5 OVERVIEW OF THE LONG TERM CONTROL PLAN UPDATE (LTCPU)

5.1 MODEL DEVELOPMENT PROCESS AND TOOLS

This section presents the tools, methods and development processes used in conducting numerical analyses of the LTCPU alternatives and options. Computer modeling and data processing provided the necessary means to evaluate and estimate the current CSO conditions throughout each watershed as well as to estimate the impact on CSO reduction from incorporating green stormwater infrastructure practices, implementing a variety of storage elements and sizing storage tunnels and conveyance pipes. Additional details on modeling tools employed can be found in Supplemental Documentation Volume 4: Hydrologic and Hydraulic Modeling.

Tools and methods were developed to conduct quality assurance checks on input data to the computer models and to the computer model parameters themselves. Supplemental hydrologic analyses and programs to aide in the quality assurance tasks and to bring parameter data current were created and used. These include calculations of Rainfall Dependent Inflow and Infiltration (RDI/I) and Directly Connected Impervious Area (DCIA) estimates based on collected flow monitor and updated GIS data, which were discussed in previous sections.

Inherited models from previous LTCP analyses were updated to ensure proper representation of the City's infrastructure after implementation of system modifications due to constructed projects since the previous LTCP model development (*e.g.*, Nine Minimum Controls, Capital Projects, etc). Calibration and validation of the updated baseline models were completed to verify model results were accurately simulating the observed data. From the baseline models, hydrologic features and hydraulic infrastructure were modified and/or added to represent various alternatives intended to mitigate CSOs within each watershed for evaluation within this LTCPU. To more accurately simulate concepts such as tree canopy interception or benefits produced from implementing green infrastructure throughout the City, other supplemental tools were created and subsequent analyses performed.

After model Quality Assurance/Quality Control (QA/QC), calibration and validation were completed and development of alternative model representations were created, it was necessary to organize and analyze the resulting data from these models in an efficient and consistent manner. All alternative and baseline model results were summarized with the same SAS post-processing tool in order to maintain consistency for result comparison purposes. Spreadsheet analyses were applied to a number of alternatives, such as the parallel interceptor and satellite treatment facility alternatives, to facilitate efficiency in determining the feasibility of these controls. All alternative results had the estimated costs associated with design layouts, design element dimensions, lengths, volumes and other parameters calculated with the use of a costing spreadsheet tool. The results produced from these analyses are presented in further detail in subsequent sections.

The following section describes the methods and programs used during the course of the LTCPU model development process. Baseline and alternatives model development details follow, which presents specific tasks and information required to build these models. The last section summarizes the alternatives analysis process.

5.2 OVERVIEW OF ANALYSIS TOOLS AND METHODS

This section briefly outlines the programs and other tools used in the development and assessment of current and potential alternatives for the LTCPU. The tools and analysis methods for the LTCPU may be categorized into the following sections:

- Precipitation analysis
- Monitored flow analysis
- Special analyses
- Hydrologic and hydraulic analysis
- GIS analysis
- Alternatives costing
- Economic impact model

5.2.1 Precipitation Analysis

PWD maintains a large collection of historical precipitation data and continues to collect current data through its 24 rain gage network, as well as the National Weather Service Cooperative Station located at the Philadelphia International Airport. The PWD rain gauge data are analyzed through extensive QA/QC procedures to identify bad or missing data and fill with nearby gauge data, and perform bias adjustment using a combination of Microsoft Excel and Access, and SAS software tools developed by PWD for these purposes.

The development of a typical year precipitation record to represent average annual hydrologic conditions over the Philadelphia area is critical for the evaluation of combined sewer system (CSS) performance for the LTCPU. Statistical analyses of the long-term record are performed using the Philadelphia International Airport data to determine the average frequency, volume, duration, and peak intensity of rainfall events. Similar analyses are performed on the bias adjusted PWD rain gauge data in order to identify periods requiring minor adjustment to represent long-term average conditions. Performing these analyses and adjustments required the use of NetSTORM in addition to data processing and analysis tools developed by PWD using Excel, Access and SAS software. More details on precipitation analysis can be found in Supplemental Documentation Volume 5: Precipitation Analysis.

NetSTORM is discussed in the following subsection.

5.2.1.1 NetSTORM

NetSTORM is CDM's computer program for rainfall and planning-level rainfall-runoff storage-treatment analysis. NetSTORM adapts selected algorithms originally included in the HEC-STORM (USACE, 1977) program into a modern interface, extends the HEC-STORM methodology to simulation of linked structures in a complex collection system, performs intensity – duration – frequency analysis (IDF) of precipitation data and disaggregates daily and hourly precipitation data to higher resolutions for use in rainfall – runoff modeling. While these functions and others included in the program have been explored and improved upon by other researchers, NetSTORM possesses a unique collection of tools for rapid assessment of precipitation data and urban runoff assessment. NetSTORM has been used in the development of the LTCPU for both evaluation of long-term rainfall IDF analyses and for screening level evaluation of CSS performance.

5.2.2 Monitored Flow Analysis

Efficiently analyzing collected flow data is equally as important as the precipitation data with regard to shaping the LTCPU. Applying quality control measures to the data and disaggregating the hydrograph into specific components to more accurately define how and when rainfall and runoff enter the CSS are an integral part of the development process. The tools used to create a set of flow data to calibrate and build the LTCPU baseline and alternative models included quality assurance spreadsheets and CDM SHAPE software. RTK analysis spreadsheets were also created – RTK parameters being three values used to define a unit hydrograph. Specifically, they are the ratio of rainfall entering the sewer system (R), the time elapsed to reach the peak of the unit hydrograph (T) and the ratio of the length of the recession limb of the unit hydrograph to the time to peak (K). These three tools are discussed in further detail below.

5.2.2.1 QA/QC Spreadsheets

Flowmeter data collected at a variety of strategically placed locations throughout the City were imported into template QA/QC spreadsheets where missing, errant or otherwise unusable data could be identified, flagged and either removed or filled using averaging techniques. The spreadsheet is a facilitating source for organizing, documenting and fixing monthly flow data into a more useful form. The spreadsheet allows the flow data to be plotted and qualitatively assessed (alongside quantitative analyses) for anomalies that may have otherwise gone unnoticed.

The spreadsheets also allow for easy recognition of flowmeters requiring maintenance. For situations where a meter produced unusable data for extended periods of time, the data was flagged within the spreadsheet and data from that particular time period was not used in calibration assessments.

5.2.2.2 SHAPE Software

SHAPE is designed to manipulate a complete series of flow monitoring data. The program uses a Microsoft Access database to contain all the data used in RDI/I analyses. Data preparation features allow flow and rainfall monitoring data to be imported from several sources into the database. Once flow and rainfall data are imported into the database, the program offers the ability to manipulate the raw data. For instance, missing flow data can be filled in by interpolation. Once these data have been imported and altered, it is not necessary to further manipulate the raw flow and rain data again.

After flow and rain data are present in the database, dry weather evaluations allow dry weather weekend and weekdays to be identified from the period of record. The weekend and weekday dry weather flow patterns are different and require individual evaluation. The selected days with normal dry weather flows are used to determine the average, maximum and minimum dry weather flows for a monitoring location. The dry weather flows include groundwater infiltration (GWI) and base wastewater flows (BWF). Average weekday and weekend day dry weather flow hydrographs are computed, which are then subtracted from observed flows to determine the RDI/I flows during rainfall events.

Wet weather flow evaluations allow the determination of RDI/I flow volumes and peak flows for individual events. SHAPE computes the percentage of rainfall over the sewered area that enters the sewer system, or the total R-value. SHAPE also allows the fitting of triangular unit hydrograph parameters to simulate RDI/I flows from observed rainfall using the SHAPE methodology. For the purposes of this LTCPU, a more specialized set of spreadsheet tools (described below) were employed to develop the RTK values incorporating the use of a unit hydrograph methodology through an iterative process. Figure 5-1 is a flowchart of the processing steps used within the SHAPE software.

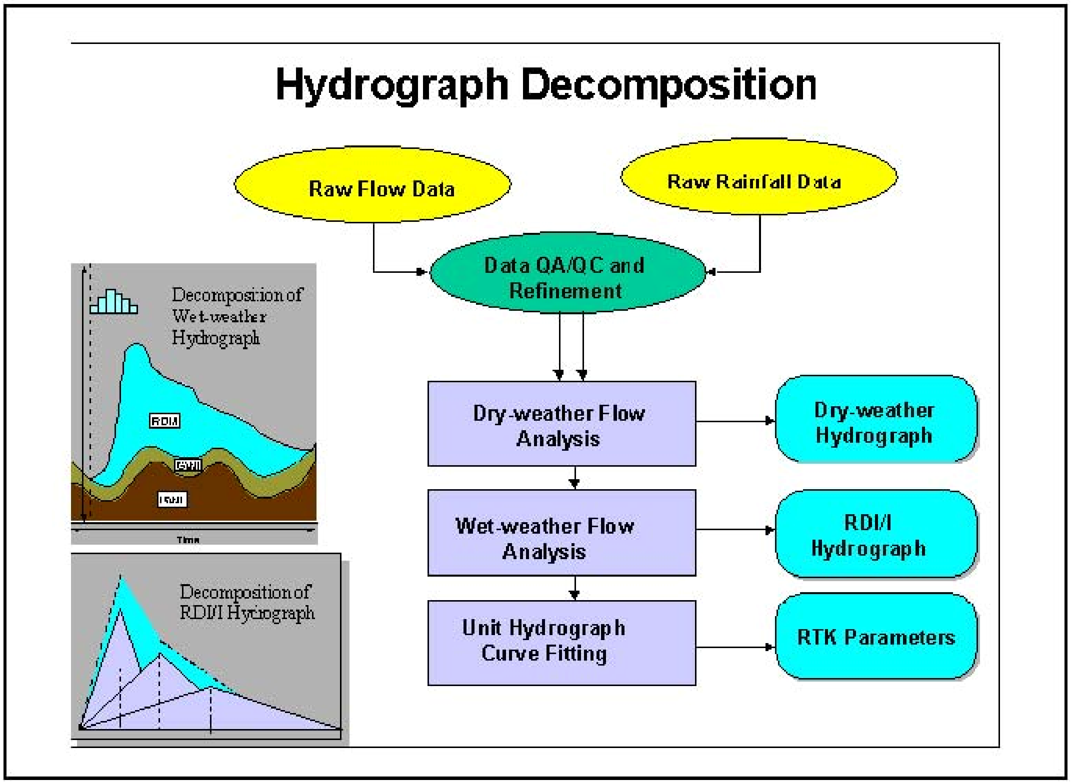


Figure 5-1 Processing Steps and Outputs from the SHAPE Software

5.2.2.3 RTK Analysis Spreadsheets

The RTK method is similar to the unit hydrograph methods commonly used to simulate flows in stormwater runoff analyses. This method is based on fitting three triangular unit hydrographs to an actual RDI/I hydrograph derived from flow meter data. A unit hydrograph is defined as the flow response that results from one unit of rainfall during one unit of time. Figure 5-2 presents a visualization of the RTK hydrograph and its components.

The development of the R, T and K elements to characterize RDI/I for sanitary sheds (discussed in greater detail in Section 5.3) was a multi-stage analysis process requiring the creation and use of two spreadsheet tools to analyze the output produced from the SHAPE software described above. The first analysis tool compares the observed temporary flowmeter data with simulated RTK responses to determine a first cut estimation of the RTK parameters at each site having sufficient data to analyze. The purpose of this analysis was to determine which flow monitoring sites provided the most consistent and fewest errors in the data for use as templates to distribute to the remaining flow monitoring sites. These sites were used as the templates and foundations for the second phase of the RTK processing within the second spreadsheet tool. The template data were used to adjust the remaining flow monitoring sites to more closely follow seasonal and monthly RDI/I variations. Following is a summary of the spreadsheets, the data used in them and the processing steps. Further details can be found in Supplemental Documentation Volume 4: Hydrologic and Hydraulic Modeling.

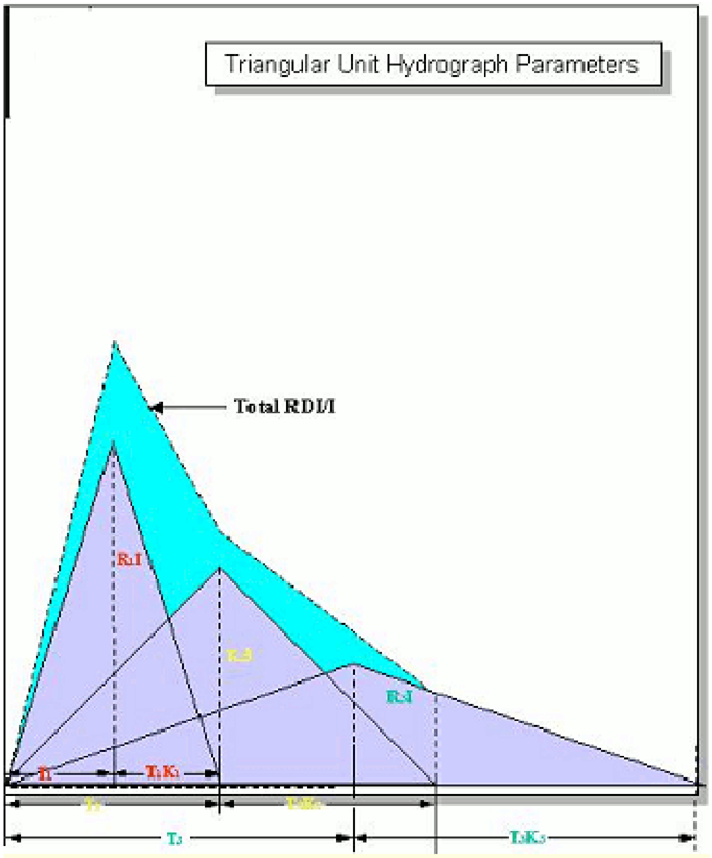


Figure 5-2 Decomposition of RDI/I Hydrograph into Three Unit Hydrographs with SHAPE Software

5.2.2.4 RTK Template Analysis Spreadsheet

The output from the SHAPE analysis – described previously in Section 5.2.2.2 – serves as input to the RTK Template Analysis Spreadsheet. The total R-value for defined event boundaries, which is the total fraction of RDI/I volume for the event, is divided into three parts representing the fast, medium and slow hydrograph response of the time series. T- and K-values are also defined for each response. The simulated RTK values are plotted and compared against observed flow data for each individual event. A best-fit volume line and scatter plot of the total event volume are created within the spreadsheet to show the tightness of fit of the individual events to the best-fit line between the observed and simulated RDI/I responses.

Based on the time-series comparison and the best-fit plot, the RTK values are adjusted and the data re-plotted. When a match has been achieved for one event, a new event for the same flowmeter site is plotted to compare the hydrographs and best-fit scatter plot volume with the new RTK values. If the simulated data does not satisfactorily match with observed data, adjustments to the RTK values continue. This process is iterative and continues until the best possible matches can be achieved among all the observed event data.

5.2.2.5 RTK Seasonal and Monthly Variation Spreadsheet

The output data from the previously described spreadsheet was used as input into the seasonal and monthly adjustment spreadsheet tool. Each month's RTK values were imported into the spreadsheet. The unit hydrograph is plotted for the imported data and adjusted to remove any anomalies that may produce a complex hydrograph or, in other words, more than one peak. For the template sites a month is chosen that has the most reliable data available to use as a datum to determine the seasonal variation. The spreadsheet calculates the ratios for the monthly values first and then uses those values to apply the seasonal ratios to calculate the final set of R-values.

Table 5-1 shows the ratio information for Site 44. The monthly ratios are determined by dividing the total R value for that month by the individual R1 (fast response value), R2 (medium response value) and the R3 (slow response value). To determine the seasonal ratio, the month with the most data and best correlation results as compared to the observed data was chosen for each template site. For Table 5-1, March was the chosen month. The R-values for every other month were divided by the March R-values.

Table 5-1 Ratio Information for Site 44

Month	R1	R2	R3	Total R (R1+R2+R3)	Monthly Ratios			Seasonal Ratios		
					R1/ Total R	R2/ Total R	R3/ Total R	R1/ March R1	R2/ March R2	R3/ March R3
January	0.0081	0.0074	0.0070	0.0225	0.3593	0.3292	0.3114	1.0096	1.0571	1.0769
February	0.0081	0.0074	0.0070	0.0225	0.3593	0.3292	0.3114	1.0096	1.0571	1.0769
March	0.0080	0.0070	0.0065	0.0215	0.3721	0.3256	0.3023	*	*	*
April	0.0080	0.0070	0.0065	0.0215	0.3721	0.3256	0.3023	1	1	1
May	0.0075	0.0065	0.0060	0.0200	0.3750	0.3250	0.3000	0.9375	0.9286	0.9231
June	0.0075	0.0051	0.0055	0.0181	0.4142	0.2812	0.3046	0.9375	0.7273	0.8485
July	0.0075	0.0051	0.0055	0.0181	0.4142	0.2812	0.3046	0.9375	0.7273	0.8485
August	0.0075	0.0051	0.0055	0.0181	0.4142	0.2812	0.3046	0.9375	0.7273	0.8485
September	0.0078	0.0057	0.0061	0.0196	0.3973	0.2917	0.3110	0.9750	0.8182	0.9394
October	0.0078	0.0064	0.0061	0.0203	0.3848	0.3139	0.3012	0.9750	0.9091	0.9394
November	0.0080	0.0070	0.0065	0.0215	0.3721	0.3256	0.3023	1	1	1
December	0.0081	0.0070	0.0065	0.0216	0.3743	0.3244	0.3012	1.0096	1	1

5.2.3 Special Analyses

A number of concept specific analyses were done for this LTCPU requiring creation of a set of tools to be built in order to interpret the preliminary results prior to fully implementing the conceptual model within SWMM4. These tools were meant to reduce model development time, while at the same time facilitate development of a sufficient "first-cut" estimation for a number of control alternatives that incorporate green infrastructure at varying levels of implementation.

5.2.3.1 Capture Program

The capture program was written within the FORTRAN environment and is used to calculate the volume captured and sent to the water pollution control plants (WPCPs) as well as the volume that overflows into the receiving body from a regulator. The capture program uses an input file to identify the dry weather capture and the wet weather overflow pipes associated with each regulator for which the capture calculations are performed. An inter-event time is also specified for event generation. For the LTCPU the inter-event time is set to six hours.

The output from the capture program is the capture volume, overflow volume, the respective storm and sanitary portion of the captured volume, overflow volumes and percent capture for each regulator for each of the respective wet weather events. Percent capture is determined by summing the total "captured" flow during a wet weather event, which is the volume of flow directed to the interceptor and ultimately to the WPCP. If all flow entering the regulating chamber is diverted to the interceptor, it is considered 100% capture. For events where a portion of the total flow entering the regulating chamber is overflowed, the captured volume is divided by the total volume entering the regulator to determine the percent capture. The results from the capture program may be further summarized to annual numbers using an external program written in the SAS environment.

5.2.3.2 SAS End-of-Pipe (EOP) Processing Tool

A SAS program was written to analyze the treatment rates required at each of the outfalls in the CSS so that a targeted overflow frequency can be achieved. For example, if an outfall overflows fifty (50) times a year and the treatment capacity exists to treat the third largest overflow among the fifty (50), then there will be only two storm events that will cause an overflow and the rest of the 48 events can be treated.

The specific steps followed to identify the treatment rate requirements are available in Supplemental Documentation Volume 4: Hydrologic and Hydraulic Modeling. Essentially, the overflow volume produced for every outfall and the output from the capture program described in Section 5.2.3.1 are used as input to the SAS program. These data are summarized into annual overflow numbers for a respective overflow goal (1 to 25 overflows/year) to be used in preliminary estimates of required satellite treatment and parallel interceptor alternatives analysis.

5.2.3.3 Parallel Interceptor Transmission Spreadsheet

The purpose of this tool is to determine parallel pipe segment dimensions using the existing interceptor as a guide prior to building a conceptual model for specific alternatives having a certain green-infrastructure implementation level. The tool is spreadsheet based and does not simulate flow through pipes, rather, it serves as a first cut estimation of pipe sizing for all possible parallel interceptor alternatives at every overflow goal between the values of 1 and 25 overflows per year for each potential level of green-infrastructure implementation. The parallel conveyance pipes use the slope of the respective existing interceptor segment and the cumulative overflow at that regulator (output produced from the SAS EOP tool discussed in the previous section) within the Manning's flow equation to calculate a pipe dimension. The spreadsheet tool also sums the total peak flow and resulting CSO (untreated overflow) volume for each system for every overflow goal. Details of this spreadsheet tool are available in the Supplemental Documentation Volume 4: Hydrologic and Hydraulic Modeling.

5.2.3.4 Parallel Interceptor with Satellite Treatment Spreadsheet

Similar to the Parallel Interceptor Transmission spreadsheet described in Section 5.2.3.3 above, the Parallel Interceptor with Satellite Treatment is a spreadsheet-based tool that does not simulate flow through pipes; instead, it sizes pipes based on peak flow values and existing interceptor slope values for overflow goals of 1, 4, 10 and 25 overflows per year. To determine the pipe sizes, the spreadsheet uses the Manning's equation in the same manner as outlined above. Where the two spreadsheets diverge is in the calculations to determine satellite treatment locations. Generally, the Parallel Interceptor with Satellite Treatment spreadsheet sums the total peak overflow value for a particular interceptor system and places the satellite treatment unit at the regulator where half the cumulative total peak flow for the system is reached or exceeded.

There are locations predetermined to be suitable for placing and constructing satellite treatment facilities specific to each drainage district. For these situations, the automated process of locating the satellite treatment location within the spreadsheet is manually overridden. The same procedures for calculating pipe dimensions are applied in this situation. More details of this spreadsheet tool are available in Supplemental Documentation Volume 4: Hydrologic and Hydraulic Modeling.

5.2.4 Hydrologic and Hydraulic Analysis Tools

5.2.4.1 Storm Water Management Model Version 4 (SWMM4)

The US EPA SWMM4 was used to develop the watershed-scale model for the LTCPU. The components of the SWMM4 model used in the development of the Philadelphia watershed and wastewater conveyance model were the RUNOFF and EXtended TRANsport (EXTRAN) (Huber and Dickinson, 1998) modules. The physical parameters and their initial estimations for each module are discussed individually in Supplemental Documentation Volume 4: Hydrologic and Hydraulic Modeling.

5.2.4.2 RUNOFF Module

The RUNOFF module was developed to simulate the quantity and quality of runoff in a drainage basin and the routing of flows and contaminants to sewers or receiving waters. The program uses a precipitation (rainfall or snowfall) hyetograph to perform a step by step accounting of infiltration losses in pervious areas, surface detention, overland flow, channel flow and water quality constituents leading to the calculation of one or more hydrographs and/or pollutagraphs at a certain geographic point such as a sewer inlet. The driving force of the RUNOFF module is precipitation, which may be a continuous record, single measured event, or artificial design event. The RUNOFF module also simulates RDI/I in separate sanitary areas using three sets of unit hydrographs defined by R, T and K – described in Section 5.2.2 above – values to represent the shape of the RDI/I hydrograph response to the input precipitation hyetograph.

