Managing Heavy Rainfall with Green Infrastructure

An Evaluation in Pittsburgh’s Negley Run Watershed—Appendix A

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Sponsored by the Henry L. Hillman Foundation, the Heinz Endowments, and 3 Rivers Wet Weather
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 acknowledgement 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 volume presents Appendix A of the main report, which is intended to inform local utilities, policymakers, and stakeholders engaged in stormwater and green space planning in Pittsburgh. The report 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.

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Community Health and Environmental Policy Program

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Appendix A. Negley Run Flood Investigation Model Report

This appendix presents a report, lightly edited but otherwise supplied in its entirety, prepared for the RAND Corporation by Hazem Gheith, Qiuli Lu, and Khaled Abdo of Arcadis.
NEGLEY RUN FLOOD INVESTIGATION MODEL REPORT

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1 INTRODUCTION

The City of Pittsburgh experiences chronic street flooding conditions at a few locations within the Negley Run combined flow basin. Flood conditions could be attributed to high storm intensities, steep topography, the limited capacity of the collection system and the interceptor shafts, high river stage conditions, or the large impervious area at the downstream end of the basin. In some areas, local flooding could be attributed to storm inlets capacity limitation and streets surfacing conditions. The extent and severity of flooding could be reduced through regional and localized stormwater control practices.

To achieve stormwater source control goals, a dynamic surface flow routing model is necessary. The dynamic hydrologic/hydraulics model (H/H model) will take into consideration the high rainfall reoccurrence levels and intensities, the surface flow routing, the storm inlets capacity, the collection system capacity, the backup conditions due to the tunnel shaft capacity, and the river high stage conditions.

This report provides documentation for the recalibration and enhancements of the Negley Run collection system model, performed by Arcadis. The purpose of this report is to provide documentation on the development and model calibration.

1.1 Project Overview

The model is a planning-level tool to be used for evaluating improvement alternatives and predict system performance towards achieving approved levels of control.

The recalibrated model is a tool that can be used to:
- Understand the performance of the collection system under various rainfall conditions
- Provide a tool that can be used to understand the existing collection system limitations
- Identify houses with potential sewage backups due to pipes' capacity conditions
- Identify houses with potential surface flooding risk.

Model update efforts included:
- Runoff catchment delineation at storm inlets level
- Break down the delineated catchments into hydrologically independent runoff areas and groundwater sources.
- Model selected streets as open channels to help in identifying the houses with potential surface flooding risk.

1.2 Overview of Report

This report provides a range of information, including technical discussion of modeling tool updates, flow monitoring data that was used for model recalibration, model development, calibration results, houses with surface flooding risk potential and basement with sewage flow backup potential. The following paragraphs provide a brief overview of subsequent report sections and provide the reader with a consolidated summary of the overall scope of the report.

Section 2 – Overview of Modeling Framework: Section 2 presents an overview of the Negley Run modeling framework, including the model at the source modeling approach by Dr. Hazem Gheith that was key to properly represent the model hydrologic features. This modeling approach provided a modeling framework capable of meeting the objectives of the project.
**Section 3 – Rainfall and Flow Monitoring Data:** Section 3 presents the flow and rainfall data that was provided to Arcadis to use it in model recalibration.

**Section 4 – Hydrologic Model Refinements:** Section 4 presents the refinements incorporated in the hydrologic components of Negley Run collection system model. These refinements are of two types:

- Updates and improvements to the level of detail as necessary in the surface hydrology contained in the model, and
- Addition of the Inflow/Infiltration (I/I) modeling approach that uses the groundwater routines to represent I/I contribution from the individual sources.

**Section 5 – Hydraulic Model Refinements:** Section 5 presents the refinements incorporated in the hydraulic components of the Negley Run collection system model. Refinements to the hydraulic components of the model are:

- Add storm inlets to account for their potential impact on the localized street flooding.
- Modeling street channels as an open channel.

**Section 6 – Model Calibration:** Section 6 presents the process used to update and refine the calibration of the Negley Run collection system model.

