Stormwater Analysis and Water Quality Assessment of Urban Areas

FINAL REPORT

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16. Abstract
Salt is widely used for road deicing purpose in winter, and salt application could raise stream chloride level and leads to deterioration of water quality. This study represents the first steps toward developing a comprehensive understanding of how the streams chloride levels are impacted by the salt operation. Toward this goal, this study developed a procedure for the flow path modeling of urban watersheds and applied it to two sites in Pittsburgh, PA, which are potentially susceptible to road salt application by PennDOT. The procedure was used in identifying areas contributing flows to PennDOT right-of-way, and vice versa. This study further took stream water quality samples during non-winter months for establishing baselines and during the winters of 2017 and 2018. Results show that over the non-winter months, the baseline stream chloride concentration has already exceeded criteria continuous concentration most of the time, but lies below the criteria maximum concentration of the environmental regulation. Test results on winter samples show that stream chloride concentration has risen following salt application after snow events, and has exceeded the criteria maximum concentration. The study also shows how surface model of different detail levels would affect the identified contributing areas related to target watersheds, and the importance of properly incorporating roadway features such as curves and bridges.

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Statement of credit

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Executive summary

The application of road salt (i.e., sodium chloride) introduces anthropogenic chloride to environment and has been reported to have negative impacts on both groundwater and surface water quality [1 - 5]. Under Pitt WO #014 project "Stormwater Analysis and Water Quality Assessment of Urban Areas", a comprehensive study is conducted to further our understanding toward disturbance in stream chloride level due to road salt application activity. There are two main objectives for this project: (1) to develop a procedure that can be used in determining the flow contributions from different jurisdictions; and (2) to carry out stream water sampling and laboratory testing in assessing of highway salt operation's overall impacts during winter storms on stream water quality. The ultimate goal of the study is to lay the foundations for a comprehensive study and hydrological modeling of urban watersheds at a later date. Details of the modeling procedures are presented in this report together with the results from the stream water sampling. Based on the two sets of LiDAR data of different resolutions for the study area, this study found that in order to obtain the right flow path, a higher-resolution LiDAR dataset together with the proper incorporation of curb and bridge features of roadways are essential. Flow path has an important role in hydrological modeling of how salt is transmitted to streams. To fulfill the second objective of the project stream water samples were taken and their chloride levels were analyzed and compared with environmental regulations. Baseline chloride concentration levels in the streams were first established during non-winter months. It was found that even without roadway salt operation, the baseline stream chloride levels have exceeded criteria continuous concentration most of the time, but lay below the criteria maximum concentration. During the winter months, the criteria maximum concentration has been exceeded. However, the study also found that the chloride concentration level in the stream drops rapidly with time. Considering the short-duration nature of the salt impact and the lack of continuous stream chloride measurement in current study, it is more than likely that the peak chloride concentrations were not captured by our current sampling activities. To resolve this issue, some form of continuous stream water quality monitoring, and a coordination between sampling and road de-icing activities needs to be established. This study did not measure stream flow velocity which also has an impact on how chloride concentration evolves with time. Furthermore, weather conditions also affect chloride concentrations in the streams especially when streams are frozen. This study did not take samples after frozen streams were thawed and thus could not comment on whether or not the salt operation had a delayed impact under such a scenario.

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1. Introduction

The objectives of this project are two-fold. Firstly, the project is to develop a modeling procedure that can be used in determining the flow contributions from different jurisdictions within a watershed. Secondly, the project is to carry out stream water sampling and conduct laboratory testing in assessing of highway salt operation's overall impacts during winter storms on stream water quality, and compare the measured results with environmental regulations.

This report presents results and findings of the study in three sections as follows:

Section 2 - Data collection and processing: this part covers the collection and preparation of basic data for this study, including GIS data for the study areas, surface model data, locations of sampling sites, local drainage layouts and relevant meteorological data.

Section 3 – Identification of flow path and drainage contribution areas: this part discusses methodologies for identifying flow contributing areas related to PennDOT highway in target watersheds. This part also explores how surface models of different resolutions and details affect the final result.

Section 4 – Stream water sampling and laboratory testing on water quality impacts caused by highway salt operation: this part presents stream water quality monitoring of two selected urban sites during 2017 and 2018. Details regarding stream water sampling, laboratory test methods, and result analysis are presented.

2. Data Collection and Processing

This section and its attached files constitute the deliverable for Task 1—Data Collection and Processing—of the Pitt WO #014 project "Stormwater Analysis and Water Quality Assessment of Urban Areas." Three study areas in the City of Pittsburgh, PA were selected for the project with the first site for Task 1 and Task 2, and the second and third sites for Task 3 only, each with a specific purpose under the project's scope. This document describes the information collected for Task 1 from the first site. The three study areas are:

1. ***Interstate I-376 west of the Squirrel Hill Tunnel***: fate of pollutant wash-off from the interstate's right-of-way area and from adjacent properties.
2. ***Nine Mile Run watershed***: collect water samples at 4 locations from the Nine Mile Run creek and analyze the water samples for chloride concentration, hardness and sulfate concentration.
3. ***Pine Creek watershed***: collect water samples at 3 locations from the Pine Creek and analyze the water samples for chloride concentration, hardness and sulfate concentration.

2.1 Study area 1 – Interstate I-376 west of the Squirrel Hill Tunnel

The Interstate I-376 crosses the City of Pittsburgh. In this study, we look at its span west of the Squirrel Hill Tunnel up to the South Oakland Neighborhood. This span is located mostly around residential neighborhoods and is adjacent to the south limit of Schenley Park, as shown in Figure 2.1. The figure also shows the delineation of the study area which roughly corresponds to the historic hydrographic watershed that existed in the area prior to urbanization. The west most swath of the delineated area (past the canyon of the historic run that drained the Panther Hollow watershed into the Monongahela River), shown on the left of the dotted orange line, did not belong in the same watershed. The right-of-way of the interstate, the highway itself and areas adjacent to it with the support infrastructure (including on-ramps, shoulders, bridges, protection slopes, etc.) are also shown in Figure 2.1.

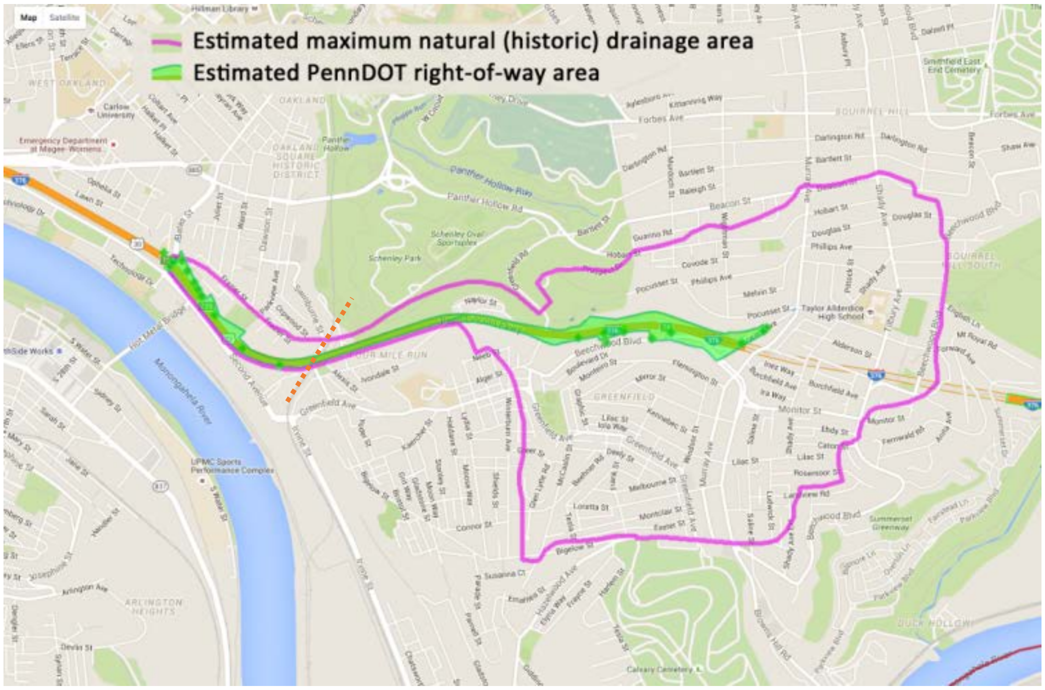

Figure 2.1. A map of the proposed study area for the Interstate I-376.

To achieve the project goals, the first step is to collect and process land-surface and meteorological information of the area. In the following sub-sections, collected data from seven main categories are presented.

2.1.1 Precipitation

The meteorological information for the study area was obtained from the following sources:

1. Next Generation Weather Radar (NEXRAD) data from http://web.3riverswetweather.org/trp:Main.calib_html;trp:
2. Rain Gauge Precipitation (#11) data from http://web.3riverswetweather.org/trp:Main.hist_html;trp:
3. Additional meteorological data from weather underground stations (KPAPITTS208 (Squirrel Hill SE), KPAPITTS234 (Greenfield), KPAPITTS218 (Squirrel Hill -

W3SLL)) from https://www.wunderground.com/personal-weather-station/,. the National Weather Service Daily Climate data in Pittsburgh (weather station near the Pittsburgh International Airport) from http://forecast.weather.gov/product.php?site=NWS&issuedby=PIT&product=CF6&format=CI&version=1&glossary=0.

The data from different Weather Underground weather stations were averaged in the study area. Data from the three sources were combined to obtain more accurate precipitation estimates. The values were averaged when no large difference was registered, and outliers were ignored. National Weather Service Daily Climate data in Pittsburgh was also considered as a reference. All precipitation data of the study area so processed since November 2016 are included in the "ClimateData.xlsx" Excel workbook. Figure 2.2 shows the precipitation, minimum daily temperature, and maximum daily temperature of the study area for this period of time. The locations of the rain gauges are shown in Figure 2.3.

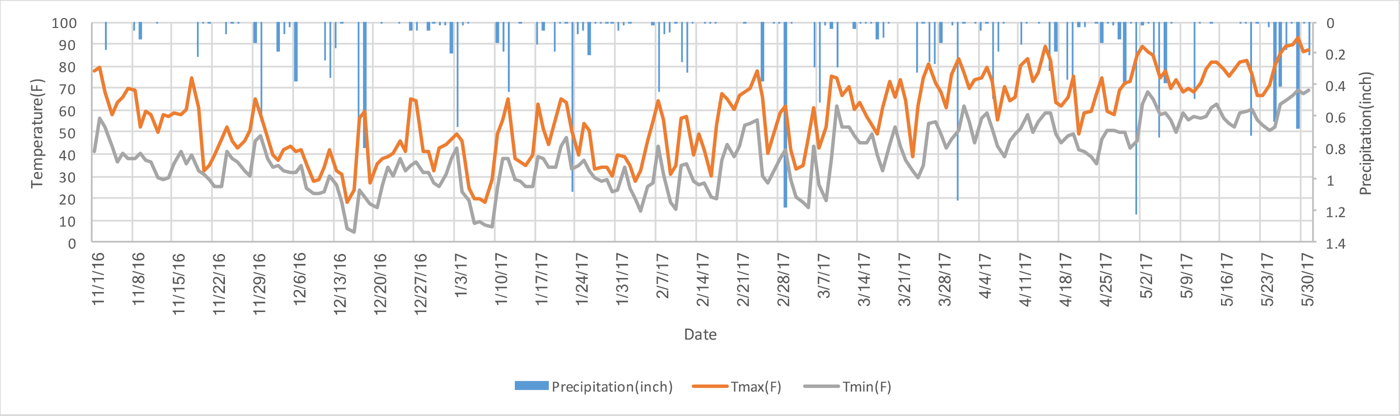

Figure 2.2. Weather information (precipitation and daily temperature variation) for the study area since November, 2016.

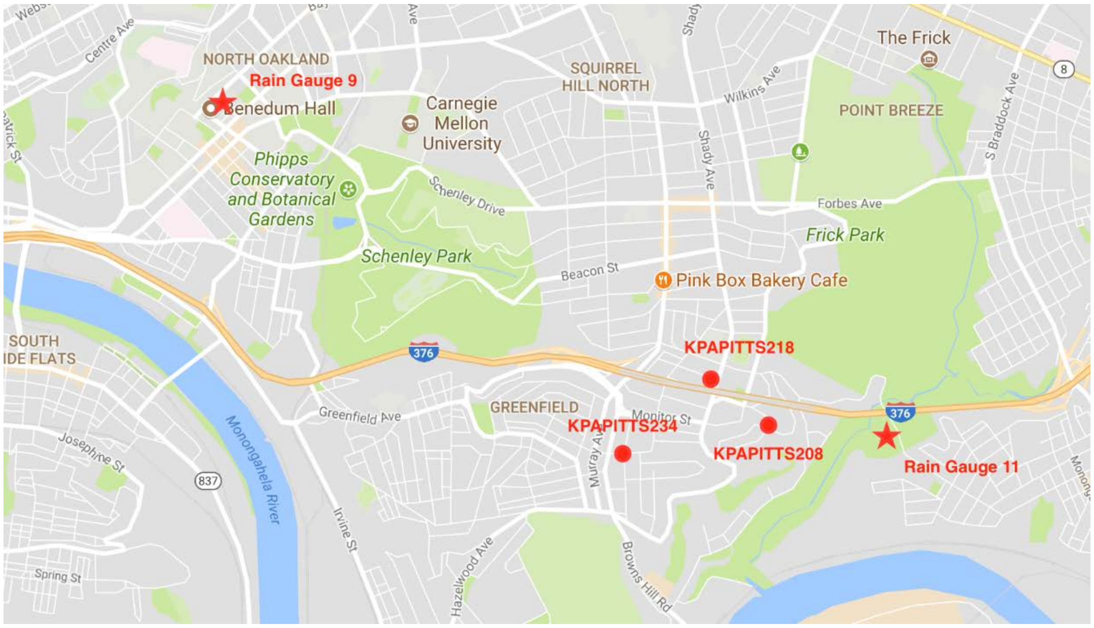

Figure 2.3. Locations of the rain gauges used for the estimation of precipitation for the study area.

2.1.2 Allegheny County LiDAR

Light Detection and Ranging or Light Imaging, Detection, and Ranging (LiDAR) point cloud data from the Allegheny County describing the land surface. The spatial resolution of the point cloud is of around two points per square meter. Lidar Digital Surface Model (DSM) data was obtained from https://lta.cr.usgs.gov/lidar_digitalelevation. The data was downloaded in LAS file format, which is a public format for the interchange of LiDAR data between vendors and customers. A plot of the data is shown in Figure 2.4.

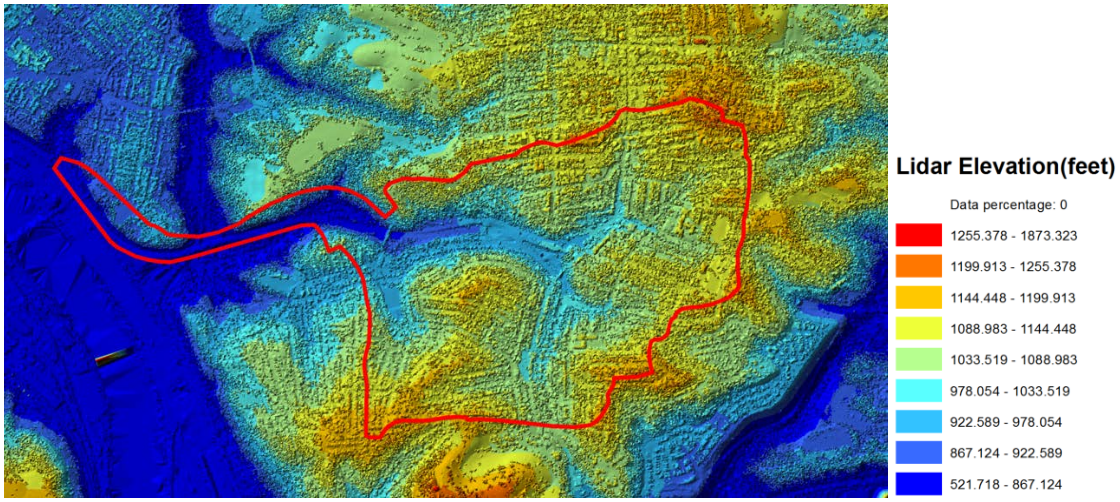

Figure 2.4. Lidar Digital Surface Model (DSM) data for the study area.

Another LiDAR-based data product (Digital Elevation Model, DEM) was also obtained from http://www.pamap.dcnr.state.pa.us/pamap/data_source.aspx. This data (shown in Figure 2.5) has a resolution of 3.2 ft (1-meter equivalent) and it is uniformly-spaced and gridded—with a raster GeoTIFF format. Each pixel in the DEM has an interpolated elevation value.

Figure 2.5. Lidar Digital Elevation Model (DEM) data for the study area.

2.1.3 Hydro-corrected digital elevation

Based on the Allegheny county LiDAR information, a post-processed DEM was developed. The modifications to the original DEM are aimed at improving the fidelity of the surface runoff. More specifically, these modifications are aimed at:

- Eliminating non-surface objects, such as buildings, cars, and trees
- Removing unrealistic sinks—locations with lower elevation that capture flow
- Enforcing flow paths imposed by small structures (like curbs) whose presence was lost due to insufficient resolution in the original data
- Ensuring adequate representation of structures like berms

In order to achieve these, a manual procedure in which additional information (such as that from the county's aerial imagery) was used to assess the behavior of the simulated water flow paths and then, iteratively, modifying the elevation information in TIN (triangulated irregular network) format with the purpose of producing the correct flow path. This process was conducted using ESRI's ArcGIS Desktop 10.X with the Spatial Analytics extension and QCoherent's LP360 Basic software packages. Figure 2.6 shows the most current version of the modified DEM in raster format[1]. Figure 2.7 shows the breaklines in order to make the modifications on the TIN elevation data[2].

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[1] GIS layer name: PittHydro_v21 in the attachments.

[2] GIS layer name: UrbanHydroBreaklines in the attachments.

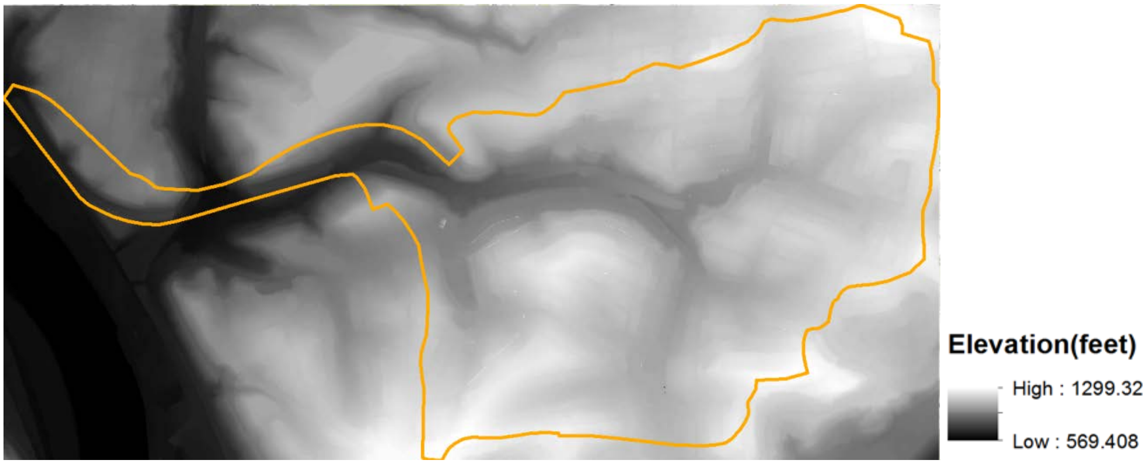

Figure 2.6. Digital Elevation Model (DEM) in raster format from LiDAR and aerial imagery data, modified to improve the surface runoff behavior of the simulated terrain.

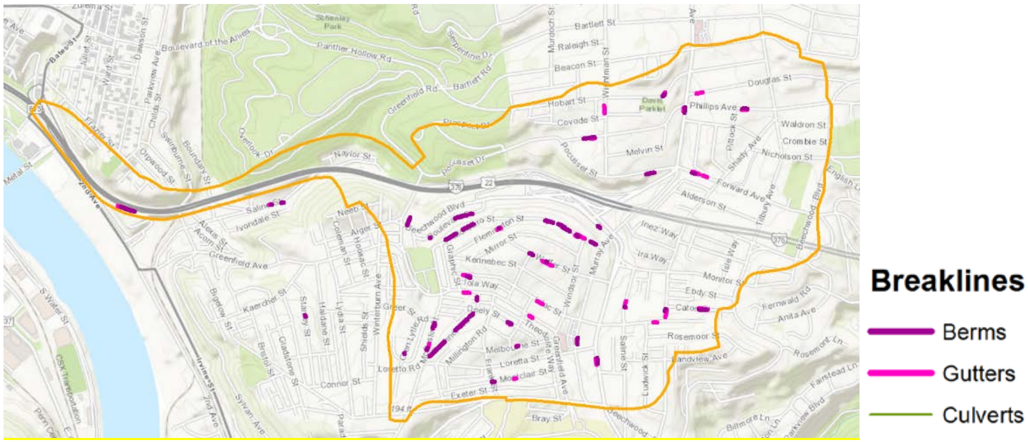

Figure 2.7. Breaklines defined to modify the TIN elevation to produce the corrected DEM in Figure 2.6.

The preceding DEM modification process is time-consuming, but provides a more accurate representation of the surface. This study has found that the modified version of DEM using 2-point LiDAR is preferable as it provides better resolution and facilitates the flow path determination.

2.1.4 PennDOT drainage layout

1. I-376 storm water inlets identified are presented in Figure 2.8. Methods used in identifying those inlet locations include field observation and PennDOT drawings (summarized in GIS database field ‘meta_Feature_Confidence’). Combined with knowledge on current estimated pipe connections (see Figure 2.9 and Figure 2.10), Inlets are classified based on the flow destination of water entering the inlets. This map layer is used to analyze where PennDOT water will flow after entering an inlet, in order to estimate area affected by water originating on PennDOT property.

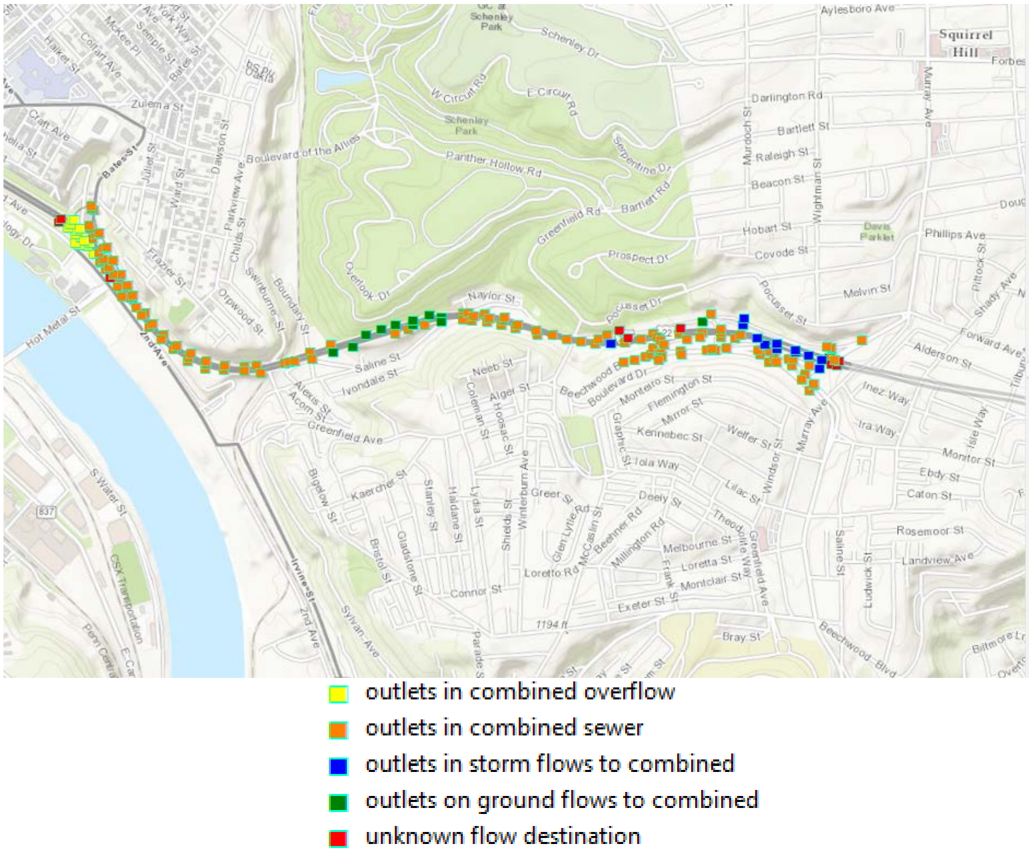

Figure 2.8. PennDOT storm water inlets on I-376. Obtained by overlaying layer ‘LBs_Identified_Storm_Structure_LBs_v09u’ with ArcGIS topographic basemap. Displayed by database field = ‘meta_Feature_Confidence’.