The RUNOFF module requires the input of several physical parameters to determine the rainfall-runoff response from modeled combined-sewer subcatchments. These include:

- Subcatchment area
- Subcatchment width (used to determine overland flow length)
- Percent DCIA (effective impervious area)
- Subcatchment ground slope
- Manning's roughness coefficient for pervious and impervious areas
- Depression storage for pervious and impervious areas
- Soil infiltration parameters
- RDI/I parameters or user input hydrographs for sanitary sheds
- Baseflow data
- Precipitation data
- Evaporation data

5.2.4.3 EXTRAN Module

The EXTRAN module was developed to simulate hydraulic flow routing for open channel and/or closed conduit systems. The EXTRAN module receives hydrograph inputs at specific nodal locations by interface file transfer from an upstream module (*e.g.*, the RUNOFF module) and/or by direct user input (*e.g.*, user defined hydrographs for sanitary sheds). The module performs dynamic routing of stormwater and wastewater flows through drainage systems and receiving streams. To calculate the flow in the sewers SWMM4 uses values for the following variables:

- Pipe data including shape, cross-sectional area, length, width, depth, hydraulic radius and slope
- Junction data including ground and invert elevations, storage volume (if necessary) and baseflow
- Orifice data (if necessary) including type, cross-sectional area, discharge coefficient, invert elevation, depth and width
- Weirs including length, width and a weir coefficient
- Pump data including type and pumping rate
- Outfalls

5.2.5 GIS Analysis Tools (ArcTools)

ArcGIS Hydro is a collection of tools that analyzes various GIS layers for hydrologic modeling. It provides a consistent method for developing watershed and stream networks by analyzing digital elevation models (DEMs). Terrain pre-processing is performed on the DEMs. For example, one function performed during the terrain processing is sink pre-processing where unnatural depressions are filled. Flow direction, flow accumulation, stream definition, drainage line delineation and catchment polygon processing result in a stream and watershed network. With the network created watersheds can be generated from any point on the network.

ArcGIS and its components were used in nearly every aspect of LTCPU data processing. It was used extensively in analyses involving impervious cover definitions, highway and waterfront disconnection analyses and all subcatchment area delineation adjustments involved in the model development for both the baseline and generic green-infrastructure models.

5.2.6 Alternatives Costing Tool (PWD Capital Projects Cost Estimating Tool)

The Alternatives Costing Tool (ACT) provides planning-level cost estimates to facilitate the evaluation and comparison of preliminary alternatives and the preparation of feasibility reports. The ACT is an EXCEL spreadsheet based program. It calculates capital and operation and maintenance (O&M) costs of wet weather conveyance, storage and treatment facilities in one of two ways. It scales complete treatment facility costs based on costing algorithms developed from evolving and expanding national data sets and other regional capital and O&M cost data. Otherwise, it assembles construction and O&M costs from smaller components (*e.g.*, material cost of a particular type and size of pipe, energy cost for pumping at a specific total dynamic head, flow rate, duration and electrical rate, etc). Further details can be found in Supplemental Documentation Volume 3: Basis of Cost Opinions. Key outputs from the ACT include:

- Current year capital cost
- Current year O&M costs
- Present worth based on capital costs and projected O&M costs

A user of the ACT develops control alternatives, including conceptual level determinations of facility size, type and configuration. This information is then entered into the costing tool through standardized templates. All assumptions and calculations are viewable by the user. The ACT has a number of input parameters that use fixed values (*e.g.*, the discount rate for present worth calculations). The user is able to override these fixed values.

The following control technologies were included in the ACT and were used to develop opinions of cost:

Source Controls
- Land-based stormwater management
    - Green roofs
    - Porous pavement
    - Bioretention and similar surface vegetated practices
    - Subsurface infiltration

Transmission
- Pump stations
- Open cut pipe
    - Gravity sewer
    - Force main
- Short-bore tunnel (trenchless)
    - Microtunneling
    - Pipe jacking

Storage
- Conventional tunnels (storage/conveyance)
- Tank storage

Treatment
- Retention treatment basins

The following control technologies were included in the ACT, but were not used to develop opinions of cost:

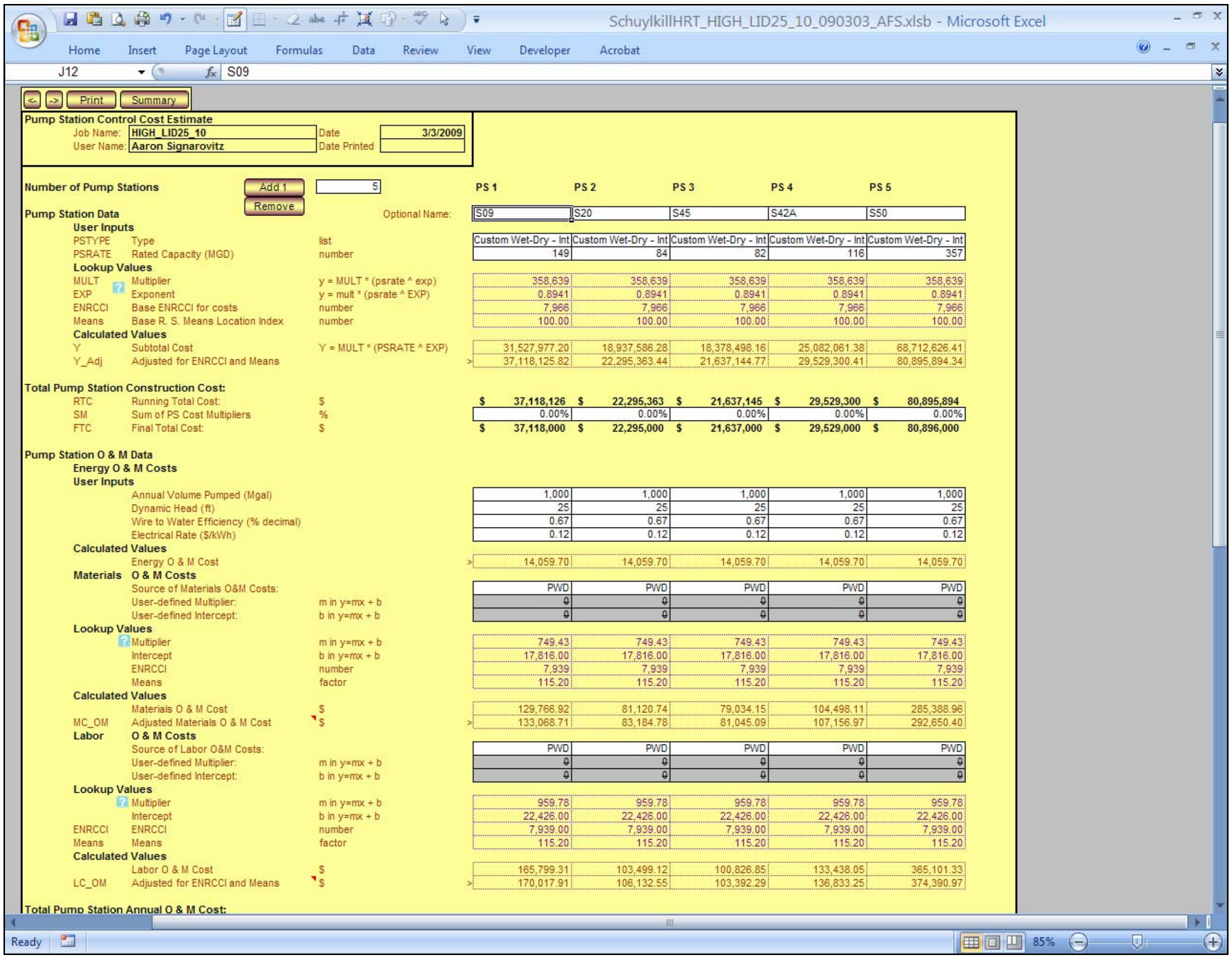
Not Used
- Private and municipal I/I reduction
- Sewer separation
- Vortex separation
- High rate clarification
- Screening
- Disinfection

Other opinions of cost were developed outside of the ACT including sewer separation and satellite treatment. Further details on costing methods for all controls can be found in Supplemental Documentation Volume 3: Basis of Cost Opinions.

5.2.6.1 Input Formats and Organization

The ACT is organized into groups by control technology; these groups within the ACT are called modules. Modules can contain large numbers of individual items (*e.g.*, multiple pump station facilities, multiple pipeline segments, etc.). Figure 5-3 shows an example of multiple items in the

Pump Station Module. Figure 5-4 shows an example of multiple control technology costs that make up an alternative cost.


SchuylkillHRT_HIGH_LID25_10_090303_AFS.xlsb - Microsoft Excel

Pump Station Control Cost Estimate

Job Name: HIGH_LID25_10 Date 3/3/2009

User Name: Aaron Signarovitz Date Printed

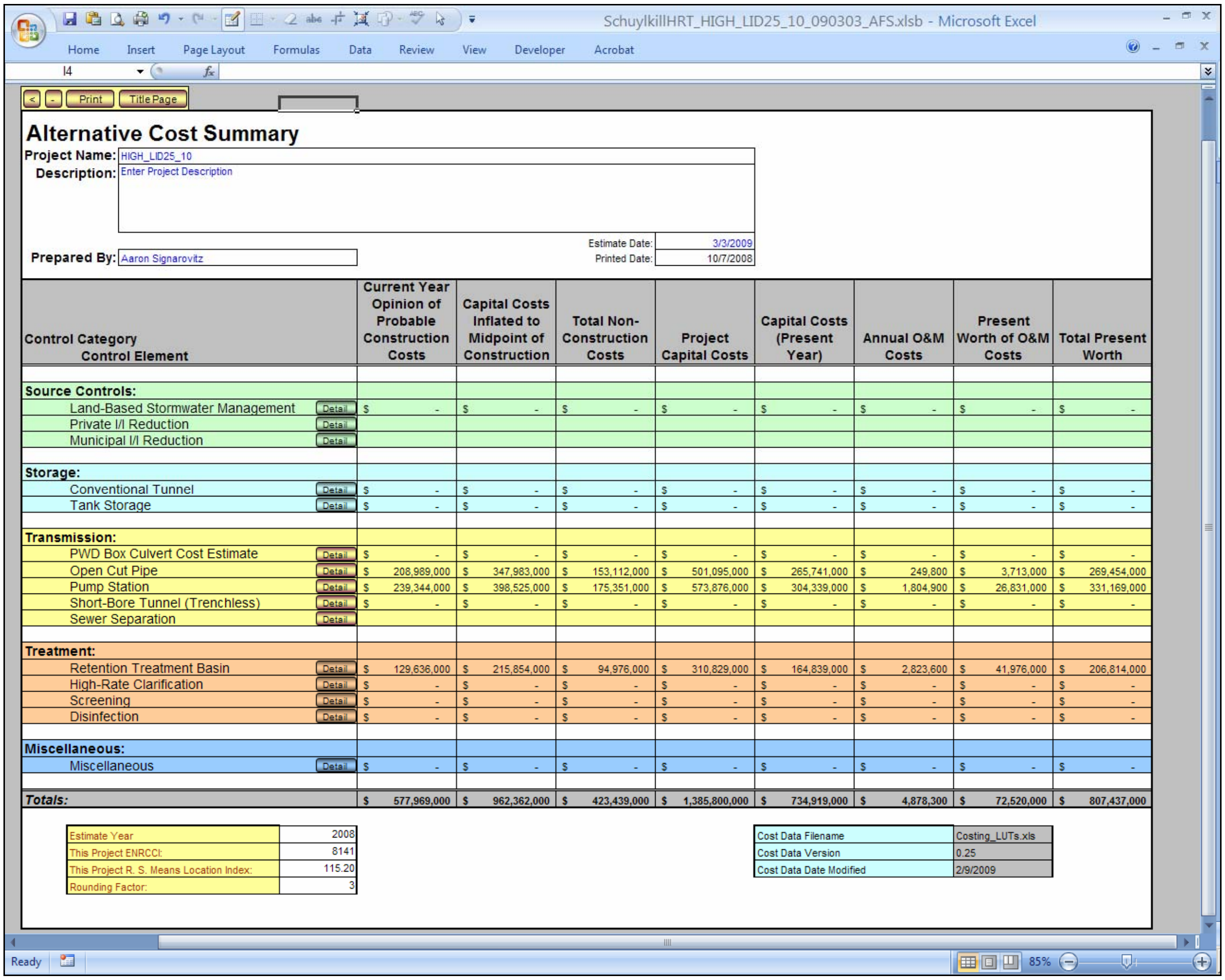
Number of Pump Stations: 5

			PS 1	PS 2	PS 3	PS 4	PS 5
Pump Station Data		Optional Name:	S09	S20	S45	S42A	S50
User Inputs							
PSTYPE	Type	list	Custom Wet-Dry - Int	Custom Wet-Dry - Int	Custom Wet-Dry - Int	Custom Wet-Dry - Int	Custom Wet-Dry - Int
PSRATE	Rated Capacity (MGD)	number	149	84	82	116	357
Lookup Values							
MULT	Multiplier	y = MULT * (psrate ^ exp)	358,639	358,639	358,639	358,639	358,639
EXP	Exponent	y = mult * (psrate ^ EXP)	0.8941	0.8941	0.8941	0.8941	0.8941
ENRCCI	Base ENRCCI for costs	number	7,966	7,966	7,966	7,966	7,966
Means	Base R. S. Means Location Index	number	100.00	100.00	100.00	100.00	100.00
Calculated Values							
Y	Subtotal Cost	Y = MULT * (PSRATE ^ EXP)	31,527,977.20	18,937,586.28	18,378,498.16	25,082,061.38	68,712,626.41
Y_Adj	Adjusted for ENRCCI and Means		37,118,125.82	22,295,363.44	21,637,144.77	29,529,300.41	80,895,894.34
Total Pump Station Construction Cost:							
RTC	Running Total Cost:	$	$ 37,118,126	$ 22,295,363	$ 21,637,145	$ 29,529,300	$ 80,895,894
SM	Sum of PS Cost Multipliers	%	0.00%	0.00%	0.00%	0.00%	0.00%
FTC	Final Total Cost:	$	$ 37,118,000	$ 22,295,000	$ 21,637,000	$ 29,529,000	$ 80,896,000
Pump Station O & M Data							
Energy O & M Costs							
User Inputs							
	Annual Volume Pumped (Mgal)		1,000	1,000	1,000	1,000	1,000
	Dynamic Head (ft)		25	25	25	25	25
	Wire to Water Efficiency (% decimal)		0.67	0.67	0.67	0.67	0.67
	Electrical Rate ($/kWh)		0.12	0.12	0.12	0.12	0.12
Calculated Values							
	Energy O & M Cost		14,059.70	14,059.70	14,059.70	14,059.70	14,059.70
Materials	**O & M Costs**						
	Source of Materials O&M Costs:		PWD	PWD	PWD	PWD	PWD
	User-defined Multiplier:	m in y=mx + b	0	0	0	0	0
	User-defined Intercept:	b in y=mx + b	0	0	0	0	0
Lookup Values							
	Multiplier	m in y=mx + b	749.43	749.43	749.43	749.43	749.43
	Intercept	b in y=mx + b	17,816.00	17,816.00	17,816.00	17,816.00	17,816.00
	ENRCCI	number	7,939	7,939	7,939	7,939	7,939
	Means	factor	115.20	115.20	115.20	115.20	115.20
Calculated Values							
	Materials O & M Cost	$	129,766.92	81,120.74	79,034.15	104,498.11	285,388.96
MC_OM	Adjusted Materials O & M Cost	$	133,068.71	83,184.78	81,045.09	107,156.97	292,650.40
Labor	**O & M Costs**						
	Source of Labor O&M Costs:		PWD	PWD	PWD	PWD	PWD
	User-defined Multiplier:	m in y=mx + b	0	0	0	0	0
	User-defined Intercept:	b in y=mx + b	0	0	0	0	0
Lookup Values							
	Multiplier	m in y=mx + b	959.78	959.78	959.78	959.78	959.78
	Intercept	b in y=mx + b	22,426.00	22,426.00	22,426.00	22,426.00	22,426.00
ENRCCI	ENRCCI	number	7,939.00	7,939.00	7,939.00	7,939.00	7,939.00
Means	Means	factor	115.20	115.20	115.20	115.20	115.20
Calculated Values							
	Labor O & M Cost	$	165,799.31	103,499.12	100,826.85	133,438.05	365,101.33
LC_OM	Adjusted for ENRCCI and Means	$	170,017.91	106,132.55	103,392.29	136,833.25	374,390.97
Total Pump Station Annual O & M Cost:							

Figure 5-3 Example ACT Pump Station Module with Multiple Items

5.2.6.2 Land-Based Stormwater Management Module Overview

There are four different land-based stormwater management control types that are listed as follows: green roofs, porous pavement, bioretention and subsurface infiltration. The construction costs for each control type are divided into two different construction types: retrofit and redevelopment. Retrofit costs include the full cost of installing a control technology at an existing location, whereas redevelopment costs represent a cost savings that can occur when installation is conducted concurrently with traditional building activities (*e.g.*, sidewalk restoration). Construction and O&M costs are based on materials and labor required to construct controls. For large-scale, long-term planning purposes, engineering cost opinions are normalized on a per-acre basis.


SchuylkillHRT_HIGH_LID25_10_090303_AFS.xlsb - Microsoft Excel

Alternative Cost Summary

Project Name: HIGH_LID25_10

Description: Enter Project Description

Prepared By: Aaron Signarovitz

Estimate Date: 3/3/2009

Printed Date: 10/7/2008

Control Category / Control Element	Current Year Opinion of Probable Construction Costs	Capital Costs Inflated to Midpoint of Construction	Total Non-Construction Costs	Project Capital Costs	Capital Costs (Present Year)	Annual O&M Costs	Present Worth of O&M Costs	Total Present Worth
Source Controls:								
Land-Based Stormwater Management	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Private I/I Reduction								
Municipal I/I Reduction								
Storage:								
Conventional Tunnel	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Tank Storage	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Transmission:								
PWD Box Culvert Cost Estimate	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Open Cut Pipe	$ 208,989,000	$ 347,983,000	$ 153,112,000	$ 501,095,000	$ 265,741,000	$ 249,800	$ 3,713,000	$ 269,454,000
Pump Station	$ 239,344,000	$ 398,525,000	$ 175,351,000	$ 573,876,000	$ 304,339,000	$ 1,804,900	$ 26,831,000	$ 331,169,000
Short-Bore Tunnel (Trenchless)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Sewer Separation								
Treatment:								
Retention Treatment Basin	$ 129,636,000	$ 215,854,000	$ 94,976,000	$ 310,829,000	$ 164,839,000	$ 2,823,600	$ 41,976,000	$ 206,814,000
High-Rate Clarification	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Screening	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Disinfection	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Miscellaneous:								
Miscellaneous	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Totals:	$ 577,969,000	$ 962,362,000	$ 423,439,000	$ 1,385,800,000	$ 734,919,000	$ 4,878,300	$ 72,520,000	$ 807,437,000

Estimate Year	2008
This Project ENRCCI:	8141
This Project R. S. Means Location Index:	115.20
Rounding Factor:	3

Cost Data Filename	Costing_LUTs.xls
Cost Data Version	0.25
Cost Data Date Modified	2/9/2009

Figure 5-4 Example ACT Alternative Cost

5.2.6.3 Pump Station Facility Module Overview

The pump station module represents pump station facility construction and O&M costs. The construction costs are comprised of two different wastewater pump types: submersible and custom built wet-dry well. A range of cost curves are presented for each pump type based on the total dynamic head and use of standby power. The key input used to calculate construction cost is pump station flow rate capacity. The key inputs used to calculate O&M include: annual volume pumped, total dynamic head, wire to water pump station efficiency and electrical rate.

5.2.6.4 Open Cut Pipe Module Overview

The open cut pipe module estimates the complete construction and O&M cost for pipes installed through the open cut method. The total construction costs are assembled through many smaller component costs. It can estimate construction costs for a range of pipe features and additional cost factors, which are listed as follows:

- Pipe features
    - Size
    - Material

    - Depth to invert
    - Circular, or box shape
    - Length in street or through open land
    - Length in soil or rock
- Additional cost items
    - Manholes
    - Service laterals
    - Utility crossing
    - Curb and sidewalk restoration
    - Traffic control
    - Dewatering
    - Flow maintenance
- Additional cost placeholders (calculated outside of ACT or in another module)
    - Railroad crossing costs
    - Stream crossing costs
    - Additional force main costs
    - Miscellaneous

The key inputs used to calculate construction cost include: pipe shape, pipe material, length (in street/out of street), average depth to pipe invert, percent rock excavated, number of manholes, manhole diameter and others. The key inputs used to calculate O&M costs include length of pipe and number of manholes.

5.2.6.5 Short-Bore Tunnel (Trenchless) Module Overview

The short-bore tunnel (trenchless) module estimates construction and O&M cost for pipes installed through trenchless methods. The construction costs were comprised of two trenchless methods: microtunneling and pipe jacking. The key inputs used to calculate construction costs include: pipe size, pipe material, laying conditions (*i.e.*, soil, rock, mixed), pipe length between pits, pit type (*i.e.*, jacking or receiving), pit depth in soil, and pit depth in rock. The key inputs used to calculate O&M costs include length of pipe and number of manholes.

5.2.6.6 Conventional Tunnels (Storage/Conveyance) Module Overview

The conventional tunnel module is used to list complete construction and O&M costs for large diameter conventional tunnels, dewatering pump stations and secondary tunnel structures. The cost estimation for conventional tunnels is performed with supplementary spreadsheets outside of the ACT; the results are copied or linked into the conventional tunnel module. Cost estimation of conventional tunnels requires significant geotechnical data and expertise.

5.2.6.7 Tank Storage Module Overview

The tank storage module represents complete tank storage facility construction and O&M costs. The key input used to calculate construction cost is storage tank volume. The key inputs used to calculate O&M include storage tank volume and labor rates.

5.2.6.8 Retention Treatment Basins Module Overview

The retention treatment basin module represents complete retention treatment facility construction and O&M costs. The key inputs used to calculate construction cost include peak treatment flow rate and design detention time. The key inputs used to calculate O&M include: peak treatment flow rate, design detention time, labor rates, annual non-event hours and annual event hours.

5.2.7 Economic Impact Model

The US EPA suggests that a financial capability assessment should be included in the CSO LTCPU in order to establish the burden of compliance on both ratepayers and the permittee. The purpose of the financial capability assessment is twofold.

First, US EPA allows flexibility in scheduling completion of CSO compliance measures, based on the financial capability of the area served. The results of the capability assessment serve as documentation for negotiating enforcement orders and scheduling implementation of CSO-related projects with US EPA. Second, a financial capability assessment is the basis for determining funding needs by agencies providing loan and grant monies for capital projects

US EPA suggests a two-phase approach to a financial capability assessment. The first phase is the calculation of a residential indicator and the second phase is the analysis of the permittee's financial capability indicator.

The residential indicator is the percentage of median household income expended on wastewater and stormwater treatment. The financial capability indicator is an assessment of the permittee's debt burden, socioeconomic conditions and financial operations. These two measures are subsequently entered into a financial capability matrix, suggested by US EPA, to determine the level of financial burden that wastewater/stormwater treatment and CSO compliance measures will place on residential customers and the permittee.

In addition to following guidelines for these two measures, US EPA encourages inclusion of any information that would have a financial impact on CSO compliance by the permittee in the capability report. This assessment, therefore, includes extensive discussion of socioeconomic trends in the Philadelphia area because of the financial challenges that the region faces.

5.3 Baseline Model Development

Development of the baseline model for the LTCPU was important as it is the foundation from which all alternatives were built and results compared. Accurately simulating the current hydrologic conditions and hydraulic infrastructure was essential to producing valuable and reliable results. The methods and input data utilized in order to create the baseline model with respect to the hydrology, hydraulics and the calibration and validation, are discussed in the subsections following.
More details on the baseline model development subsections can be found in Supplemental Documentation Volume 4: Hydrologic and Hydraulic Modeling.

5.3.1 Hydrologic Model Development

The baseline model was developed using the US EPA SWMM4 software discussed in previous sections. The RUNOFF module in SWMM4 requires the input of several physical parameters to determine the rainfall-runoff response from modeled combined-sewer and separate sanitary sewer subcatchments. To reiterate from the previous section, these include:

- Subcatchment area
- Subcatchment width (used to determine overland flow length)
- Percent DCIA (effective impervious area)
- Subcatchment ground slope
- Manning's roughness coefficient for both pervious and impervious areas
- Depression storage for both pervious and impervious areas (initial abstraction)
- Soil infiltration parameters
- RDI/I parameters
- Baseflow ranges
- Precipitation input data
- Evaporation input data
- Temperature input data and snowmelt

A brief description of each parameter and the source data follow in the subsections below.