**Section 7 – Flooding Risk and Basement Water Backups:** Section 7 presents suggested procedure to identify the houses with potential flooding risk and basements that might experience water backups.
2 OVERVIEW OF MODELING FRAMEWORK

This section provides an overview of Negley Run modeling framework, including discussion of key modeling tool features.

2.1 Modeling Software

RAND shared with Arcadis the Negley Run model for the A41-A42 area. The hydrologic and hydraulic model was developed in SWMM 5.0. The Negley Run model continued to use SWMM as the modeling platform. The most recent SWMM version SWMM 5.1.012 was used.

2.2 Collection System Features and Processes

The collection system includes features and processes critical to the system’s wet-weather response. This section provides background on the key components of the system.

The Negley Run collection system is made up mainly of a combined sewer system.

The combined system receives inflows, made up of some combination of the following types:

1. **Dry Weather Flow (DWF)** – diurnally-varying wastewater from private residences and from commercial/industrial flows. DWF is tributary to sanitary and combined systems only.

2. **Surface Runoff** – the portion of rainfall that flows overland until reaching a storm inlet. This is the dominant source of flow within Negley Run collection system.

3. **Infiltration and Inflow (I/I)** – portion of rainfall that enters the sewer system through unintended pathways like groundwater infiltration through foundation drains, lateral house connections, main sewers, and manhole structures. For Negley Run collection system, this portion of the flow is small compared to the surface runoff component. However, replicating this component is still important in terms of matching the total flow volume that the system experiences during rainfall events.

Each inflow source in the collection system requires unique representation in the model. Dry-weather flow (DWF), surface runoff, and I/I are each represented separately.

DWF is defined as the sum of sewage and minimum basin flow contributions that are not dependent on rainfall. DWF is developed based on flow monitoring data and includes a diurnal pattern.

Surface runoff is predicted by the model based on surface catchments delineated to cover the entire combined sewer area. Using rainfall as an input, the model accounts for initial abstractions, evaporation, and infiltration and then routes the remaining surface water as sheet flow to a defined receiving inlet (or loading manhole) in the pipe network.

I/I is represented using the Groundwater module in SWMM. This approach maintains a link to the physical I/I process by accounting for infiltration to a perched water table and then releasing volume stored in the perched water table to a defined receiving manhole using rate coefficients developed through model calibration.
2.3 Modeling at the Source Approach

The Negley Run model was enhanced by expanding the level of detail in catchment delineations to allow for modeling flows at their source. This approach provided a benefit in modeling both surface runoff and I/I flows, as described below. The modeling at the source approach has been previously used by Arcadis for the following modeling efforts:¹

- City of Columbus, Ohio (Combined/Separate Sewers): The approach was used to enhance the City’s collection system model during the development of Columbus’s Integrated Plan. The Integrated Plan was submitted in September 2015 to, and received approval from, the Ohio EPA in December 2015.
- City of Fort Wayne, Indiana (Separate Sewers): The approach was used to enhance the City’s collection system model in conjunction with an I/I reduction study.
- MSD (Cincinnati, Ohio) (Combined Sewers): The approach was used to enhance a model used to support design implementation of storm separation projects within the MSD combined service area.
- City of Indianapolis, Indiana (Separate/Combined Sewers): The approach was used to enhance the City’s collection system model currently being used to confirm and optimize their approved LTCP plan.
- City of Marysville, Ohio (Separate Sewers): The approach was used to develop a collection system model to support development of Marysville’s Wastewater Master Plan.
- Region of York (Ontario, Canada): The approach was used to enhance the Region of York’s collection system model in conjunction with an I/I reduction study.
- DC Water (Separate Sewers): The approach was used to enhance DC Water’s collection system model used in conjunction with an I/I reduction study.

2.3.1 Surface Runoff Flow

Traditional runoff subcatchment delineation defines one subcatchment for multiple storm inlets and manholes, with one total area, one set of runoff parameters, and one loading node. This practice is appropriate when the study’s goal is to obtain the total flow from the larger catchment area for evaluating system improvements downstream of the catchment. However, it does not provide sufficient detail for accurate evaluation of the hydrologic impact of source control solutions or local stormwater improvements. Therefore, to develop a tool capable of assessing local stormwater solutions, the Negley Run model incorporated a higher level of detail throughout the combined sewer system through application of the model at the source modeling approach.

