adopting an integrated, watershed-based approach for other areas of focus across the region.**

This study serves as a proof of concept for how an integrated, quantitative, scenario-planning approach, building on DMDU techniques, can help to guide a range of stormwater policy, planning, and design efforts conducted by different entities for the same watershed of focus. We believe a similar approach could benefit planners in other local or regional watersheds facing a similar range of stormwater challenges and future uncertainties.
Bibliography


ALCOSAN—See Allegheny County Sanitary Authority.

Allegheny County/City of Pittsburgh/Western PA Regional Data Center, “PGH SNAP Census Data,” 2017. As of July 1, 2020: https://catalog.data.gov/dataset/pgh-snap


———, “Development of the Typical Year Precipitation for the ALCOSAN Service Area,” 2009.


———, “Executive Summary,” ALCOSAN Clean Water Plan, 2019d.


Environmental Protection Agency Region 3, ALCOSAN Settlement Modified with Green Infrastructure as It Improves Water Quality for Allegheny, Monongahela, Ohio Rivers, news release, Washington, D.C., September 19, 2019. As of July 1, 2020: https://www.epa.gov/newsreleases/alcosan-settlement-modified-green-infrastructure-it-improves-water-quality-allegheny


As of August 17, 2020:
http://www.rand.org/pubs/monograph_reports/MR1626


———, *Negley Run Was Here!*, undated-b. As of August 1, 2020:
http://www.a42.livingwaterspgh.org/wp-content/uploads/2015/06/NRWH-02-Pamphlet.150611.pdf


As of August 29, 2020:


Mearns, L., “The North American Regional Climate Change Assessment Program Dataset,” National Center for Atmospheric Research Climate Data Gateway data portal, Boulder, Colo., 2007. As of July 1, 2020:
https://www.earthsystemgrid.org/project/NARCCAP.html


As of July 1, 2020:
https://www.mvvainc.com/project.php?id=47


MJ Partners Real Estate Services, “EZ Storage Pittsburgh Portfolio,” undated. As of July 1, 2020:

Mott MacDonald and Pittsburgh Water and Sewer Authority, *PWSA City-Wide Green Infrastructure Assessment—Draft Report: A42 Washington Boulevard and Negley Run*, 2016a. As of July 1, 2020:
https://apps.pittsburghpa.gov/pwsa/6.3_A42_Washington_Boulevard_and_Negley_Run.pdf

———, *PWSA City-Wide Green Infrastructure Assessment Executive Summary*, Pittsburgh, Pa., 2016b.


UB Regional Institute at University of Buffalo, *The First Generation of Green Infrastructure in Buffalo: Rain Check 1.0*, Buffalo, N.Y., 2018.


Western Pennsylvania Regional Data Center, “Allegheny County Property Assessments,” web page, undated. As of July 1, 2020: https://data.wprdc.org/dataset/property-assessments


Urban stormwater management is a growing challenge in many U.S. cities. Continued population growth, urbanization, and inadequate investment in storm- and wastewater infrastructure have left many cities exposed to sewer overflows, stormwater flooding, and reduced water quality. Climate change is expected to add to this challenge by increasing the intensity or volume of rainfall from storms in many regions. There is also a growing acknowledgment that these vulnerabilities are environmental justice and equity challenges, as flooding and other negative outcomes disproportionately affect low-income or majority-minority neighborhoods. Pittsburgh’s Negley Run watershed is a prime example of these stormwater management challenges, draining a diverse area of Pittsburgh’s East End, including neighborhoods that have suffered heavily from underinvestment. It also represents an urgent flood-risk challenge in the city, as heavy rainfall in the area leads to regular flooding of a key road corridor. In this project, RAND researchers use simulation modeling to evaluate present and future risks in Negley Run from sewer overflows and flooding given future rainfall uncertainty. The authors then evaluate proposals for a phased series of green stormwater infrastructure (GSI) investments. In addition to estimating stormwater benefits and implementation costs, the authors provide economic estimates of recreational, amenity, and other cobenefits to local residents; compare total benefits to costs; and explore potential trade-offs. Results show that a centralized system of stormwater management in Negley Run could yield cost-effective sewer-overflow reduction, reduce street flooding, and provide positive net economic benefits across a range of assumptions about future rainfall and implementation costs.