5.3.1.1 Subcatchment Area

Natural stormwater drainage subcatchment area can be determined by constructing drainage divides on topographic maps and is dependent upon the detail of the topographic information. Combined sewer subcatchment area is determined based on detailed sewer plats within the City and the topographic maps needed to determine surface drainage to sewer inlet locations. The delineation of sanitary sewer subcatchment area both inside and outside of the City is based solely on detailed sewer plans. The complete hydrologic model consists of 2098 subcatchments representing the entire PWD service area.

5.3.1.2 Subcatchment Width

The width of the subcatchment is the physical width of overland flow. Since real subcatchments are not rectangular with properties of symmetry and uniformity, it is necessary to adopt other procedures to obtain the width for more general cases. This is important because if the slope and roughness are fixed, the width can be used to alter the hydrograph shape. For the PWD LTCPU CSS models, width was initially taken to be double the square root of the subcatchment's area and later treated as a calibration parameter.

5.3.1.3 Percent DCIA

The percent imperviousness of a subcatchment is a parameter that can be reasonably estimated from aerial photos or land use maps. However, not all of the impervious area is directly connected to the drainage system, or is "effective" when simulating a hydrologic response from these areas. For example, if a rooftop drains onto pervious area, this should not be included as directly connected. The total percent impervious area was used as the initial effective impervious area and then reduced during the calibration process to best simulate the observed hydrologic response over a range of precipitation events.

For all areas within the City of Philadelphia, GIS coverage of impervious areas delineated from 2004 orthodigital photographs was used. This coverage delineated all land use in the City into pervious or "natural surfaces," comprised of lawns, parks, marshes, golf courses, wooded areas and cemeteries, as well as several different classifications of impervious areas. Impervious land uses were broken down into the following types:

- Alleys
- Buildings
- Building centers
- Concrete/asphalt slabs/patios
- Ditches (asphalt or concrete)
- Driveways
- Institutions
- Lakes
- Medians
- Parking
- Pedestrian bridges
- Parking islands
- Pond
- Pools
- Railroad ballast
- Railroad bridges
- Reservoirs
- Rivers
- Sidewalks
- Shoulders
- Streams
- Tanks
- Travel bridges
- Travelways

For each RUNOFF subcatchment, the area of these land uses was summed to generate a total impervious area. Impervious areas in each subcatchment were summed and divided by the total area in order to get the first estimate of subcatchment "effective" impervious area.

5.3.1.4 Slope

The subcatchment slope should reflect the average slope along the pathway of overland flow to inlet locations. For a simple geometry, the calculation is simply the elevation difference divided by the length of flow. Subcatchments containing highway ramps underwent a more technical slope procurement procedure in order to prevent distortion of the slopes due to the grade of the ramp. ArcGIS was utilized in order to calculate the slopes for these subcatchments. Two different procedures were documented and applied for scenarios inside the City and those existing outside the City. Generally, the topographic lines representing the ramps were removed and new raster layers were created. From the new raster layers, slopes were calculated using the remaining topographic lines.

5.3.1.5 Manning's Roughness Coefficient

Manning's roughness values must be estimated for both pervious and impervious overland flow. Roughness is an empirical value and was treated as a calibration parameter when necessary.

5.3.1.6 Depression Storage

Depression (retention) storage is the rainfall abstraction volume that must be filled prior to the occurrence of runoff on both pervious and impervious areas. By default, the model assumes 25% of the impervious area has zero depression storage. This default value was not altered in the LTCPU model setup. In the model, water stored as depression storage on pervious areas is subject to infiltration and evaporation. Water stored in depression storage on impervious areas is depleted only by evaporation. Depression storage is an empirical value and was treated as a calibration parameter when necessary. Following calibration, impervious depression storage was set to values selected based on literature review and past modeling experience with the City's existing hydrologic models of combined sewer areas.

5.3.1.7 Pervious Area Infiltration Parameters

The rate of infiltration is a function of soil properties in the drainage area, ground slopes and ground cover. For the LTCPU hydrologic model, the Green-Ampt method is used to simulate infiltration rates within the RUNOFF module. The Green-Ampt equation for infiltration has physically based parameters that can be estimated based on soil characteristics. Soil information for the Philadelphia watersheds was obtained at the beginning of the PWD CSO program in the early 1990s from the U.S. Department of Agriculture's (USDA) Natural Resources Conservation Service, which is responsible for collecting, storing, maintaining and distributing soil survey information for privately owned lands in the United States. Initial infiltration parameters were assigned to each subcatchment based on soil texture classification. The saturated hydraulic conductivity parameter was treated as a calibration parameter within reasonable bounds.

5.3.1.8 RDI/I

RDI/I – shown in Figure 5-5 – into sanitary sewer systems has long been recognized as a major source of operating problems, causing poor performance of many sewer systems. RDI/I analyses are done to more accurately account for excess rain water entering the sanitary sewers through a combination of inflows from illicit connections of downspout pipes, sump pumps and foundation drains. Contributions may also come from manhole openings and large pipe defects along streams as well as infiltration through saturated soils and elevated groundwater levels into small cracks in degraded sewer pipes and joints. RDI/I decreases the available sewer capacity available to convey stormwater runoff through the trunks and into the interceptor during wet weather events.

To define the City of Philadelphia's Sanitary Sewer RDI/I response for the LTCPU, the RTK hydrograph generation method was used. RDI/I analysis was applied to subcatchments with separate sanitary sewers contributing to the CSS. The RUNOFF module uses three sets of unit hydrographs defined by R, T and K values – detailed descriptions of these parameters are available in Section 5.2.2 of this report - to represent the shape of the RDI/I hydrograph.

To define the RTK values for the City, a selection of flowmeter sites was made from 39 sites. Selection of the flowmeter sites was based on the quantity and quality of data existing at each site. Out of the 39 sites, 13 provided a satisfactory amount of observed flow data. The selected flowmeter site ID, contributing area and the location (district) are shown below in Table 5-2.

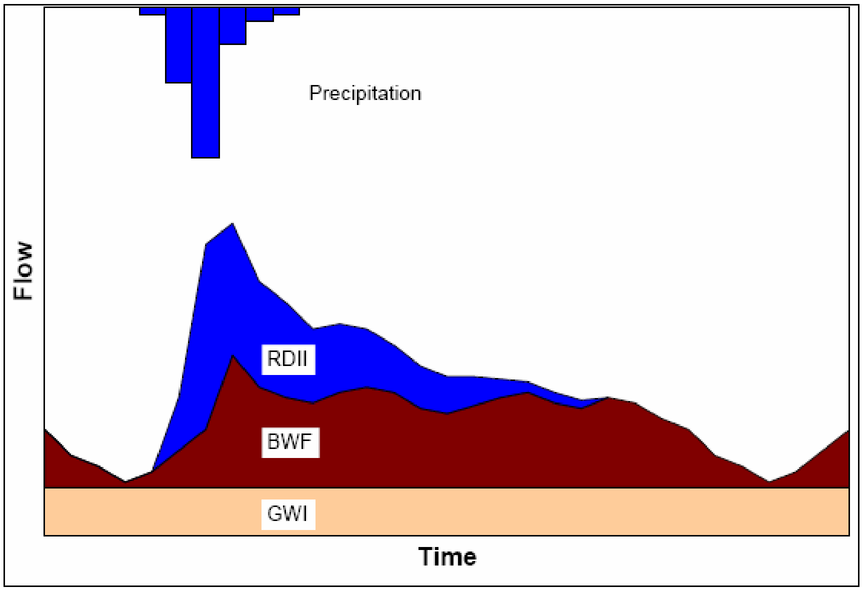


Figure 5-5 The Three Major Components of Wet Weather Wastewater Flow into a Sanitary System - BWF, GWI and RDI/I (US EPA, 2007)

QA was carried out on the data from the above sites. The flow data was checked for date/time inconsistencies, unusable data due to flowmeter malfunctions or missing data. Flags were used to help calculate statistical information on the data and to facilitate identification of anomalies in subsequent data processing steps (*e.g.*, subsequent SHAPE analysis). Data having previous QA checks were re-evaluated and brought up to current quality standards.

Following QA of the flow data, CDM SHAPE software was used to determine the estimated ratio of rainfall entering the sewers from each dataset. More details of the SHAPE software and processes involved are available in Section 5.2.2.

Results of the SHAPE analysis were further refined using Excel spreadsheets to compare monitored or observed data with the generated hydrographs using the estimated R, T and K parameters produced from the SHAPE analysis. An example of an acceptable matching hydrograph and corresponding best-fit volume scatter plot are shown in Figures 5-6(a) and (b).

The results from the spreadsheet analysis (Table 5-2) were further refined to have seasonal and monthly variability by processing through the Seasonal and Monthly Variation Spreadsheet (Section 5.2.2.5).

Figures 5-6(a) and (b) provide examples of an acceptable observed to simulated data hydrograph and best-fit volume scatter plot match from the RTK template analysis spreadsheet tool. The red line represents the ideal best-fit line, green representing the calculated actual fit line computed with a y-intercept value set to 0 (slope = 0.9952) and the black line representing the actual fit line with a computed y-intercept value (slope = 0.9035).

Four sites were chosen as templates for the remaining 26 flowmeter sites and all remaining un-metered sanitary sewershed loading points. Selection of the four sites to use as templates was based on flowmeter data consistency, accuracy and precision of observed hydrographs compared to estimated hydrographs. The size of the contributing area to the flowmeter was used as the criteria for distributing the templates to the un-metered sheds. Table 5-3 outlines the four sites selected as templates.

Table 5-2 Sites chosen for full RTK analysis

Site ID	Contributing Area (ac)	District	Date Range
5	9361	NE	6/2000 to 9/2001
27	674	NE	8/1999 to 4/2000
29	656	NE	9/1999 to 10/1999
40	4557	SW	8/1999 to 9/2001
44	1986	NE	11/1999 to 4/2000
49	1784	SE	5/2000 to 8/2002
57	164	SW	6/2000 to 9/2001
70	276	NE	6/2000 to 9/2001
72	301	NE	3/2001 to 5/2005
75	179	NE	6/2001 to 7/2004
77	162	NE	9/2000 to 7/2002
95	3540	NE	6/2004 to 5/2006
96	12594	NE	6/2004 to 5/2006

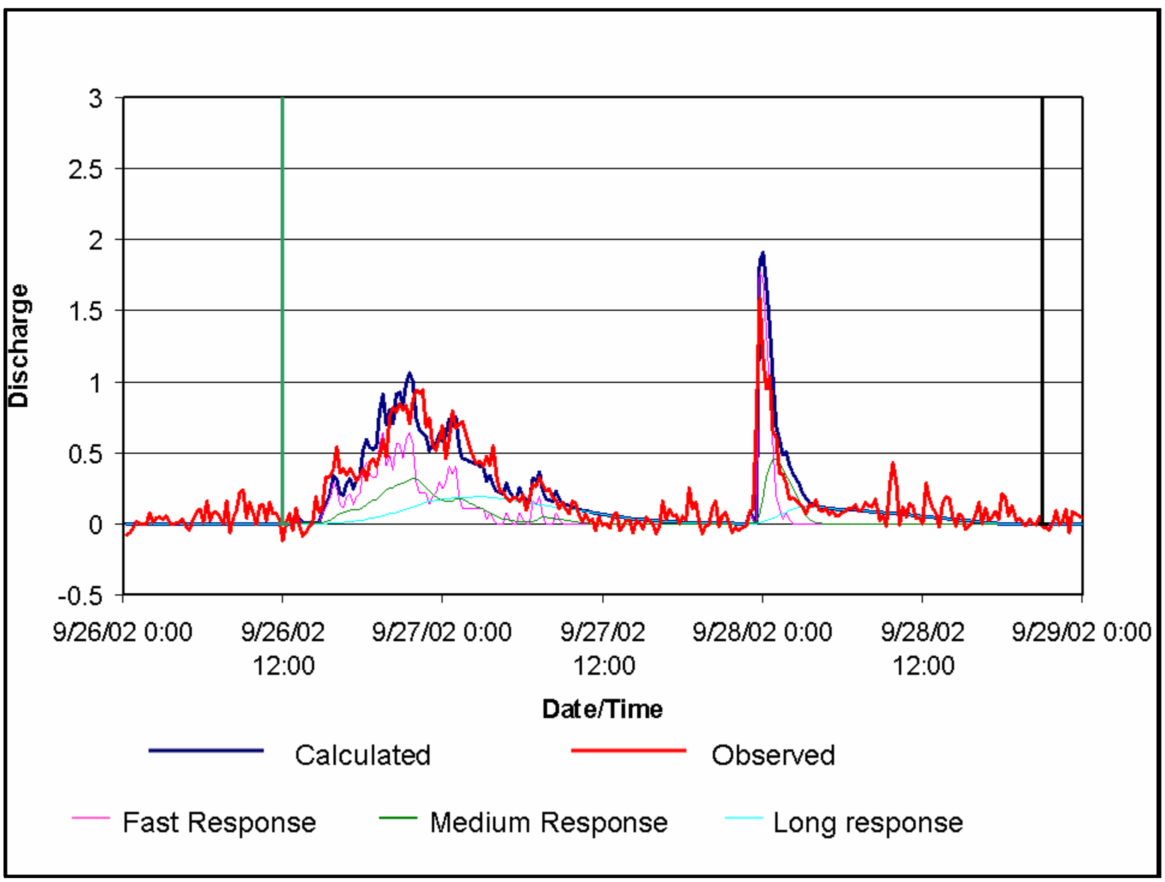


Figure 5-6(a) Hydrograph Used to Fit RTK Values

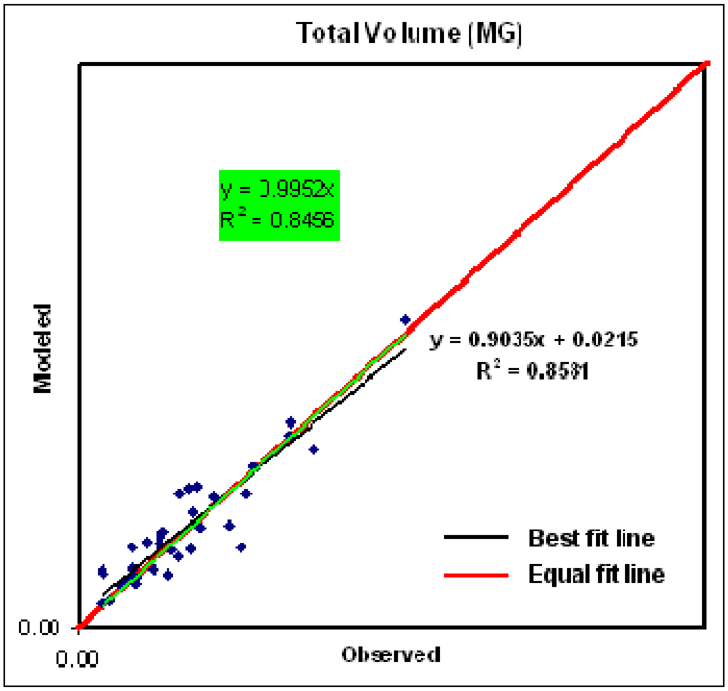


Figure 5-6(b) Best-Fit Line from a Volume Scatter Plot Used to Fit RTK Values

Table 5-3 Listing of the Sites Chosen as Templates and the Corresponding Ranges of Application

Site ID	Contributing Area (ac)	Area Range to Apply
75	179	area < 300 ac
70	276	300 ac ≤ area ≤ 1000 ac
40	4557	1000 ac ≤ area ≤ 5000 ac
5	9361	area > 5000 ac

5.3.1.9 Outlying Community User Input Hydrographs

The amount and quality of data from the outlying community flowmeters was insufficient to appropriately define the RTK values and analyze with SHAPE software, therefore an alternative method of representing the sanitary sewer flow was adopted for these sheds. For outlying community separate sanitary sewered areas, time-series data was loaded to the SWMM4 model through the user input hydrograph option line. A representative annual time series was created from available monitoring data. The time-series data underwent a QA process where missing or suspicious data was filled with hourly averaged values.

5.3.2.10 Baseflow Ranges

High and low average annual dry weather flow rates are used to establish upper and lower estimates of available wet weather treatment capacity (worst and best case scenarios) for LTCPU alternatives evaluations. The baseflow values representing the 80th, 50th and 20th percentiles for each WPCP were selected for determining high, median and low baseflow estimates, respectively. These low, median and high baseflow estimates are expressed as a fraction of current SWMM4 EXTRAN model dry weather WPCP influent flow. These baseflow multiplication factors are presented in Table 5-4 for each drainage district model.

Table 5-4 Baseflow Modifier Values Used Within the SWMM4 Model to Adjust the Baseflow to Represent Upper and Lower Limit Baseflow Estimates

WPCP	SWMM EXTRAN Baseflow Multiplier Factors		
	Low	Median	High
SE	0.938	1.003	1.073
NE	0.911	0.980	1.088
SW	0.892	0.979	1.049

5.3.1.11 Precipitation Input Data

Precipitation hyetographs are the fundamental input data of the RUNOFF module for the duration of the simulation. Precipitation data usually is obtained from gages maintained by government agencies such as the National Weather Service. Synthetic "design" events frequently used in planning or design studies also may be used as input to the model.

Identification of long-term average hydrologic conditions is often based primarily upon average annual and monthly precipitation volumes determined from the long-term precipitation record. Comparisons are made between the annual precipitation volumes and the long-term average to identify relatively 'wet' and 'dry' years. CSO occurrence, however, is a complex function of storm-event characteristics such as total volume, duration, peak intensity and length of antecedent dry period or inter-event time. In addition to annual precipitation volumes, event based analysis of the long-term precipitation record is used to identify short-term periods that best represent average annual CSO frequency and volume statistics for evaluation of collection system performance. In order to identify short-term continuous periods likely to generate CSO statistics representative of the long-term record, continuous 12-month periods selected from the recent PWD 24 rain gage record (1990-2006) were evaluated against the period of record based on the total annual precipitation volume, the annual number of precipitation events and the distribution frequency of event peak hourly precipitation intensity. Details of the event based analysis and procedure may be found in the Supplemental Documentation Volume 5: Precipitation Analysis.

5.3.1.12 Evaporation Input Data

Evaporation data is required by the model in the form of average monthly evaporation rates, although finer time increments may be input as negative flows by creating an evaporation time series. Average monthly evaporation (inches per day) are used for all SWMM4 models determined from New Castle County, Delaware recorded daily evaporation data from 1956 through 1994.

5.3.1.13 Temperature Input Data and Snowmelt

Temperature time series input data can be used to run a snowmelt routine in SWMM44. The average snowfall volume and frequency for Philadelphia, however, does not account for a significant portion of the average annual precipitation. Therefore, the snowmelt routine was not employed. Instead several snowfall events that occurred during the year 2005, which was selected as the basis for the typical year, were modified to represent snowmelt time series based on PWD non-heated raingage observations, Philadelphia International Airport observed hourly snowfall, daily snow cover, and daily maximum temperatures.

5.3.2 Hydraulic Model Development

This section describes the process by which the hydraulic model of PWD's combined and separate sanitary sewer system has been developed. The hydraulic model was developed using EXTRAN. Section 3 describes the sources of the data and the inventory used to develop the Tier 2 hydraulic models. The Tier 2 models were developed by refining and adding hydraulic elements to the Tier 1 EXTRAN models. The Tier 1 EXTRAN models in combination with the U.S. Army Corps of Engineers' Storage, Treatment, Overflow, Runoff Model (STORM; Hydrologic Engineering Center, 1977) were used to represent the hydraulic elements and evaluate alternatives for the 1997 LTCP.

The EXTRAN module of SWMM4 is used to analyze and simulate flow through the CSS. EXTRAN uses a link-node description of sewer and open channel systems facilitating the physical prototype and the mathematical solution of the gradually-varied unsteady flow (St. Venant) equations, which forms the mathematical basis of the model. The links transmit the flow from node to node. To reiterate the list of elements required by SWMM4, which was initially presented in Section 5.2.4, to calculate the flow in the sewers, values for the following variables are necessary:

- Pipes
- Junctions
- Orifices
- Weirs
- Pumps
- Outfalls

The information required to accurately represent these elements within the model were obtained from the return plans (as-built), contract drawings and drainage plats available through the Engineering Records Viewer developed by the City of Philadelphia. Values which did not match the drawings were modified to bring them current with plan drawings. Individual descriptions of these elements follow below.

5.3.2.1 Pipes

Pipes are the conveyance element in the EXTRAN models. For the EXTRAN model the following pipe information is required.

- Pipe name
- Pipe’s upstream and downstream nodes
- Initial flow in the pipe
- Shape of the pipe
- Pipe dimensions
- Offsets of pipes
- Manning’s roughness coefficient – used to characterize the pipe material and conditions
- Minor losses
- Sediment depth in the pipe

Generally, the pipes within the LTCPU EXTRAN module representing the wastewater collector systems of the City can be separated in to four categories; trunk sewers, dry weather flow pipes, interceptors and the wet weather overflow pipes. Trunk sewers collect sanitary and wet weather flow from elements such as house lateral branches and street inlets and convey that flow to the regulators. The dry weather flow pipes take all of the dry weather sanitary and a percentage of the wet weather flow to the interceptor. Interceptors collect the flows from the dry weather flow pipes and deliver the flows to another downstream interceptor system or to the WPCPs. The wet weather overflow pipes convey flow to receiving waters that cannot be accommodated in either the dry weather pipes or interceptor.

5.3.2.2 Junctions (Nodes)

Nodes are the connection points for the pipes. Flow and volume continuity are calculated at nodes in the EXTRAN model. The nodes in the model can be actual manholes or places where there is pipe size, slope or material change or there is a hydraulic control structure in the pipe network. The following information is required to model a node in EXTRAN:

- Junction name
- Ground elevation/top of the node
- Invert elevation (bottom of the junction)
- Constant inflow, if any, into the junction
- Initial water depth in the junction above invert
- Junction location data (x,y) for spatial location
- Junction volume calculation parameters

Data to define a node in the LTCPU hydraulic model was reviewed and verified using sewer return plans managed by the City of Philadelphia Electronic Records Viewer system.

5.3.2.3 Orifices

Two types of orifices are used within the LTCPU model – static and variable. Static orifice opening sizes remain constant over the length of a simulation. The opening of variable orifices is controlled by either a set of time closure rules or head level in a control node. EXTRAN internally converts the orifices to equivalent pipes of 200 ft and a Manning's coefficient representing the same head loss as the orifice.

Following are the parameters necessary to define an orifice in EXTRAN:

- Upstream and downstream nodes
- Type of orifice
- Orifice coefficient
- Orifice offset from the bottom of the junction invert
- Orifice dimensions
- Orifice control information

5.3.2.4 Weirs

For EXTRAN models used in LTCPU analyses, all weirs were modeled as equivalent pipes with the head loss and flow characteristics simulating those that would be produced from a weir. The information required to model a weir is:

- Upstream and downstream junctions for the weir
- Type of weir
- Weir length and height to the crest of the weir
- Weir coefficient

5.3.2.5 Pumps

Pumps in EXTRAN are modeled to lift the flows to a higher head at a pre-specified rate. Pump station and WPCP data, wet well depths and corresponding pumping rates were studied to determine the type of pump and curves used for the EXTRAN model for LTCPU analyses. All pumps simulated in the models used for LTCPU analyses were represented as variable speed inline pumps. To model a pump the following information was required:

- Pump type
- Pumped junction name
- Pump discharge junction name
- Pairs of pumped junction depth and corresponding pump rates
- Pump on and off water levels in the pumped junction

5.3.2.6 Outfalls

Outfalls represent the discharge points in the EXTRAN models. The outfalls can either have a boundary condition the head has to overcome for outflow to occur or the outfalls can be free outfalls without any boundary conditions. For most of the sections in the EXTRAN model where the outfalls are in the tidal sections of the rivers – for instance, the Schuylkill and Delaware watersheds – the outfalls have boundary conditions equal to the mean tide. For the non-tidal sections in the model the outfalls do not usually have outfall boundary conditions. For special conditions – like the gravity flow into the WPCPs, where the plant boundary had to be overcome to reach the plant or computer controlled outflows – the appropriate boundary conditions were applied.