The underlying principle for this process was to delineate features that have unique runoff characteristics within the catchment. For example, roof areas were delineated separately by approximation using satellite imagery. House roofs are completely impervious and have constant/high slopes and negligible depression storage. Parking lots and streets are represented with their true slope and sheet flow widths using parameters calculated from Negley Run GIS data. Figure 2.1 shows the unique subcatchments defined for each runoff catchment, as well as how flow was routed between unique subcatchments. Details of how the subcatchments are identified are presented in Section 4.3.

The model at the source approach facilitates the study of green infrastructure (GI) technology as source control facilities. For example, by isolating commercial and industrial buildings as individual subcatchments, the model is configured to allow for accurate evaluation of green roofs applied to the low-slope roof.

¹ See, for example, City of Columbus, “City of Columbus Integrated Plan Report,” submitted to Ohio EPA in September 2015, approved December 2015; Buffalo Sanitary Authority, “Buffalo Sanitary Authority Long Term Control Plan Model Update report,” submitted to USEPA December 2018.
surfaces of these buildings. Similarly, singling out streets allows for more accurate evaluation of permeable pavement and porous curb and gutter units, since they intercept runoff from streets before it arrives at the storm inlets. Representing the unique hydrologic components also reduces the uncertainty in the runoff parameters during calibration and application. In doing so, there were many benefits: the accuracy of the hydrologic model to mimic observed data was increased, the calibration process was accelerated, and calibrated parameters were kept within their physical limits. In addition, the hydrological impact of the GI program on the catchment’s runoff is better understood, and an understanding of the performance of the GI program in meeting regulatory objectives could be evaluated with a higher level of confidence.

2.3.2 I/I Flow

The model at the source approach applied in the Negley Run’s collection system uses the Groundwater module in SWMM to generate the I/I flow. An advantage of this approach is that it can represent the physical processes that contribute to I/I in a collection system.

The approach uses the same set of subcatchments presented on Figure 2.1. Those subcatchments with a pervious surface component have the potential to contribute subsurface flow and are each associated with a subsurface aquifer within the model. These aquifers are effectively representations of the different manmade trenches or perched water tables within the service area. The full hydrologic cycle, which includes surface runoff, surface infiltration, evapotranspiration, deep percolation, and I/I processes as shown in Figure 2.2, is then appropriately configured for each I/I source using SWMM’s Runoff, Aquifer and Groundwater modules.

In a combined system both I/I and Runoff are captured into the same combined sewer system.
Hydrologic parameters for each I/I source were selected to represent the degree of soil disturbance. For example, there is typically a fast I/I stage associated with sources from foundation of houses with basements. Soil media around the house perimeter is typically a granular material at the foundation level, topped with soil layers that are in a highly disturbed condition due to excessive roots and planting activities. These conditions cause the surface runoff to percolate at a high rate around the foundation. These percolated flows can quickly enter the sanitary system, either through a directly connected foundation drain (if present) or through loose connections between the house service pipe and the lateral service pipe. This fast-response process is represented in SWMM by using a high infiltration capacity in the buffer areas around the house perimeter.

Lateral pipes are usually placed under pervious surface at the front or back of the house and extend towards the main collector sewer. In addition to subsurface flow from the foundation drains, surface water over the lawn area can also percolate into the lateral pipe trenches. Once in the trench, subsurface water can enter lateral pipes, which are prone to high defect conditions due to soil movements and root intrusion. Further, as part of past construction practices, the lateral pipe was often connected to the main collector sewer by punching a hole in the main sewer. This connection is typically performed poorly, causing a leakage path for the lateral trench subsurface water to enter the main sewer. Main sewer trenches can also collect water if placed under a previous surface or under cracked impervious pavement areas. Defects in the main sewer and the manhole structures can cause the trenched waters to enter the main sewer as I/I. This process is represented in SWMM by assuming a lower infiltration capacity than values assumed in the house perimeter.