2. I-376 estimated storm water pipe locations identified are shown in Figure 2.9. Information from Pittsburgh Water and Sewer Authority (PWSA), PennDOT construction surveys, field observations under bridges, and educated guesses were used to determine current pipe connections. Process used to establish each pipe segment is summarized in GIS database field ‘meta_Feature_Confidence’. The destination of inlet intercepted storm water is summarized in GIS database field ‘meta_Flow_Destination’, based on the current estimated pipe segment connections and the available maps and drawings. This map layer is used to analyze where PennDOT water will flow, in order to identify area affected by PennDOT runoff.

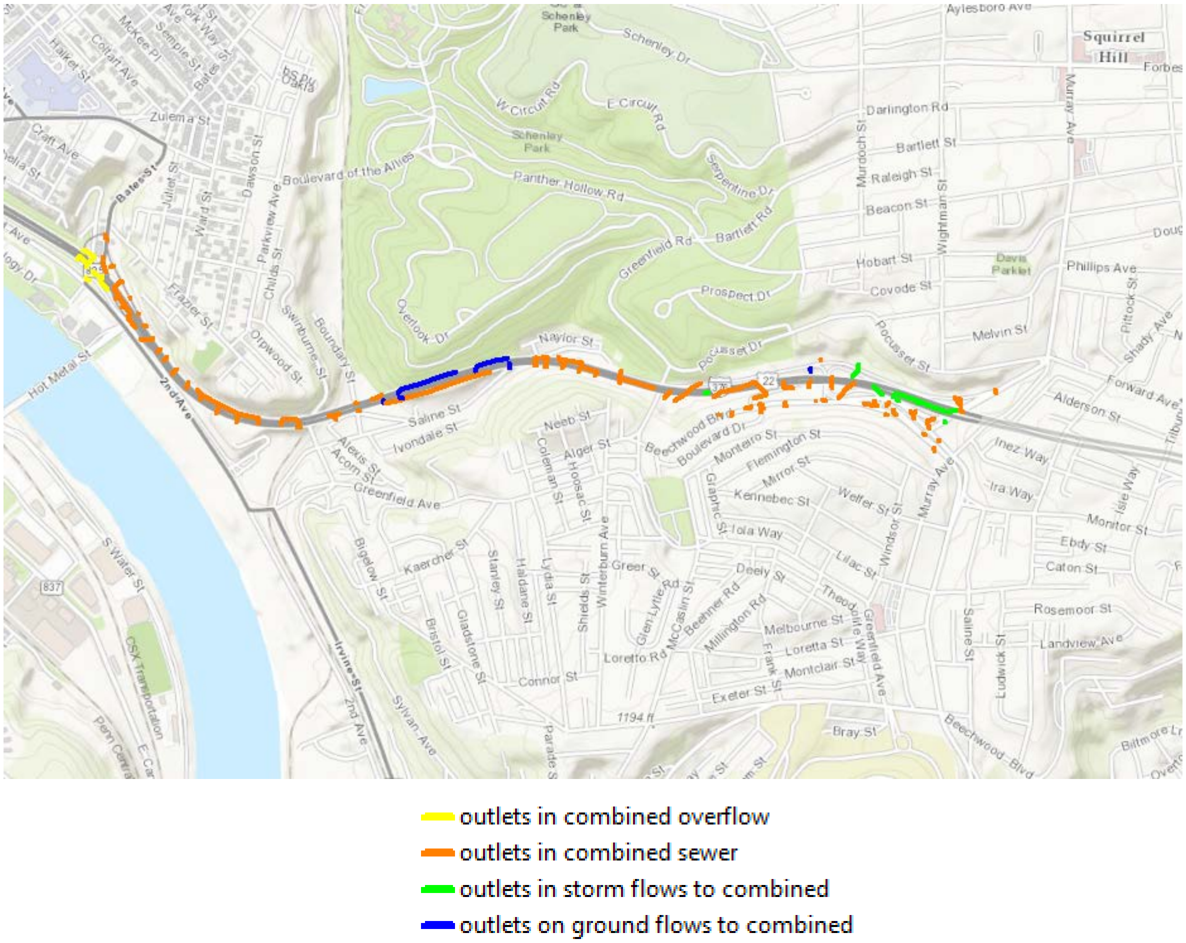

Figure 2.9. Estimated storm water pipe locations on I-376. Obtained by overlaying ArcGIS layer ‘LBs_Estimated_Storm_Pipe_Features_LBs_v09u’ with ArcGIS topographic basemap. Displayed by database field = ‘meta_Flow_Destination’.

2.1.5 Storm water and sewer pipe system

1. PWSA database of point features of the drainage system (Figure 2.10)[3]. The source of this feature is PWSA. This feature is obtained by merging five different source point databases (End_Caps, Inlets, Junctions, Manholes, Outfalls) into a single database file and added the field 'object_type' to clarify the structure represented by each point. Note: 'Junctions' are underground pipe connections without a manhole structure.

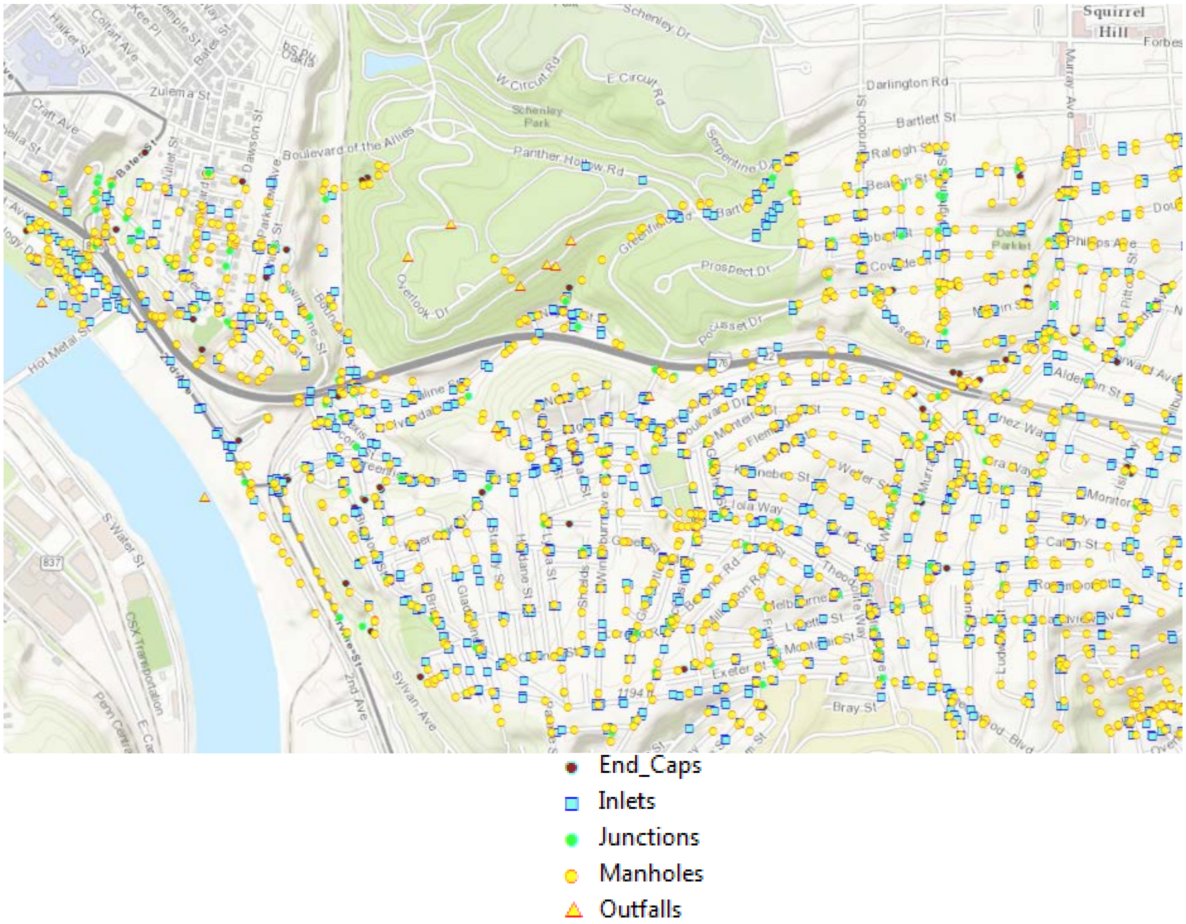

Figure 2.10. Point features of PWSA's drainage system. Obtained by overlaying ArcGIS layer 'PWSA_Source_Drainage_Structure_LBs_v01_point in the attachments' with ArcGIS topographic basemap.

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[3] GIS layer name: PWSA_Source_Drainage_Structure_LBs_v01_point in the attachments.

2. PWSA database of drainage pipes (Figure 2.11)[4]. The database field 'SEWER_USE' is employed to visually classify by color the four primary types of sewer pipes in the database: brown = combined sewer pipes, red = combined overflow pipes, green = sanitary sewer pipes, blue = dedicated storm water pipes. This layer is used to establish pipe connections in the study area.

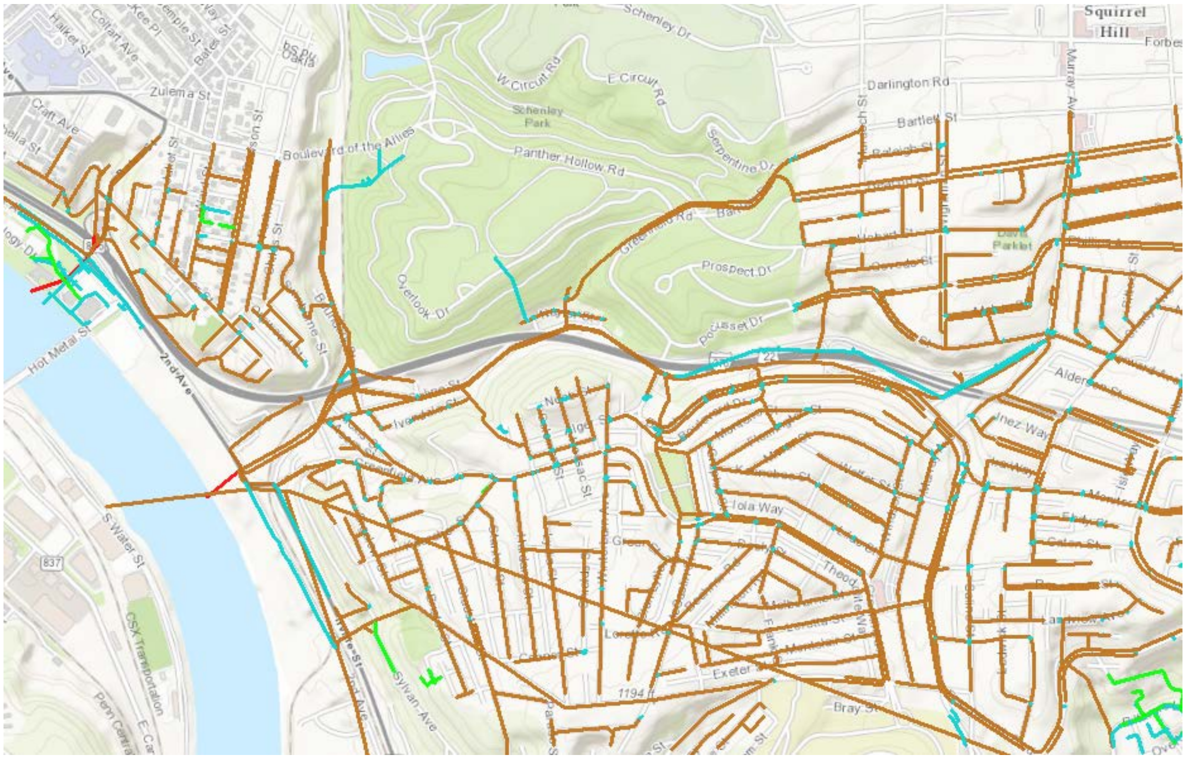

Figure 2.11. PWSA drainage pipes. Obtained by overlaying ArcGIS layer 'PWSA_Source_Pipe_Features_LBs_v01' with ArcGIS topographic basemap. Displayed by database field = 'SEWER_USE'.

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[4] GIS layer name: PWSA_Source_Pipe_Features_LBs_v01 in the attachments.

3. Outfall structures (Figure 2.12)[5]. Outfall structures are pipe outlet to allow storm water combined with sewage to flow into the environment during and/or after higher flow events. These structure locations are from the regional sewer network database, and are part of the combined sewer network.

4.

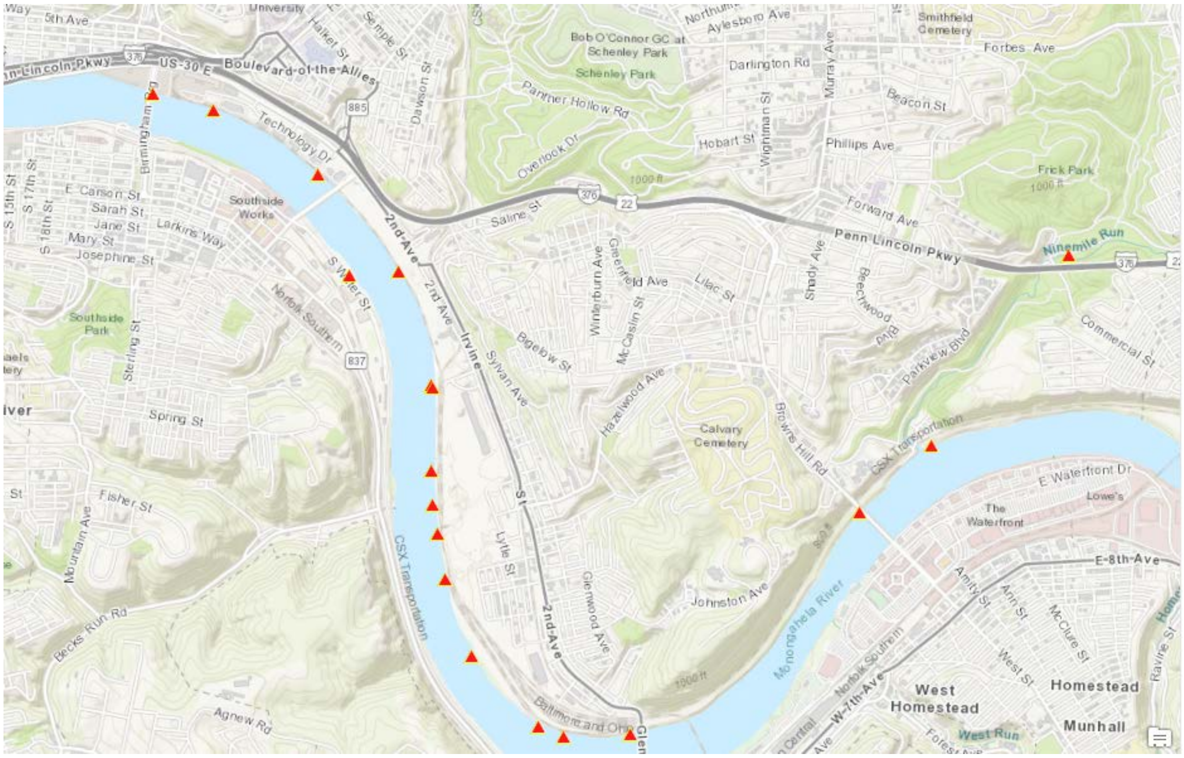

Figure 2.12. Outfall structures. Obtained by overlaying ArcGIS layer ‘Outfall_Structure_Locations_LBs_v13_point’ with ArcGIS topographic basemap.

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[5] GIS layer name: Outfall_Structure_Locations_LBs_v13_point in the attachments.

2.1.6 Administrative boundaries

1. Municipal boundaries (Figure 2.13)[6]. Obtained from the Allegheny County office. The shared boundaries between the municipalities and Pittsburgh neighborhood boundaries are synchronized.

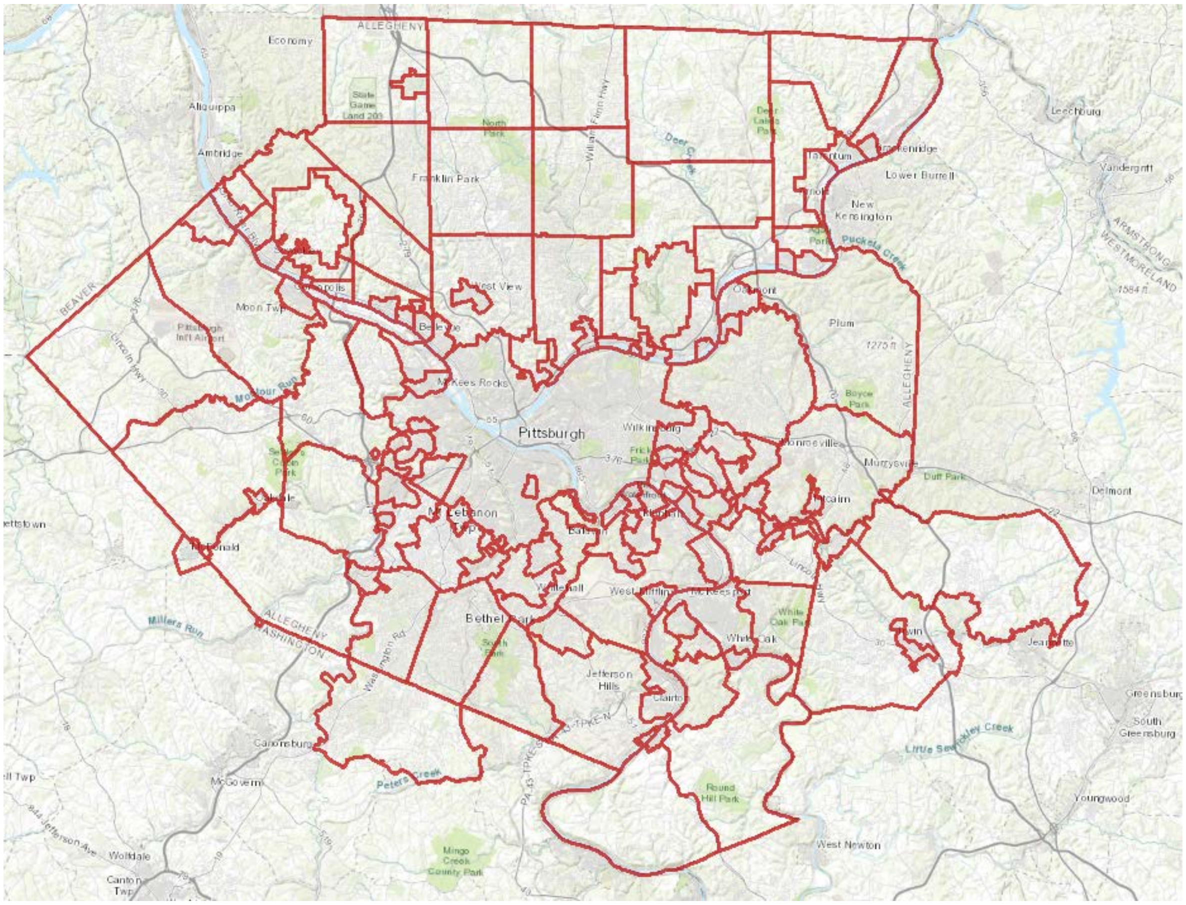

Figure 2.13. Municipal boundaries. Obtained by overlaying ArcGIS layer 'Municipal_Bounadries_LBs_v14_region' with ArcGIS topographic basemap.

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[6] GIS layer name: Municipal_Bounadries_LBs_v14_region in the attachments.

2. Neighborhood boundaries (Figure 2.14)[7]. Obtained from Pittsburgh's data office. This layer is used for identifying areas affected by runoff generated from PennDOT properties and areas responsible for generating runoff flowing onto PennDOT properties.

Figure 2.14. Neighborhood boundaries. Obtained by overlaying ArcGIS layer 'Pittsburgh_Neighborhoods_LBs_v14_region' with ArcGIS topographic basemap.

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[7] GIS layer name: Pittsburgh_Neighborhoods_LBs_v14_region in the attachments.

3. Allegheny County parcels (Figure 2.15)[8]. Data obtained from Allegheny County, used for identifying areas affected by runoff generated from PennDOT properties and areas responsible for generating runoff flowing onto PennDOT properties.

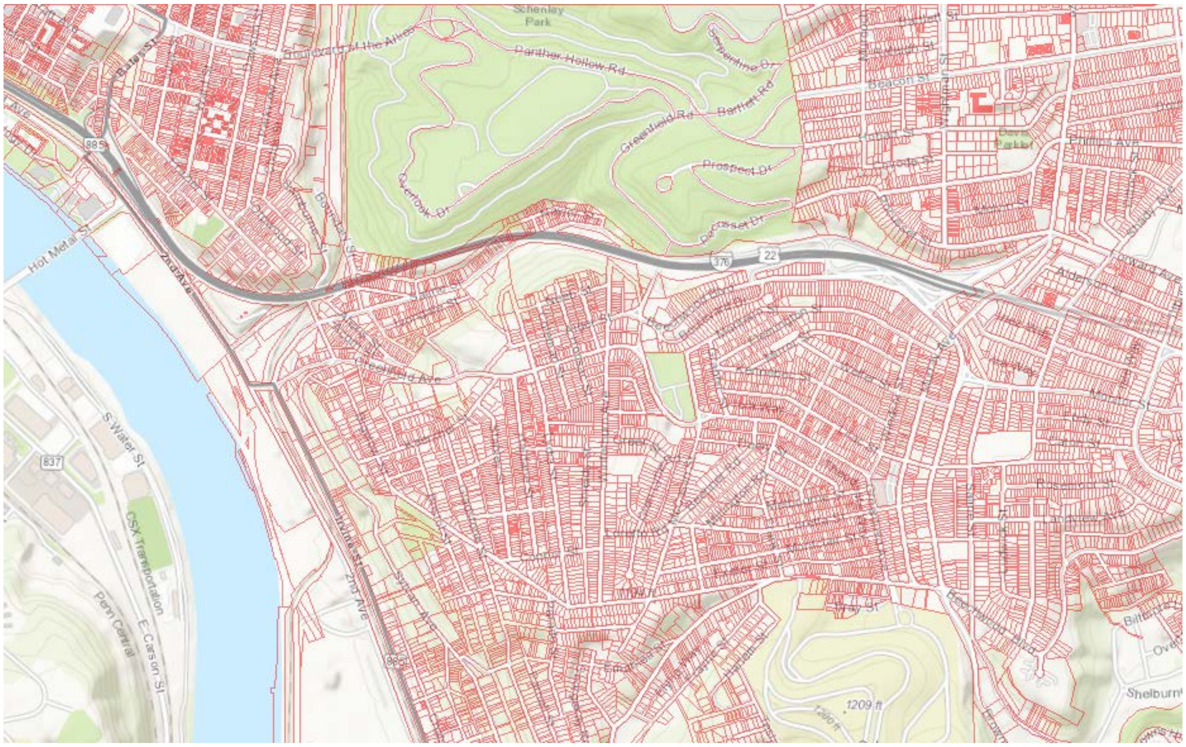

Figure 2.15. Allegheny County parcels. Obtained by overlaying ArcGIS layer ‘Allegheny_County_Parcels_LBs_v33_region’ with ArcGIS topographic basemap.

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[8] GIS layer name: Allegheny_County_Parcels_LBs_v33_region in the attachments.

2.1.7 Other data collected

1. Surface cover (Figure 2.16)[9]. This composite surface cover database was generated by cleaning up and merging five separate spatial databases: buildings (from Allegheny County buildings), paved surfaces (from Allegheny County parking edges), road surface (from Allegheny County edge of pavement), vegetation (from lidar), water (from Allegheny County hydro layers), and ground surface (in the absence of the previous five sources). This data can be used for setting up a drainage model using SWMM.