To model an outfall in EXTRAN the following information was needed:

- Name of the outfall
- Boundary condition to be applied

5.3.2.7 Regulators

A regulator's function is to divert all the dry weather and part of the wet weather flow (*e.g.*, storm flow) into a dry weather pipe (DWO) that feeds the interceptor pipes, delivering the flows to the WPCPs. Any excess wet weather flow that cannot be accommodated in the DWO goes into the storm overflow pipe (SWO) and overflows to the receiving water by way of an outfall. Significant differences in design approaches and philosophies can be observed from system to system. The various types of regulators include weir diversions into side or bottom orifices, float-controlled gates, tipping-plate gates, vortex drop shafts, leaping weirs, motor-operated sluice gates and a number of other configurations. Detailed descriptions of the various regulator devices are beyond the scope of this report and are presented in the literature (*e.g.*, American Public Works Association, 1970 and Water Pollution Control Federation, 1989). The characterization section – Section 2.2 – describes the various regulator types throughout the City.

There are five types of common regulators simulated in the EXTRAN models:

- Slot
- Sluice gate
- Water hydraulic
- Computer controlled
- Brown and Brown (B&B)

Three types of additional structures are used for storm relief and control:

- Dams
- Side overflow weirs
- Tide gates

5.3.2.8 Model Simplification

Once all the information is compiled into the model, test simulations and error checks are performed to find mathematical and implementation problems. The models were put through a thorough QA procedure. The EXTRAN model gets inflow information from the preceding hydrologic and or hydraulic model runs. This model was then simplified by reducing the number of nodes and pipes within the network. The goal of the simplification process was to increase the efficiency by decreasing run-time, while keeping the integrity of the model results. The simplification process followed the steps outlined below:

- Increase the minimum length of the pipes for all feasible situations to 1000 ft
- Most non-critical branches shorter than 1000 ft were identified and eliminated
- All pipes in a branch with the same shape and slope were combined
- Branches having pipes of varying capacities or shapes and not having a series of equivalent pipe sizes to combine to a length of 1000 ft were combined regardless and the hydraulic characteristics of the combined section was made so as the represent the original
- If slopes were changed to meet the 1000 ft pipe length requirement, the Manning's coefficient was adjusted accordingly
- If baseflow existed at a node to be eliminated, the baseflow was transferred to the downstream node if less than 500 ft from the eliminated node, otherwise it was loaded to the upstream node
- Equivalent pipes were avoided, where possible, to conserve volumes

The resulting simplified model allowed for a larger time step to be used without violating the Courant conditions and, thus, decreasing the computational burden of the model. Continuous simulations were performed using the RUNOFF and EXTRAN models and the results from the simulations were directly or indirectly used to evaluate effects of various alternatives for the LTCPU.

5.3.3 Model Calibration / Validation

Development of the SWMM4 model for the LTCPU was followed by calibration and optimization of the parameters for both the RUNOFF and EXTRAN modules. During the calibration of any model, it should not be expected that simulated results will match perfectly the measured data, since the measured data is subjected to some degree of error, while the model is an approximation of the system hydrology and hydraulics. Therefore, the measured data must be thoroughly reviewed and any limitations must be identified before adjusting calibration parameters. Note that the model calibration is accomplished by finding the best comparison between simulated and measured runoff characteristics over a range of storm events.

Model calibration was accomplished by adjusting initial estimates of the selected variables, within a specified range, to obtain a satisfactory correlation between simulated and measured flow and volume. The variables selected to adjust or calibrate were parameters that typically cannot be measured accurately - percent impervious, soil infiltration parameters, etc. - and which have the greatest effect on the accuracy of the results. The calibration parameters were prioritized according to their influence on the model results, which can vary from one drainage system to another and on several model simulations (sensitivity analyses) on the PWD LTCPU.

For the hydrologic calibration, the following data were assessed:

- Precipitation data
- CSS Trunk Monitor data
- DCIA calibration
- RTK distribution

For the hydraulic validation, the following elements were considered:

- WPCP inflow and pumping data
- Measures of “goodness-of-fit”
- Validation results

5.3.3.1 Hydrologic Model Calibration

Calibration of the hydrologic model was an iterative process by which RUNOFF module parameters were changed, within acceptable ranges based on available data, from initial estimated values to ones that quantitatively provide the best match between modeled results and observed data.

5.3.3.2 Precipitation data

The main goal in acquiring precipitation data is to get the most detailed and consistent - temporally and spatially – data available for the periods in which hydraulic data were available for the Philadelphia CSS service area. It was determined after extensive review and QA assessment that the PWD 24-raingage network data required bias adjustment and normalization to provide the spatial and temporal consistency necessary for the calibration process. Further details can be found in Supplemental Documentation Volume 5: Precipitation Analysis.

The SWMM4 RUNOFF module requires assignment of an input rainfall time series for each stormwater runoff or sanitary sewer RDI/I basin in the model. Inverse distance-squared weighting was used to estimate rainfall in areas between rain gages. A 1 km^2 grid was imposed over the PWD service area. Next, a rainfall value for every time step was assigned to each grid element by inverse distance-squared weighting of the rainfall values from three nearby surrounding gages. Finally, the gridded precipitation values were area-weighted to provide average rainfall values for each individual sewershed in the model. In this manner, the bias adjusted 15 minute accumulated rainfall data for the PWD 24 rain gage network is distributed to RUNOFF model basin areas using the Inverse Distance Weighted (IDW) method.

Specific rainfall event boundaries were defined using SHAPE software – previously described in Section 5.2.2 – with rain gage data as input for each flowmeter site as listed in Table 5-5. The initial selection criterion included a minimum rainfall depth of 0.1 in. QA of the events was done after event boundary delineation to remove events affected by errant data, snow or malfunctioning rain gages. These selected rainfall event boundaries were used along with the IDW basin average rainfall time-series throughout the model calibration process.

5.3.3.3 CSS Trunk Monitor Data

Flow data taken from flow monitors located in trunk sewers throughout the combined sewer area were analyzed and then used to adjust calibration parameters for the hydrologic models. There were six combined trunk sewer monitors having sufficiently usable data to perform calibration analyses. These six flow monitors are presented below in Table 5-5. Included in the table are the model pipe names of the monitor location, the area draining to the monitor, the calibration period and corresponding drainage districts.

Hydrograph decomposition was performed on the data from the above flow monitors to extract the wet weather portion. This flow was used to compare to the simulated model flow. To assess the goodness-of-fit of the model output to observed data, a series of plots were created including scatter plots of event volumes, time to peak and peak flows, Cumulative Frequency Distributions (CFDs), cumulative mass regression plots and time-series plots for each event. A selection of result plots for monitor 83 is presented collectively as Figure 5-7 (a) and (b) below. The R-squared value, slope, intercept and the equal fit line from the scatter plots and the qualitative assessment of the time-series plots were used to determine the level of fit for model output as compared to observed data.

The results for each model run were organized into a performance spreadsheet and the best-fit calibration scenario was chosen. The criteria from the best-fit calibration scenario were applied to the entire combined sewer district for all sheds without monitors. For sheds draining to the six selected trunk monitors, the site specific calibrated data were used.

Table 5-5 Trunk Monitor Calibration Information

Monitor	District	Pipe Name	Data Range	Drainage Area (ac)
79	SW	TS27-3308	1/1/2002-9/2/2002	4.33
83	SW	TS16-104	1/1/2004-12/31/2004	19.65
84	SW	TS13-108	1/13/2004-5/2/2006	25.11
85	SW	TC06-112	10/25/2002-7/28/2004	98.56
S42-130	SW	TR25-104	4/26/2006-9/19/06	73.05
D54-15	SE	TD54-604	5/26/2006-9/15/2006	167.19

5.3.3.4 Directly Connected Impervious Area (DCIA)

For all sewersheds with monitored trunk sewers, DCIA in the best-fit model was lower than gross impervious cover derived from aerial photography. The ratio of DCIA to total gross impervious area ranged from 50% to 100%. Because the majority of sewersheds are unmonitored and the measurements themselves have uncertainty associated with them, it is reasonable to present this value as a range. Presented below are ranges associated with specific areas in the drainage district.

- 5 monitors in trunk sewers: Adjustments in the best-fit model range from 50% to 95% of gross impervious cover (*i.e.*, effective impervious cover was estimated to be 50% to 95% of total impervious cover)
- Cobbs Creek Watershed model: Adjustments were made watershed-wide based on USGS streamflow records. Adjustments were made in combined and separate areas and in areas inside and outside the City. This calibration process had a higher level of uncertainty than the trunk monitors. Adjustments ranged from 50% to 100% of total impervious cover
- Tookany/Tacony-Frankford Creek Watershed model: Adjustments were made watershed-wide based on USGS streamflow records. Adjustments were made in combined and separate areas and in areas inside and outside the City. This calibration process had a higher level of uncertainty than the trunk monitors. Adjustments ranged from 50% to 75% of total impervious cover

Based on the histogram shown below (Figure 5-8), the mean and most common adjustment is 70% of DCIA. This value is used in the best-fit model, with the exception of monitored sheds.

5.3.3.5 RTK Distribution

The purpose of this task was to determine an acceptable average R-value range within the simplified SWMM4 model to represent RDI/I volumes across all un-monitored separate sanitary sewer areas. The existing RDI/I values from the 39 flow monitoring sites discussed previously were used in this process. The full range of R-values showed no apparent correlation to population density, geographic location or size of monitored shed, therefore, the analysis included:

- Ranking of the 39 sites based on R-value
- Creation of a histogram and cumulative frequency distribution plot
- Upper (80^{th} percentile) and lower (20^{th} percentile) limit determination based on the central tendency about the median

The resulting histogram is presented as Figure 5-9 below. The final median R-value to represent the watershed area is 0.0401.

5.3.3.6 Hydraulic Model Validation

Once the hydrologic models for all districts were calibrated based on combined trunk and sanitary sewer monitoring data, the system hydraulic models were validated against observed WPCP influent flow and level data for the calendar year 2005. PWD monitors level and inflow at its three WPCPs. These flows were compared to simulated flows for a range of storm events during the calendar year 2005. WPCP influent flow and pump wet-well level data are stored in average hourly time intervals. A QA process was performed on the flow data, during which errant or missing data were removed. The observed flow time increments were interpolated to a 15-minute time interval before being imported into the SHAPE program along with the rainfall data for analysis. The data underwent hydrograph decomposition and the wet weather portion of the flow coming to the plant was extracted.

The model parameters adjusted to best match the monitored WPCP influent flow and level data included plant head boundaries, pump curves, metering head losses and QA of regulator gate settings.

5.3.3.7 Measures of "Goodness-of-Fit"

Simulations were performed using different model settings and compared using a combination of quantitative and qualitative measures. The measures were applied to the following event characteristics:

- Event volume
- Event peak flow
- Time to peak

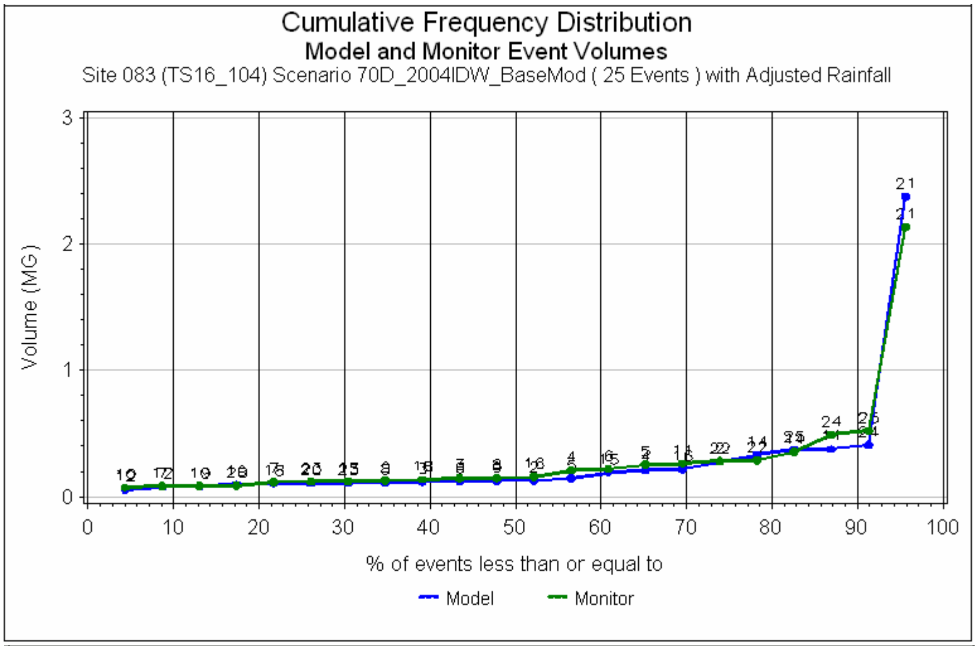
5.3.3.8 Validation Results

The calibration and validation results for each drainage district are discussed below using the quantitative and qualitative best-fit measures outlined above as a guide for model result accuracy.

5.3.3.8.1 Southeast Drainage District

The results of final Southeast drainage district (SEDD) hydraulic model validation, performed using SE WPCP influent hydrograph separated wet weather flow data, are presented in Figures 5-10 through 5-12. Linear regression analysis is performed comparing model estimated SE WPCP influent wet weather flow volumes (y-axis) to monitored event volume (x-axis) using IDW rainfall data for the calendar year 2005. The events that have been excluded from the regression analysis based on the protocols described previously are presented in the scatter plots with different symbols and shading so they can be distinguished from those events included in the regression. Ideally the plots would reveal a one to one relationship, meaning that the model estimated volumes equal to the exact monitored runoff volume for each event.

Figure 5-10 is a scatter plot with the linear regression analysis results used to determine quantitatively how well the model simulated total event volumes treated at the SE WPCP. The red line is the 45-degree line that would indicate a perfect fit with an R-squared value of 1. Figure 5-11 is an overlay of model and monitored SE WPCP influent wet weather event volume cumulative frequency distribution (CFD) plots. Figure 5-12 is an overlay of model and monitored hydrograph time-series plots for the October 22, 2005 storm event. The plots display a good correlation between



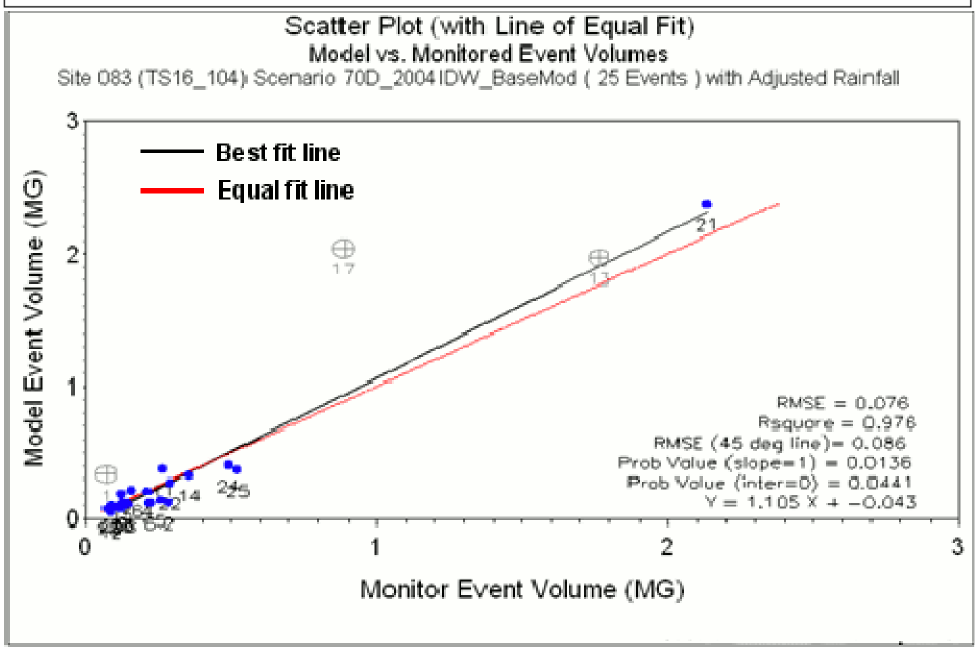


Figure 5-7(a) Result Plots for Site 83 Including the CFD, Event Volume Scatter Plot

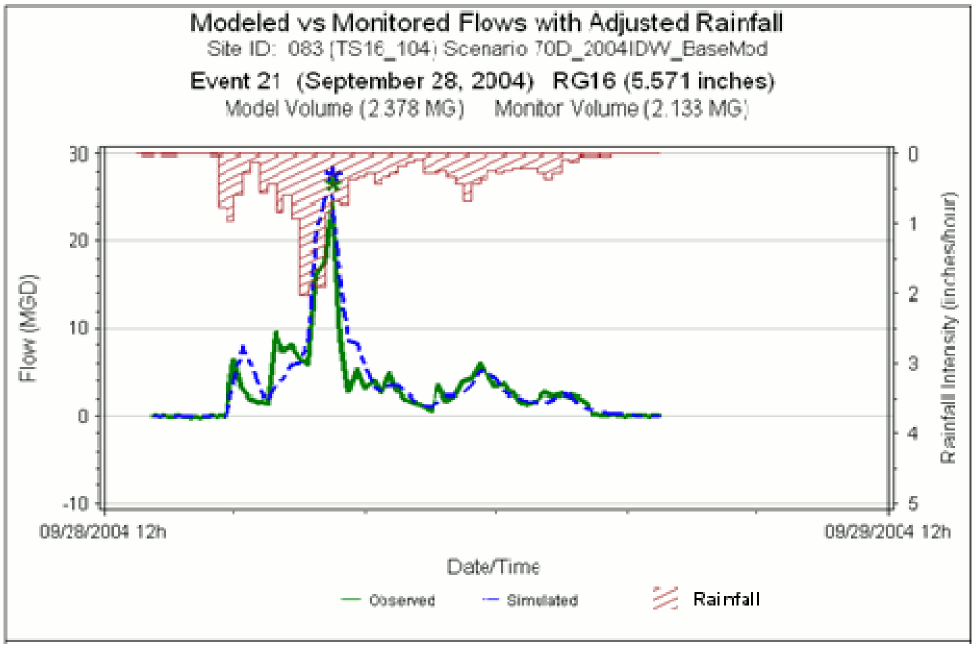


Figure 5-7(b) Result Plots for Site 83 Including the CFD, 2004 Event Time-Series Plot

observed and simulated event volumes over the full range of events analyzed. Any significant systematic deviation between simulated and observed data would indicate events of a certain volume range were not being adequately simulated by the model.

5.3.3.8.2 Southwest Drainage District

Final validation plots for the Southwest drainage district (SWDD) hydraulic model are presented in Figures 5-13 through 5-16. The plots are presented separately for the two interceptor systems that feed the Southwest Water Pollution Control Plant, the Southwest Low Level (SWLL) and the Southwest High Level (SWHL). The events that have been excluded from the calibration analyses, using the set of protocols described previously are presented in the scatter plots with different symbols and shading so they can be distinguished from those included in the regression analyses.

Figure 5-13 shows the linear regression analysis used to determine quantitatively how well the SWLL simulated the wet weather event volumes. The monitored wet weather event volumes are on the horizontal axis and the modeled event volumes are on the vertical axis. (The red-dashed line is the 45-degree line that would indicate a perfect fit with an r-squared value of 1.0). Figure 5-14 shows the cumulative frequency distribution (CFD) plots of the monitored and the modeled wet weather volume from the SWLL, this plot is used to check if the wet weather volumes being simulated are different from the observed in various sized storms. Similarly Figures 5-15 and 5-16 show the linear regression analysis and the cumulative frequency distribution plots for the SWHL interceptor system.

The curves at the SW interceptors match each other reasonably well without significant deviation for each plot.