A slower I/I hydrograph takes place as the water from the natural, more condensed soil material outside the trenches starts to seep into the manmade trenches. This slow I/I seepage stage can extend for more than a month in clay soils. This slow I/I process is also represented with the groundwater/aquifer approach for the nondisturbed pervious portion of the catchment using appropriate calibration parameters.

A key benefit of modeling I/I flows at their source is the ability to model I/I mitigation on a per-source basis. Once the technology efficiency and participation rate are assumed for a particular source mitigation
strategy, those assumptions can be applied uniquely to the affected source. This overcomes a key weakness of other I/I modeling techniques, which all represent I/I as a lumped source phenomenon.

### 2.4 Areal Coverage of New Negley Run Model

The model extent includes sewer diameters ranging from 18” to 108”. A comparison of model level-of-detail metrics between the original model and the enhanced Negley Run 2018 model is included in Table 2.1 below. In addition, Figures 2.3 and 2.4 show an example for the Runoff catchment improvement and the whole coverage for the new runoff catchments delineation.

<table>
<thead>
<tr>
<th>Model Metric</th>
<th>Original Negley Run Model</th>
<th>Negley Run 2018 Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of storm inlets incorporated</td>
<td>N/A</td>
<td>427</td>
</tr>
<tr>
<td>Average area per subcatchment (acres)</td>
<td>56</td>
<td>3.5</td>
</tr>
<tr>
<td>Total number of runoff catchments (GIS delineation)</td>
<td>69</td>
<td>1,035</td>
</tr>
<tr>
<td>Total number of street segments</td>
<td>N/A</td>
<td>849</td>
</tr>
</tbody>
</table>

![Figure 2.3 – Example for Runoff Catchment Delineation Enhancement](image-url)
Figure 2.4 – Negley Run Runoff Catchment Coverage
3 RAINFALL AND FLOW MONITORING DATA

Rainfall data and flow data are the fundamental information required for model calibration. An important prerequisite for successful calibration of any model is adequate data coverage. In other words, both rainfall and flow data need to be collected at enough sites, in the right locations, for an enough matching time period.

Figure 3.1 shows the historical flowmeters locations across the modeling area. The flow monitoring program included 10 flowmeters, of which 6 flowmeters were within the modeled network and considered in the calibration process. The rainfall data and the flow meter data were available for the year 2008 and were used in this study.

Figure 3.1 – 2008–2009 Flowmeters Locations
4 HYDROLOGIC MODEL REFINEMENTS

This section describes elements of the hydrologic model included as part of the Updated Negley Run model development.

Hydrologic components refer to flow formation and flow routing mechanisms on the surface and through subsurface media before flow reaches the collection system network. Representation of these components ensures that the model generates accurate inflow volumes and peak flows.

4.1 Application of SWMM Runoff and Groundwater Modules

The SWMM model is made up of a grouping of modules to represent different aspects of urban hydrology and collection system hydraulics. In early versions of SWMM, these modules were distinct program subroutines, each accessed independently by the user. In the current version of SWMM, these modules are integrated and accessed as “one model” through the user interface. However, each module still performs tasks specific to one aspect of hydrology and hydraulics, and so it is useful to present the modules in terms of their function. Two modules are of interest to Negley Run’s hydrologic model refinements—the Runoff module and the Groundwater module. Much of the following information on the theory behind the SWMM modules has been derived from “User’s Guide to SWMM5,” 13th Edition, by CHI Press, which itself borrowed heavily from the original USEPA SWMM documentation.  

4.1.1 Runoff Module

As previously noted, the collection system consists of combined sewers. For combined sewers, the flow is dominated by surface runoff contributions. Peak flows are largely determined by surface runoff. Within SWMM, this portion of the flow contribution is calculated using the Runoff module. Every SWMM wet-weather simulation begins with the definition of a rainfall time series that falls on the modeled service area. The Runoff module determines the fate of that rainfall through one or more mechanisms:

- Depression storage, or the depth of rainfall that is retained in or on surface features. This is equivalent to the term “initial abstractions” used in traditional hydrology.
- Infiltration through the topsoil.
- Evaporation from the surface.
- Surface runoff.