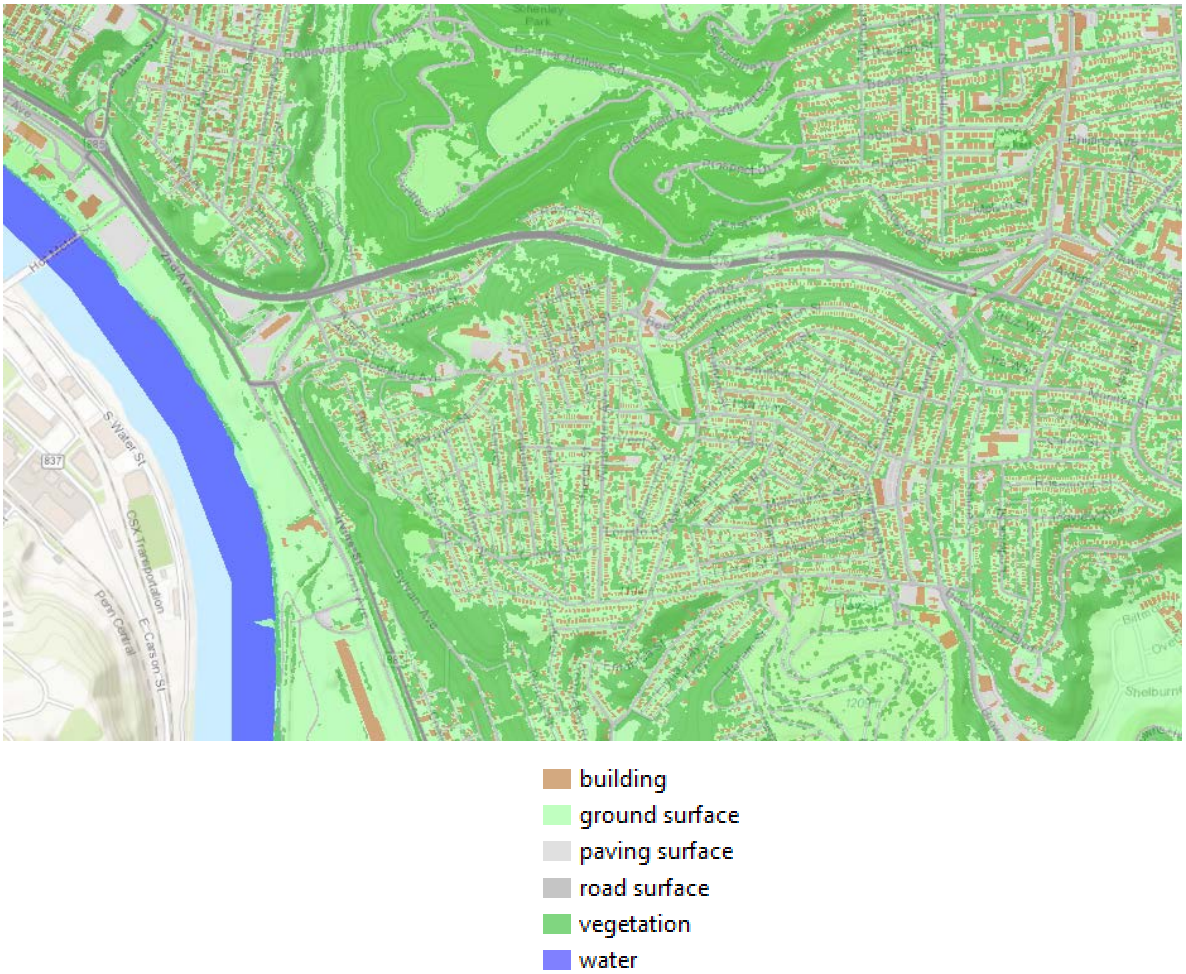

Figure 2.16. Surface cover. Obtained by overlaying ArcGIS layer ‘Surface_Cover_PennDOT_LBs_v47_region’ with ArcGIS topographic base map.

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[9] GIS layer name: Surface_Cover_PennDOT_LBs_v47_region in the attachments.

2. Soil type (Figure 2.17)[10]. Obtained from the NRCS database (https://sdmdataaccess.nrcs.usda.gov). The database field 'composite hydro drain short' was added to summarize theoretical USDA soil drainage rate classifications. This data can be used for setting up a drainage model using SWMM.

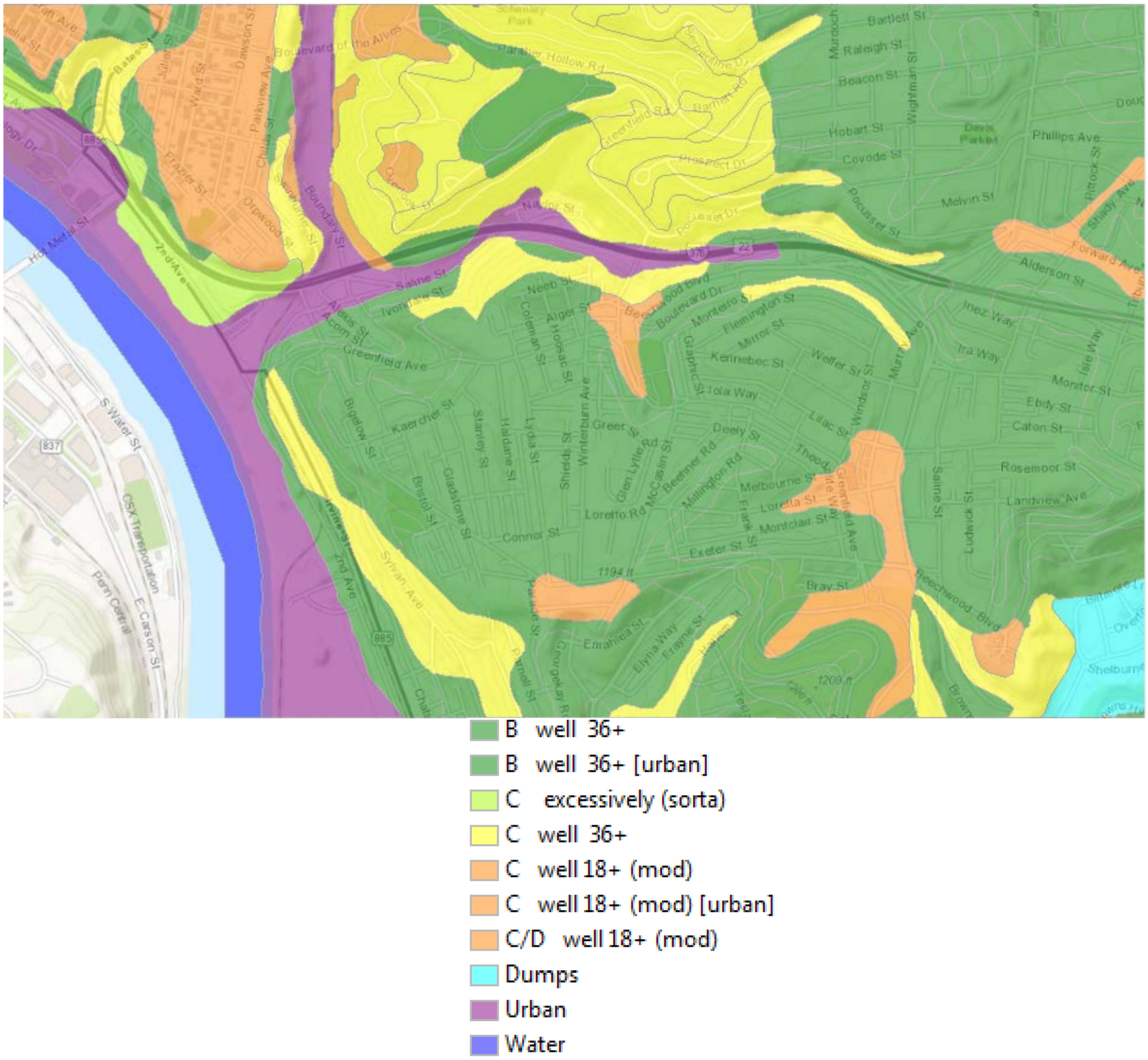

Figure 2.17. Soil type. Obtained by overlaying ArcGIS layer 'NRCS_soils_LBs_v07_region' with ArcGIS topographic basemap.

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[10] GIS layer name: NRCS_soils_LBs_v07_region in the attachments.

3. Interstate I-376 1980 plans (Figure 2.18)[11]. Scanned PennDOT PDF documents are used to find plans that included storm water inlet and pipe information. The subset of selected PennDOT PDF drawings was scanned at high resolution and rectified into a spatially consistent seamless coverage of the I-376 project area.

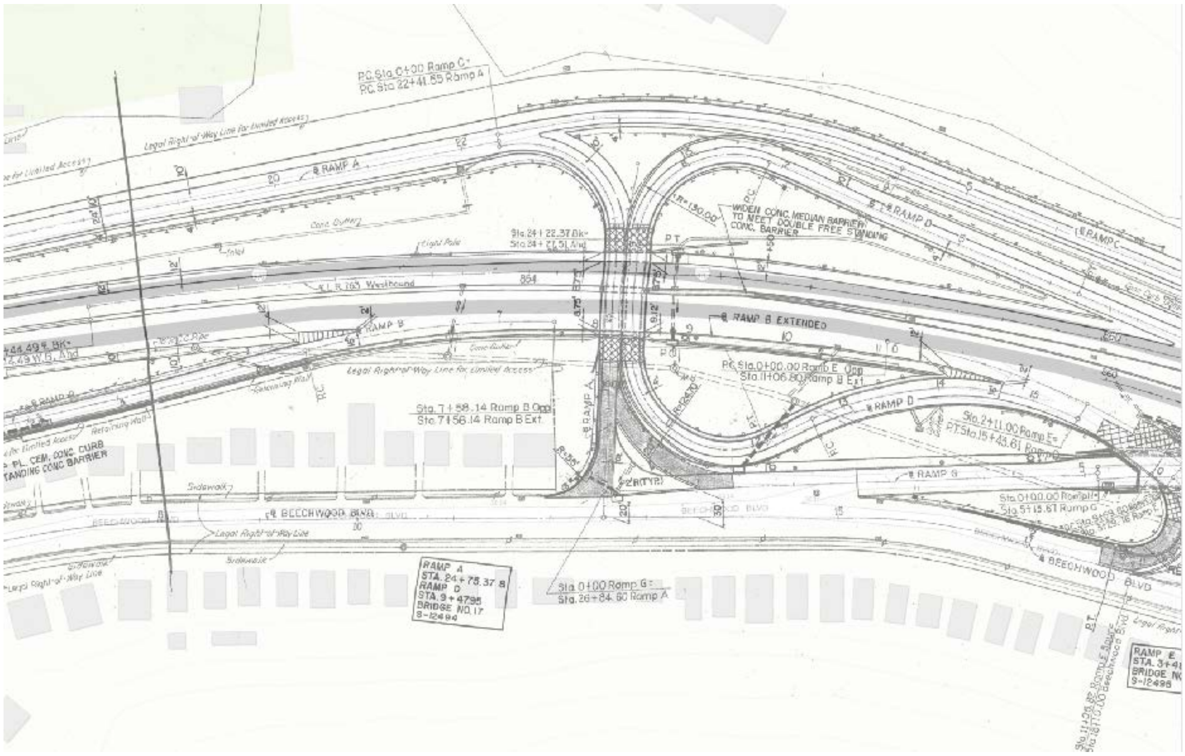

Figure 2.18. Interstate I-376 1980 plans. Obtained by overlaying ArcGIS layer ‘PennDOT_376_Drawings-1980.tif’ with ArcGIS topographic basemap.

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[11] GIS layer name: PennDOT_376_Drawings-1980.tif in the attachments.

2.2 List of files

ArcMap file: PennDOT Pitt Runoff Study Base Map1.mxd

Folder: spatialDB_mdb, spatialDB_raster, and spatialDB_shp

- LBs_Identified_Storm_Structure_LBs_v09u
- LBs_Estimated_Storm_Pipe_Features_LBs_v09u
- PWSA_Source_Drainage_Structure_LBs_v01_point
- PWSA_Source_Pipe_Features_LBs_v01
- Outfall_Structure_Locations_LBs_v13_point
- Municipal_Bounadries_LBs_v14_region
- Pittsburgh_Neighborhoods_LBs_v14_region
- Allegheny_County_Parcels_LBs_v33_region
- Surface_Cover_PennDOT_LBs_v47_region
- NRCS_soils_LBs_v07_region
- PennDOT_376-1980.tif

Folder:PittBreaklines.gdb

- UrbanHydroBreakline

Folder: Elevation_raster

- PittHydro_v1(Before modified)
- PittHydro_v21(After modified)

3. Identification of Flow Paths and Drainage Contribution Areas

This section constitutes the deliverable for Task 2—Identification of flow path and drainage contribution areas of the Pitt WO #014 project "Stormwater Analysis and Water Quality Assessment of Urban Areas." One study area in the City of Pittsburgh, Pennsylvania (PA) was selected for the project for Task 2.

The purpose of this section is to describe the methodology that was used in creating a flow model of the selected watershed in order to identify contributing areas related to the PennDOT highways in the watershed. This methodology could be used in identifying contributing flow areas for watersheds that interact with highways.

The study area covers parts of ***Interstate I-376 west of the Squirrel Hill Tunnel***. This document describes the procedures and results of determining the areas contributing flow into the PennDOT highway right-of-way and the areas affected by flow downstream from the PennDOT highway right-of-way. ArcGIS was the primary tool extensively used for this purpose. Two LiDAR datasets with different resolutions were used to demonstrate the impacts on the estimated contributing flow areas from LiDAR dataset resolution.

Generally, high-resolution LiDAR dataset is desirable and features like curbs and bridges need to be considered for modeling flow path accurately, which is important for modeling how salts are transported from their sources to streams.

3.1 Correct and modify digital surface model

The process begins by obtaining a digital surface model from an available source. For the study area selected, the following domain remote sensing datasets from Allegheny County were acquired.

2014 LiDAR (Meeting USGS QL2 Standards)
2014 Orthoimagery

Based on these two datasets, an iterative approach was employed to develop a modified Digital Surface Model (DSM) that is hydrologically correct. The modified surface model is capable of accurately depicting surface flow paths in an urban environment. The approach of this study made use of the following software with the surface model:

ArcGIS Desktop 10.X with the Spatial Analyst extension (ESRI Software)
LP360 Basic (QCoherent Software)

The tasks of performing this iterative process have been partitioned into seven (7) separate task groups as described below. This describes the methodology that could be used for any watershed of interest. The target audiences for the process documentation are users/analysts who may wish to duplicate the process. Table 3.1 describes features used and generated from the process.

Table 3.1 Feature list in correct and modify Digital Surface Model

File/Feature Class		Description
Breaklines		Vector format- lines
Initial Classified LiDAR point file		LAS format
Updated Classified LiDAR point file		LAS format
Initial Digital Elevation Model(DEM)	PittHydro_v1_elev.flt	
	PittHydro_v1_fill_3ft	
	PittHydro_v1_FloDir	
	PittHydro_v1_FloAcc	
	PittHydro_v1_sink	
	PittHydro_v1_elev.flt	
Updated Digital Elevation Model	PittHydro_v25_elev.flt	3ft DEM based on LiDAR ground points only, including breakline enforcement of culverts, berms, artificial sinks, and culverts.
	PittHydro_v25_fill_3ft	3ft DEM that was “filled” using z-threshold of 3ft
	PittHydro_v25_FloDir	Raster result of the flow direction process
	PittHydro_v25_FloAcc	Raster result of the flow accumulation process
	PittHydro_v25_sink	Raster result of the sink process
	PittHydro_v25_hillshade	Raster result of the hillshade process
Urban_Drainage_Model_Basic		ArcGIS Module

3.1.1 Getting started

The following is the sequence of operations that was performed to create the GIS model of the watershed. These are operation descriptions of the ArcGIS software used:

1) Set up ArcGIS Extensions - Turn on the LP360 and Spatial Analysts extensions
2) Add the LP360 toolbars: the main one is the LP360 toolbar
3) Use the LP360 “add LiDAR data” button to bring LiDAR into ArcGIS, NOT the “normal” add data button for GIS data. Can add individual LAS files or a whole folder.
4) Ensure they ***are open for read-write***. For a big area, load only the footprints.
5) Build pyramids for display efficiency.

The LiDAR uses the data format known as LAS. The LAS layer properties have several symbology and display options. One can manipulate the display of the LiDAR points from the LP360 toolbar.

This is further followed by adding the imagery, and/or adding (or creating) a geodatabase for breakline features (e.g., polylines). After completing these operations, a basic GIS model is available for modification to create a functional tool for analysis purposes.

3.1.2 Setting up the initial iterations

These steps were used to create the flow model.

1) Export an initial DEM from the LiDAR data using the LP360 export wizard. This initial DEM will be replaced in each following iteration by a new, modified DEM.
2) Run the toolbox model (or ArcGIS tools) to create 5 derived raster layers:
   FilledDEM (using 3ft z-threshold),
   Hillshade,
   FlowDir,
   Sinks, and
   FlowAcc (Flow Accumulation) which gives flowacc as output.
3) Symbolize sinks as a single class with one color.
4) Symbolize flowacc as 2 classes with value of 0-200 being “clear” and value >200 being colored. Manipulate the display properties by using the “classification” option on the Display properties tab changing the value thresholds.

Note: this 200 cells accumulation threshold is selected based on the acceptable results and can be changed in order to display different levels of detail in the flow accumulation layer.

3.1.3 Evaluating Sinks

Sinks were created in this step to simulate the outflow locations in the watershed.

The initial model uses a threshold value of 3ft to fill sinks in the DEM. In this task group, re-run the Fill command and evaluate this threshold.

This is part of the iterative process and will need to be repeated on each newly exported DEM. Once an appropriate fill threshold is established, it will remain constant for the remainder of the model development.

Reclassify each sink output to one class and give each layer a different color so they can be visually compared. Look at the Sinks with the “Tin with points” view in LP360. The primary goal of this task is to use the automated tools as much as possible to reduce the number of surface sinks to a manageable number without “overfilling” the surface.

The vast majority of sinks are small indentations in the LiDAR surface that can be automatically removed with the fill command. A reasonable starting point for a sink threshold is 3ft. Depending on the size of the area, the total number of sinks can be reduced from 10,000+ to just several hundred.

Reclassify LAS points from “ground” class to “Class 20” until the TIN is smooth in that area.

However, not all sinks should be removed. In some cases, sinks are legitimate and should be left alone. At the conclusion, save the ArcGIS project and re-export a new DEM from LP360.

Once the new DEM has been exported from LP360, re-run the raster model from Task Group #1, ensuring that any new fill parameter is updated as part of the Fill command. This will result in five new rasters. Rename all of them together for the next iteration.

At this point, MOST of the sinks that need to be removed have been removed either manually or automatically, and one can begin to evaluate the need to add gutter, berm, and culvert breaklines.

3.1.4 Creating breakline features

Breaklines are required in order to correct flow patterns from the GIS model

Zoom to 1:1000 or 1:2000 magnification to pan and look for issues/errors in the flow accumulation layer (see symbology instructions in Task Group #1). Evaluate issues at 1:400 magnifications, edit and digitize at 1:200 magnifications.

When a new feature class is created, check the box to ensure it has Z values (i.e., 3D polyline). Add the “LP360 Digitize Breakline” toolbar. There are a number of conflation tool of options, many of the options are pre-configured.

To dynamically show the impact of one’s new breaklines, use the display tab of the LAS layer properties and select the feature class being edited to enforce breaklines. The breakline will be enforced dynamically based on the conflate tool settings you choose.

Make sure the LAS files are open for R/W. Make sure the right points are displayed (ground points only) because they will be reclassified to the destination point class (check the “from” and the “to” classification settings). The goal here is to go From Ground To Class 20.

There are stamp tools, paintbrush style tools, and draw tools to support selecting points to be re-classified. Hit spacebar to say “done” and commit the changes with re-classifying. Even after “removing” the points from the ground class, the TIN may still block the flow, hence breaklines may have to be added.

Save edits, save project.

3.1.5 Raising the elevation of the Berms using ArcGIS

1) In Arc Catalog Delete any old versions of Berms_100 (if it exists)
2) In ArcCatalog, Copy Berms (right mouse click on Berms-> copy)
3) Paste and rename (right mouse click the Breakline Feature Dataset->paste, rename from Berms_1 to Berms_100)
4) Run the Data Management-> Features-> Adjust 3DZ tool on the Berms_100 features.

Make sure the Berms 100 feature class is added to your ArcGIS Project so that it can be used for breakline enforcement in the DEM Export process.

3.1.6 Exporting a new DEM from LP360, enforcing breaklines

This step starts the next iteration sequence to calibrate the model. Be consistent with iteration numbering. Each time a new DEM is exported, assign the next iteration number to it and all subsequent derivative layers.

Use the Export LiDAR data tool on the LP360 toolbar. This brings up the three-step wizard. Tell it which points (just ground) and make sure the breakline enforcement is checked and choose the feature class you want to include (e.g., Berms_100, Gutters, Culverts).

Choose just ground points, set the cell size (i.e., 3ft).

Surface method = TIN, use Binary Raster for the export (cleanest and fastest).

Can use any extent for the export for testing purpose. Doesn't have to be the limit of LiDAR data, can be just a particular AOI, watershed boundary, buffered area around the boundary, etc.

Export to a location, be diligent about version controls.

The end of this step is a newly extracted DEM that had some sinks removed by hand (through point classification) and has been "hydro-enforced" with one or more feature classes of breaklines (e.g., berms, gutters, culverts). In some cases, other points have also been reclassified to make the surface perform properly (e.g., around gutters). Every export REPLACES the previous export. Ultimately all the previous surfaces can/will be deleted. It is good to keep copies for a while to figure out how things have changed with each iteration, particularly when things aren't working as you might expect.

3.1.7 Iterations

To create a calibrated model iteration is required.

This new DEM export (each new iteration) needs to have sinks filled, new flow direction, new sinks and new flow accumulation performed and the results evaluated against the previous results for changes. Each breakline needs to be checked to ensure it had the intended effect.

If a breakline didn't work correctly, examine closely the surrounding elevation values in the TIN and find out why the breaklines are not working before simply re-drawing. By evaluating the surrounding elevations, one can determine where the flow will go after the breakline is enforced. Once a comprehensive set of breakline edit is completed (end of 1.3), go back to 1.4 and re-elevate the berms, export a new DEM and continue to iterate through breaklines until all areas have been cleared for proper surface flow behavior.

A module named **Urban_Drainage_Model_Basic** is built to export sinks, flow direction and flow accumulation from surface model directly in each iteration.

Once all issues have been resolved, the final DEM is ready for artificial stream and catchment delineation.

3.2 Identify drainage contributing areas

In order to create a model that specifies how different sources of runoff in the watershed impact the outflow, contributing flow areas need to be identified. Table 3.2 describes features used and generated in that chapter.

Table 3.2 Feature list in identify drainage contributing areas

File/Feature Class		Description
Highway		Vector format- lines
Low resolution DEM data		Raster, from PAMAP
Curbs		Vector format- lines
3High resolution DEM data In LowDEM.gdb	ArtificalStream_v21_2500	Artificial Stream with accumulation threshold 2,500 cells
	ArtificalStream_v21_20000	Artificial Stream with accumulation threshold 20,000 cells
	ContribArea_Bridge	Contribution area considering bridges and curbs
	ContribArea	Contribution area without considering bridges and curbs
	Outlets_bridge	Outlets of each contribution area located at highway (highway entrance points) considering bridges
	Outlets	Outlets of each contribution area located at highway (highway entrance points) without considering bridges
Low resolution DEM data in ModifiedHighDEM.gdb	ArtificalStream_v21_2500	Artificial Stream with accumulation threshold 2,500 cells
	ArtificalStream_v21_20000	Artificial Stream with accumulation threshold 20,000 cells
	ContribArea_Bridge	Contribution area considering bridges and curbs
	ContribArea	Contribution area without considering bridges and curbs
	Outlets_bridge	Outlets of each contribution area located at highway (highway entrance points) considering bridges
	Outlets	Outlets of each contribution area located at highway (highway entrance points) without considering bridges

3.2.1 Creating artificial streams and catchments

The definition of catchment areas is developed by creating artificial streams to identify and delineate them.

With modified DEM created in Chapter 1, new flow direction and flow accumulation features can be generated as shown in table 1.