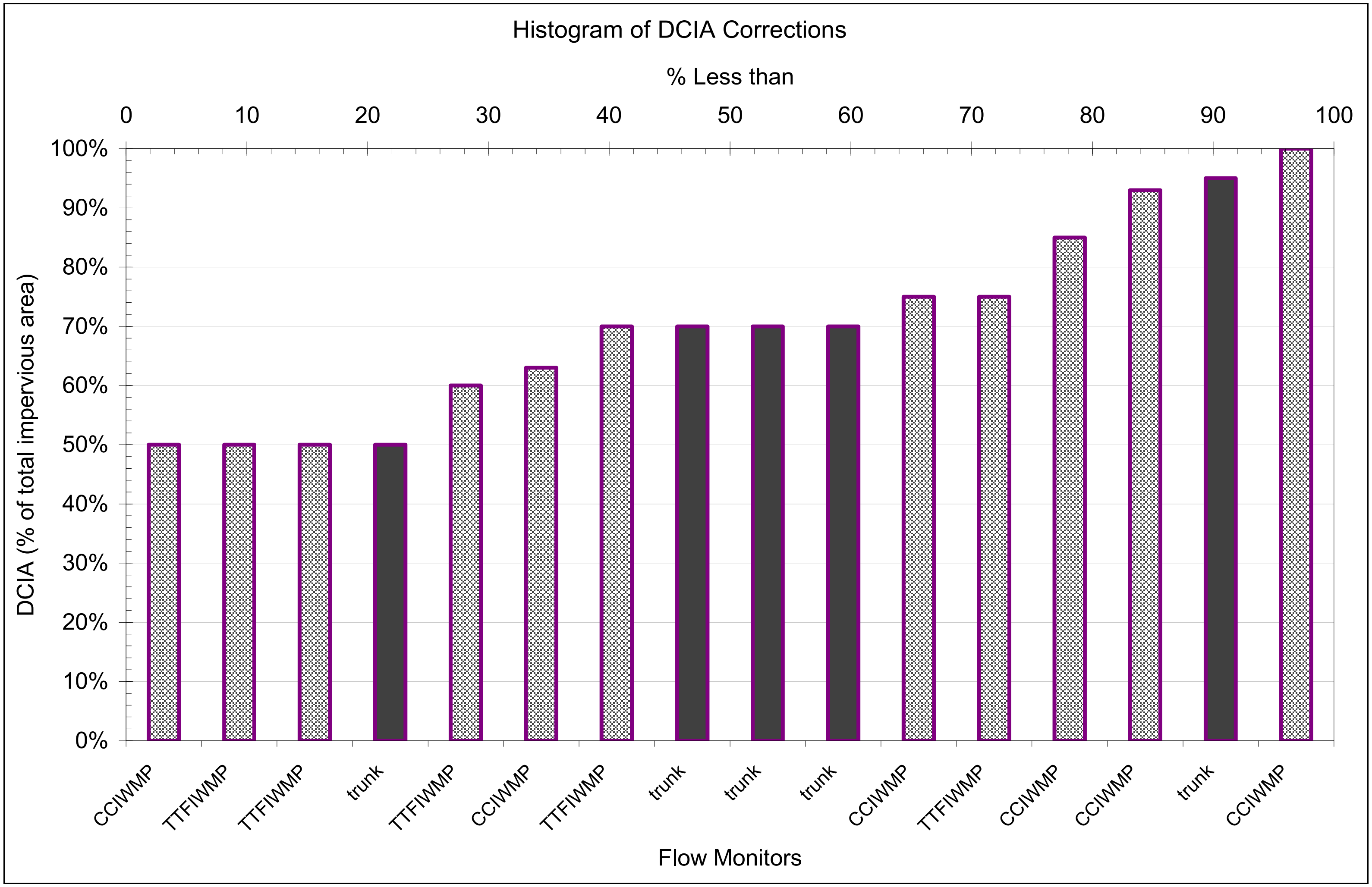


Figure 5-8 Histogram of Resulting Calibrated DCIA Percentages of Gross Impervious Area for Available Monitors Within the Drainage District

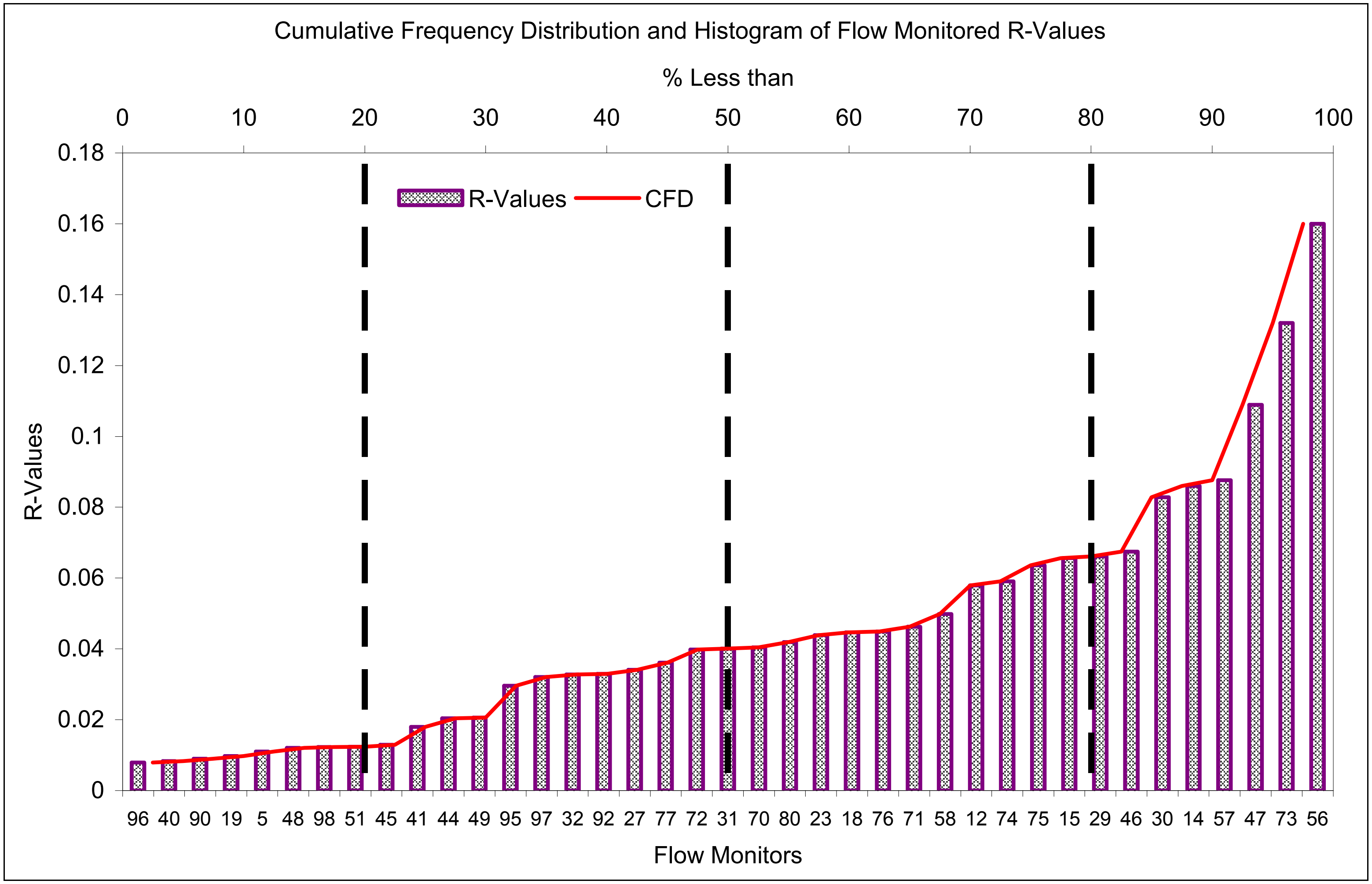


Figure 5-9 Histogram of Resulting Calibrated R-Values for Selected Monitors Within the Drainage District

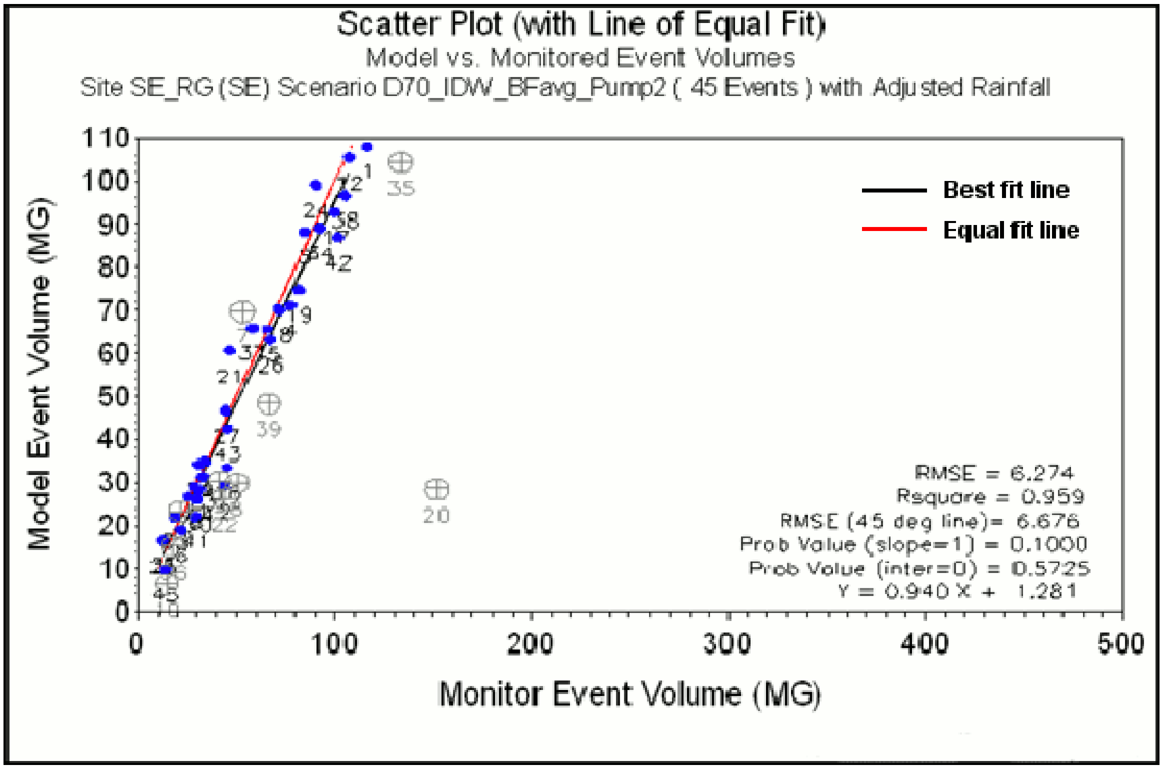


Figure 5-10 SE WPCP Linear Regression of Modeled Versus Monitored Event Volumes

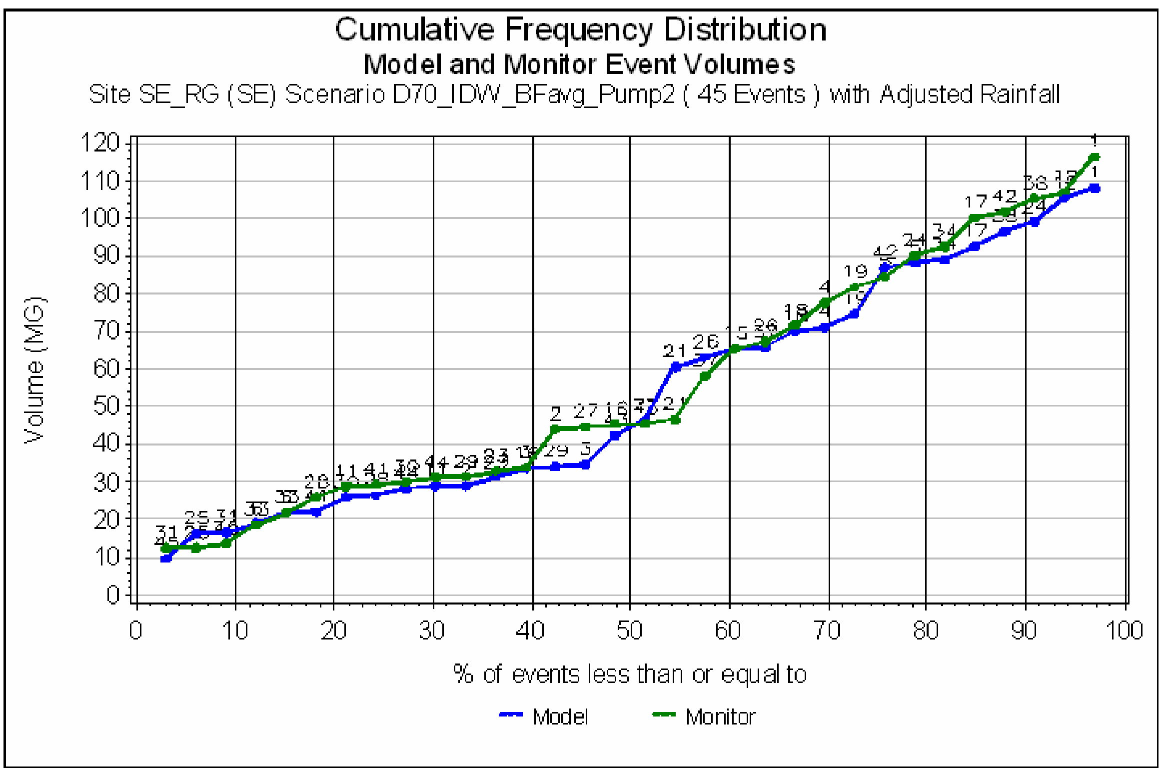


Figure 5-11 SE WPCP CFD Plots of Monitored and Modeled Event Volumes

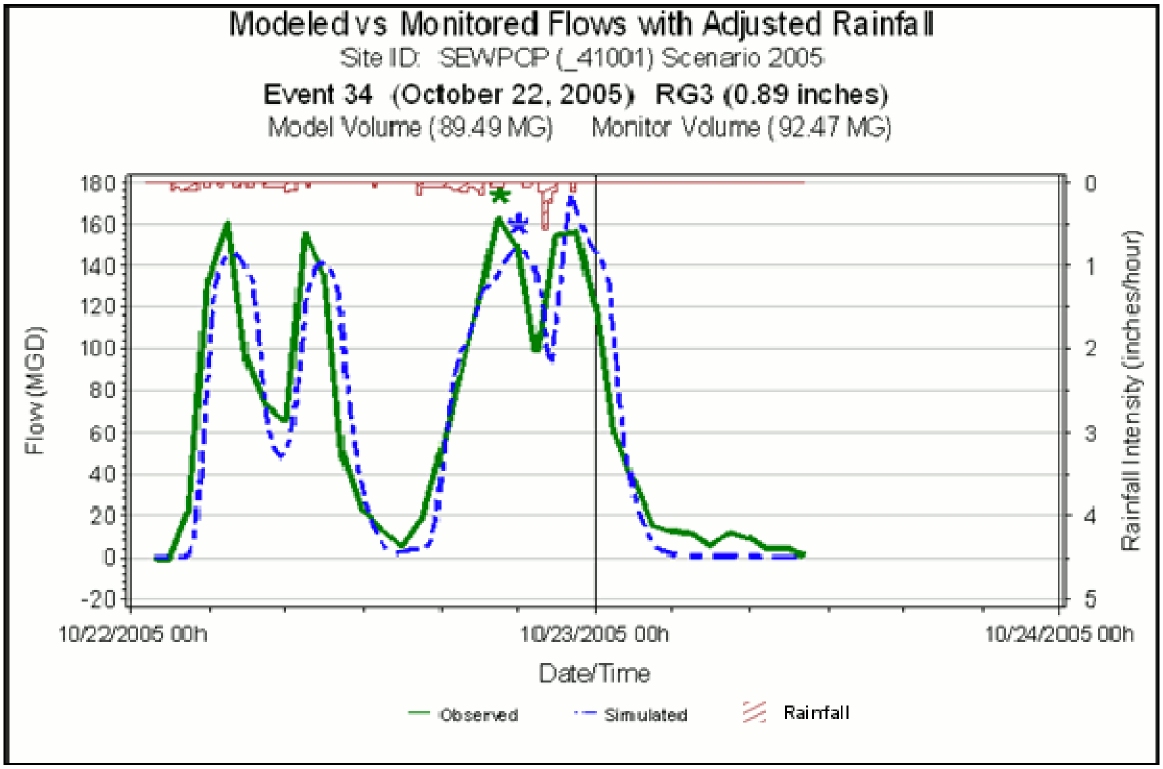


Figure 5-12 SE WPCP Model and Monitored Wet Weather Flow Time-Series Plot for the October 22, 2005 Event

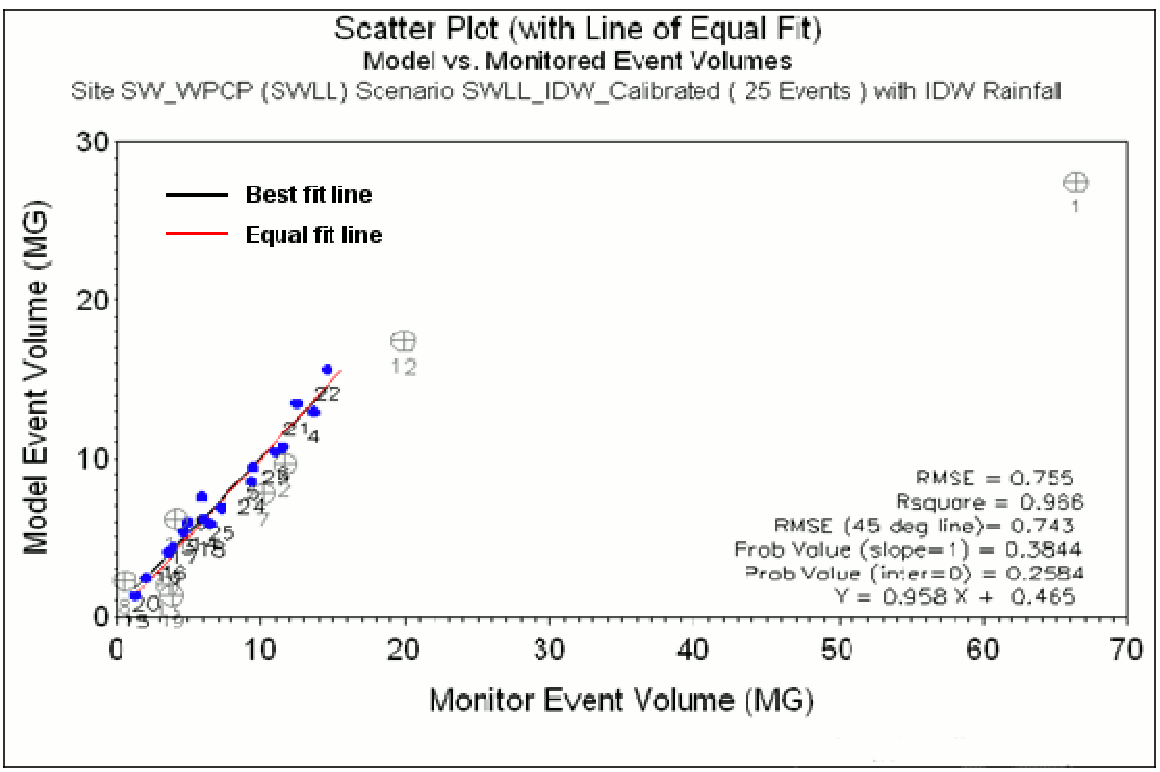


Figure 5-13 SWLL Linear Regression of Modeled versus Monitored Event Volumes

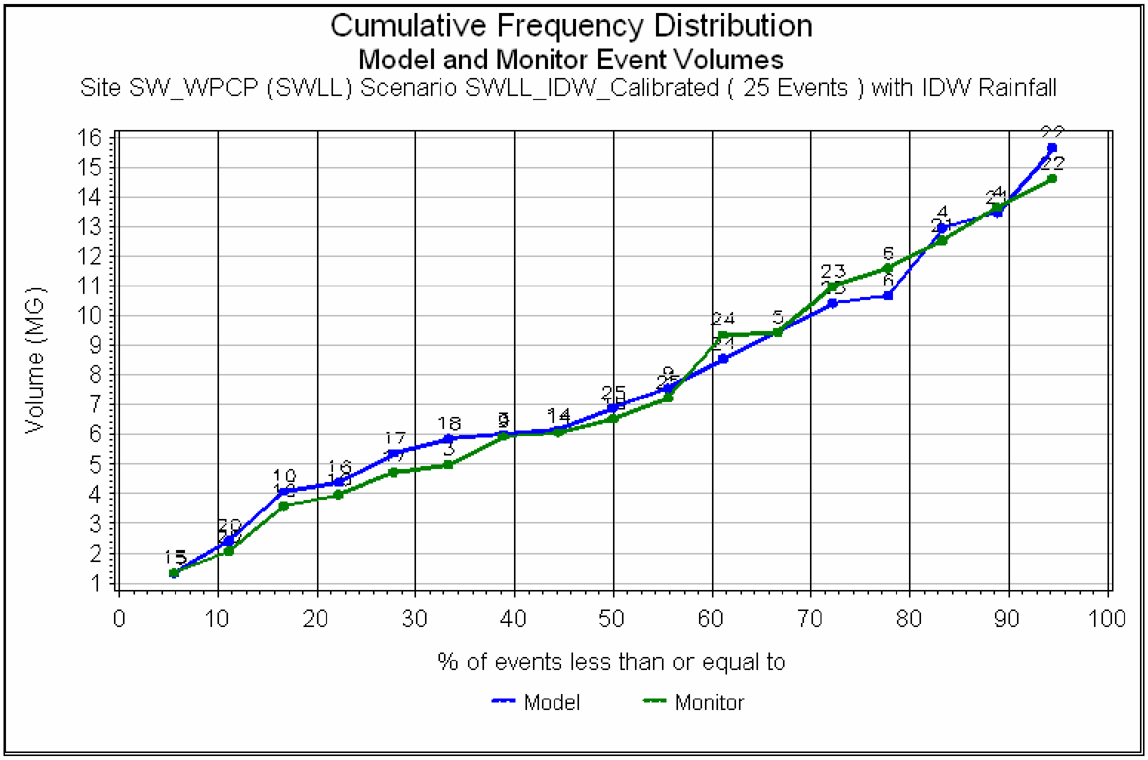


Figure 5-14 CFD Monitored and Modeled Event Volumes SWLL

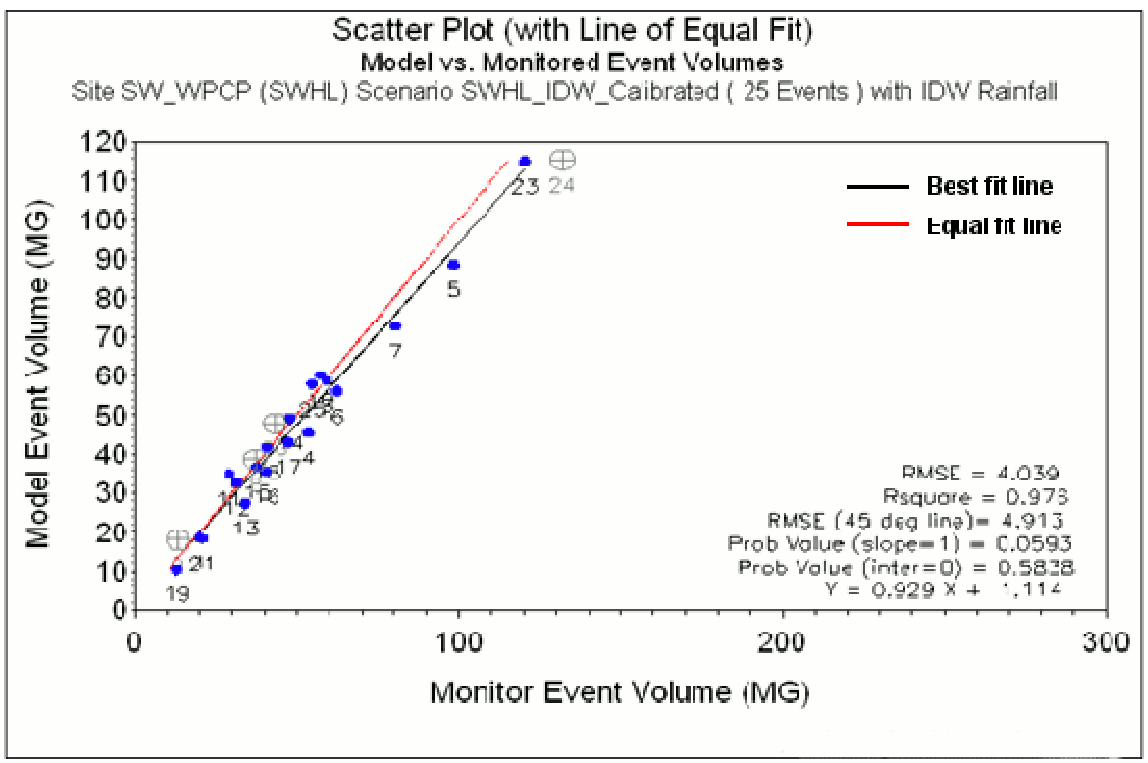


Figure 5-15 SWHL Linear Regression of Modeled Versus Monitored Event Volumes

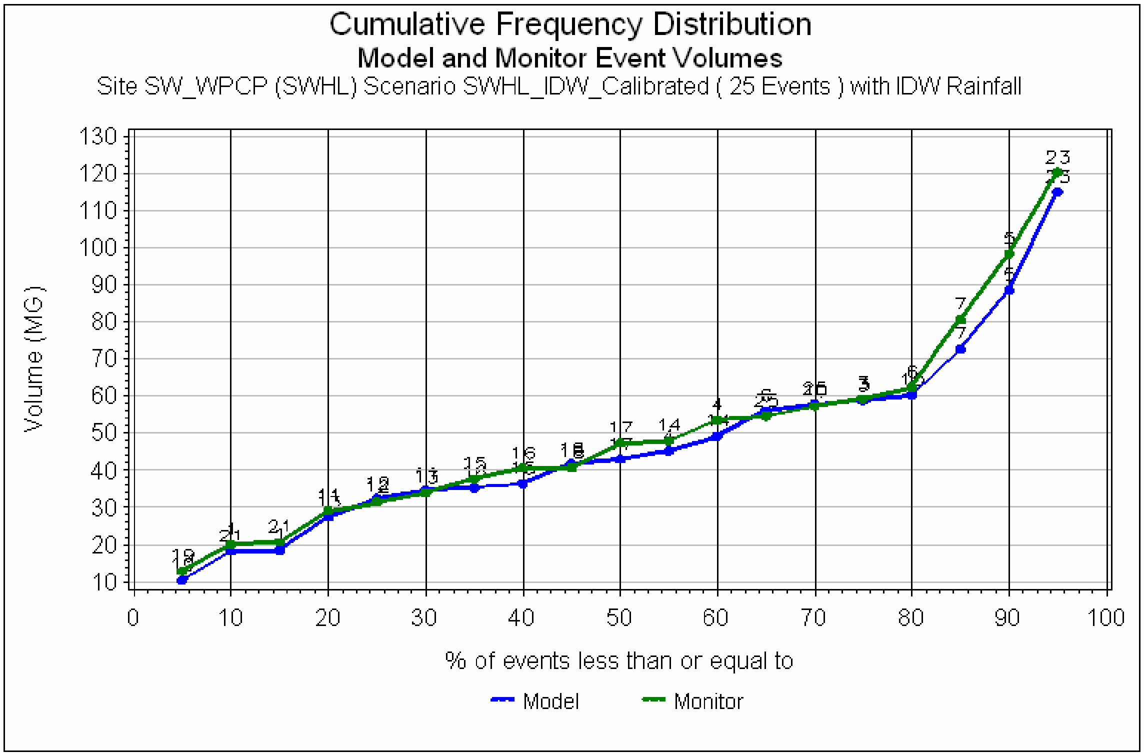


Figure 5-16 CFD Monitored and Modeled Event Volumes SWHL

5.3.3.8.3 Northeast Drainage District

The Northeast Water Pollution Control Plant (NE WPCP) receives combined sewer flows by gravity from the Northeast High-Level system (NEHL) and through pumping from the Northeast Low-Level system (NELL). These two drainage systems connect at the NE WPCP and can be modeled separately or as a single combined model. The NEHL is comprised of two interceptor systems: the Frankford High Level (FHL) and the Tacony (T). The NELL is comprised of five interceptor systems: the Somerset Low-Level (SOM), the Upper-Frankford Low-Level (UFLL), the Lower Frankford Low-Level (LFLL), the Upper Delaware Low-Level (UDLL) and the Pennypack (P).