Any excess rainfall that remains after filling the depression storage and, after accounting for losses to infiltration and evaporation, becomes surface runoff. The Runoff module uses the classic “non-linear reservoir” solution to calculate surface runoff flow rate, applying Manning’s equation to represent sheet flow at a given depth over a sloped surface with defined roughness characteristics. Calculated surface runoff can be directed to a collection system inlet (entering the Hydraulics module) or routed onto a downstream Runoff subcatchment as run on (in addition to rainfall).

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4.1.2 Groundwater Module

The second SWMM module used in incorporating the refinements to the model was the Groundwater module. This module was used to represent I/I contributions to the collection system. The contribution of I/I to the total flow in combined sewers is small compared to that of surface runoff, particularly with respect to the peak flow. However, accounting for this flow component is necessary to properly modeling overall event flow volumes, which is the driving metric for some solution technologies.

The groundwater subroutine in SWMM simulates two zones: an upper (unsaturated) zone and a lower (saturated) zone. Calculated infiltration (from the Runoff module) into the unsaturated zone can subsequently flow from the unsaturated to the saturated zone via a percolation mechanism, represented by a percolation equation in the module. For the upper unsaturated zone, the losses are through percolation to the lower saturated zone and evapotranspiration. For the lower saturated zone, losses can be via deep percolation, saturated zone evapotranspiration, sump pumps for groundwater accumulating around and beneath the house perimeter, or groundwater flow inflow and infiltration (I/I) to the sanitary system. I/I is calculated as a power function, scaling with water table stage and, if chosen, depth of water in the receiving system.

The model at the source approach was adopted to properly represent the I/I process in an urban collection system. The manmade trenches around home foundations, laterals, and mainline sewers are separated as local aquifers with groundwater levels that rise and fall with wet-weather inflows.

This recognition of the applicability of the Groundwater module to I/I hydrology, combined with the modeling at the source approach described in Section 2.1, provides a tool to model I/I by individual source.

4.2 Perviousness and Imperviousness

The Runoff block of SWMM simulates wet weather from a modeled basin via impervious and pervious runoff. Impervious runoff represents the portion of flow generated from paved surfaces (e.g., parking lots, roads, driveways) and from other connected surfaces such as roof drains. The percent imperviousness of a basin is a good indicator of the level of development of the basin. Pervious runoff represents the portion of flow generated from the open surfaces in a basin which is dependent on soil type and level of soil saturation. Subsurface water can also enter the collection system via I/I processes. Since the modeled collection system exists in a highly urbanized area, impervious surface runoff drives both peak flows and total runoff volumes for most storms. Total imperviousness is generally related to an area’s land use. For the Negley Run Basin service area, the following land use coverages were considered, estimated using a combination of GIS processing and reviews of satellite imagery:

- Building
  - Residential
  - Commercial
- Roads
- Parking lots
  - Parking lots with private storm inlets
  - Parking lots without private storm inlets
- Garages
- Pervious lawn area
The area associated with the Lawn subcatchment was calculated by summing the areas of defined impervious source-level subcatchments and then subtracting this from the total catchment area. The Lawn subcatchments included sidewalks and driveways, as these areas were not accounted for in the other impervious subcatchments. For this reason, a portion of the Lawn subcatchment was defined as impervious within the model. **Figure 4.1** shows considered land use of Negley Run Basin.

![Figure 4.1 – Negley Run Basin Land Use](image)

### 4.3 Surface Runoff and Subsurface I/I Subcatchments

The first step in the process for the detailed surface hydrologic model was delineating the runoff catchments. Runoff catchments were delineated to:

- The furthest upstream manholes incorporated in the model
- Manholes where sewers that are not in the model tie into modeled sewers
- Clusters of storm inlets.

Runoff catchments were delineated using the following sources:

- Sewer mains and manholes GIS layers
- Storm inlets GIS layer
- Topographic (Allegheny County DEM [resolution = 6’ x 6’ cells])
- Satellite images (Bing Maps underlay built into ArcGIS).
More than 1,035 runoff catchments were identified.