Run the toolbox model Spatial Analyst > Set Null, set flow accumulation feature (e.g. PittHydro_v25_FloAcc) as input conditional rater. Use expression such as to Value < 2000 in this step, any raster grid with VALUE below the set threshold would be changed to Null. Save the output as SetNullZ, replacing “Z” with the flow accumulation threshold (e.g. 2000).

Run “Set Null” tool in Spatial Analyst toolbox

Output raster: SetNullZ (Replacing "Z" with the flow accumulation threshold (e.g., 2000 cells)

Run the Spatial Analyst -> Hydrology -> Stream to Feature tool:

Input stream raster: "SetNullZ"

Input flow direction raster: "FlowDir",

Output polyline features: ArtificalStreams_Z.

Then create artificial catchment under select stream network.

Using tool Spatial Analyst -> Hydrology -> Stream Link:

Input: SetNullZ, flow direction

Output: StrLnkZ.

Using tool Spatial Analyst -> hydrology -> Watershed:

Input: StrLnkZ(replacing Z with the flow accumulation threshold)

Output: WatershedZ

Finally using toolbox Raster to Polygon convert raster watershed WatershedZ to polygons named CatchmentsZ.

A module, "Urban_Drainage_Model_Catchments", is built incorporating above steps, using user-provided elevation, flow direction, flow accumulation and threshold to create artificial stream and catchment directly.

3.2.2 Evaluating flow accumulation Threshold

A minimum threshold needs to be established to create catchment areas with significant flows.

Try and iterate the above module to obtain streams and catchments with different threshold values to generate stream layer with complexity appropriate for analysis. The purpose is to locate stream flow entrance point to PennDOT property right-of-way. Those entrance point is identified by intersecting stream polyline with PennDOT right-of-way boundary. These entrance point has been used for finding the corresponding flow contributing area.

For the study, an accumulation threshold of 20000 cells is considered appropriate for determining flow entrance to highway right-of-way. To include more details on small contributing area, an accumulation threshold of 2500 cells is selected.

3.2.3 Identifying entrance points to highway right-of-way from other properties

In order to identify contributing flows that are not highway related, entrance points need to be identified for these pervious flow areas on private property.

In Arc Catalog, create new point shapefile named outlet. Open editor tool, click “start editing”, select “outlet” shapefile as editing feature. In editor tool bar, click “create feature”.

Locate intersection points between flow path (ArtificalStream20000) and highway right-of-way boundary. Click on each intersection point to create point feature in outlet shapefile.

Open ArtificalStream2500 to check if there are missing intersection points for main stream flow path. Add missing points to the outlet feature.

3.2.4 Delineation of contributing area

This is the final step to identify contributing areas.

After getting entrance points to the highway right-of-way, contributing area corresponding to each entrance point could be generated by using the entrance point identified as outlets in watershed delineation.

In Arc Toolbox, open toolbox Spatial Analyst > Hydrology > Watershed. Input flow direction (FloDir) and input entrance points (outlet) as pour point, save output as ContribArea. This produces a contribution area for each entrance point (outlet).

3.3 Compare flow path and drainage area from different resolution LiDAR data

3.3.1 Data source

Once the model is established, the impacts of the resolution of LiDAR data on the results can be determined. This procedure for doing so is given below.

The first dataset we focus on is 2014 LiDAR (Meeting USGS QL2 Standard) remote sensing datasets from Allegheny County. The first chapter is also based on this dataset. Another public-available lower-resolution LiDAR dataset which only meets USGS QL1 standard was used for comparison. The lower-resolution LiDAR dataset is obtained from PAMAP (dataset is also freely available from PASDA). Web links to the dataset are listed here:

http://www.pamap.dcnr.state.pa.us/pamap/data_source.aspx
http://www.pasda.psu.edu/

Data processing procedure described in Chapter 1 is only applied to high-resolution LiDAR dataset because small elevation changes in reality (e.g. road curbs) can only be identified by dataset with high enough resolution. When the elevation data resolution is not high enough, the flow paths may not appear naturally (for they would not follow the roadway when they should have).

3.3.2 Comparing “flow-to-PennDOT highway right-of-way” area without considering curbs and bridges using different resolution datasets

Curbs and bridges are important features and their inclusion affects the results obtained. This section describes the results obtained without including them in the modeling. These results do not consider bridge as an elevated partially-confined structure.

By using the method presented in Chapter 2, we obtained the areas contributing flow to PennDOT highway right-of-way from both LiDAR dataset. Figures 3.1 and 3.2 are the respective identified contributing areas.

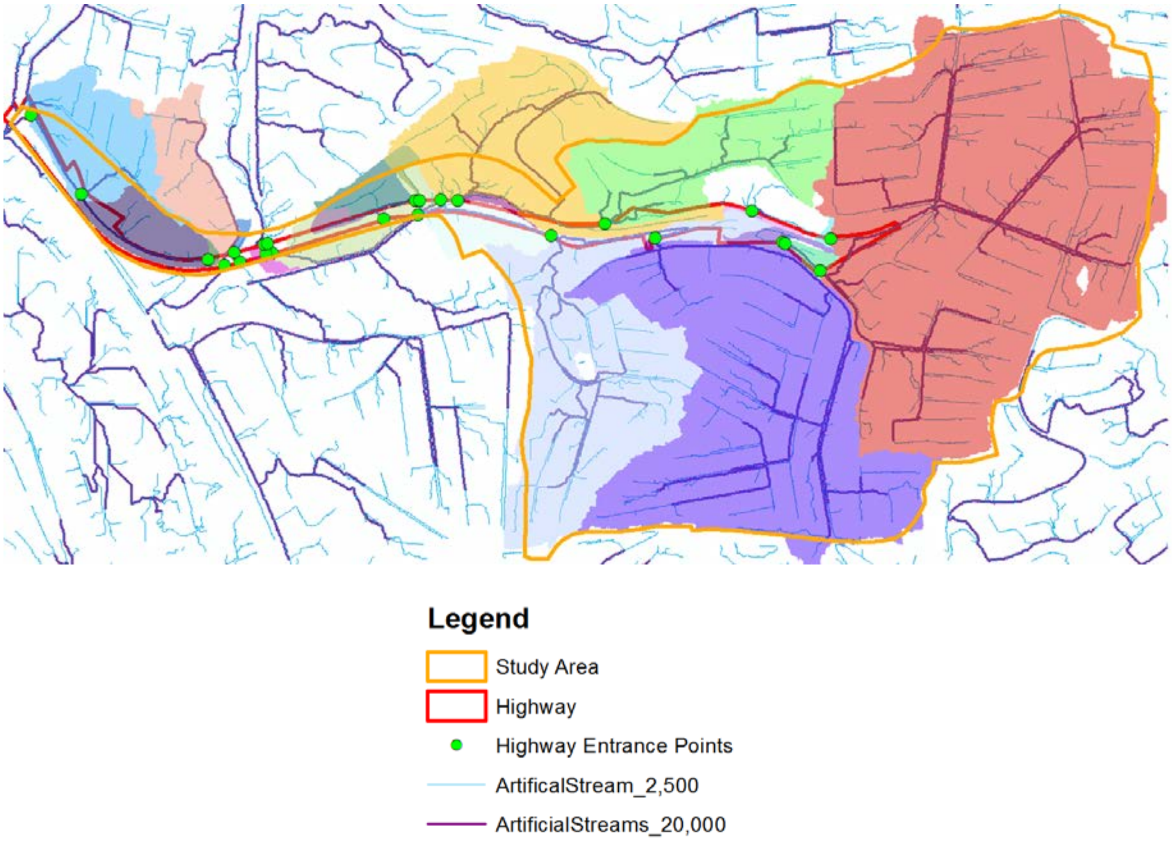


Figure 3.1 Contributing area to highway based on modified high-resolution (QL2, 2 pt/m^2) LiDAR data

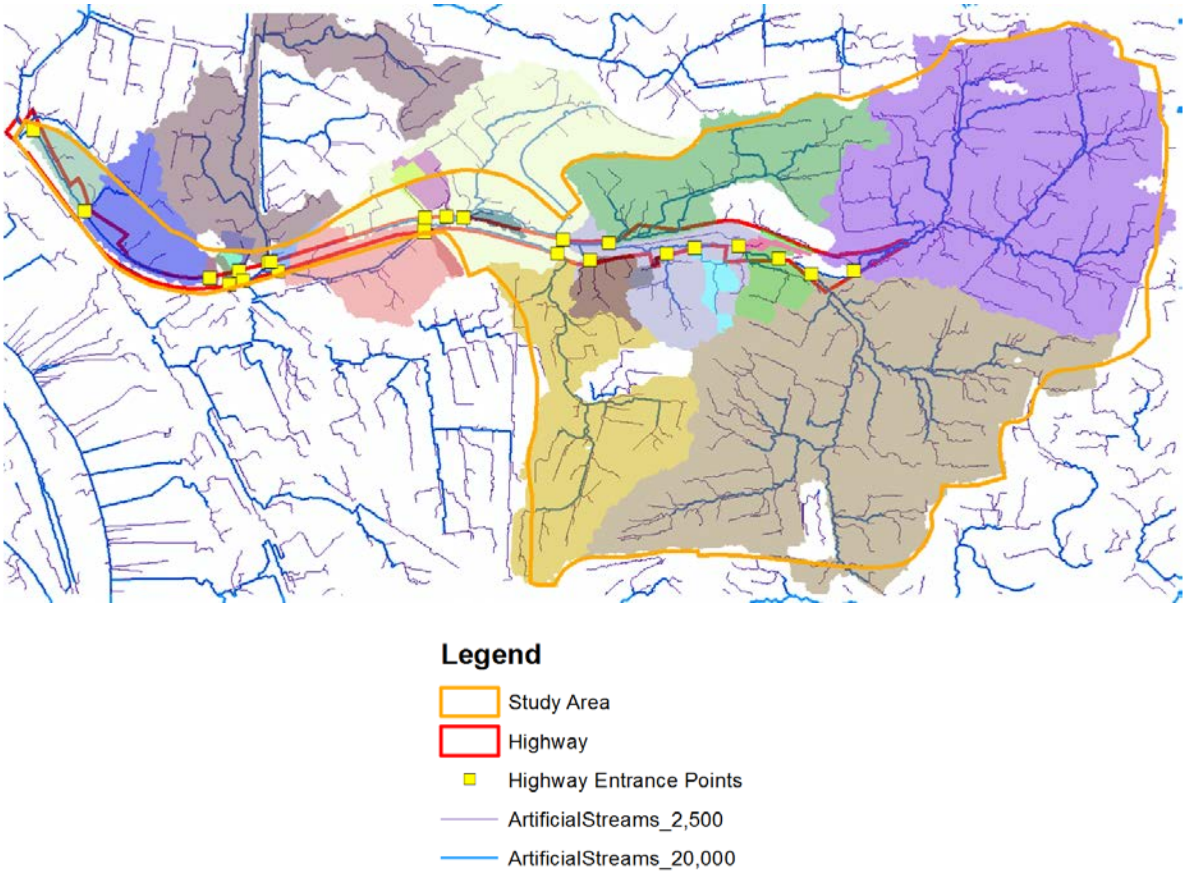


Figure 3.2 Contribution area to highway based on low-resolution (QL1,1 pt/m^2) LiDAR data

The two identified contributing areas are similar in terms of total areas, but differences are seen at locations near the bridge, in which the use of low-resolution dataset gave larger contributing area.

The two different resolution elevation datasets have different results in the shape and area for each of the small contributing area. Similar differences were observed in the outlet locations of each small contributing area. Therefore, depending on the areas where salt is applied, the flow path differences could potentially impact the chloride concentration estimation on affected areas.

3.3.3 Comparing "flow-to-PennDOT highway right-of-way" area considering curbs and bridges using different resolution datasets

This section describes the results obtained with curbs and bridges included in the model and how the results changed based upon these features.

Both datasets discussed in this study only contain ground elevation—this is the norm, as a result two bridge segments along PennDOT highway are not properly represented because of curbs leading to a bridge and the bridge itself are elevated structure. That is, water can only move along the curbs and flow onto the bridge. Furthermore, water on the bridge cannot move freely out of the bridge borders unless through a draining system.

As part of the highway is often curbed which changes runoff flow path to move along the road direction. These curb structures are identified using google map street view. Figure 3.3 shows the identified the curb and bridge locations.

To examine bridge and curb effect, a detailed stream flow path (created by setting threshold = 250) is used to see if water interacts with the curbs and bridges correctly. Figures 3.4 and 3.5 show the areas contributing flow when bridges and curbs are considered. Compare to the results without accounting for them as shown in Figures 3.1 and 3.2, the main differences occurred in the areas around the bridge. In the locations where both curb and bridge are present, alteration to flow path could be observed. But for other locations, the effect is not significant.

After incorporating bridge and curbs, the total flow contributing areas of these two datasets are still similar, while using low-resolution dataset leads to a little bit larger contributing area. The sizes of each small contributing area are again different for the two datasets.

Figure 3.3 Highway and curbs around the highway

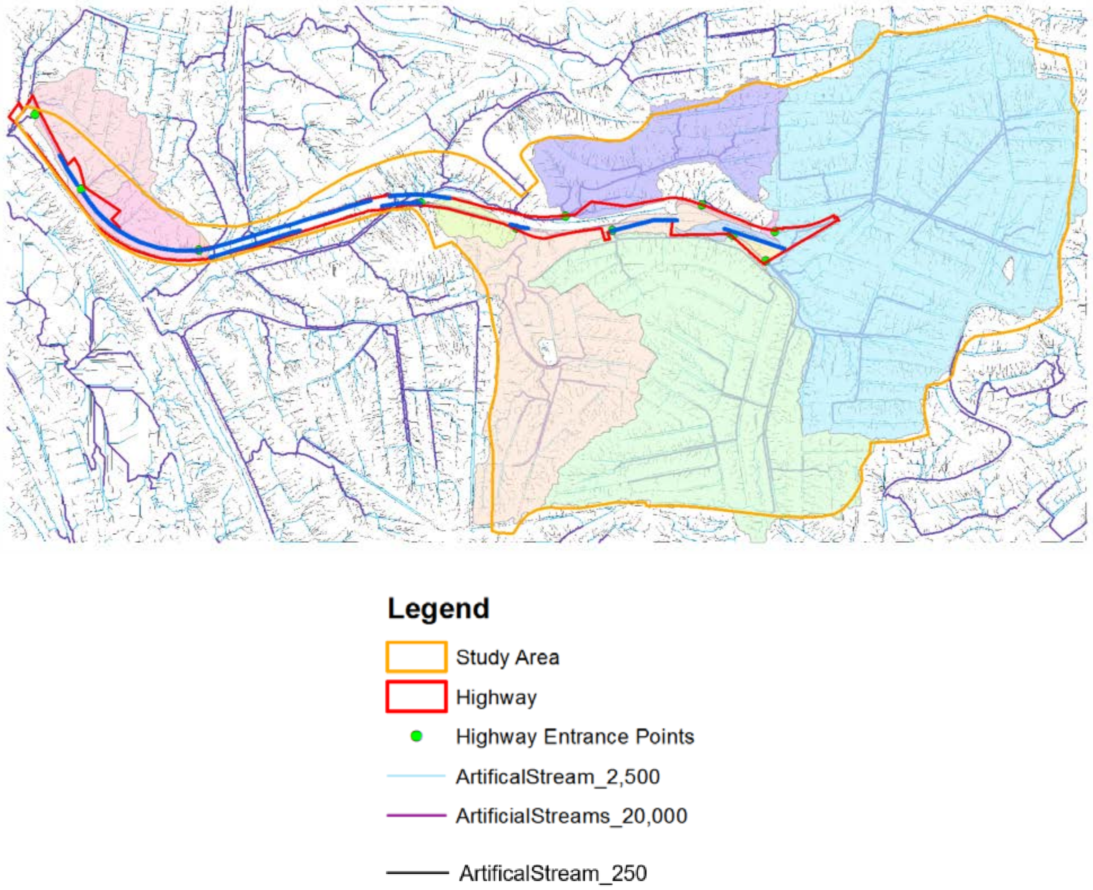


Figure 3.4 Contribution area to highway based on modified high-resolution (QL2, 2 pt/m^2) LiDAR data with bridge and curb effect considered

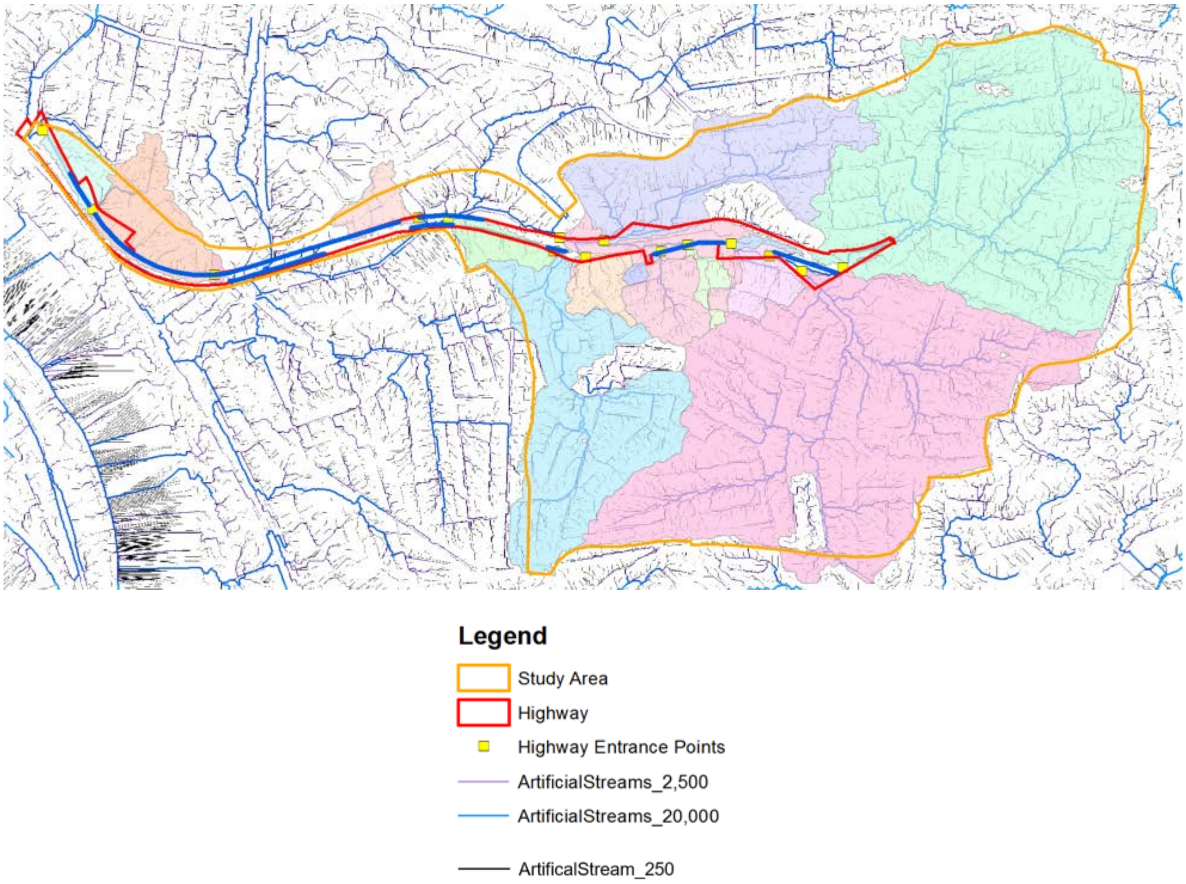


Figure 3.5 Contribution area to highway with low-resolution (QL1,1 pt/m^2) LiDAR data with bridge and curb effect considered

3.4 Generate areas affected by flow from PennDOT highway

Another goal of the modeling is to identify the areas in which flow from PennDOT highway enters. How those areas were identified is described herein. Table 3.3 summarizes the features that have to be built for delineating the flow areas.

Table 3.3 Feature list for obtaining areas affected by flow from PennDOT highway

File/Feature Class		Description
High resolution DEM data In LowDEM.gdb	HighwayboundayFullHigh	txt file Latitude and longitude of highway boundary points
	HighwayboundaryFullNoBridgeHigh	txt file Latitude and longitude of highway boundary points without bridge parts
	HighAffectedArea	Vector format- points Affected Area without bridges effect
	HighAffectedArea_bridge	Vector format- points Affected Area with bridges effect
Low resolution DEM data in ModifiedHighDEM.gdb	HighwayboundayFulLow	txt file Latitude and longitude of highway boundary points
	HighwayboundaryFullNoBridgeLow	Txt file Latitude and longitude of highway boundary points without bridge parts
	LowAffectedArea	Vector format- points Affected Area without bridges effect
	LowAffectedArea_bridge	Vector format- points Affected Area with bridges effect
GetHighwayPoint		ArcGIS module
GetHighwayPoint_ConsiderBridge		ArcGIS module
TraceDownStream		ArcGIS module Get affected area points

3.4.1 Identifying areas into which the flow from PennDOT highway enters

After identifying the contributing areas of flow into PennDOT highway right-of-way, we also estimated the areas affected by flow generated from PennDOT highway right-of-way.

To determine the areas affected by flow from PennDOT highway, we need to know downstream flow path for each pixel on the highway. The procedure encompasses the following steps:

1) Obtain the highway boundary points as input.

   This part of work is calculated based on point features, and therefore requires every relevant component be converted to points first.

   The first step is to convert highway boundary polyline to points. The way to convert polyline to pixel points is as follow:

   Conversion Tools -> To Raster -> Polyline to Raster. Note: the cell size needs to be the same as the elevation data you use.

   Conversion Tools -> From Raster -> Raster to Point. Output point shapefile is saved as “HighwayFullZ” or “HighwayFullZ”, replacing “Z” with “High” or “Low”. Here High and Low means the high-resolution dataset and low-resolution dataset you use.

   GIS tool GetHighwayPoint is built to include all above processes. Highway boundary polyline and cell size should be provided. Cell size information could be obtained from the property of elevation dataset.

   If bridge feature is to be considered, boundary points corresponding to the bridge segments should be deleted, so that these points won’t act as a source of water flowing to other properties (water on bridge surface cannot move freely to another area due to the semi-confined nature of bridge surface). These mentioned points could be either manually deleted from “HighwayFullZ” based on the curbs location and map in editing mode, or done by taking advantage of the GIS Erase tool to remove points using “HighwayFullZ”as mask. Save the modified point shapefile as “HighwayFullZB”.

   Tool GetHighwayPoint_ConsiderBridge is built to include above processes with highway polyline, bridge polygon and the cell size as required input. Cell size information could be obtained from the property of elevation dataset.

   Add X and Y coordinates to point shapefile. Right click “HighwayFullZ” or “HighwayFullZB” to open attribute table, add field with “double” type, name the field to “X”. Right click “X”, select Calculate Geometry, select “X Coordinate of Point” in “Property” column. Then one gets the x coordinate of each point. Add y coordinates in a similar way.

   After getting both x and y coordinates of points, export it to a “.txt” file. Right click “HighwayFullZ” or “HighwayFullZB”, select “Data” and “Export Data”. Save output feature class to “HighwayFullZ.txt” or “HighwayFullZB.txt”.

2) Import elevation data to generate flow direction using Fill and Flow direction tools.

   Convert raster to arrays to get upper left(x,y), cell width, and cell height. This enables the access to the raster value of the cell associated with our point.

3) Move start point from its current location to the next downstream cell according to flow direction (8 direction) within the raster.

Check the value (1,2,4,8,16,32,64) of flow direction grid and move the point accordingly. If the value of flow direction cell isn't the eight-direction value, which means the cell is part of a sink, the point will not move to the next point but stop. That's because the fill threshold is set to 3 feet which has been explained in Chapter 1: not all of the sinks have been filled.

Get the next downstream neighbor location, increment the current (row, col) pair and return the results.

4) Repeat the process until the point moves beyond the extent of elevation dataset we import.

   Loop step 3 with return location (row, col) to find next downstream location.

5) Store all the flow points coordinates from that start point.

6) Move to next start point along the highway and repeat the process.

   Loop step 3,4 and 5 for the next start point at highway boundary.

7) Store the flow points if they didn't exist before.

8) Use the new array to store the results without repeat points. Add flow point location coordinates in step 6 which doesn't appear in step 5. The reason to do that is to free the memory. For example, the points of two flow paths would be counted twice after they Covert the points to point shapefile.

   Save the output of the module as "Affect Area" with or without bridge and curbs considered for high and low datasets.

Figure 3.6 shows an example output. The area marked with pink color is the affected area by flow from PennDOT highway. The red line refers to PennDOT highway boundary.