Final validation plots for the Northeast drainage district (NEDD) model are presented in Figures 5-17 through 5-30. These plots include scatter plots of model versus monitored WPCP influent wet weather event volumes showing linear regression analysis results, cumulative frequency distribution plots of model and monitored WPCP influent wet weather event volumes and selected model and monitored influent wet weather flow hygrographs. Plots are first presented for the total NE WPCP and the combined NELL. Calibration plots are also presented for each of the following three metered plant influent lines: FHL, the combined Somerset and Upper Frankford Low-Level (Som-Frk) and UDLL, which also includes flow from LFLL. The same event list is used for all analyses. Events are excluded from the calibration analyses based on the set of protocols described previously and are distinguished from those included in the regression plots by use of different symbols and shading.

The plots generally display a good correlation between observed and simulated event volumes over the full range of events analyzed. Any significant systematic deviation between simulated and observed data would indicate events of a certain volume range were not being adequately simulated by the model.

Significant systematic under-estimation of Som-Frk influent wet weather event volumes is indicated by the CFD and linear regression presented in Figure 5-17 and Figure 5-18. However, inspection of individual influent wet weather flow hydrographs for the January 7 and July 1, 2005 rainfall events presented in Figure 5-19 and Figure 5-20, respectively, reveal a very close overall correlation between modeled and monitored hydrographs. In fact, the correlation between modeled and monitored hydrographs for the Som-Frk appears to be much better than that for the UDLL, as illustrated in Figure 5-21 and Figure 5-22, which shows a higher correlation in the linear regression and CFD plots than the Som-Frk.

5.4 LTCPU Alternatives Model Development

Development of the alternatives model was initiated using the previously discussed baseline model as its foundation. The alternatives model analysis process was separated into two categories: land-based and infrastructure-based controls. Projects for green stormwater infrastructure implementation and those utilizing BMPs were modeled with the land-based control methodology, while designs involving elements such as tunnels and parallel interceptor systems were considered infrastructure-based controls. Descriptions of the model development for each category are presented below. More details on the LTCPU alternatives model development subsections can be found in Supplemental Documentation Volume 4: Hydrologic and Hydraulic Modeling.