The delineated runoff catchments were then broken into their hydrologically independent subcatchments (Figure 2.1). This overcomes many challenges associated with single-lumped parameters (e.g., slope, width, depression storage) inherent to the standard inlet catchment approach and allows for definition of the unique hydrologic response of each surface type. The catchments are split into up to 13 different subcatchments could be defined for each runoff catchment:

- **Residential Roofs:** Residential roofs were split into four categories:
  - (1) Roofs whose runoff routes to the street
  - (2) Roofs with disconnected downspouts that “splash” within 6 ft of the house. The distance of 6 ft is assumed to designate the approximate area around the house where infiltrated water could contribute through the house foundation drain.
  - (3) Roofs with disconnected downspouts that “splash” beyond 6 ft from the house.
  - (4) Directly Connected/Unknown Connection Roofs.
- **(5) Garage Roofs (runoff is assumed to rout to the Lawn subcatchment)**
- **Buffer Area around Residential Buildings:** Residential Buffer areas correlate to pervious areas surrounding residential homes. The width of the buffer area was assumed to be 6 ft. The buffer areas were divided into subcatchments:
  - (6) Buffer areas associated with houses where disconnected downspouts “splash” within 6 ft of the house
  - (7) Buffer areas associated with all other houses.
- **(8) Commercial Buildings:** A separate subcatchment was used for commercial building roofs.
- **(9) Parking Lots:** If internal storm inlets were observed in GIS, runoff from parking lots was routed directly to the sewer system. If not, runoff was routed to the Street subcatchment.
- **(10) Streets:** The area of the streets was determined from the available “Curb Edge” GIS layer. Runoff from the Street subcatchment was routed directly to Street channels.
- **(11) Buffer Areas above House Laterals:** The “buffer” area above the house laterals was assumed to be 12 ft wide. The buffer area for Laterals subcatchment only included the portion of this area that (a) was pervious and (b) didn’t overlap with the defined residential buffer area. Runoff was routed to the Lawn subcatchment.
- **(12) Buffer Areas above Main Sewers:** The “buffer” above the sewers was assumed to be 12 ft wide. The buffer area mains subcatchment only included the portion of this area that was pervious. Runoff was routed to the Lawn subcatchment.
- **(13) Lawns:** The remaining areas of the runoff catchments not accounted for by the other subcatchments. It could also include sidewalks and driveways, as these areas are not accounted for elsewhere. For this reason, a percent impervious area was assumed in Lawn subcatchment. Runoff from the lawn subcatchment was routed to the Street subcatchment.

Surface runoff routing between subcatchments was previously presented in Figure 2.1.

### 4.4 Evapotranspiration Analysis

Use of the Groundwater module requires careful attention to evapotranspiration, as it represents a key loss mechanism for modeled groundwater aquifers. Potential evaporation depends on multiple factors,
including climate conditions (temperature, solar radiation, humidity, and wind speed), vegetation cover and type, and season. The Hargreaves-Samani equation was used as the evaporation calculation method for the 2018 model:

\[
ET_h = \frac{0.408 \cdot 0.0023 \cdot R_a \cdot (T_m + 17.8) \cdot \sqrt{T_{max} - T_{min}}}{\text{[mm/day]}}
\]

Where:
- \(R_a\) = extraterrestrial radiation (measured on surface or calculated) \((MJm^{-2}d^{-1})\)
- \(T_m\) = mean daily temperature \(^\circ\text{C}\)
- \(T_{max}\) = maximum daily temperature \(^\circ\text{C}\)
- \(T_{min}\) = minimum daily temperature \(^\circ\text{C}\)

The Evaporation was estimated using temperature data obtained from the NOAA website for Pittsburgh Allegheny Co. Airport station. Figure 4.2 shows the calculated daily evaporation for the period from January 1, 2007, to the end of 2008. The evapotranspiration value applied within the Groundwater module is then calculated in the model as a product of the evaporation time series and the calibrated monthly coefficient of transpiration (\(C_{ET}\)).

Figure 4.2 – Calculated Daily Evaporation Values for Negley Run Model for 1/1/2007–1/1/2009
5 HYDRAULIC MODEL REFINEMENTS

This section describes refinements made to, and incorporated in, the model as part of the new model development. The model is enhanced through adding two new features to the model:

- Street channels
- Storm inlets.