When analyze the output, one should consider both the size of the affected area and the location of outlets from highway. Figure 3.7 shows the details of Figure 3.6's right end. Runoff flows out of the highway from many outlets even though the flow path is not long. Runoff flowing out from these outlets will affect the neighborhoods.

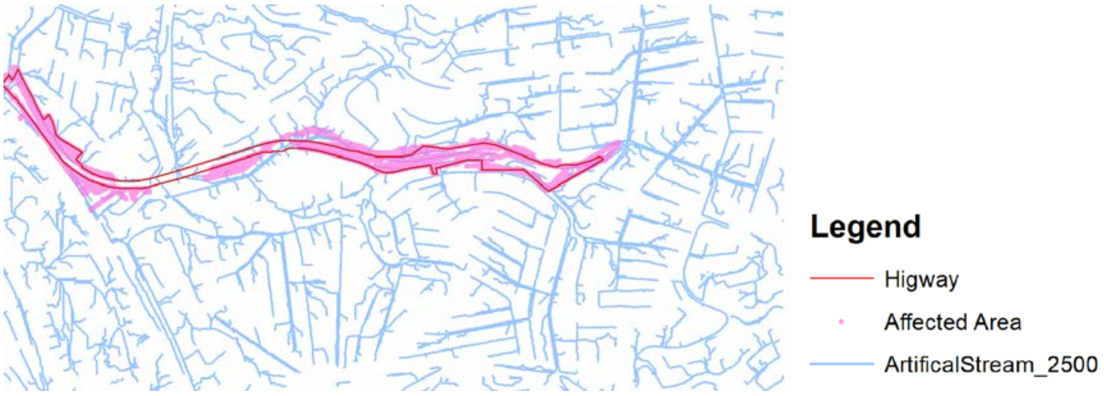


Figure 3.6 Example of module output

3.4.2 Comparing affected areas with and without considering bridges and curbs

The changes in PennDOT contributing flow areas after including bridges and curbs in the modeling are examined below.

Figures 3.7 and 3.8 show the results obtained. These results suggest, as expected, that considering bridge and curbs would result in different flow paths. The differences are more pronounced for the high-resolution dataset. For the low-resolution dataset, affected areas outside the highway with or without considering bridge are similar.

Figure 3.7 Area affected by flow from PennDOT highway based on modified high-resolution (QL2, 2 pt/m2) LiDAR data with and without bridge and curb effect considered

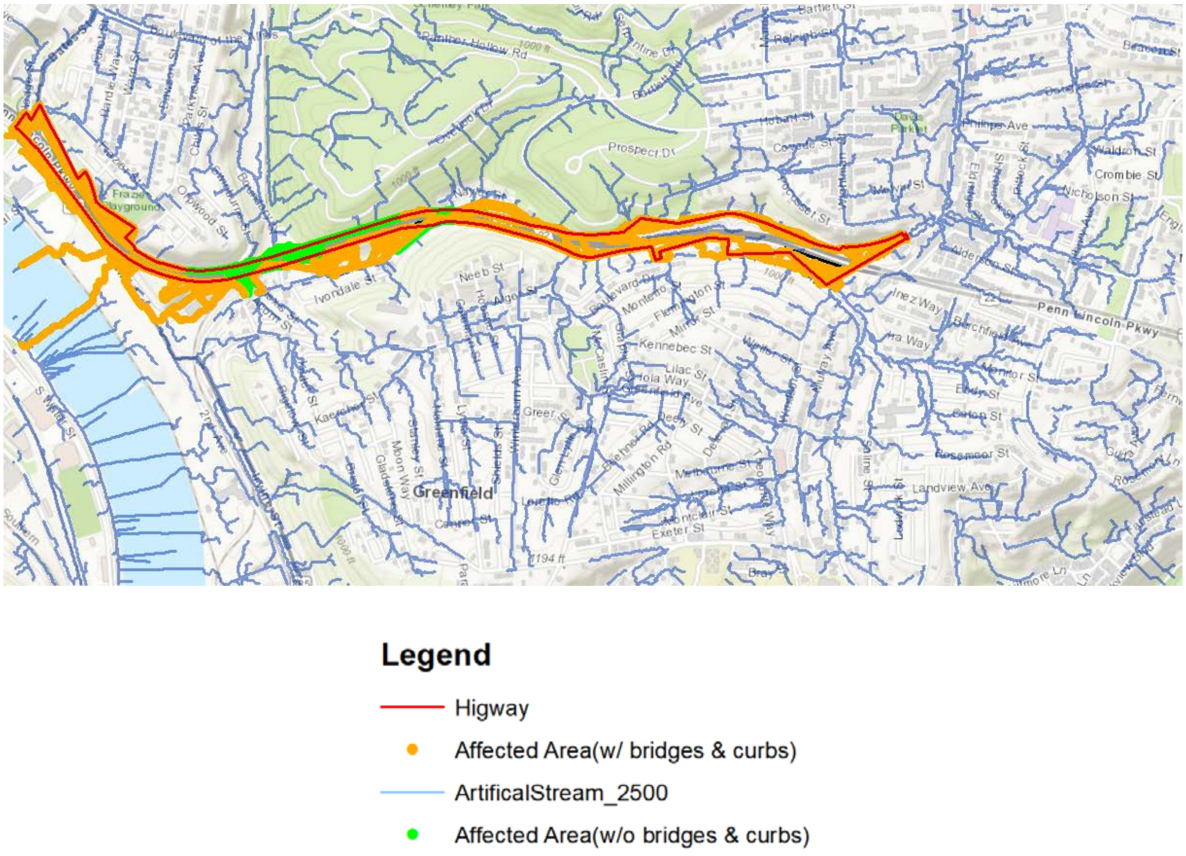


Figure 3.8 Area affected by flow from PennDOT highway based on low-resolution (QL1, 1 pt/m2) LiDAR data with and without bridge and curb effect considered

3.4.3 Comparing affected areas with different resolution dataset

The affected areas generated from low-resolution dataset are larger than those generated from high-resolution dataset with or without considering the presence of bridge and curbs. The differences in areas are located mainly at west part of the study area near the river.

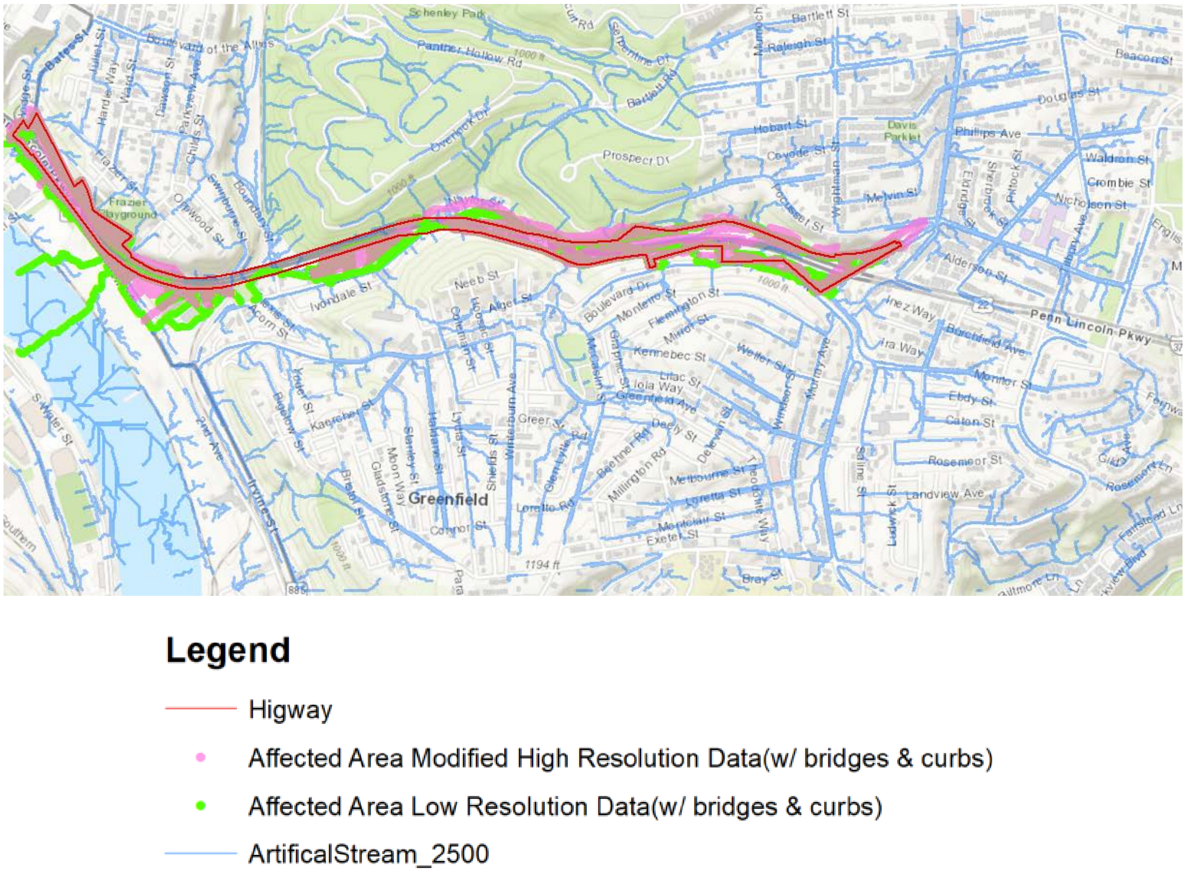


Figure 3.9 Area affected by flow from PennDOT highway based on modified high-resolution (QL2, 2 pt/m2) LiDAR data and low-resolution (QL1, 1 pt/m2) LiDAR data with bridge and curb effect considered

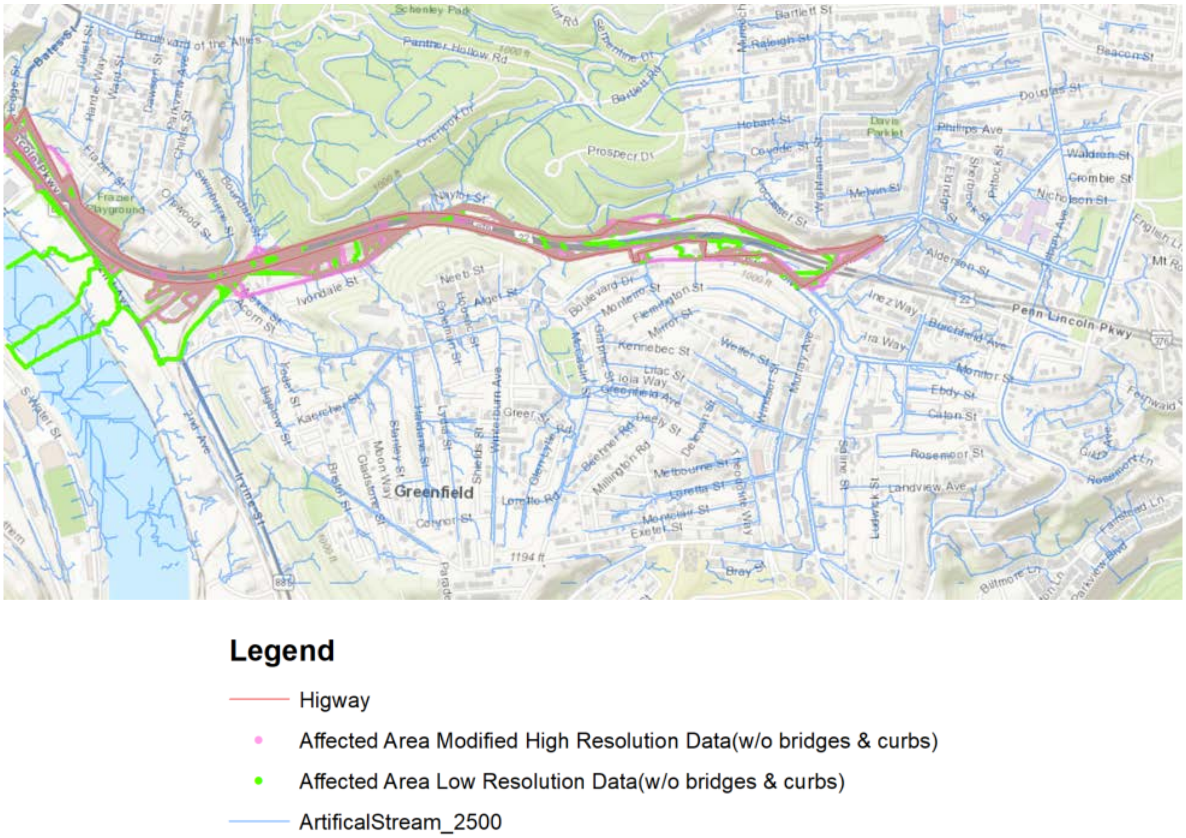


Figure 3.10 Area affected by flow from PennDOT highway based on modified high-resolution (QL2, 2 pt/m2) LiDAR data and low-resolution (QL1, 1 pt/m2) LiDAR data without bridge and curb effect considered

3.5 Summary

The results obtained show that the modified high-resolution (Meeting USGS QL2 standard, 2 pt/m^2) LiDAR data and low-resolution (Meeting USGS QL1 standard, 1 pt/m^2) LiDAR data could produce different flow paths and sub-watersheds. But the total accumulated flow may not be significantly affected by these two different sets of base data for cases studied.

In terms of the data accessibility and processing complexity, low =-resolution data is easier to download and process than high-resolution data. However, the choice of the resolution depends on the site and objectives of the study. In general, if the total contributing area for flow into highway is needed, low =-resolution data would suffice. But if accurate chloride concentration estimation is desired, high =-resolution dataset is recommended. This is because accurate chloride concentration estimation requires information like the contribution of each small basin and their outlet locations on the highway. The flow path differences could potentially affect the chloride concentration estimation depending on the areas where salt is applied.

It is important to note that regardless of the resolution of the dataset used, the locations where curbs and bridges are should be properly incorporated.

Areas affected by flow from PennDOT highway right-of-way obtained using high-resolution LiDAR data is smaller than that obtained from the low-resolution LiDAR data. Using low-resolution LiDAR data, the affected area turns out similar with or without considering bridge and curbs modification on flow path in the cases studied.

The runoffs from highway in the study area are mainly flow from the boundary of bridges and curbs. Runoffs will move across the curbs into surrounding neighborhoods if curbs do not cover the entire part of bridges. Curbs should be an important part of roadway GIS modeling. The study clearly shows that the modeling presented is capable of capturing how curbs force flow to move along the roadways into the underground pipe network through the inlets on the highway.

Wherever a river intersects a highway, runoffs from the highway may flow directly into the river through pipe inlet on the highway (e.g. Nine Mile Run and I-376 across section). Hydrological modeling could provide a critical part of analysis on how and to what extent salt applied on highway would affect the chloride concentration of the river. The presented procedure and pathway modeling framework can complement hydrological modeling and provide a comprehensive picture of where the water flows to from the highways, and, for that matter, the destination of the salts. But without comprehensive and detailed hydrological modeling, the study cannot quantify how salt is transported by flow.

It is worth mentioning that all the conclusions presented here are only for the cases investigated in this project. More study/investigation is necessary to draw more general conclusions.

4. Stream Water Sampling and Laboratory Testing on Water Quality Impacts Caused by Highway Salt Operation

This section constitutes the deliverable for Task 3—Stream water sampling and laboratory testing on water quality impacts caused by highway salt operation—of the Pitt WO #014 project “Stormwater Analysis and Water Quality Assessment of Urban Areas.” Two study sites in the City of Pittsburgh, PA, were selected for Task 3 of this project. This section describes the work carried out for Task 3. This document details the urban stream water quality monitoring, sampling activity, laboratory analytical method, and result analysis.

We found that salt operation on roadways causes a rise in stream chloride concentration in the winter time. The Criteria Maximum Concentration (CMC) regarding chloride acute toxicity has been exceeded during winter salting period for both sites we studied. However, we also found that the lower Criteria Continuous Concentration (CCC) regarding chloride chronic toxicity has been exceeded in non-winter baseline flow period even without road salt impact for both sites.

Another finding is that there is little lingering effect of road salt impact on stream chloride level based on the limited number of water samples (about 300 samples) we have collected. Stream chloride peak drops down fast after precipitation at the two study sites.

4.1 Sampling

4.1.1 Sampling site and location

Two stream water sampling sites were chosen in the City of Pittsburgh region. The Nine Mile Run (NMR) site is an urban watershed and a delineation of NMR watershed is presented in Figure 4.1. At this site, a stream runs underneath a PennDOT highway bridge and the bridge's drainage system diverts runoff from the bridge surface directly to the stream (see Figure 4.2).

Four sampling locations (Figure 4.3) are selected to study potential impact of de-icing salt applied to the bridge surface on the stream water quality of NMR. Among them, two sampling locations (#1 and #2) locate on the upstream of the bridge for monitoring background stream water quality. The other two locations (#3 and #4) locate on the downstream of the bridge allowing for examination of changes in stream chloride concentration due to runoff that carried salt from the bridge.

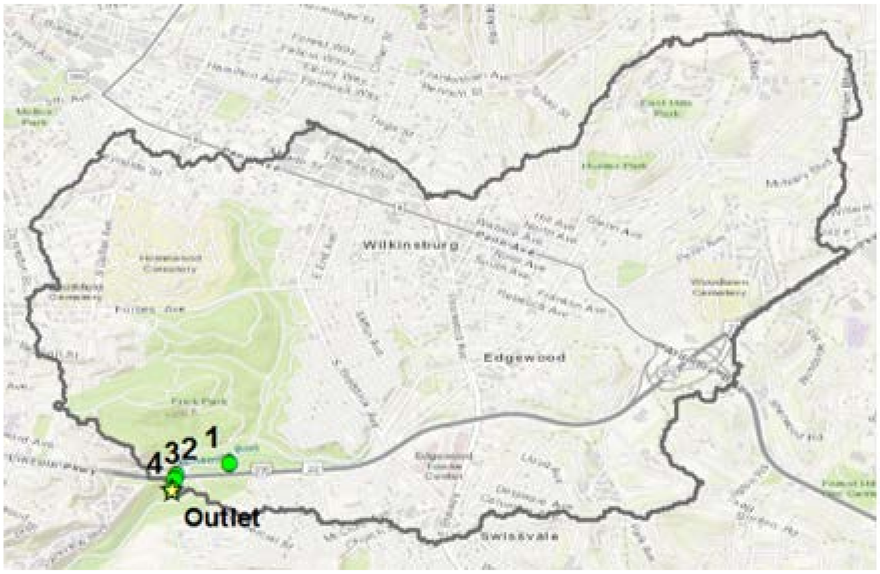


Figure 4.1 Nine Mile Run watershed delineation

Figure 4.2 Drainage pipe from PennDOT bridge to NMR

Figure 4.3 NMR sampling locations

Pine Creek (PC) is the other site located in the north of the City of Pittsburgh and the delineation of PC watershed is presented in Figure 4.4. This site is chosen to examine the impact of a PennDOT salt stockpile near the stream (see Figure 4.5). Three sampling locations are selected for the PC site as shown in Figure 4.5.

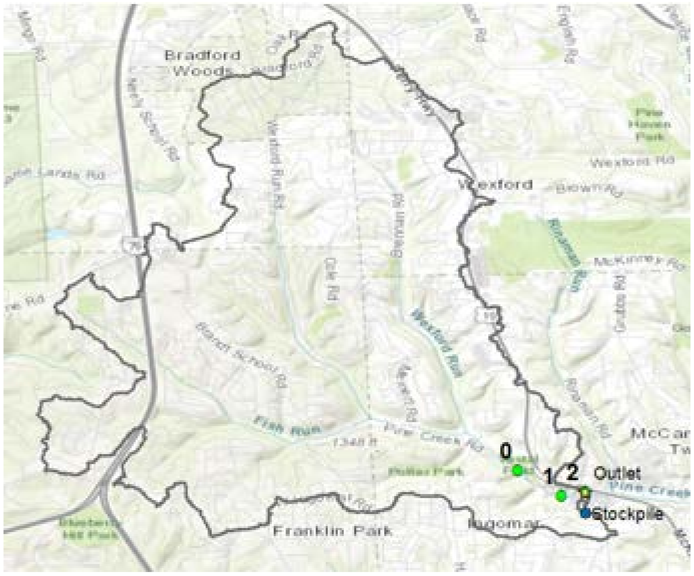


Figure 4.4 Pine Creek watershed delineation

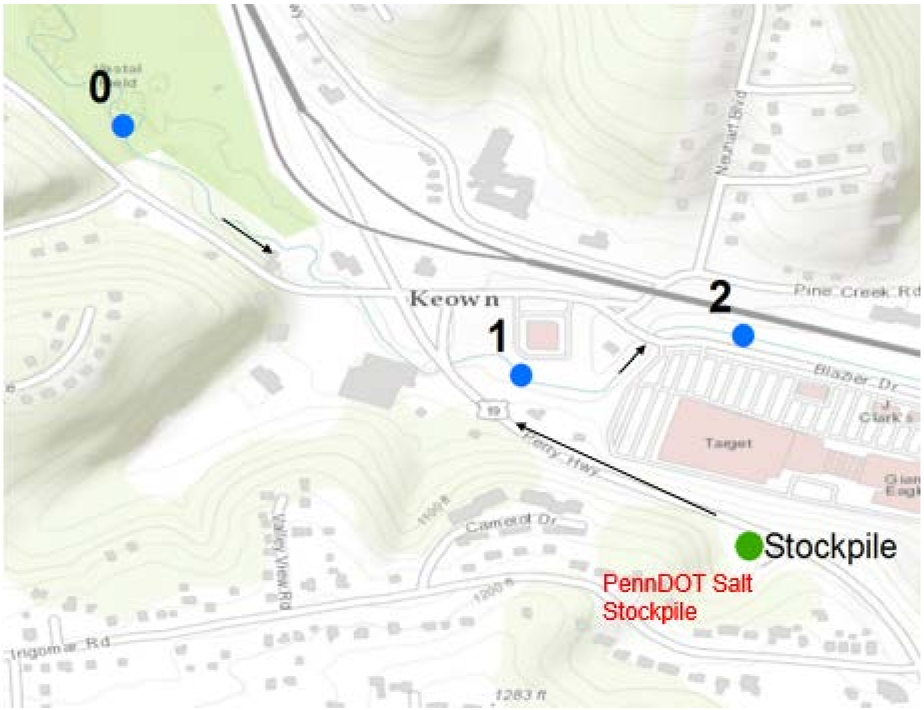


Figure 4.5 PC sampling locations

4.1.2 Sampling procedure

All samples are collected and stored in plastic bottles which are thoroughly cleaned and rinsed with deionized water before each sampling.

During snowing period, sampling is carried out following or during precipitation event when increased load from de-icing activity is expected. For computing chloride criteria maximum concentration (CMC) standard, 3 samples are taken consecutively at an interval of about 20 minutes on days with predicted stream chloride concentration peak. Such type of sampling activities is carried out on dates marked by red check marks in Tables 4.1 and 4.2.

For computing chloride criteria continuous concentration (CCC) standard, samples are taken on a daily basis for a contiguous 4-day period following a precipitation event. For other no-snow period, only single isolated sample is taken per sampling location.

For non-winter months, samples are taken to establish baseline flow. For baseline flow, samples are taken only when there is no precipitation so that dilution of stream chloride due to excessive rain water is avoided. Sampling is taken at a reduced frequency (bi-weekly or monthly) during the baseline flow period.

In cases when immediate laboratory analysis of collected samples is not feasible, samples are filtered and stored in dark and cool places for up to 28 days.

4.1.3 Sampling schedule

Table 4.1 and Table 4.2 list the dates that samples are taken. Note that the two tables only include dates within 2017 and 2018 winter study period. Samples are also taken during baseline flow period from April 2017 to November 2017, but they are not listed here.

Table 4.1 Sampling schedule of 2017 winter . Dates on which samples were taken are marked by "√". Precipitation type is "P" for rain, and "S" for snow, respectively. "P&S" indicate both rain and snow are present. Red check marks dates with increased sampling frequency (3 samples taken per hour) for better data representation of 1-hour average water quality.

	3/6	3/7	3/8	3/9	3/10	3/11	3/12	3/13
Nine Mile Run	√	√	√	√	√	√	√	√
Pine Creek			√	√	√	√	√	√
Precipitation type	P	P	P	P	P&S	S	S	

	3/14	3/15	3/16	3/17	3/18	3/19	3/20	
Nine Mile Run	√	√	√	√	√	√	√	
Pine Creek	√	√	√	√	√	√		
Precipitation type		P&S	S	P&S	P&S		Total	

Table 4.2 Sampling schedule of 2018 winter. Dates on which samples were taken are marked by "√". Precipitation type is "P" for rain, and "S" for snow, respectively. "P&S" indicate both rain and snow are present. Red check marks dates with increased sampling frequency (3 samples taken per hour) for better data representation of 1-hour average water quality.