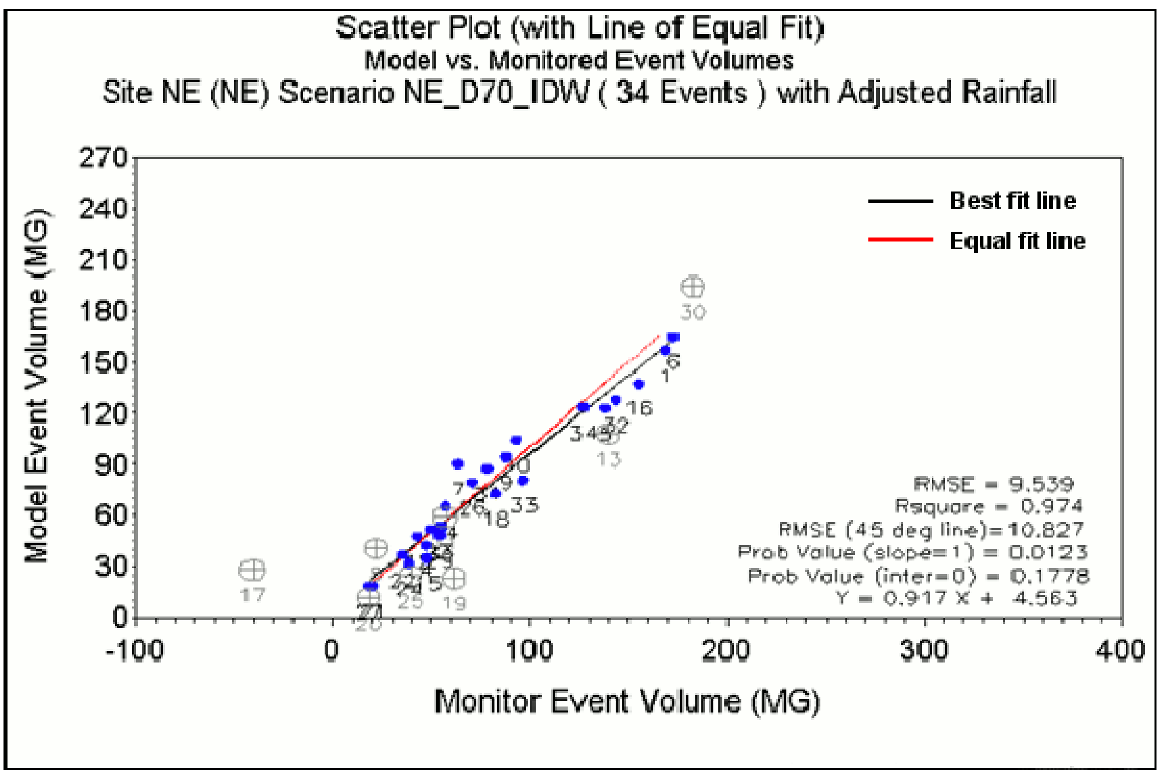


Figure 5-17 NE WPCP Linear Regression of Modeled Versus Monitored Event Volumes

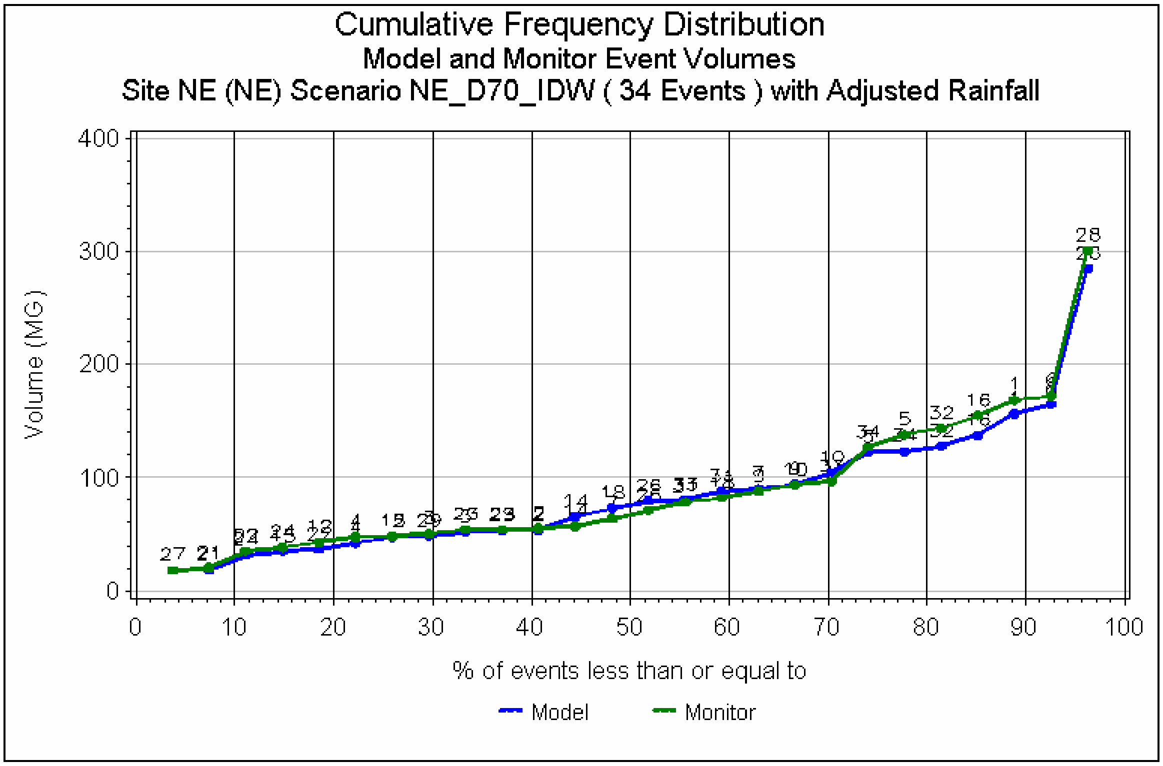


Figure 5-18 NE WPCP CFD of Modeled and Monitored Event Volumes

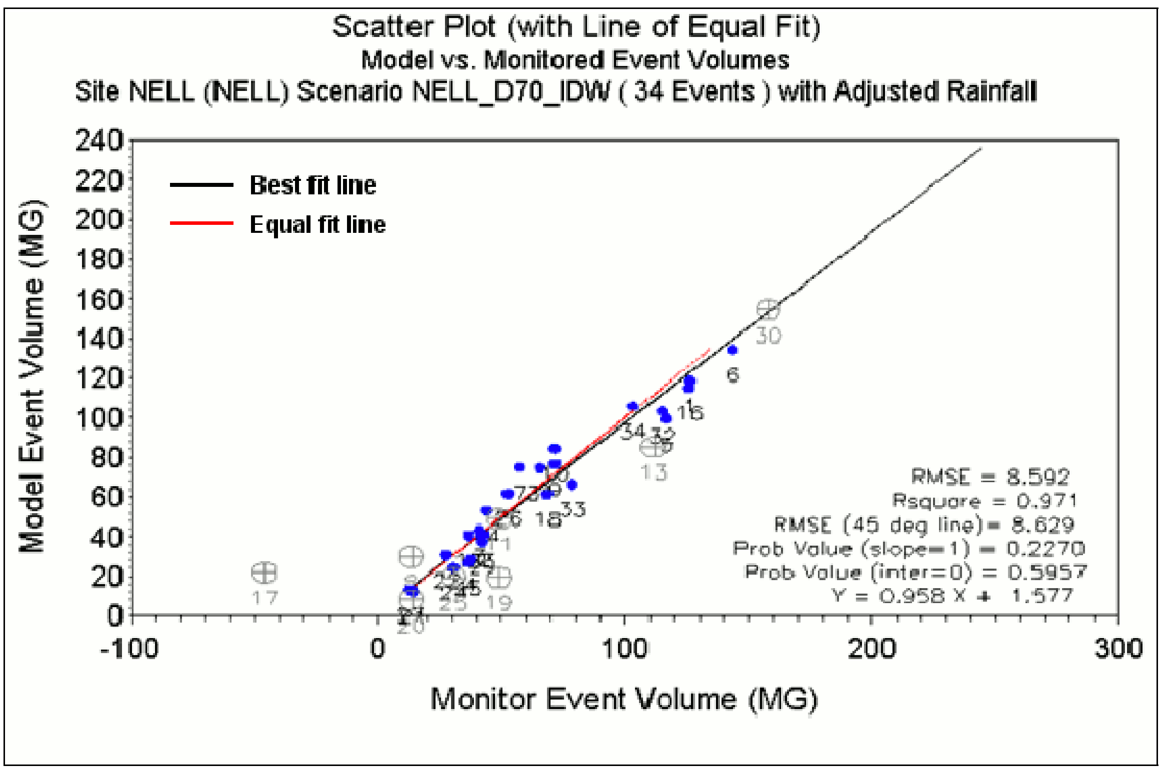


Figure 5-19 NELL Linear Regression of Modeled Versus Monitored Event Volumes

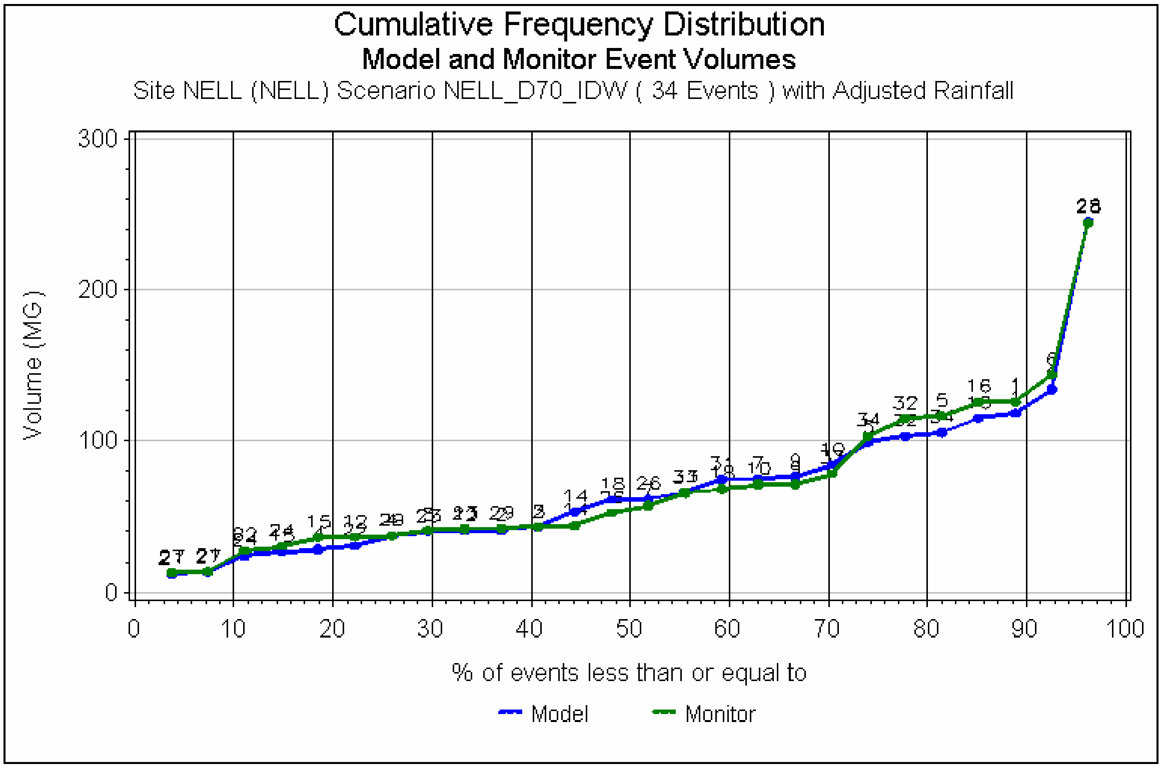


Figure 5-20 NELL CFD of Modeled Versus Monitored Event Volumes

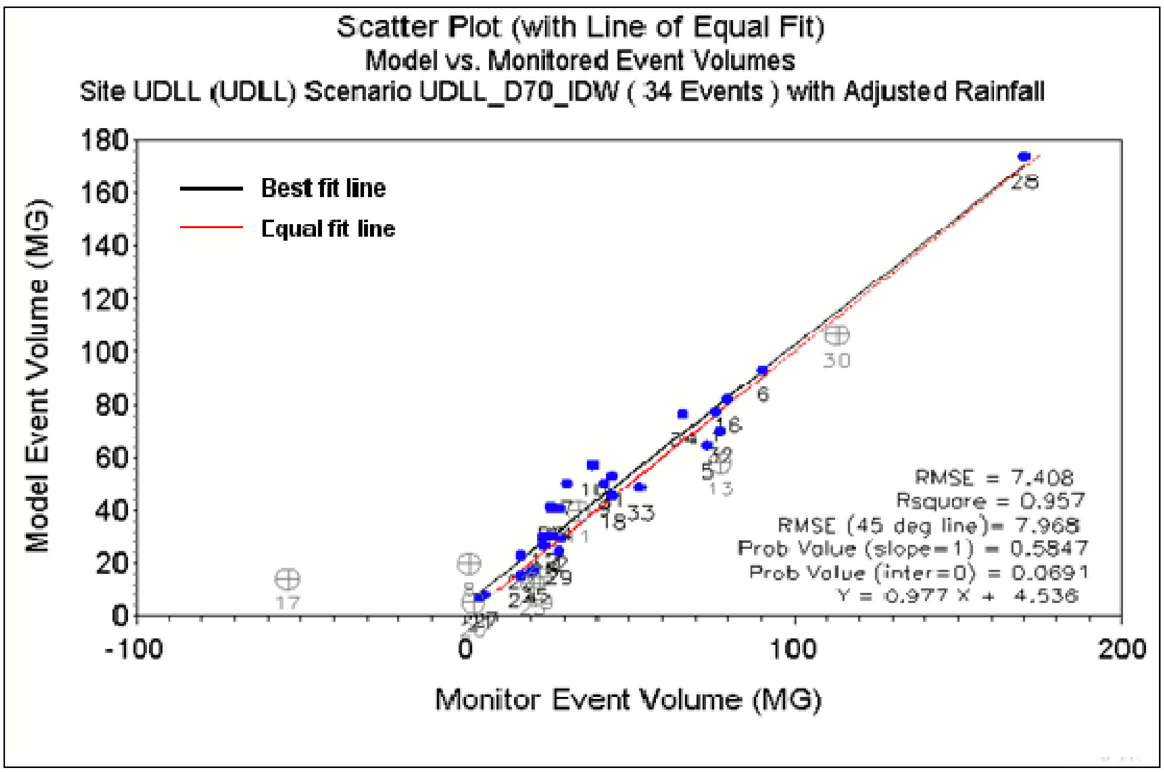


Figure 5-21 UDLL Linear Regression of Modeled Versus Monitored Event Volumes

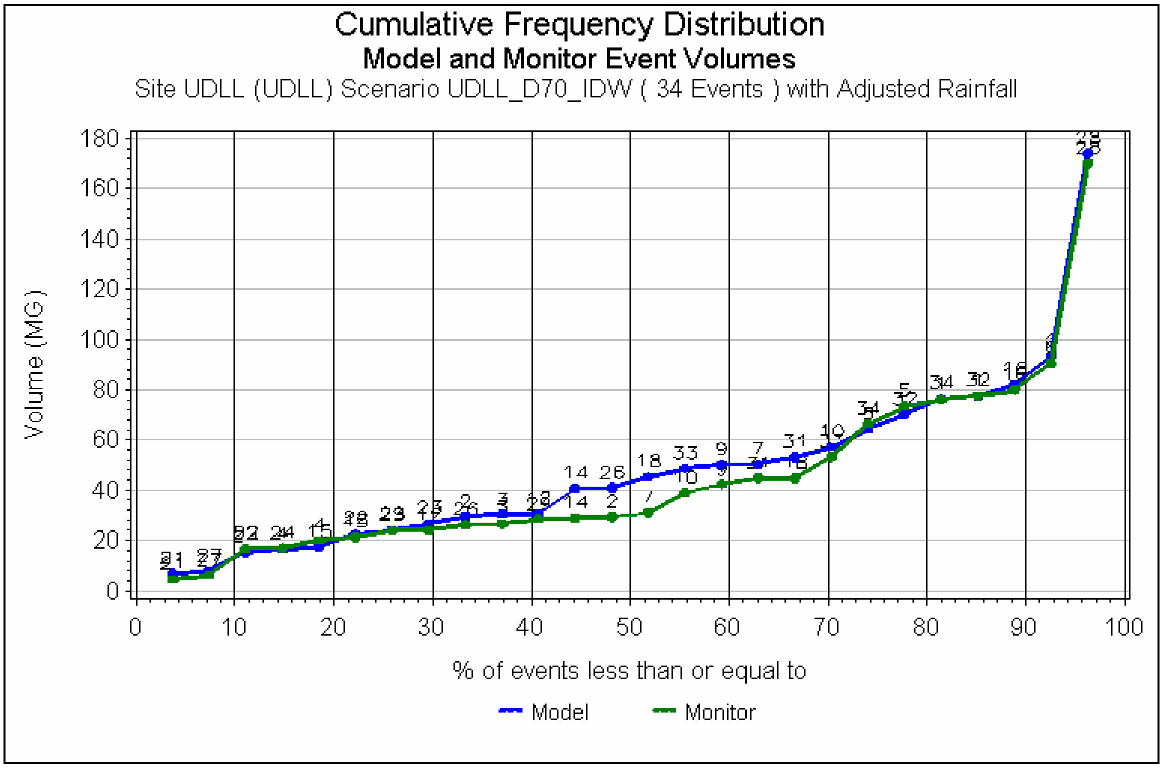


Figure 5-22 UDLL CFD of Modeled Versus Monitored Event Volumes

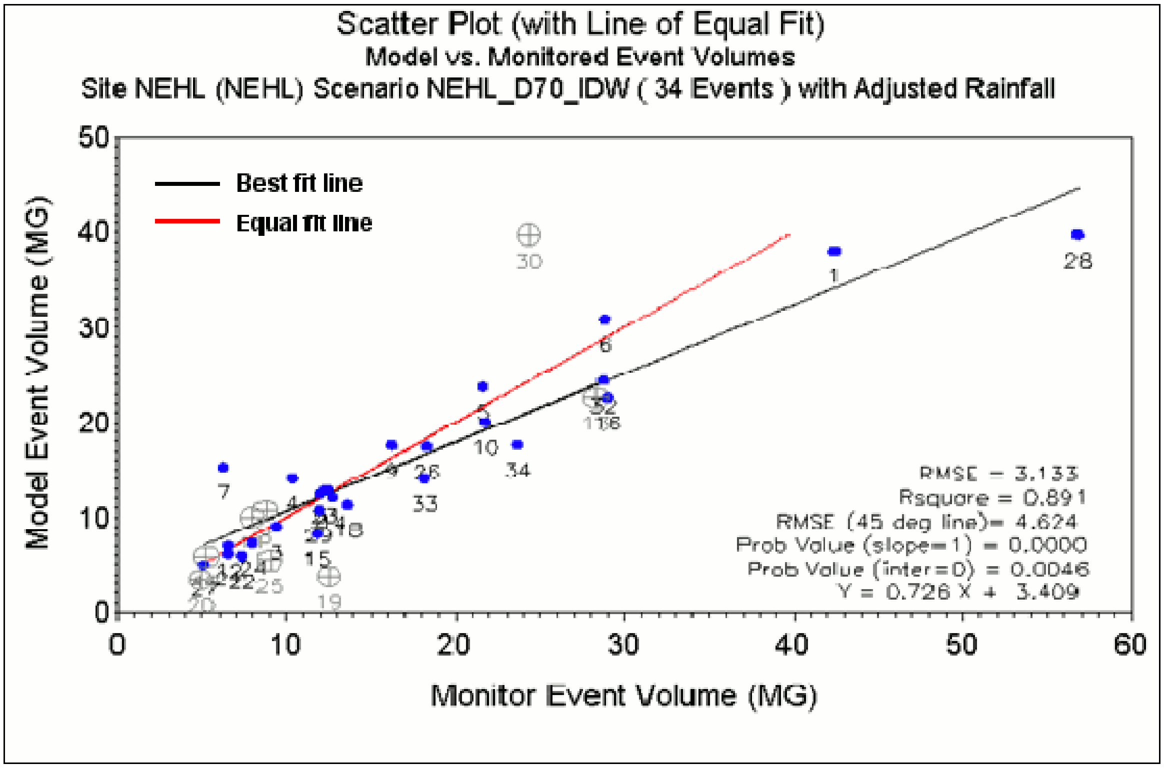


Figure 5-23 NEHL Linear Regression of Modeled versus Monitored Event Volumes

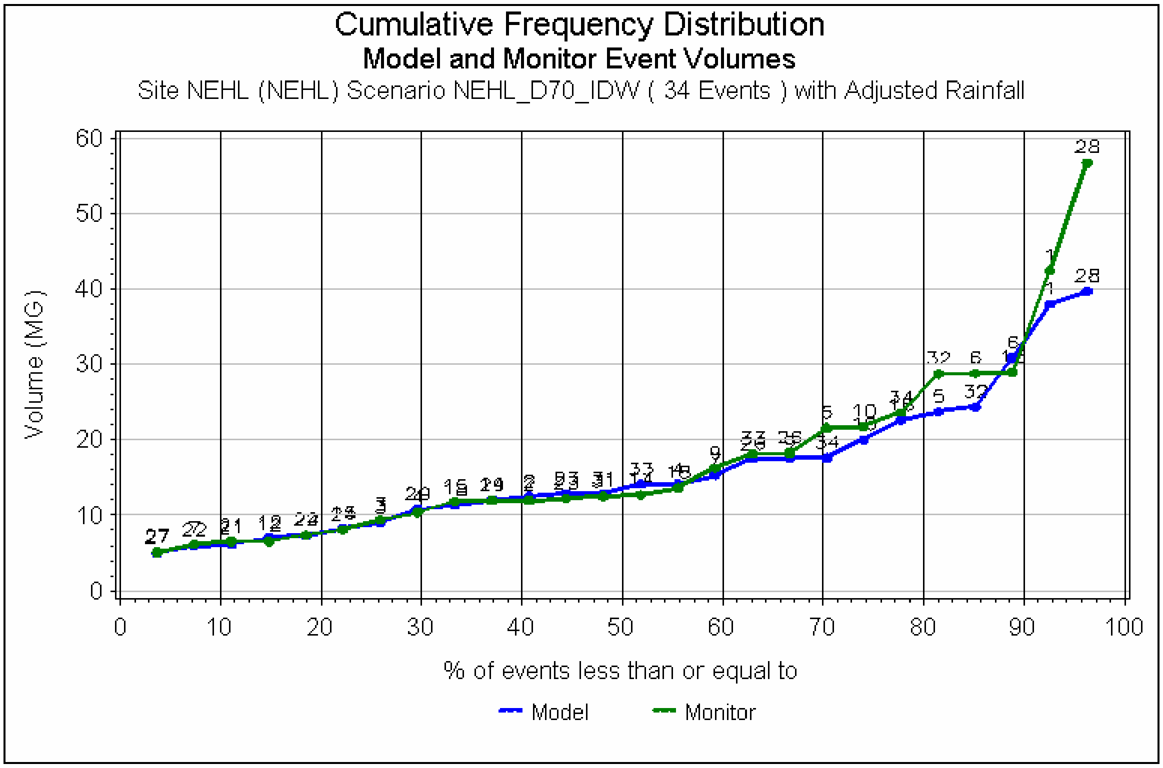


Figure 5-24 NEHL CFD of Modeled Versus Monitored Event Volumes

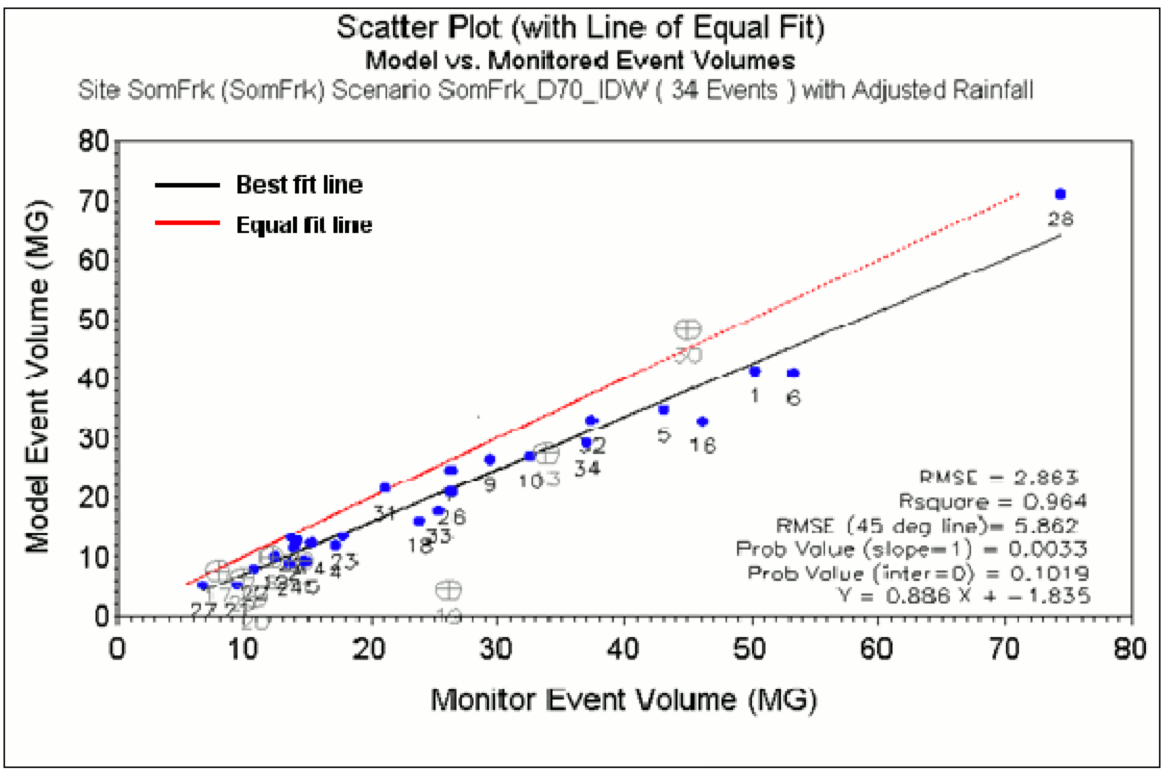


Figure 5-25 Som-Frk Linear Regression of Modeled versus Monitored Event Volumes

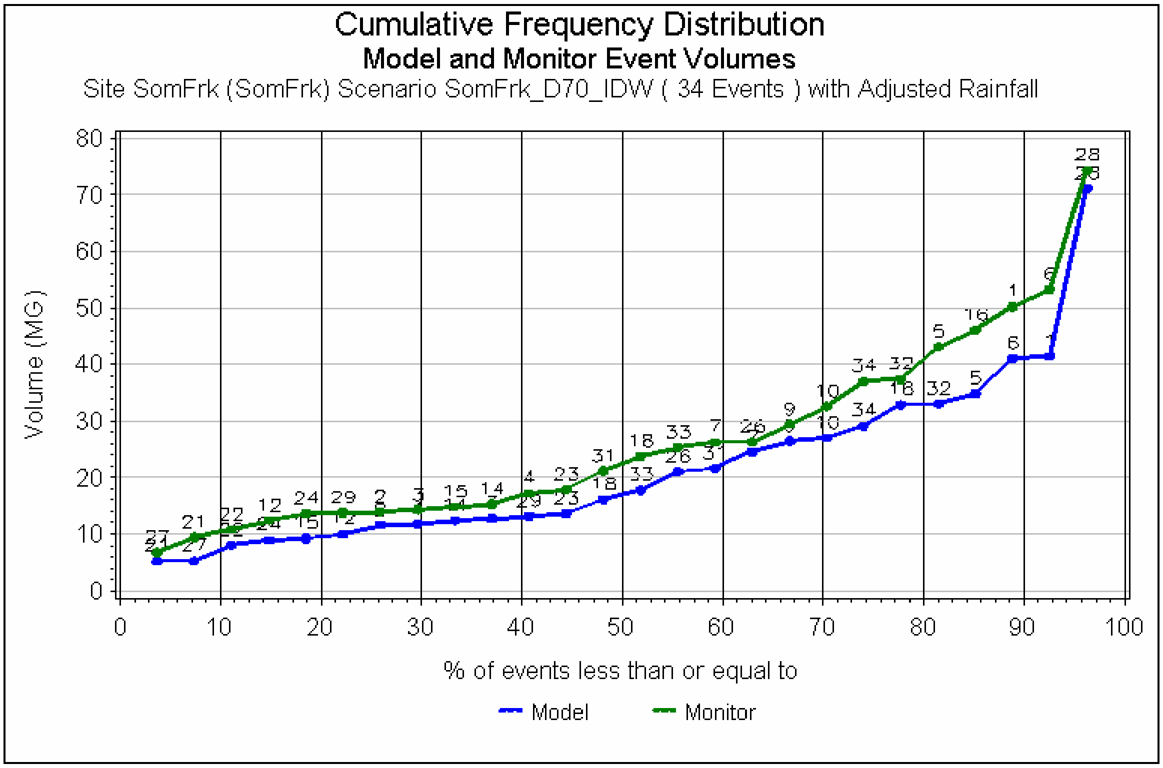


Figure 5-26 Som-Frk CFD of Modeled Versus Monitored Event Volumes

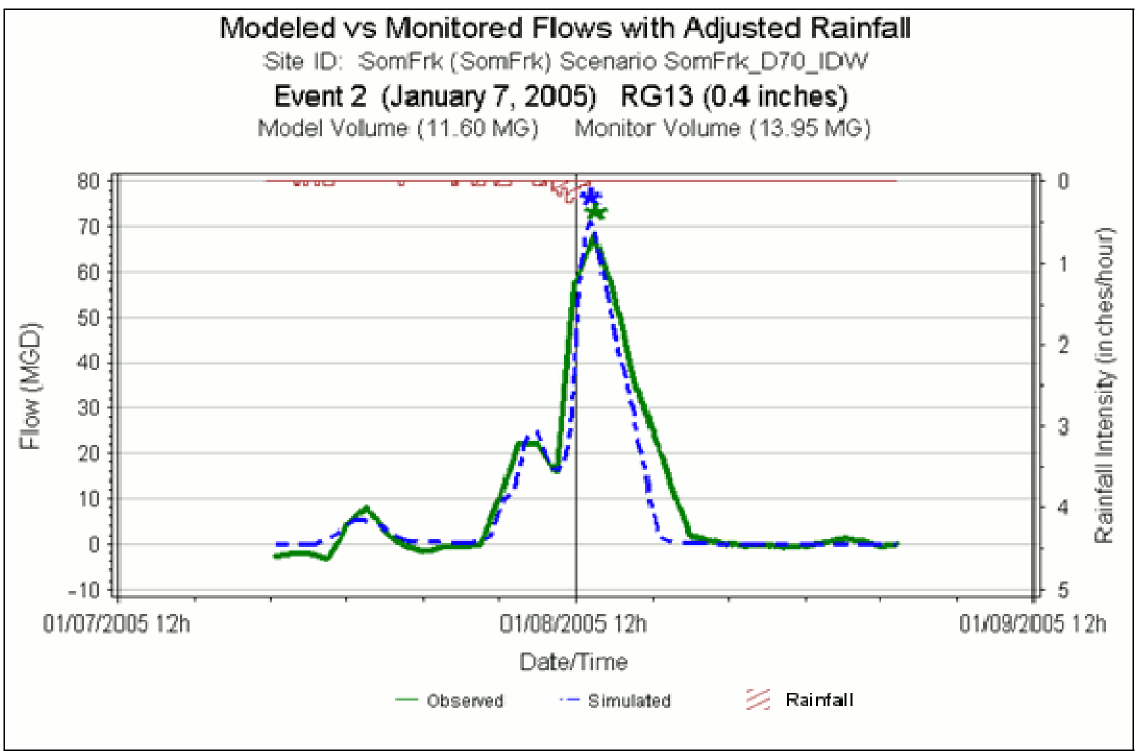


Figure 5-27 Som-Frk Model and Monitored Wet Weather Flow Time-Series Plot for the January 7, 2005 Event

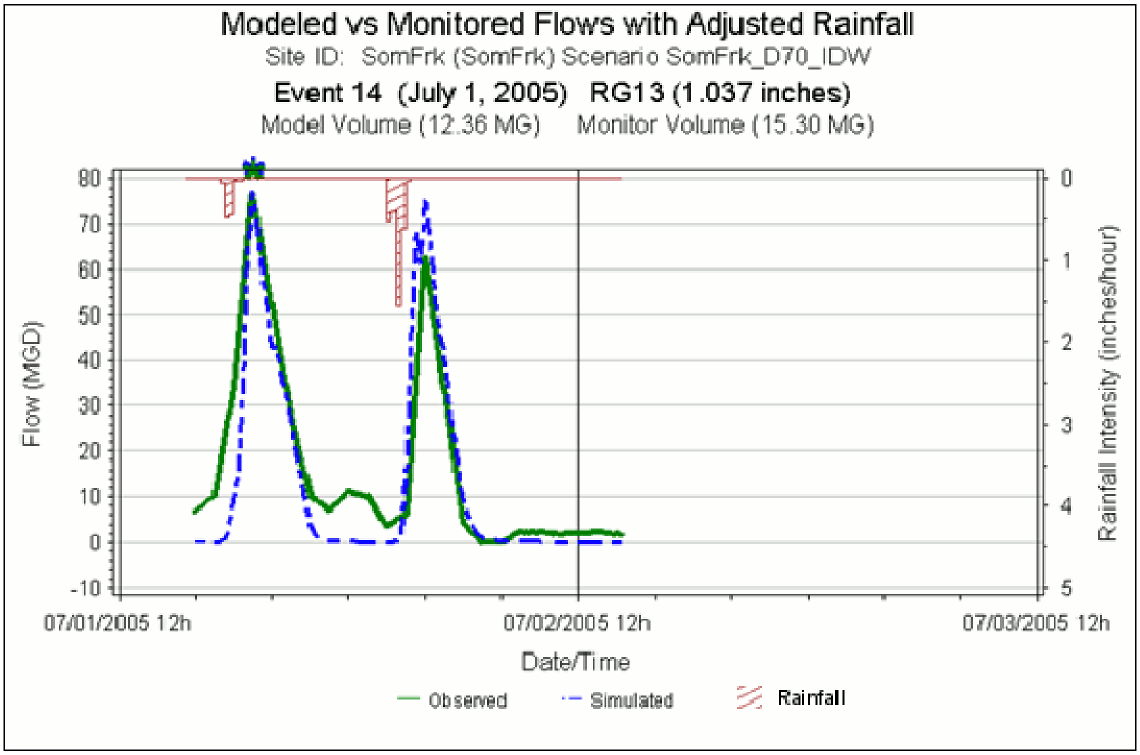


Figure 5-28 Som-Frk Model and Monitored Wet Weather Flow Time-Series Plot for the July 1, 2005 event

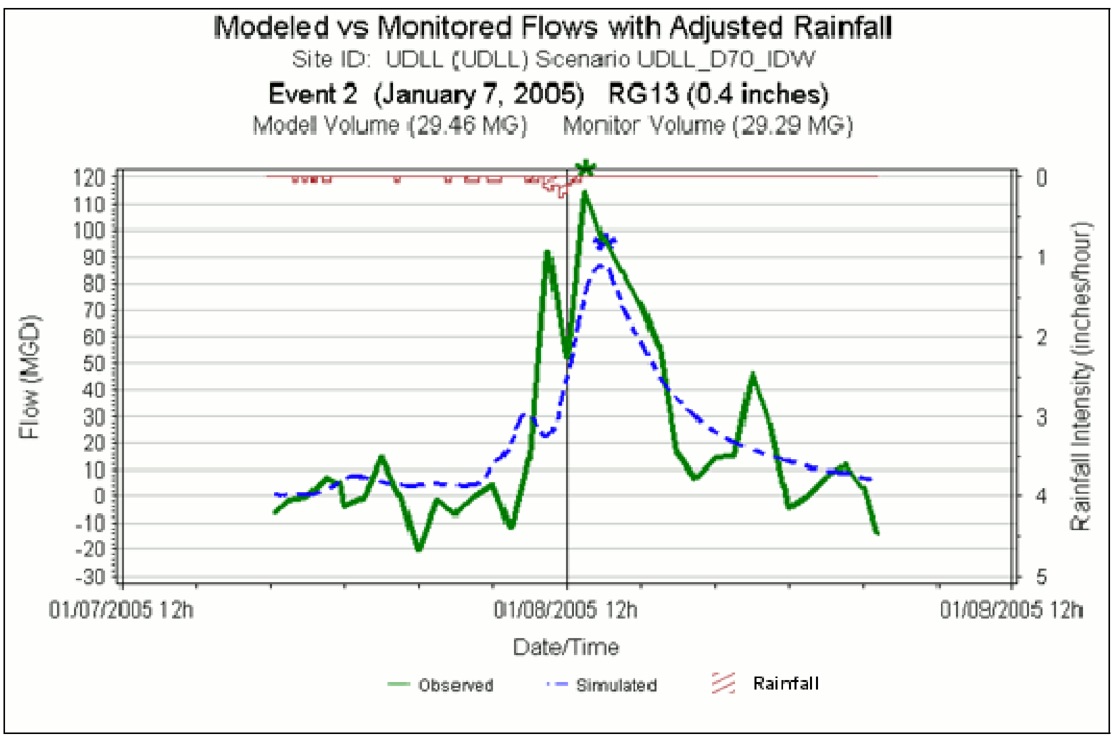


Figure 5-29 UDLL Model and Monitored Wet Weather Flow Time-Series Plot for the January 7, 2005 Event

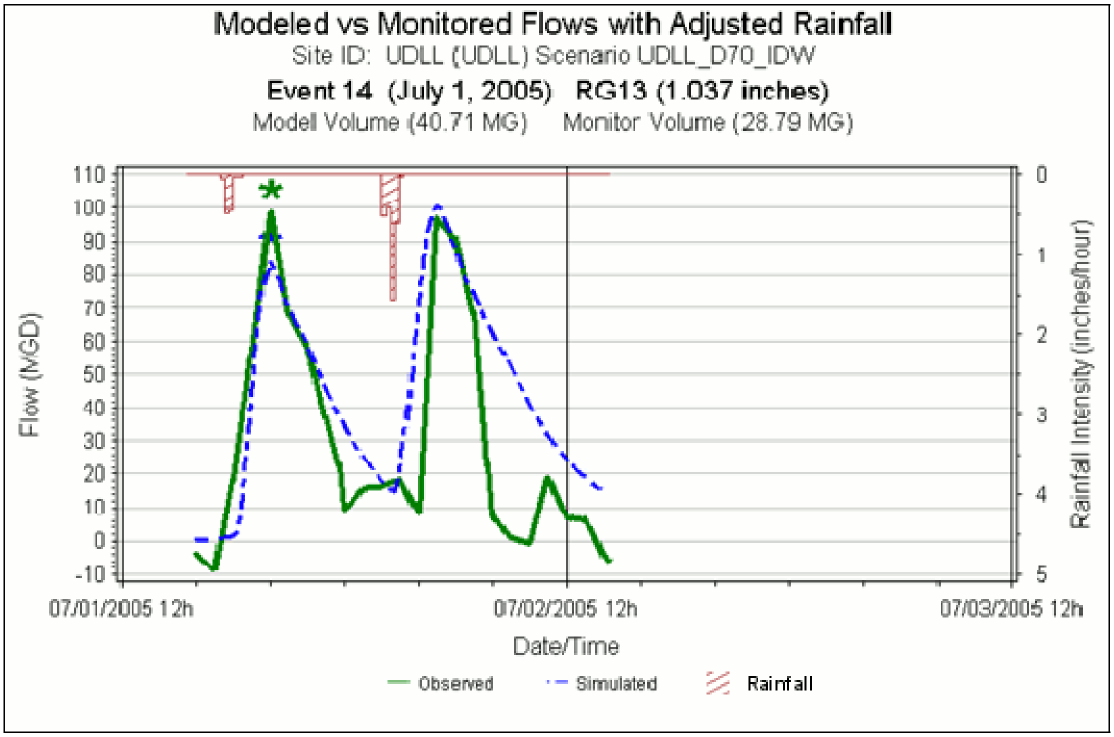


Figure 5-30 UDLL Model and Monitored Wet Weather Flow Time-Series Plot for the July 1, 2005 event

5.4.1 Land-Based Controls

Philadelphia's stormwater regulations require a minimum level of performance from post-construction stormwater management structures. To efficiently analyze this level of performance within each watershed a generalized approach was adopted in representing green infrastructure within the models. A green infrastructure tool was built to model green infrastructure and to thoroughly quantify the benefits of the stormwater ordinance, demonstration programs and incentive programs in the same terms used to evaluate capital projects on a watershed by watershed basis. In order to do so, detailed analyses of the City's impervious cover were conducted to correctly define targeted areas.

5.4.1.1 General Low Impact Development Model Approach

The City's stormwater ordinances, demonstration programs and incentive programs promote implementation of a variety of stormwater control types and require a certain level of performance. The first task in analyzing how the City's sewer systems will respond to implementing more of the green stormwater infrastructure was building a general model to represent a mix of the various types of stormwater control structures which are designed to meet or exceed the required level of performance. A general model that represents the hydraulic and hydrologic processes like storage, slow release and infiltration was adapted to represent a variety of physical structures. Standardizing the model setup allows analysis of green infrastructure option alongside other traditional infrastructure options.

To more accurately assess the potential benefit of green infrastructure a thorough analysis and assessment of Philadelphia's impervious surfaces available for green stormwater infrastructure implementation was conducted. Through the use of GIS tools and aerial photography, a comprehensive and highly detailed account of the City's impervious land cover was created. The impervious surfaces were broken down into the following categories:

- Total impervious area
- Highways
- Streets
- Private land
  - Land targeted for incentives
  - Other private land
- Public land
  - PWD property
  - Recreation department
  - Fairmount Park
  - School district
  - Vacant/abandoned land
  - Other public land (non-PWD, Recreation Dept, Fairmount Park)

Within the private and public land categories, the impervious area attributed to streets, sidewalks, parking and buildings was determined. The model manipulated these impervious area values to represent various levels of green infrastructure implementation. A more detailed account of the impervious analysis will be described subsequently in Section 6.

The model setup followed a series of model shed processing setup steps, which were carried out within an Excel spreadsheet. First, an area (or range of areas) of impervious surface was determined to be affected by the stormwater ordinance over the planning horizon – labeled in Figure 5-31 as I_o. This area may be adjusted as practices are implemented that provide a lower level of performance than the ordinance. Second, additional areas are determined to be affected by incentives for private land not subject to the ordinance and public land to be targeted for stormwater management. These areas are updated within the model and produce a range of performance results for varying levels of implementation based on the desired amount of impervious surface managed by land-based controls. Flow produced from the controlled impervious surface – identified as I_c in Figure 5-31 – is routed onto a pervious surface, labeled as P_c, to allow infiltration to be simulated. Any runoff from the pervious shed is loaded to a storage node large enough to meet required capture volume. An overflow weir simulates the overflow volume from this storage node once the storage volume has been exceeded. The storage volume is slow released into the CSS at a designated rate set by the City's regulations. The slow release flow is combined with the uncontrolled portion of flow entering the CSS. The total runoff volume from the shed, slow release structure, overflow weir and combined flow into the CSS is recorded and subsequently used to determine control structure volumes necessary to fulfill the stormwater ordinances and regulations. The hydrologic surface flow routing is shown in the Figure 5-31.