5.1 Street Channels

Surface stormwater collected by roof tops, parking lots and lawns is routed over the impervious street surface and street gutters to the storm inlets. Streets are modeled as surface open channels along each side of street. Street channels cross-section are identified using the topographic DEM data. Street channels are then connected in the model to the storm inlets. Figure 5.1 shows an example for street cross-section extraction.

The two main components of the streets include open channels (each side of street) and overflow weirs to allow for the routing of runoff from one side of the street to the other. Figure 5.2 shows an example of model street cross-section.

![Figure 5.1 – Example for Street Cross-Section Extraction](image-url)
5.2 Storm Inlets

The size and configuration of the storm inlets impact the amount of street flows that could be captured into the storm network. They also have large impact on the localized street flooding. Figures 5.3 provides photographs of the various inlet types that could be observed in field. Storm inlets are added to the model as orifice features Figure 5.4 shows a sample of storm inlet representation in the model. Storm inlets with no grates are represented in the model as side orifices. If a grate exists, then it is represented in the model as a bottom orifice.
Figure 5.3 – Examples of Storm Inlets Configuration
6 MODEL CALIBRATION

Model calibration is a fundamental component of the model development process. Calibrating the model to a range of monitored flow data provides a confidence to use the model to study periods that have not been monitored. The approach used for the updated Negley Run model was to run the model for a continuous period covering multiple seasons.

Generally, the calibration process fixes parameters known with high certainty (for example, measured drainage areas) and adjusts parameters with high uncertainty (for example, depression storages).

6.1 Calibration Approach

The calibration of the model occurs in two phases: 1) Calibration of flow under dry weather conditions and 2) calibration of flow under wet weather conditions. The approach used for each phase is outlined below.

6.1.1 Dry-Weather Flow

Calibration is first done for flow under dry weather conditions. Dry-weather flow, as defined for the model, is made up of diurnally-varying wastewater from private residences and commercial/industrial wastewater flow. The wastewater component is tributary to sanitary and combined systems only.

The total wastewater was estimated for each meter from the lowest flow days of the calibration period. The wastewater was distributed proportionally to each load node based on area.
Within SWMM, the sanitary contribution for each load node is calculated as follows:

\[
\text{Sanitary Flow} = \text{Average Wastewater Flow} \times \text{Diurnal Pattern (Weekday or Weekend)} \times \text{Daily Pattern}
\]

No monthly pattern was applied, as the seasonal differences in the dry-weather flow are accounted for through Groundwater module contributions.

The weekday diurnal, weekend diurnal, and daily patterns for the flow meter where extracted from the monitored data. The patterns were adjusted as needed to achieve a reasonable match between the modeled and monitored dry-weather flow. A unique set of patterns was determined for each meter calibrated. An example calibrated weekday diurnal pattern is shown in Figure 6.1. An example calibrated weekend diurnal pattern is shown in Figure 6.2. An example calibrated daily pattern is shown in Figure 6.3. Figure 6.4 shows the resulting dry-weather calibration results for the example meter.

![Figure 6.1 – Example Wastewater Weekday Diurnal Pattern for FM L-07](image-url)
Figure 6.2 – Example Wastewater Weekend Diurnal Pattern for FM L-07

Figure 6.3 – Example Wastewater Daily Pattern for FM L-07
6.1.2 Wet-Weather Flow

After completion of the dry-weather calibration, the next step is to calibrate to flow under wet-weather conditions. As noted previously, the wet-weather contributions are composed of two components: surface runoff (modelled via the Runoff module), and I/I (modelled via the Groundwater module). In Negley Run combined system, contributions from surface runoff dominate, but I/I contributions still have relevance with respect to the overall event volumes. Wet-weather calibration was done on a meter-basin basis.

Calibration of the surface runoff parameters was done first. Studying events occurring during the portions of the year when contributions from I/I was expected to be minimal (i.e., summer and early fall events). The following parameters served as key calibration parameters for runoff flow:

- Surface infiltration for Lawn subcatchment ($k_i$).
- Percentage of runoff routed from the impervious portion of Lawn and Buffer subcatchments to the Street subcatchment.
- Depression Storage for Pervious Areas (in): This is to account for the incidental depressions within the Lawn subcatchments.