	11/20	12/10	12/12	12/13	12/14	12/15	12/19	12/23	12/30	12/31
Nine Mile Run	√		√	√	√	√	√	√	√	√
Pine Creek		√							√	√
Precipitation type			S		S		P	P&S	S	S

	1/1	1/2	1/8	1/9	1/10	1/11	1/12	1/13	1/14	1/15
Nine Mile Run	√	√	√	√	√	√	√	√	√	√
Pine Creek	√	√			√	√	√	√	√	√
Precipitation type			P&S				P	S		S

	1/16	1/20	1/21	1/22	1/23	1/31	2/6	2/23		
Nine Mile Run		√	√	√	√	√	√	√		
Pine Creek	√									
Precipitation type	S		S	S	S	S		S		

4.2 Laboratory analytical method and data processing

4.2.1 Chloride and sulfate

Chloride and Sulfate concentration are determined based on EPA method 300.0 determination of inorganic anions by ion chromatography.

Prior to sample analysis, samples are filtered with 0.45-micron filter membrane. If samples are refrigerated for long-term storage, samples are taken out of refrigeration and kept under room temperature till sample temperature rises back to within normal range.

Filtered samples are diluted with deionized water to meet the working range of the analytical method. Nevertheless, chloride concentration in stream samples varies vastly from snow period to base flow period. As a result, dilution factor is not a fixed value but a variable ranging from 10 to 100. The dilution factor that leads to the best calculated percent recovery (see quality control session for details) is chosen for each batch of experiment.

Filtered and diluted samples are then loaded to a Dionex ICS-1100 ion chromatography for chloride and sulfate analysis. Chloride and sulfate concentration is determined by using a set of calibration standard chloride/sulfate solution with known concentration. Calibration standards are made and tested independently for each batch of experiment.

4.2.2 Total hardness

Determination of total hardness follows EPA method 130.2 (Titrimetric, EDTA). All samples are filtered and restored to normal temperature prior to the test.

4.2.3 Quality control

Quality control regarding chloride and sulfate analysis involves the analysis of replicate sample, reagent blank, laboratory fortified blank (LFB) and laboratory fortified sample matrix (LFM). For each batch of ion chromatography test, the percent recovery of laboratory fortified blank and laboratory fortified sample matrix is calculated.

A LFB or LFM sample is obtained by adding a known amount of chloride or sulfate to an aliquot of regent water or stream sample respectively, and LFB or LFM sample is analyzed the same way as a normal sample. The test result of LFB and LFM sample is used to compute percent recovery.

$$R_{LFB} = \frac{c_s}{s} * 100$$

$$R_{LFB}: percent\ recovery\ of\ LFB\ sample, \%$$

$$c_s: measured\ analyte\ concentration\ in\ fortified\ sample, ppm$$

$$s: concentration\ equavalent\ of\ analyte\ added\ to\ sample, ppm$$

$$R_{LFM} = \frac{C_s - C}{s} * 100$$

$$R_{LFM}: percent\ recovery\ of\ LFB\ sample, \%$$

$$c_s: measured\ analyte\ concentration\ in\ fortified\ sample, ppm$$

$$c: measured\ analyte\ concentration\ in\ background\ sample, ppm$$

$$s: concentration\ equavalent\ of\ analyte\ added\ to\ background\ sample, ppm$$

The percent recovery of LFB and LFM should fall within the control limit of 90-110% and 85%-115%, respectively, to suggest an accurate sample measurement. If the calculated percent recovery falls out of the range, sample dilution factor, ion chromatography settings or other experiment parameters are adjusted until the requirements are met. For the entire laboratory analysis, the average LFM is 94.9% and the maximum and minimum LFM are 111% and 79.1%, respectively.

LFB sample and regent blank sample are analyzed for each batch of experiment to make sure IC instrument is in good condition. For each batch of experiment, 2 LFM samples are prepared using samples with highest/lowest chloride concentration to evaluate measurement accuracy.

Quality control of total hardness measurement is achieved by using duplicate sample and quality control reference sample (sample with known amount of total hardness) periodically.

4.2.4 Chloride criteria calculation

The criteria maximum concentration (CMC) for evaluating chloride acute toxicity is given as:

$$CMC(mg/L) = 349 * Hardness^{0.205797} * Sulfate^{-0.07452}$$

$$Hardness: measured\ stream\ water\ total\ hardness, mg\ Ca/L$$

$$Sulfate: measured\ stream\ water\ sulfate\ concentration, mg/L$$

CMC is for acute toxicity during chloride peak concentration period. Such peak concentration period usually follows snow event. To accurately compute 1-hour average value for chloride, sulfate and total hardness, three samples are taken at each sampling location at 20-minute interval after each snow event during the study period. For other period, only 1 sample is taken per sampling location and CMC is estimated using a single value.

The criteria continuous concentration (CCC) for evaluating chloride chronic toxicity is given as:

$$CCC(mg/L) = 113 * Hardness^{0.205797} * Sulfate^{-0.07452}$$

CCC is for chronic toxicity and needs 4-day average value of chloride, sulfate and hardness for its computation. Our sampling plan involves 4-day continuous monitoring which provides daily stream water sample following snow events during the study period. For other period when single isolated sample is taken, CCC is estimated using single-day value.

4.3 Result and analysis

This section discussed water quality data from collected samples. Results are separated into three parts: the baseline period, the winter of 2017, and the winter of 2018. The baseline period shows the original state of the stream without the contribution of de-icing salt. Data from winters of 2017 and 2018 are discussed separately because of their distinct weather patterns and the resulting differences in stream hydrological conditions. Furthermore, drainage following salt operation from PennDOT’s bridge also shows significantly different characteristics for the two winters involved. In the winter of 2017, pulses of high-volume discharge can be observed pouring out of PennDOT pipes following precipitation events; while in the winter of 2018, pipes were observed partially frozen and water was seen to drip constantly, rather than steadily flowing out of them. Such observation should be taken into account when linking applied road salt to stream chloride concentration, and requires data analysis be carried out carefully.

4.3.1 Baseline flow period

Figures 4.6 – 4.9 show chloride concentration and the calculated CCC and CMC standards for samples collected from NMR site during the baseline flow period from April 2017 to November 2017. Stream water quality over this period is considered to be free from impact of de-icing salt, and therefore samples from this period reflect the “natural” or “baseline” state of the stream. There is only partial data available for NMR sampling location 4 because dense vegetation completely blocked the path, thus it requires caution when comparing location 4 data to other data.

Table 4.3 Summary of data collected for the NMR site (baseline period)

Sampling Location	1	2	3	4
Cl average conc. ppm	358	328	331	267
Cl max conc. ppm	426	393	409	397
Cl min conc. ppm	232	193	190	191
Average CMC, ppm	801	802	801	772
Average CCC, ppm	259	260	259	250

In general, NMR stream chloride level remains above or close to CCC standard, but below CMC standard for all sampling locations. Over the entire baseline period, there is a slow trend of dropping chloride concentration. Stream chloride levels at different sampling location are low with negligible differences, which is consistent with the fact that no salty water enters the stream from the PennDOT bridge for this period.

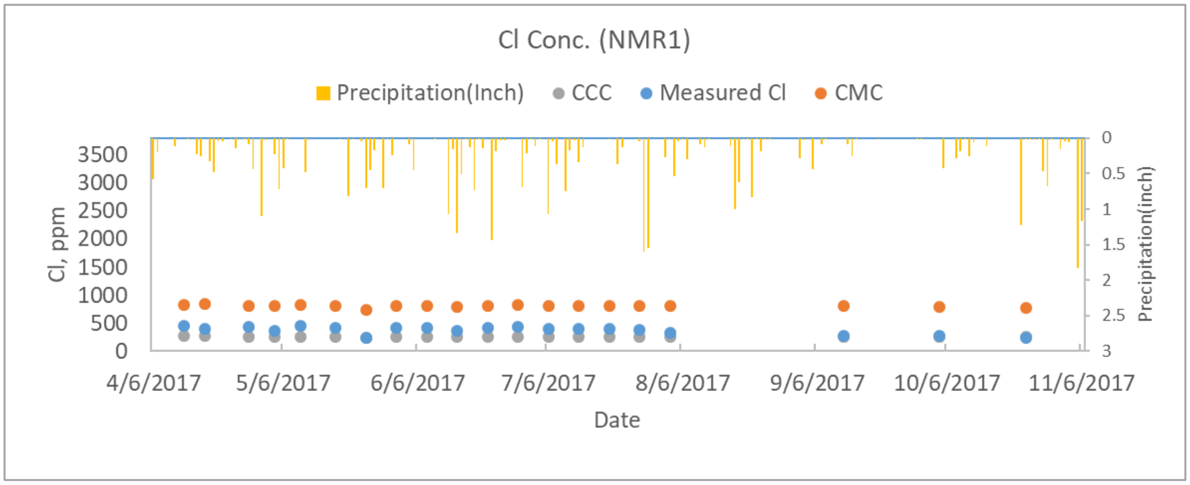


Figure 4.6 Result for NMR sampling location 1 in baseline period

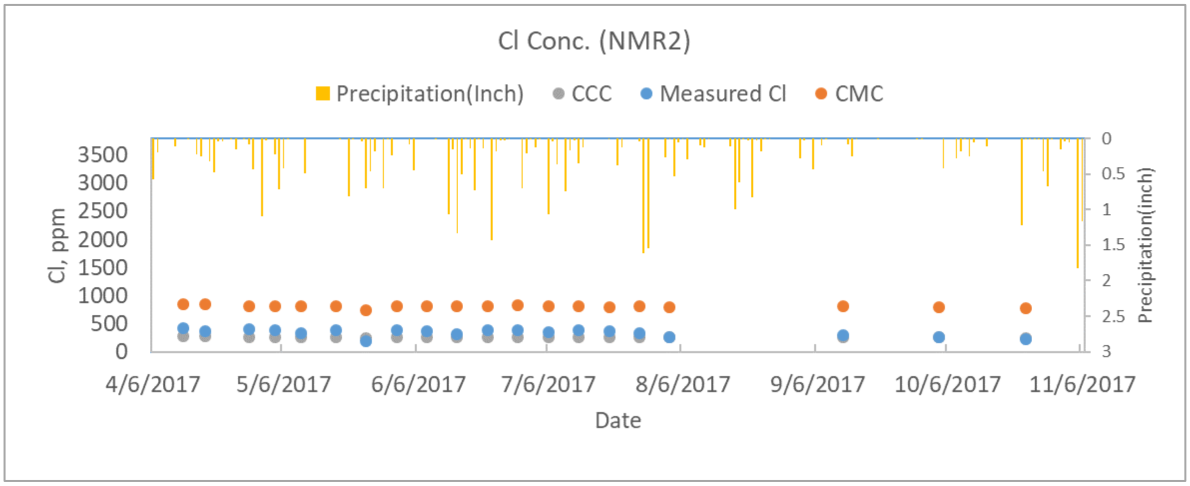


Figure 4.7 Result for NMR sampling location 2 in baseline period

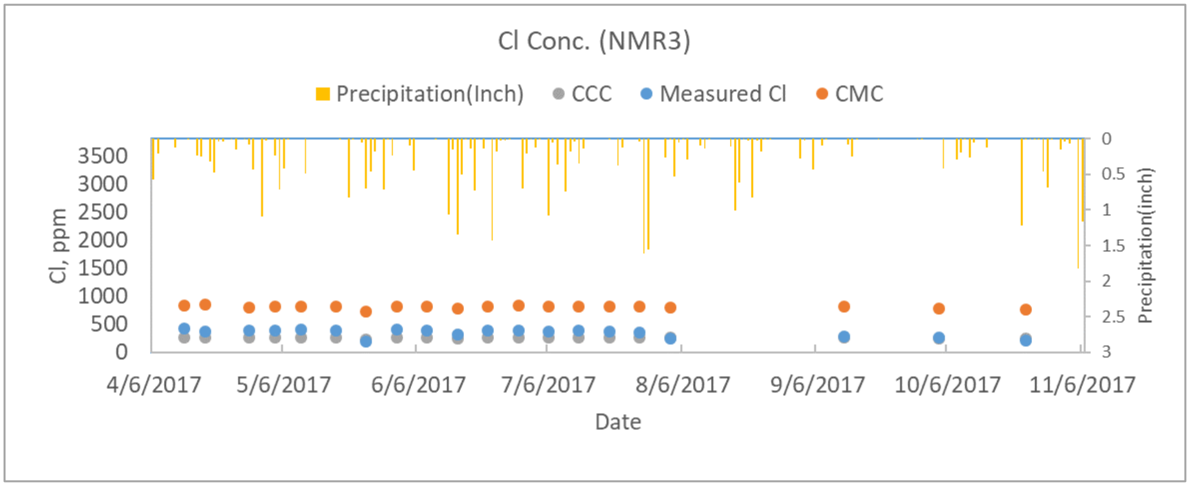


Figure 4.8 Result for NMR sampling location 3 in baseline period

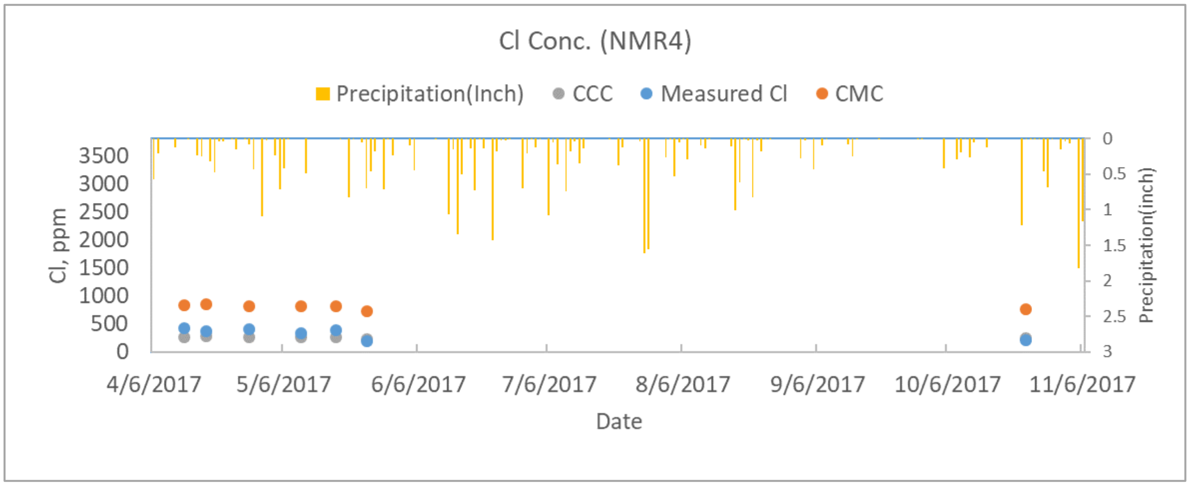


Figure 4.9 Result for NMR sampling location 4 in baseline period

Figures 4.10 – 4.12 show the chloride concentration and calculated CCC and CMC standards for samples collected from PC site during baseline period from April 2017 to June 2017. Results show similar patterns to that from the NMR site in which the baseline chloride concentration lies slightly above or closes to CCC standard but below CMC standard. Stream chloride levels at different sampling locations are similar exhibiting negligible differences, which is again consistent with the fact that de-icing salt is not administered for this period.

Table 4.4 Summary of data collected for the PC site (baseline period)

Sampling Location	0	1	2
Cl average conc. ppm	343	353	353
Cl max conc. Ppm	390	414	412
Cl min conc. Ppm	266	273	270
Average CMC, ppm	765	766	767
Average CCC, ppm	248	248	248

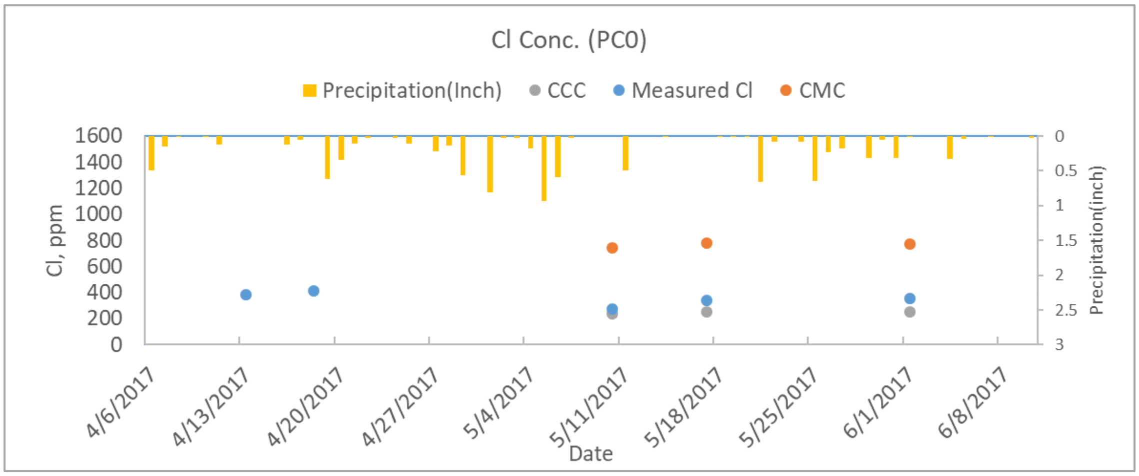


Figure 4.10 Result for PC sampling location 0 in baseline period

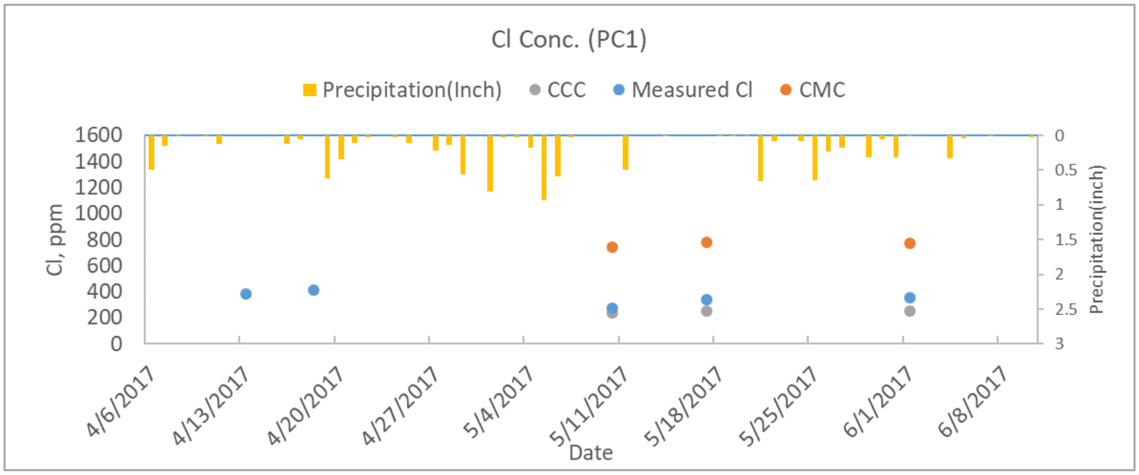


Figure 4.11 Result for PC sampling location 1 in baseline period

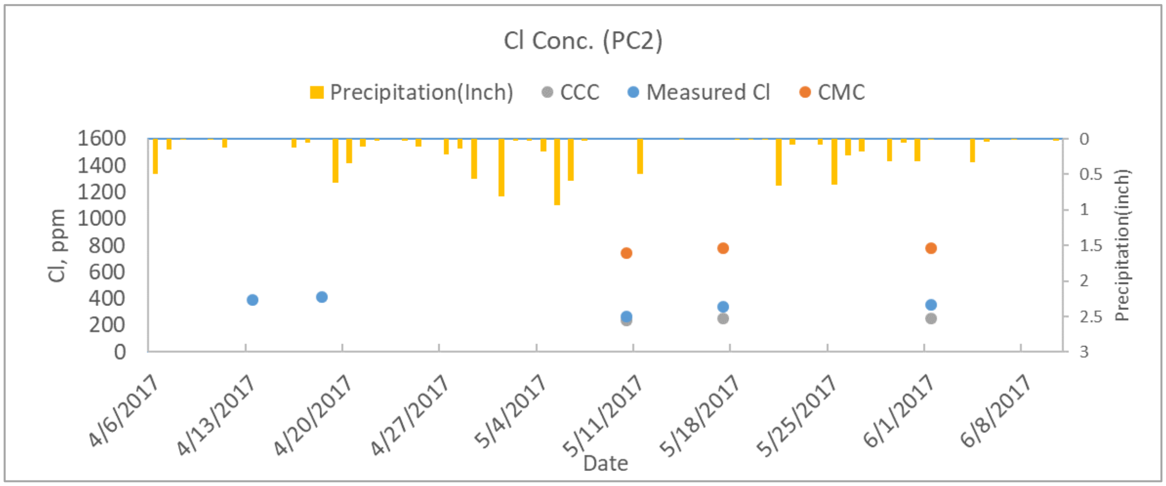


Figure 4.12 Result for PC sampling location 2 in baseline period

In summary, stream samples from both sites show that baseline chloride concentration lies slightly above or close to CCC standard but below CMC standard. This suggests that besides de-icing road salt, other factors affecting stream chloride concentration exist, and these unknown factors cause stream chloride level to exceed CCC standards. Consequently, later in our analysis of winter period samples, attention will be focused on comparing stream chloride level to CMC standard, which is better related to the impact of de-icing road salt.

4.3.2 Nine Mile Run: winter of 2017

Figures 4.13 – 4.16 show the chloride concentration and the calculated CCC and CMC standards for samples collected in NMR during the winter of 2017 from 3/6/2017 to 3/20/2017.

Table 4.5 Summary of data collected for NMR site (winter, 2017)

Sampling Location	1	2	3	4
Cl average conc. ppm	626	491	517	530
Cl max conc. ppm	1595	826	972	1022
Cl min conc. ppm	286	215	269	274
Average CMC, ppm	807	808	799	808
Average CCC, ppm	261	262	259	262

Samples collected from NMR sampling location 1 are used to identify upstream chloride level. Chloride concentration differences between location 2 and 3, or between locations 2 and 4 are used to identify impact of salt coming from the PennDOT bridge. Sampling location 3 is right behind the bridge in the downstream side, and sampling location 4 is 100 meters further downstream from the bridge. We believe samples taken at sampling location 4 is more representative because these extra 100 m stream channel allow better mixing of salty water with stream water. However, it is often the case that sampling location 4 is not accessible, and in such cases, we use sample from sampling location 3.

In general, for all 4 NMR sampling locations, stream chloride concentration is elevated during the winter compared to that of the baseline period. Stream chloride concentration level lies between CCC and CMC standard for most of the time, but it exceeds CMC standard for several days after the precipitation.

Sampling location 1 exhibits the highest stream chloride level, which suggests presence of salt source in upstream area (e.g., a road way paralleled to the stream). Samples from location 2 (right before the bridge) show the lowest stream chloride level among all 4 sampling locations, and this decreased chloride concentration between locations 1 and 2 could be explained by the fact that large tract of wetland and several creeks exist between locations 1 and 2, and they contribute water that has not been affected by de-icing activity via surface runoff and groundwater and that diluted stream chloride.

We observe a slight increase of stream chloride in samples from locations 3 and 4, compared to samples collected at location 2, especially in days with high stream chloride level (3/10/2017 and 3/18/2017). While this increase of stream chloride is not significant, it is still discernable. This rise in stream chloride concentration could be attributed to salty drainage from the bridge.

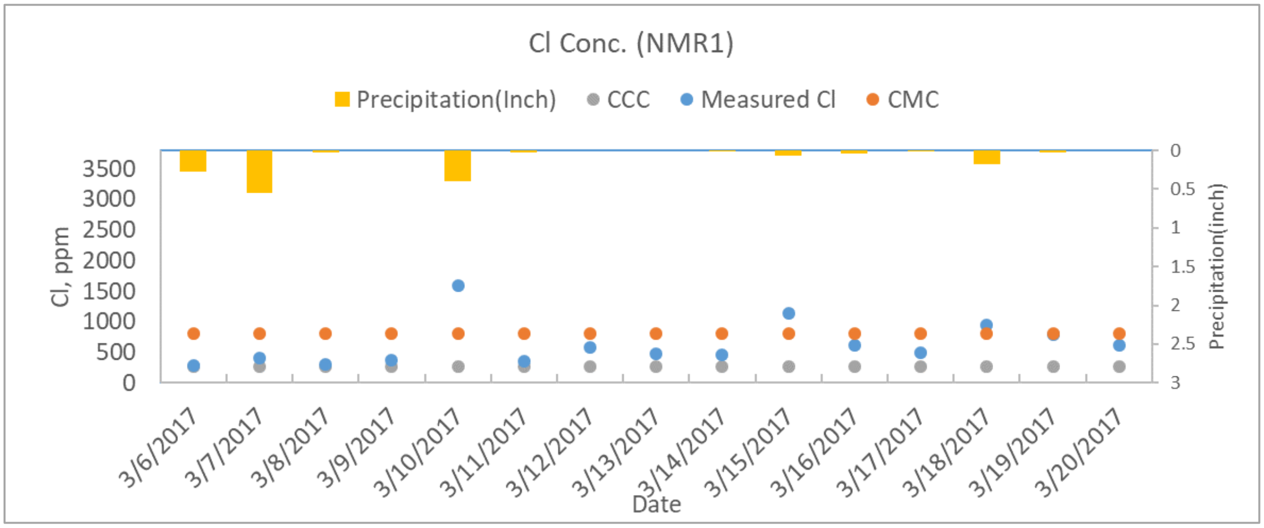


Figure 4.13 Result for NMR sampling location 1 in winter, 2017

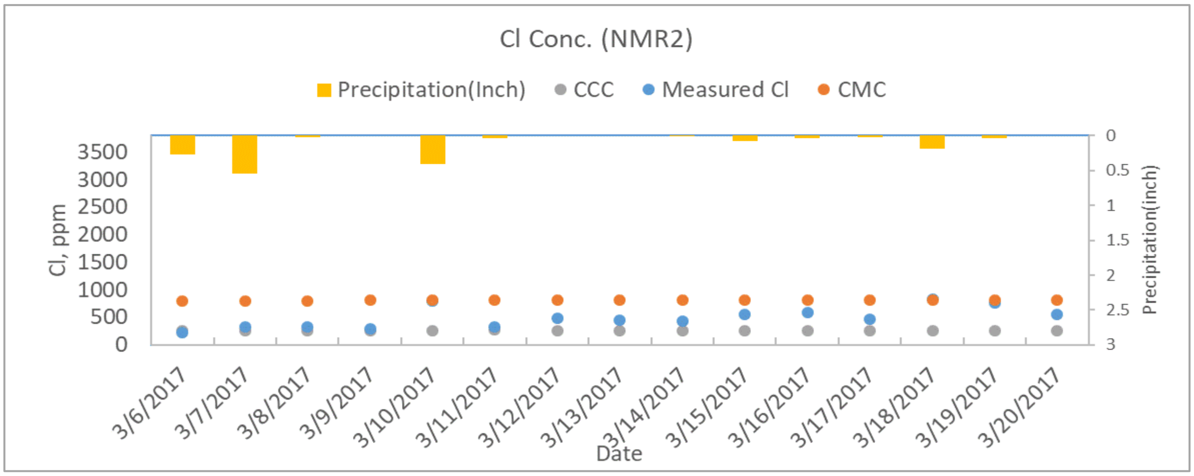


Figure 4.14 Result for NMR sampling location 2 in winter, 2017

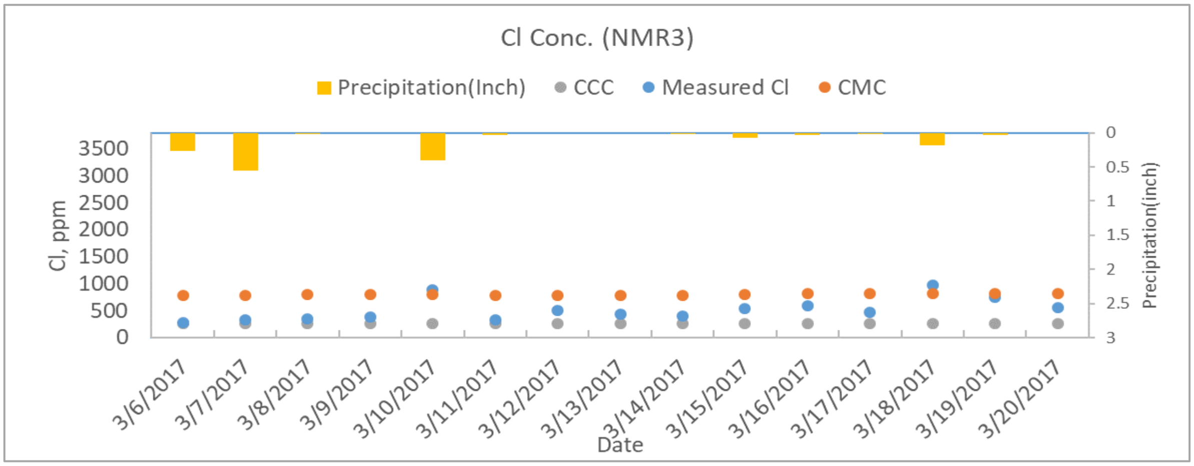


Figure 4.15 Result for NMR sampling location 3 in winter, 2017

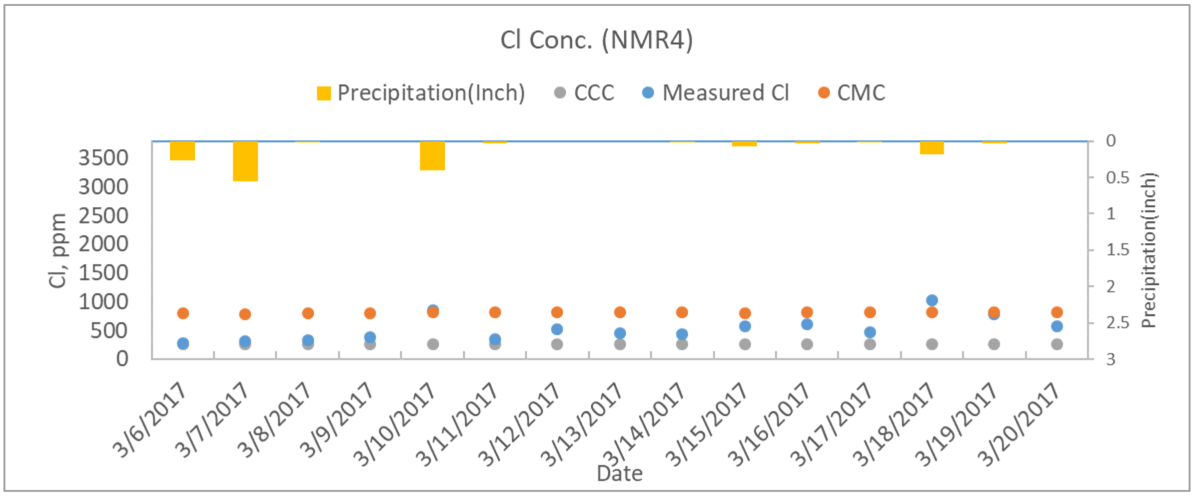


Figure 4.16 Result for NMR sampling location 4 in winter, 2017

4.3.3 Pine Creek: winter of 2017

Figures 4.17 – 4.19 show the chloride concentration and calculated CCC and CMC standards for samples collected in PC during the winter of 2017 from 3/8/2017 to 3/19/2017.

Table 4.6 Summary of data collected for the PC site (winter, 2017)

Sampling Location	0	1	2
Cl average conc. ppm	576	650	709
Cl max conc. ppm	1055	1190	1517
Cl min conc. ppm	198	210	199
Average CMC, ppm	792	794	794
Average CCC, ppm	257	257	257

Elevated stream chloride concentration is observed for all sampling locations compared to that from baseline period. Stream chloride concentration approaches or exceeds CMC standard, and could reach above 1500 ppm (location 2, 3/16/2017).

Comparing the three sampling locations, there is a trend of rising chloride concentration from upstream to downstream. Chloride source between sampling location 0 and sampling location 2 includes residential area, a shopping mall, parking lot, as well as PennDOT salt stockpile. Flow path of water from PennDOT stockpile to the stream is fairly complex. While result suggests increased chloride level due to de-icing salt in this area, it is difficult to separate the impact of PennDOT stockpile from other salt sources.

It is also worth pointing out that the stream chloride concentration drops back from peak value to normal range relatively fast. Without precipitation, stream chloride level drops back down within one day with little lingering effect.

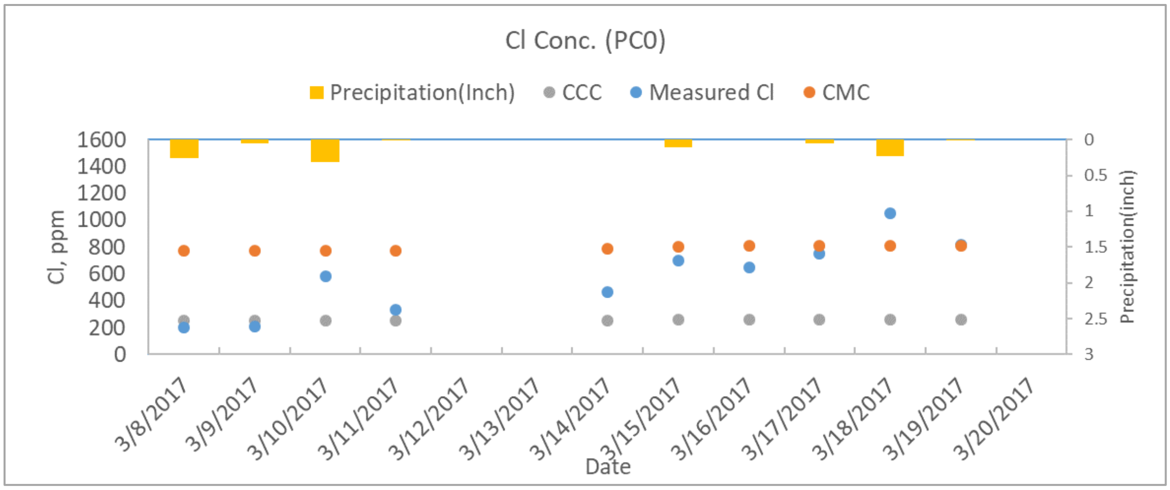


Figure 4.17 Result for PC sampling location 0 in winter, 2017

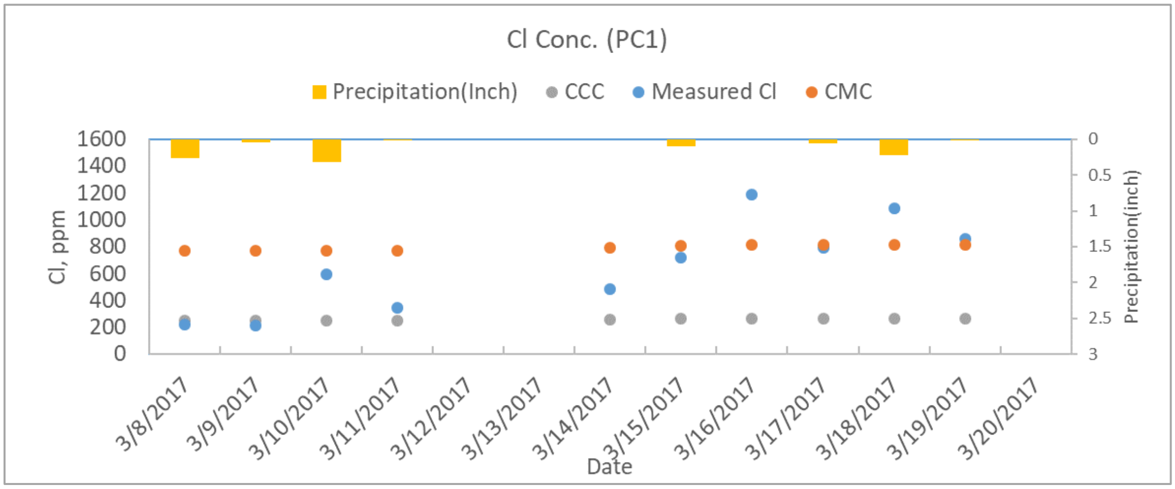


Figure 4.18 Result for PC sampling location 1 in winter, 2017

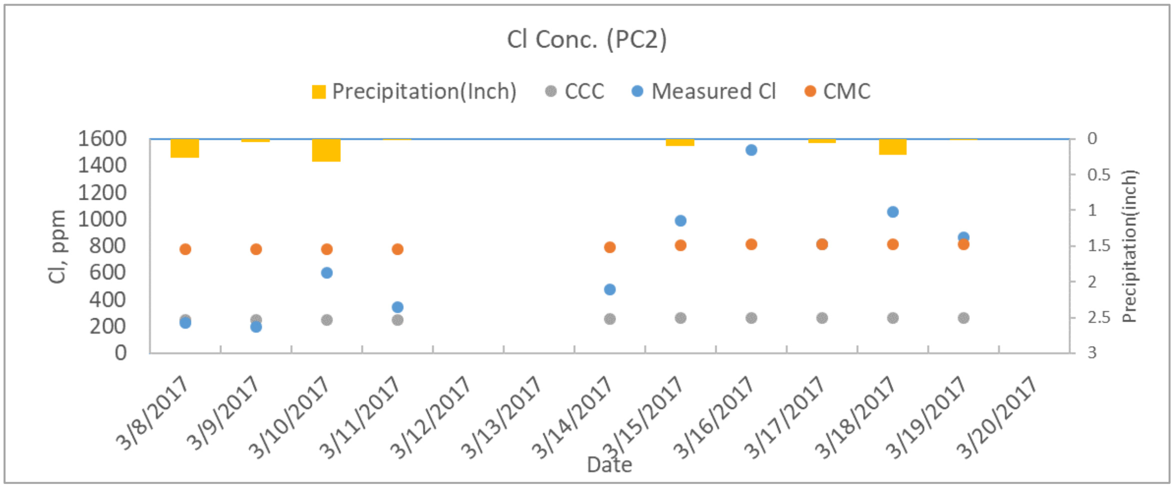


Figure 4.19 Result for PC sampling location 2 in winter, 2017

In general, samples from the winter of 2017 show increased chloride concentration level compared to those taken during the baseline period. De-icing activities cause stream chloride concentration to exceed CMC standard following precipitation events. Based on our analysis on the collected samples, PennDOT stockpile's impact is uncertain. Furthermore, de-icing salt seems not to linger long in the streams. That is to say when precipitation stops, it does not take long (~1 day) for stream chloride to drop back to a lower level.

4.3.4 Nine Mile Run: winter of 2018

Figures 4.20 – 4.23 show chloride concentration and calculated CCC and CMC standards for samples collected in NMR during winter of 2018 from 11/20/2017 to 2/23/2018.

Table 4.7 Summary of data collected for the NMR site (winter, 2018)

Sampling Location	1	2	3	4

Cl average conc. ppm	770	691	727	671
Cl max conc. ppm	1691	1772	2094	1308
Cl min conc. ppm	340	284	317	374
Average CMC, ppm	1008	1006	1008	1015
Average CCC, ppm	326	326	326	329

Elevated concentration is observed across all sampling locations compared to that from the baseline period. For most of the time stream chloride concentration lies between CCC and CMC standard. Stream chloride exceeds CMC standard in several cases following precipitation, and can reach as high as 4354 ppm (location 3, 12/14/2017). Bridge's impact on stream chloride concentration is most prominent on 12/14/2017 and 1/9/2018 based on comparison of chloride concentration differences between samples collected at location 2 and that from location 4 (or location 3). Similar to data from the winter of 2017, stream chloride level drops down quickly in the absence of further precipitation.

It is important to point out that winter of 2018 features extreme cold weather in Pittsburgh area in early January of 2018, and in this period, NMR was frozen which not only affected sample collections, but also altered the dynamics of salt water transportation. Note that, in contrast, temperatures during the sampling period in the winter of 2017 were only around 0 Celsius degree, and as a result, snow melted fast with the de-icing salt and reaches NMR with little hindrance. However, during the sampling period of the winter of 2018, temperature has dropped well below -10 Celsius degree. For the NMR site, the wetland between locations 1 and 2, and even the soil below the bridge were all observed frozen in early January 2018. This may have resulted in the reduced amount of salty drainage entering NMR.

Also note that only one sample per location was taken on 12/14/2017 at NMR, and while chloride peak was unusually high, the available data do not allow us to evaluate how long this peak would last in order to compare with CMC standard (which should be compared to 1-hour average stream chloride concentration).

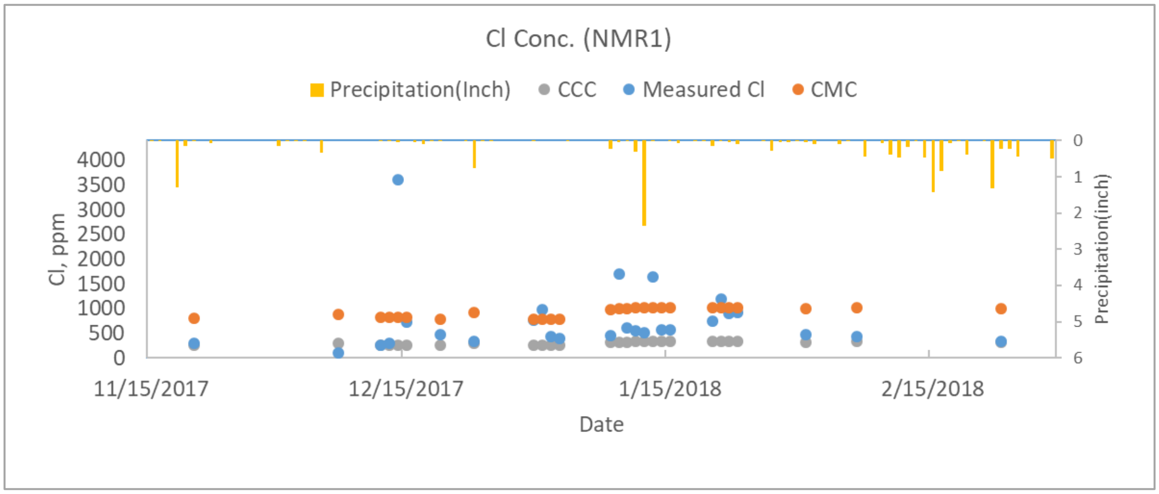


Figure 4.20 Result for NMR sampling location 1 in winter, 2018

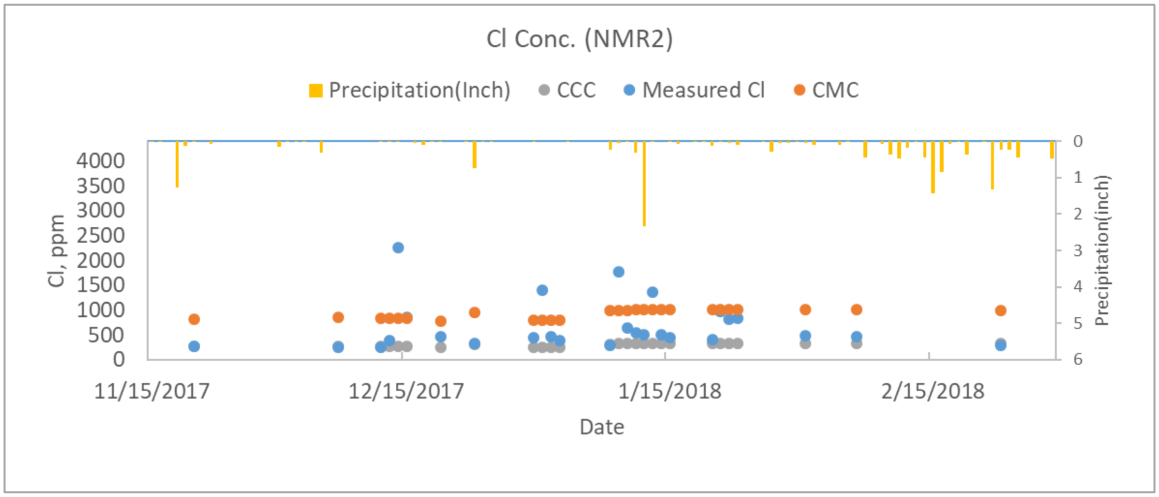


Figure 4.21 Result for NMR sampling location 2 in winter, 2018

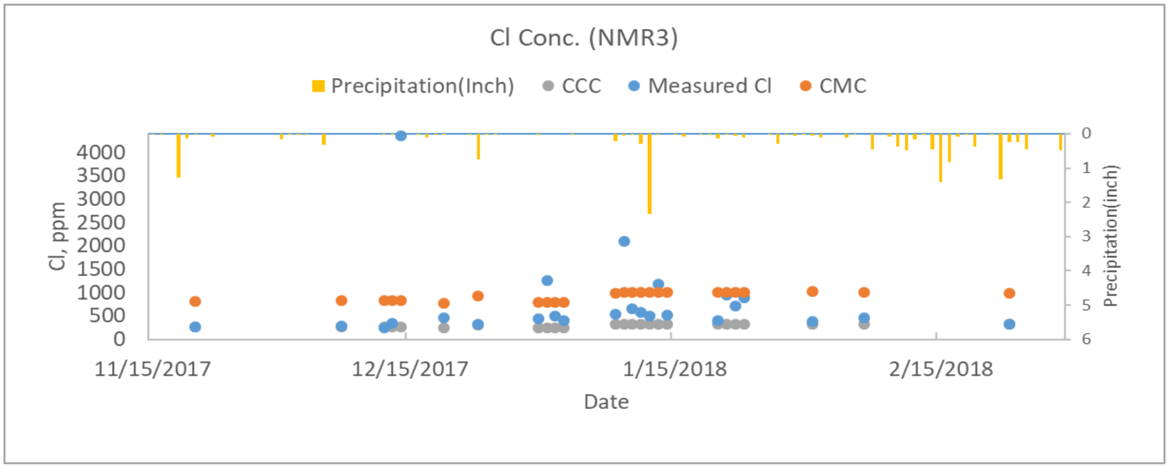


Figure 4.22 Result for NMR sampling location 3 winter, 2018

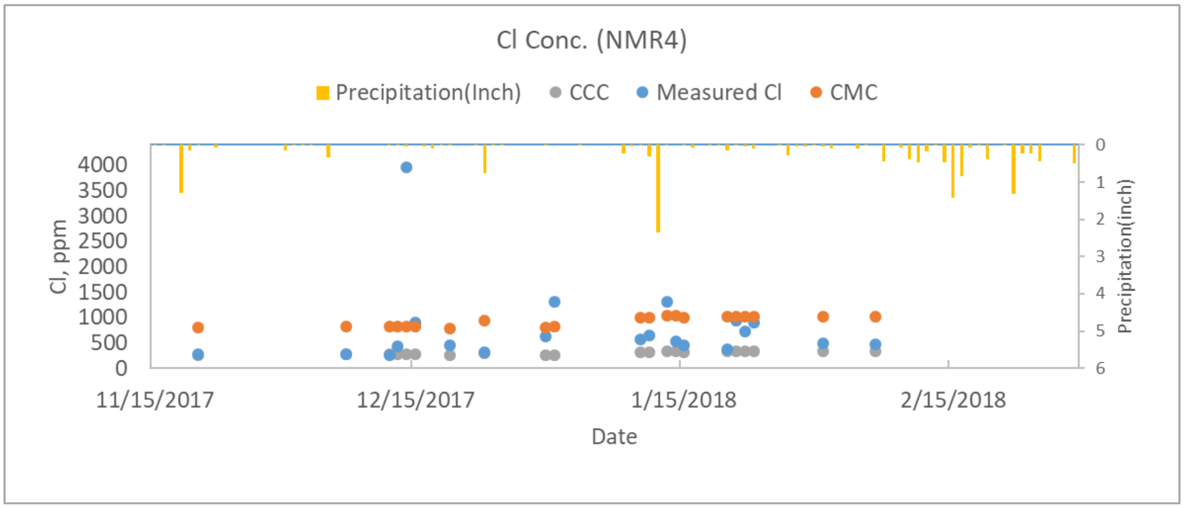


Figure 4.23 Result for NMR sampling location 4 in winter, 2018

4.3.5 Pine Creek: winter of 2018

Figures 4.24 – 4.26 show the chloride concentration and calculated CCC and CMC standards for samples collected from the PC site during the winter of 2018 from 11/25/2017 to 1/16/2017. Similar to the winter of 2017, most stream chloride values fall between CCC and CMC standards with a few cases where CMC standard was exceeded. Just like NMR site, the PC site was also frozen in early January 2018, which brings uncertainty to our analysis.