After the surface runoff is adequately calibrated, focus is then moved to calibrating the I/I flow contributions, which are typically highest during the winter and early spring periods. For I/I flow the main controlling parameters were:

- $A_1$: represents the amount and shape of defects in pipes/manholes and rate of I/I flow into system. In the model, this is defined as the “groundwater flow coefficient” and determines the quantity of inflow that gets into the sewer system from the trench represented by the aquifer.
- $DL$: represents the leakage to deep aquifers and dewatering of the saturated zone around houses.
- $C_{ET}$: the evapotranspiration coefficient, which represents the intensity of vegetation and losses to evapotranspiration at different times through the year.
Each meter in the sewer system was calibrated until an acceptable match was achieved between the modeled and observed hydrographs over the monitored data year of 2008.

6.2 Calibration Results

A total of 6 meters were used in the calibration of Negley Run model. Figure 6.5 the schematic for the calibrated flowmeters. Figures 6.6 to 6.11 shows a scatter plot comparison between the peaks for flowmeter data and the model results. The calibration results show that the model is well calibrated.

Figure 6.5 – Schematics of the Calibrated Meters
Figure 6.6 – Scatterplot of Computed vs. Observed Peak Flow for FM L-05

Figure 6.7 – Scatterplot of Computed vs. Observed Peak Flow for FM L-07
Figure 6.8 – Scatterplot of Computed vs. Observed Peak Flow for FM L-04

Figure 6.9 – Scatterplot of Computed vs. Observed Peak Flow for FM L-03
Figure 6.10 – Scatterplot of Computed vs. Observed Peak Flow for FM L-02

Figure 6.11 – Scatterplot of Computed vs. Observed Peak Flow for FM L-01
7  FLOOD RISK AND BASEMENT WATER BACKUP

After the mode is calibrated as shown in Section 6, an Excel sheet was developed and delivered to RAND that uses the model output to estimate the houses with potential flood risk and the basements with the potential of sewage backups. A brief description for the steps to use the Excel sheet is presented.

7.1  Surface Flooding Analysis

Houses that might face the surface flooding risk are determined by comparing the ground elevation around each house to the maximum water elevation in the closest street channel. If the water elevation in the street is equal to or greater than the house ground elevation, that house will be at the risk of surface flooding.

House ground elevation is estimated at the house polygon centroid using the DEM. Maximum water elevation in the nearest street in front of the house is estimated based on the water depth in the upstream and downstream of the street channel and the location of the house relative to the street.

7.2  Sewer Backup Analysis

Water in basement analysis depends on comparing elevation of house basements to the HGL in the combined sewer. If the basement elevation is less than the receiving conduit HGL, water in basement is expected.

Basement elevation is assumed to be 7 feet from the ground elevation. This value can be adjusted in the provided Excel sheet as needed.

7.3  Flood Risk and Water Backup Tool Database/Inputs

Calculations in the developed Excel tool depends on

- Modeled conduits information: conduit name, upstream and downstream coordinates, invert elevations and inlet/outlet manhole ID.
- Modeled streets: street ID in the model, coordinates for upstream and downstream of the street segments, inlet/outlet street junctions in the model.
- Houses’ basement information.

All this information is built in the Excel file. Users can update the basement information for any of the listed parcels in the Excel file database.

After running the model, the user needs to do the following

a. open the report file (.rpt) and copy the Node section
b. Open the Excel file and delete the information in the sheet called “Copy junction sec. from_rpt” and paste the new results to cell A1.
c. Use Text Import wizard as needed to distribute the text to columns.
d. The sheet will calculate the maximum HGL in the modeled conduit and street in front of each house to determine if there is a flooding potential or a water in basement potential.
e. Sheet “Houses Conduit Table” shows the houses with potential water in basement.
f. Sheet “Houses Street Table” shows the houses with potential flooding during the simulated storm.

A shapefile for the houses was delivered to RAND with a unique ID for each house polygon. Users can use this unique ID to link the Excel sheet output to the houses shapefile and hence a map for houses with flooding risk or water in basement risk can be prepared.