Table 4.8 Summary of data collected for the PC site (winter, 2018)

Sampling Location	0	1	2
Cl average conc. ppm	600	642	631
Cl max conc. ppm	1366	1417	1371
Cl min conc. ppm	240	276	187
Average CMC, ppm	903	902	907
Average CCC, ppm	292	292	294

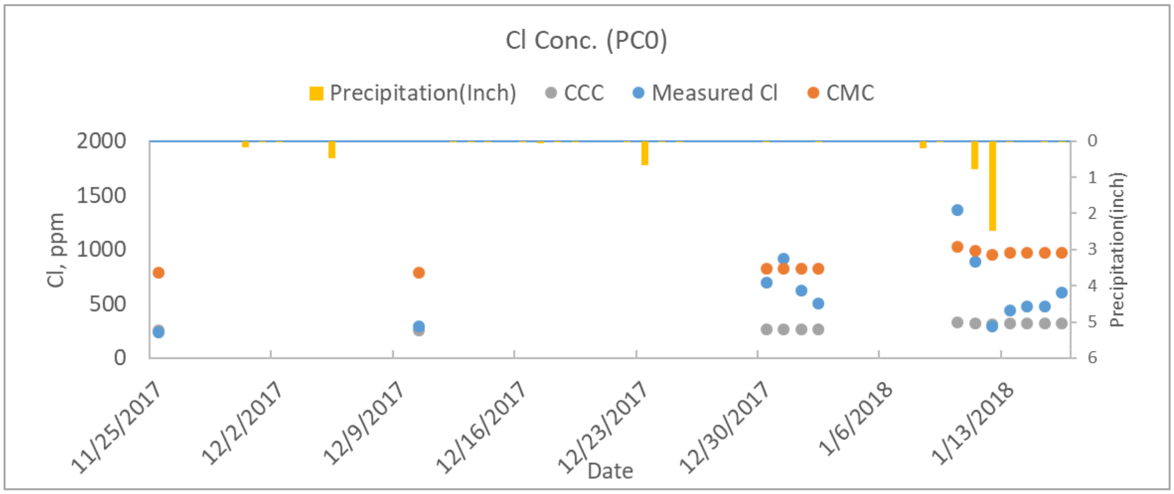


Figure 4.24 Result for PC sampling location 0 in winter, 2018

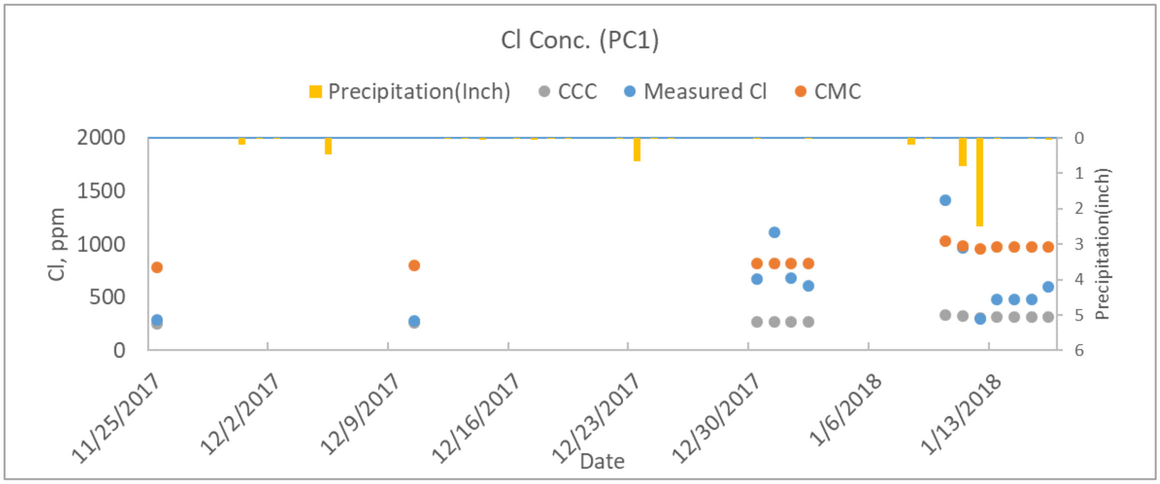


Figure 4.25 Result for PC sampling location 1 in winter, 2018

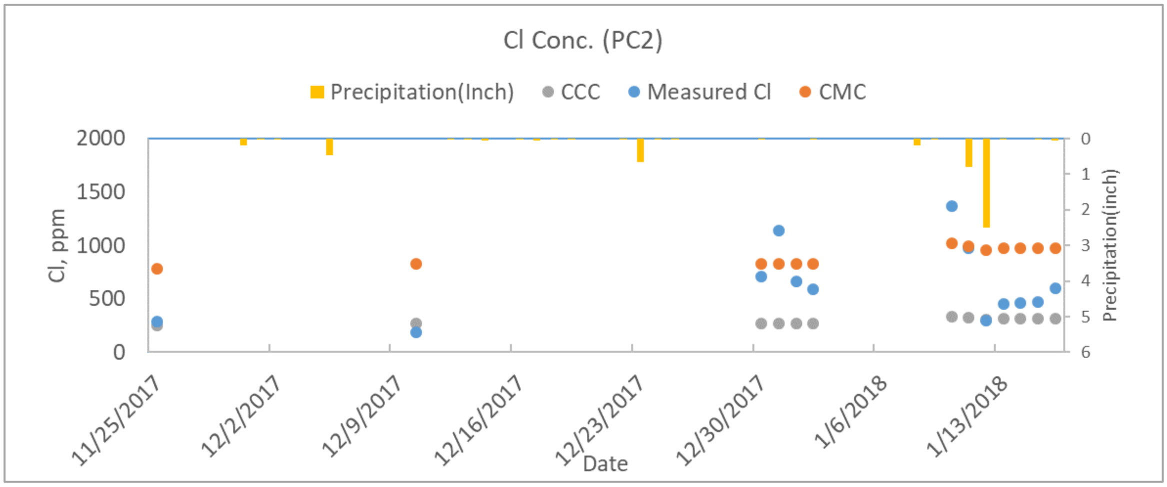


Figure 4.26 Result for PC sampling location 2 in winter, 2018

In general, data collected in the winter of 2018 are similar to those from 2017 in terms of chloride concentration magnitude (except one isolated case which has unusually high chloride peak). It is observed that in most cases stream chloride concentration remains between CCC and CMC standards but precipitation and the de-icing could trigger a rise in stream chloride level to exceed CMC standard. However, stream chloride concentration is not found to be proportional to precipitation amount. This could be attributed to the fact that increased precipitation, while carries more salt to stream, may also dilute chloride. This is consistent with our result where most samples with high stream chloride concentration level usually follow small precipitation event.

The relatively severe cold winter of 2018 adds a layer of complexity in the dynamics of de-icing salt transportation in the environment and calls into question the representativeness of measured chloride concentrations, even with care taken in the analysis involving this part of data.

4.3.6 Summary of PennDOT salt impact

This section discusses impact of PennDOT winter salt operation on stream water quality in terms of chloride concentration. Herein, impact of PennDOT winter salt activity is evaluated by examining changes in stream chloride concentration between two control points (or, sampling points). For the NMR site (Figure 4.27), the chloride concentration difference between sampling location 2 and location 4 (or location 3 when location 4 is inaccessible) is used to consider impact of the salt operation on bridge. For the PC site (Figure 4.28), the chloride concentration difference between sampling location 0 and location 2 is used to reflect the impact of any ongoing salting activities and drainage from the salt stockpile.

Note that for the NMR site, drainage system from PennDOT bridge is the only local chloride source, and its impact on water quality is directly reflected by comparing chloride concentration change between the two control points. On the other hand, the PC site is more complex since multiple chloride sources (PennDOT road, PennDOT salt stockpile, local residential and commercial area, and local parking lots) exert their impact simultaneously, and therefore data collected from the PC site only reflect the combined effect of all of the chloride sources, and are not limited to PennDOT-related source.

Data are divided into two groups and shown in Figures 427 and 4.28, respectively, as “detectable impact” and “non-detectable impact”. “Detectable impact” group consists of data with chloride concentration change greater than 10% (compared to background or upstream chloride concentration). “Non-detectable impact” group consists of data with chloride concentration change less than 10%. Only data from the “Detectable impact” group is considered for the impact of salting activity because our laboratory test method introduces an error of about 10% (as reflected by our quality control method). Any chloride concentration changes less than 10% could be due to error associated with the laboratory testing process.

For the NMR site, Figure 4.27 shows that PennDOT winter salting activity could cause rise in the stream chloride concentration ranging from a few hundred ppm to over 1600 ppm. No detectable impact was observed during the baseline flow period which is consistent with the fact that there was no salting operation for that period. Both winters of 2017 and 2018 present some events with detectable impact of flow from the PennDOT bridge, and especially so in the winter of 2018 during which isolated events with extreme chloride concentrations were recorded. While PennDOT bridge does not seem to induce long-lasting impact on stream chloride concentration, it is, however, very difficult to record and study using conventional monitoring method for the short-term change.

We also notice that peak chloride concentration does not necessarily correspond to peak precipitation. It is important to note that stream discharge volume also affects the chloride concentration in the streams which was not measured in this study.

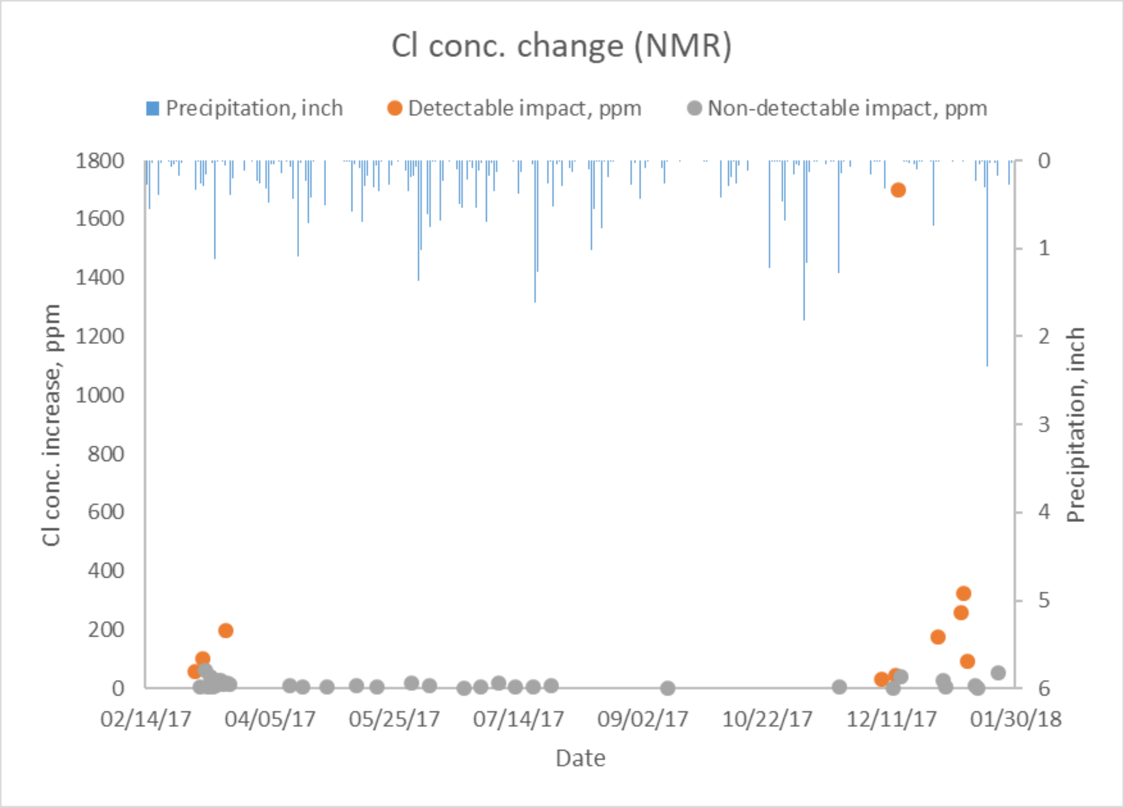


Figure 4.27 Summary of Cl concentration increase due to winter salting activities for the entire study period (NMR site). "Detectable impact" group is data with chloride concentration change greater than 10%. "Non-detectable impact" group is data with chloride concentration change less than 10%.

Figure 4.28 shows the results for the PC site and the data suggest that similar high variability in salt impact. For the PC site, the chloride concentration rise ranges from a few hundred ppm to over 800 ppm. This site is much more complex than the NMR site because multiple chloride sources exist simultaneously as stated. Our results do demonstrate that winter salting activities have impacts on the PC stream water quality, and the impact could be significant.

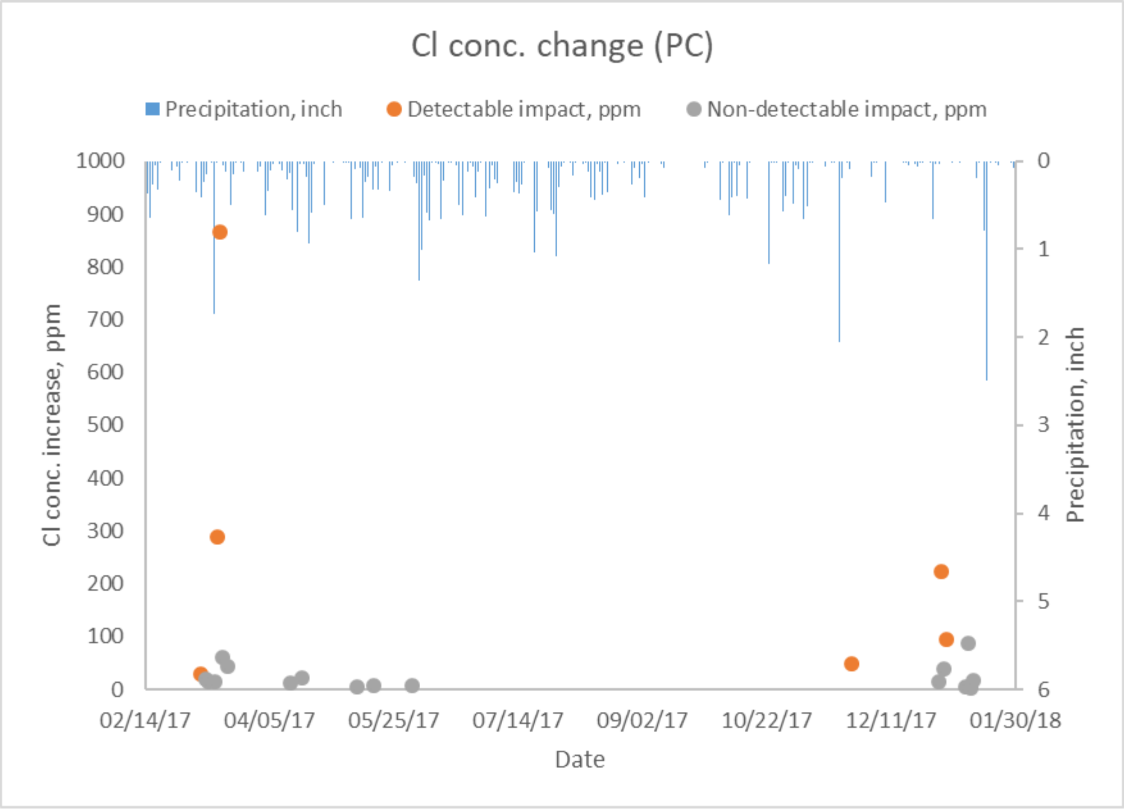


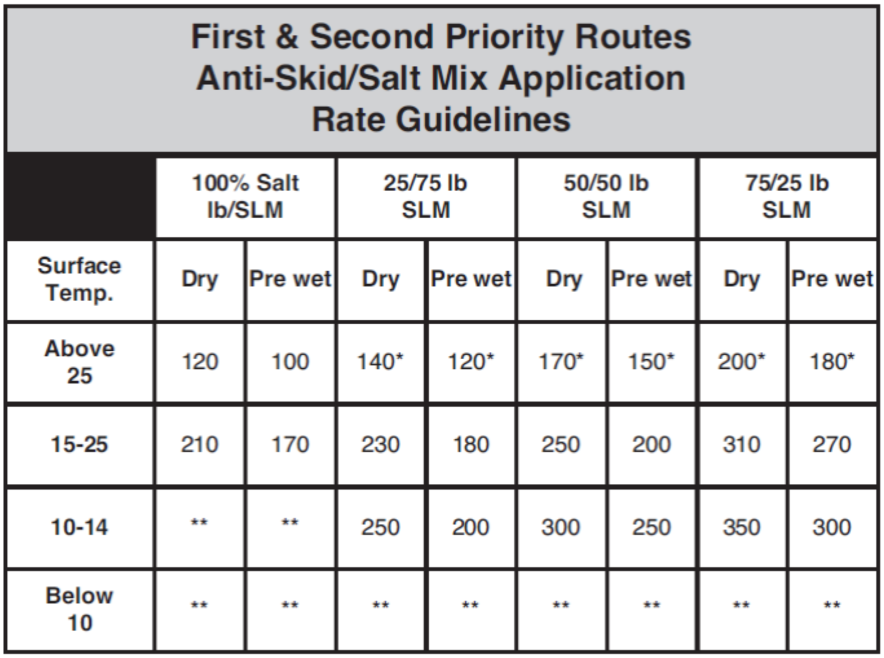
Figure 4.28 Summary of Cl concentration increase due to winter salting activities for the entire study period (PC site). "Detectable impact" group is data with chloride concentration change greater than 10%. "Non-detectable impact" group is data with chloride concentration change less than 10%.

4.4 Limitations

One limitation of this study is that no stream velocity or discharge measurements were taken in the study period. Stream discharge measurements, if available, would allow us to convert stream chloride concentration to chloride mass, which can be better related to the amount of salt applied to the roadways.

Another limitation of the study is the uncertainty associated with identifying peak stream chloride concentration. Stream chloride concentration peak is believed to follow precipitation event when surface runoff carries road salt to the streams. Our sampling plan calls for taking multiple samples within one hour time span to compute 1-hour average and CMC standard. This was done without the knowledge of when the peak chloride level would take place. The much colder winter of 2018 has hindered us from taking enough samples to represent stream water quality. What we measured show that the winter of 2018 has a different chloride build-up pattern from that of the previous year. This study did not take samples after frozen streams were thawed and could not comment on whether or not the salt operation had a delayed impact under such cold weather scenario.

To provide a reference point as to how much salt might have been applied, PennDOT's guidelines for salt spread operation as specified in the PennDOT Maintenance Manual is reproduced as Table 4.9 below.



First & Second Priority Routes
Anti-Skid/Salt Mix Application
Rate Guidelines

	100% Salt lb/SLM		25/75 lb SLM		50/50 lb SLM		75/25 lb SLM	
Surface Temp.	Dry	Pre wet	Dry	Pre wet	Dry	Pre wet	Dry	Pre wet
Above 25	120	100	140*	120*	170*	150*	200*	180*
15-25	210	170	230	180	250	200	310	270
10-14	**	**	250	200	300	250	350	300
Below 10	**	**	**	**	**	**	**	**

Table 4.9 PennDOT salt spread guidelines listed in "Chapter 4 Winter Services" of the PennDOT Pub 23 Maintenance Manual (Rev 12-17), where SLM stands for Snow Lane Mile. Annotation of the guidelines states that salt or salt/anti-skid mix may be used on second priority routes to accommodate high volume traffic as conditions warrant (salt/anti-skid mixture is recommended). It also states that the guidelines serves as general statewide guidance; and that if treating down the center of a highway application rates should be doubled while consider lowering rates on subsequent passes; and further that local decision on type of roadway and ice and snow conditions will dictate application rate decisions.

4.5 Summary

Salt operation on roadways causes a rise in stream chloride concentration in the winter time. The CCC criterion has been exceeded in baseline flow period most of the time without road salt impact for both sites. The CMC criterion has been exceeded during the winter salting period for both sites we studied.

However, we also found that there is little lingering effect of road salt impact on stream chloride level based on the limited number of water samples we have collected. Stream chloride peak drops down fast after precipitation.

For the NMR site, the impact of road salt from PennDOT bridge on the stream chloride concentration is not significant in most cases. But in one single event (12/14/2017), a significant impact linked to the bridge drainage has been observed.

For the PC site, the existence of other salt sources in the area makes the determination of the PennDOT salt stockpile impact on stream water quality difficult.

Considering the short-duration nature of the salt impact and the lack of continuous stream chloride measurement in current study, it is more than likely that the peak chloride concentrations was not captured by our current sampling activities.

5. Conclusions

This study has established a data processing procedure for the flow path modeling of urban watersheds. Also about 300 stream water samples have been taken during the course of study in determining the chloride concentration in the streams and the results were compared with environmental regulations.

For the flow path modeling, the results obtained show that the base maps produced using the modified high-resolution (Meeting USGS QL2 standard, 2 pt/m^2) LiDAR data and low-resolution (Meeting USGS QL1 standard, 1 pt/m^2) LiDAR data could produce different flow paths and sub-watersheds, even though the total accumulated flows were not significantly different using these two different sets of base data for cases studied.

The choice of the base map resolution depends on the site characteristics and objectives of study. In terms of chloride concentration estimation, high-resolution dataset is recommended. This is because accurate chloride concentration estimation in any follow-up modeling work would require information like the contribution of each small basin and their outlet locations in a watershed. The low-resolution base map simply could not provide accurate flow path which potentially affects the chloride concentration estimates as they depend on the areas where salt is applied.

It is important to note that regardless of the resolution of the base map dataset used, the roadway features such as curbs and bridges should be properly incorporated.

Areas affected by flow outward from PennDOT highway right-of-way obtained using high-resolution LiDAR data is smaller than that obtained from the low-resolution LiDAR data. Using low-resolution LiDAR data, the affected area turned out similar with or without considering bridge and curbs modification on flow path in the cases studied.

The runoffs from highway in the study area are mainly flow from the boundary of bridges and along curbs. Runoffs will move beyond the curbs into surrounding neighborhoods if curbs do not cover the entire part of bridges. Curbs should be an important part of roadway GIS modeling. The study clearly shows that the flow path modeling framework presented is capable of capturing how curbs could force flow to move along the roadways into the underground pipe network through the inlets on the highway. Thus, the model presented also has applications in roadways design regarding where to channel the runoffs.

Wherever a river intersects a highway, runoffs from the highway may flow directly into the river through pipe inlet on the highway (e.g., Nine Mile Run and I-376 across section). Hydrological modeling, which accounts for how surface flow impacts stream flow, is an indispensable part of analysis on how and to what extent salt applied on highway would affect the chloride concentration of the river. The presented procedure and the flow path modeling framework can complement hydrological modeling and provide a comprehensive picture of where the water flows to from the highways, and, for that matter, the destination of the salts.

Salt operation on roadways causes a rise in stream chloride concentration in winter time. The CCC criterion has been exceeded most of the time in non-winter baseline flow period without road salt impact for both sites. The higher CMC criterion has been exceeded sometimes during the winter salting period for both sites we studied.

However, based on the limited number of water samples we have collected, we also found that there was little lingering effect of road salt impact on stream chloride level. Stream chloride peak drops down fast after precipitation.

Among the two sites studied, at the NMR site, the impact of road salt from PennDOT bridge on the stream chloride concentration is not significant for most cases. But in one single event (12/14/2017), a significant impact linked to the bridge drainage has been observed.

As for the PC site, the existence of other salt sources in the area makes the determination of the PennDOT salt stockpile impact on stream water quality difficult. It would have been preferable to study a more isolated site in which only a single PennDOT roadway or stockpile lies within the watershed, which could then facilitate establishing cause-effect links between salt spread operation and stream chloride levels.

Considering the short-duration nature of the salt impact and the lack of continuous stream chloride measurement in current study, it is more than likely that the peak chloride concentrations were not captured by our current sampling activities. To resolve this issue, some form of continuous stream water quality monitoring, and a coordination between sampling and road de-icing activities needs to be established.

Stream flow velocities or discharges also impact on the evolution of chloride concentrations with time, this important factor was not considered. This study showed that a much colder winter in which samples taken when the streams were frozen may not provide reasonable chloride concentration as different flow dynamics were at play. But this study did not take samples after frozen streams were thawed and could not comment on whether or not the salt operation had a delayed impact under such a scenario.

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