I_O is equal to the impervious area controlled (I_C + P_C). The remaining impervious area is labeled as I_{NC}. The existing pervious area not associated with a green-stormwater infrastructure control structure is identified as P_{NC}.

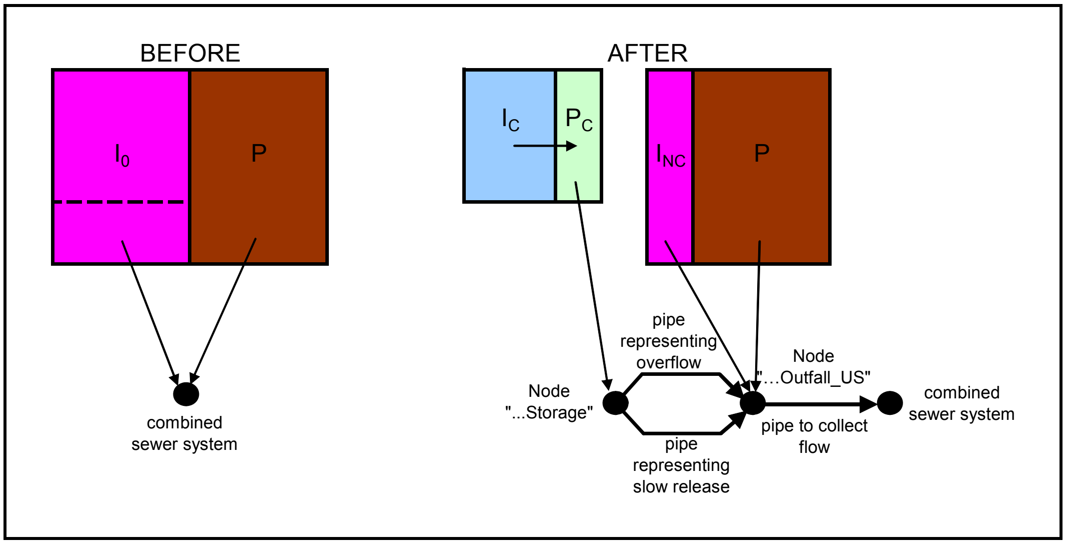


Figure 5-31 Visual Representation of How a Portion of a Subcatchment is Controlled and Routed Through Green Infrastructure Within the Model

Other urban communities have incorporated street trees in an effort to quickly and inexpensively incorporate rainfall interception mechanisms into the urban environment. Street trees by themselves provide a level of control lower than that defined by the PWD Stormwater Regulations and what may be simulated by the general model approach. Due to the complexity of street tree analysis a literature review, followed by a detailed analysis specific to Philadelphia, was conducted to define an appropriate equivalency ratio to supplement the general model for land-based control analyses.

Simulation of a single tree canopy and comparison to a previously uncontrolled area retrofitted to meet the PWD Stormwater Regulations requirements was done to derive a runoff reduction ratio. This defined the relative difference in benefit between the two scenarios. Results produced a ratio of 0.875, meaning the tree canopy specific model total runoff reduction was 87.5 percent of the total runoff reduction produced by the model meeting the stormwater regulations requirements.

The area of implementation of street trees is limited, therefore it was necessary to adjust this ratio to represent the city-wide benefit of street tree implementation. The process to determine the available street area for tree implementation involved a literature review of other cities' street tree ordinances and regulations and an available sidewalk/street impervious area analysis from the information produced from the impervious analysis mentioned previously.

A significant reduction in the equivalency ratio was expected at the end of this analysis due to the limitations for planting street trees. The adjustments applied to the preliminary equivalency ratio of 0.875 produced a reduced runoff reduction equivalency ratio of approximately 0.287 or 28.7 %. Ultimately, the ratio states that 1 ac of impervious surface covered by tree canopy results in the same total runoff volume reduction as approximately 0.287 ac of impervious surface draining to an infiltration bed meeting the stormwater regulations requirements.

5.4.2 Infrastructure Based Controls

5.4.2.1 Sewer Separation – Highway and Waterfront Disconnection

PWD is considering a long-term policy to require disconnection of waterfront property from the CSS where appropriate. Runoff from these properties will be discharged directly to the Delaware River after water quality pre-treatment. Some properties may be allowed to connect to PWD's outfall pipe downstream of the combined sewer regulator structure, while other properties may be required to construct and permit a new outfall.

Through the use of GIS, sewersheds intersecting I-95 were identified and the total area of highway and impervious area between the highway and the Delaware River were calculated for each shed. The affected shed area was then removed from consideration and the total impervious percentage was recalculated for the sewershed. Table 5-6 provides the total shed areas for each drainage district and Figure 5-32 highlights the areas affected by the waterfront disconnection for the SEDD and NEDD. Areas in the SWDD affected by I-676 and I-76 eligible for sewer separation were removed from the model and simulations were performed to determine the magnitude of change in runoff volume. The effects were negligible and, therefore, further analysis of waterfront disconnection within the SWDD was not done.

Table 5-6 Sewershed Areas and Percent Impervious Area Removed Due to Waterfront Sewer Separation Analysis

Land Location	Combined-Sewered Impervious Area (ac)				Combined-Sewered Impervious Area (% of total)		
	City-Wide	SEDD	NEDD	SWDD	City-Wide	SEDD	NEDD
Non-Waterfront	43,414	8,700	20,060	14,654	95.8	91.5	98.4
Between Major Highways and Rivers	1,507	578	234	695	3.5	6.6	1.2
Highway	315	165	94	56	1.1	1.9	0.5
Waterfront + Highway	1,822	743	327	752	4.2	8.5	1.6

5.4.2.2 Deep Tunnels

For a tunnel storage alternative, CSO flows in excess of the interceptor capacity are diverted via a modified or new diversion structure to a series of secondary tunnel structures that convey flow into the storage tunnel. The approach to model the tunnels for all three districts was to simulate the tunnels as storage nodes. To model the tunnels as a storage node, the length of the tunnel to be modeled is obtained by doing a preliminary tunnel alignment. Once the length is determined models are set up for varying tunnel diameters. The tunnel is assumed to be circular. The diameters range from 15 to 35 ft and are increased by an interval of 2.5 ft for each simulation. Using the tunnel length and the diameter a volume is calculated. Using eighty percent (80%) of the calculated volume, a storage node 20 ft deep with constant surface area is simulated. The storage section representing the tunnel volume itself has a plan surface area that will satisfy the tunnel volume requirements. The maximum tunnel drain down rate was set so that the tunnel would drain down in 24 hours when the capacity of the WPCP is available. All the outfalls that will contribute to the tunnel are connected to the storage node. Figure 5-33 shows a visual representation of the tunnel in the models. The sub-sections that follow describe the model details specific to each drainage district.

The planning level alignments were based on proximity to the existing CSO diversions and Water Pollution Control Plants (WPCP), available geotechnical boring data, avoidance of significant underground property easements and the tunnel boring machine's turning radius. Conceptually, the tunnel alignments can be represented as broad cross sectional corridors.

The secondary structures of the tunnel include a near surface drop shaft, vertical drop shaft, de-aeration chamber and connecting tunnel. The process of combining and conveying flow from multiple diversion structures is called flow consolidation. The flow consolidation strategy for a particular storage tunnel alternative was primarily selected through a least cost comparison of flow consolidation versus conveying the flow to the tunnel. This cost comparison was made at each regulator and the cheaper option selected. The cost to consolidate flow was based on the lengths, sizes and depths of the consolidation piping. The length of the consolidation piping was based on the distance between adjacent diversion structures, existing rights of way, the existing street and property layout and the selection of alignments that balances longer pipeline lengths with shallower pipeline depths. The lengths were measured with ArcGIS utilities and the consolidation alignments largely followed the existing interceptor's path. The sizes of the consolidation piping were based on SWMM4 model predictions of the peak design flow rates and various assumed design slopes and velocities. The depths of the consolidation piping were calculated as the differences between the diversions' overflow elevation and the average ground surface elevation along the pipeline alignment.

The cost to convey flow to the tunnel was based on the depths, sizes and lengths of the secondary structures. The depths of the near surface drop structures were based on the differences between the diversions' overflow elevation or the consolidation piping invert elevations and the ground surface elevation at the near surface drop structure locations. The sizes and specific designs of the near surface drop structures, vertical drop shaft structures, de-aeration chambers and adits – which may be described as access points to the tunnel –were based on the same design flow rates used to size the consolidation piping. The lengths of the adits were based on the distances between the drop shaft locations and the planning level tunnel alignments.

The volume captured by the tunnel over the course of a one-year simulation was calculated as the difference between the overflow produced from the simulated tunnel scenario and the corresponding baseline scenario. There are two baseline scenarios, each representing the upper and lower boundary of an uncertainty range for DCIA, baseflow and RDI/I watershed characteristics. Each baseline scenario has the interceptors draining to the plant with pumping boundary conditions limiting the high level interceptors' inflow into the WPCP. The baseline plant capacities for the SEDD, NEDD and SWDD are 280, 435 and 480 MGD, respectively.

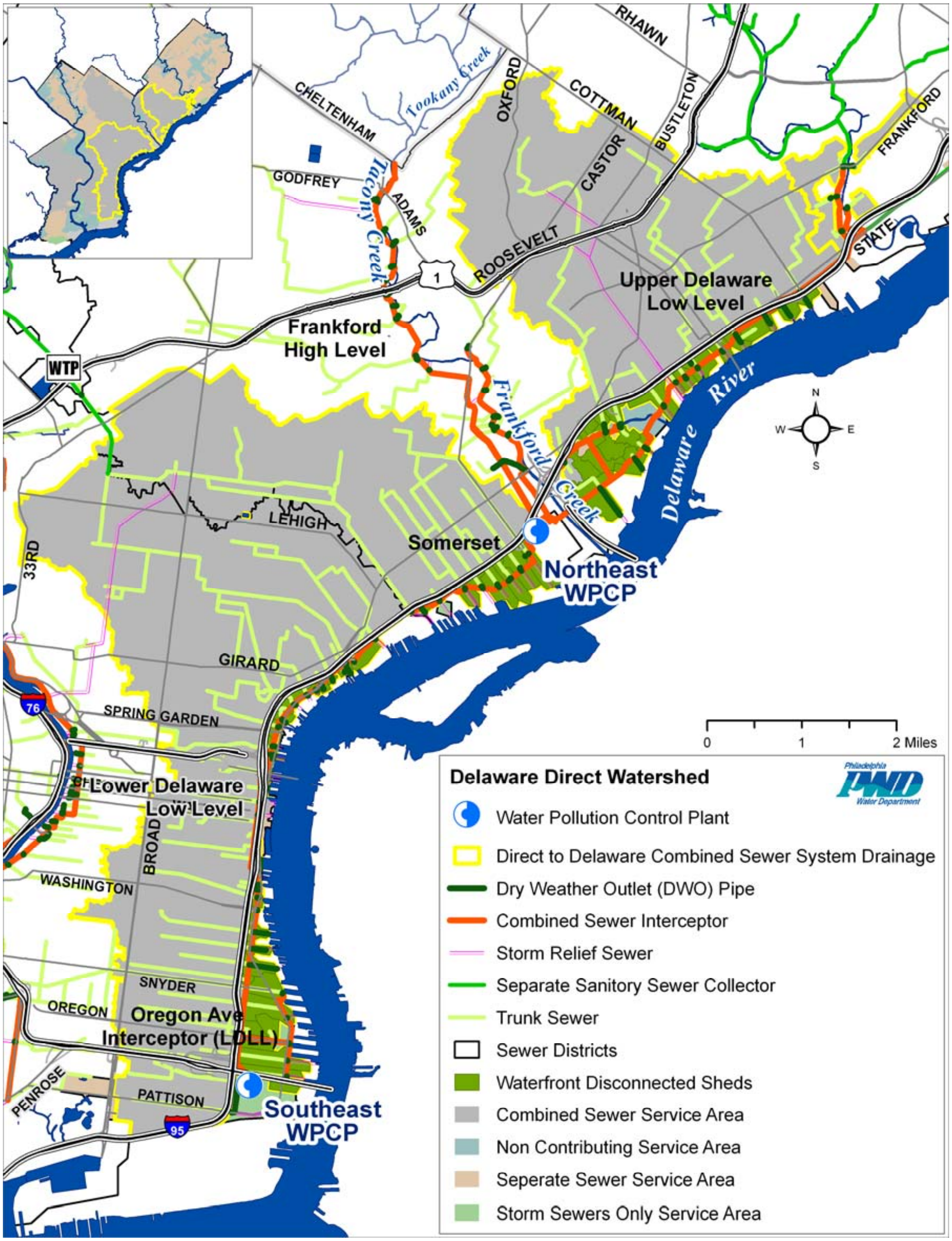


Figure 5-32 CSO Areas Affected by the Waterfront Sewer Separation (Green Highlighting)

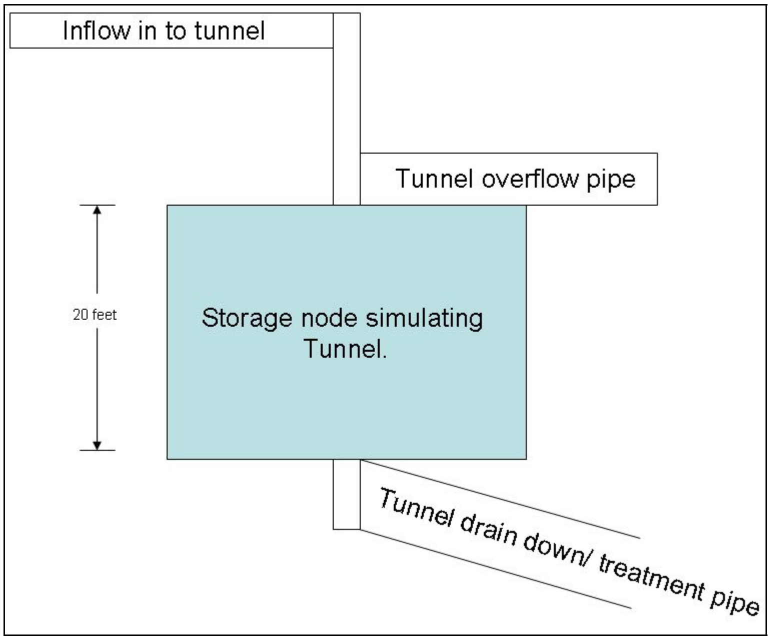


Figure 5-33 Storage Depicting the Tunnel

5.4.2.2.1 SEDD Tunnel

The SEWPCP was assumed to be expanded to treat 330 MGD. The total length of the tunnel, excluding the drain down section, was 5.9 mi. The inflow into the tunnel model is the total flow produced from each regulator's outfall. Table 5-7 presents the tunnel length and corresponding volume of the storage node for the SEDD tunnel. The volumes shown in the first row represent the total tunnel volume and the second row shows the 80% tunnel volume that was used for the simulations.

Table 5-7 Length and Volume Data for the SEDD Tunnel Model

			Tunnel Diameter (ft)								
			15	17.5	20	22.5	25	27.5	30	32.5	35
	Length (ft)	Length (mi)	Tunnel Volume (MG)								
SEDD	31340.0	5.9	41.4	56.4	73.7	93.2	115.1	139.3	165.8	194.6	225.6
Volume used For simulation	**31340.0**	**5.9**	**33.2**	**45.1**	**58.9**	**74.6**	**92.1**	**111.4**	**132.6**	**155.6**	**180.5**

5.4.2.2.2 NEDD tunnel

It was assumed the NEWPCP will be expanded to treat 650 MGD. The total NEDD tunnel length is estimated to be 10 mi. The tunnel length along the Delaware was estimated as 5.3 mi and along Tacony as 4.7 mi. It is also assumed all tunnels will be interconnected. Table 5-8 presents the tunnel length and corresponding volume of the storage node. The volumes shown in the first row are the total volumes of the tunnel and the 80% volume used for simulations is presented in the second row.

Table 5-8 Length and Volume Data for the NEDD Tunnel Model

			Tunnel Diameter (ft)								
			15	17.5	20	22.5	25	27.5	30	32.5	35
	Length (ft)	Length (mi)	Tunnel Volume (MG)								
NEDD	53000.0	10.0	70.1	95.4	124.6	157.7	194.7	235.6	280.3	329.0	381.6
Volume used for simulation	**53000.0**	**10.0**	**56.1**	**76.3**	**99.7**	**126.2**	**155.7**	**188.5**	**224.3**	**263.2**	**305.3**

The NEDD also includes all regulators draining to the Upper Frankford Low Level (UFLL), Lower Frankford Low Level (LFLL) and the Pennypack (PP) interceptor systems in addition to the regulators draining to the UDLL, SOM and TAC interceptor systems. The flow was directed to the tunnel for these interceptor systems using the same methodology as described previously.

5.4.2.2.3 SWDD Tunnel

It was assumed the SWWPCP will be expanded to treat 540 MGD. The total SWDD tunnel length is estimated to be 13.7 mi. The tunnel length along the Schuylkill was estimated as 6.4 mi and along Cobbs Creek as 7.3 mi. It is also assumed all tunnels will be interconnected. Table 5-9 presents the tunnel length and corresponding volume of the storage node. The volumes shown in the first row are the total volumes of the tunnel and the 80% volume used for simulations is presented in the second row.

Table 5-9 Summary of SWDD Tunnel Volume and Length Data

			Tunnel Diameter (ft)								
			15	17.5	20	22.5	25	27.5	30	32.5	35
	Length (ft)	Length (mi)	Tunnel Volume (MG)								
SWDD	72491	13.7	95.9	130.5	170.4	215.7	266.3	322.2	383.4	450.0	521.9
Volume used for simulation	**72491**	**13.7**	**76.7**	**104.4**	**136.3**	**172.5**	**213.0**	**257.8**	**306.7**	**360.0**	**417.5**

5.4.2.3 Parallel Interceptors – Transmission Systems

Prior to modeling, a preliminary spreadsheet was created to align a parallel conveyance system to capture and convey flow to the respective WPCP of the existing interceptor system being paralleled. Output from the SAS EOP processing tool served as input to the spreadsheet. The SAS tool identifies a peak flow value and overflow volume for each overflow goal at every regulator in the system having an outfall. The spreadsheet analyzes each regulator producing an overflow for each green-stormwater infrastructure implementation scenario for all overflow goals 1 through 25 – which were previously discussed in Section 5.2.3.

The spreadsheet sizes the conveyance pipe segments based on the cumulative flow as it is captured at the regulator outfall and is moved downstream to the plant. Once the cumulative flow requires a pipe larger than a 12 ft x 12 ft box sewer, a second parallel interceptor must be considered to convey

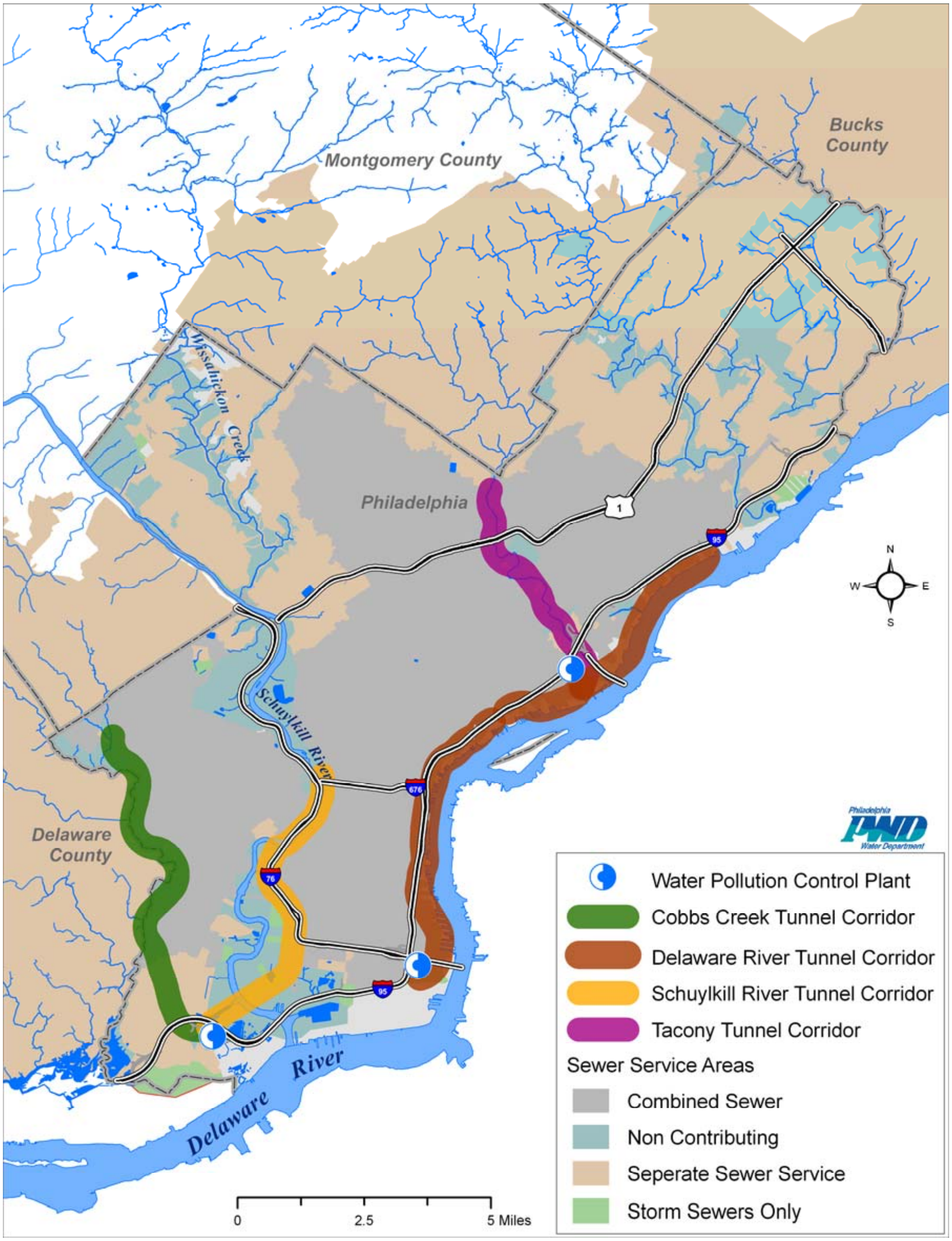


Figure 5-34 Potential Tunnel Alignment

the excess flow to the plant in order to reach the target overflow goal for the respective target overflow goal. Figure 5-35 presents a potential transmission parallel interceptor conveyance layout for the Cobbs Creek Watershed.

5.4.2.4 Satellite High Rate Treatment

Prior to implementing the conceptual modeling design of conveyance pipes routed to a satellite treatment plant into SWMM4, a preliminary spreadsheet analysis was performed to determine the feasibility of this family of alternatives. At each implementation level of land-based controls, the required end-of-pipe treatment rates were determined using the SAS EOP program, which was described in Section 5.2.3. The SAS program uses capture regulator data, land-based control general green infrastructure model simulation output and an outfall list as input. Depending on the desired performance level, the program determines the corresponding event peak treatment rate that satisfies the target performance overflow rate. The peak treatment rate is used to size the parallel interceptor for transmission to the plant, with the maximum pipe diameter limited by constructability, taken to be a 12 ft x 12 ft concrete box sewer.

For the purposes of the spreadsheet analysis, at a minimum, the plant receives the maximum flow that may be delivered by the existing interceptors and the base wastewater flow (BWWF) as defined by the results of the stress test updated in the attached plant capacity report completed in March 2009, which is attached in Supplemental Documentation Volumes 6, 7 and 8 (Stress Testing of the Northeast WPCP, Stress Testing of the Southeast WPCP and Stress Testing of the Southwest WPCP). The peak flow from the outfalls of the existing interceptor systems are collected and conveyed through a parallel interceptor system to satellite treatment facilities until the size of pipe equals the constructability limit. The total flow delivered to the satellite treatment facility determines the required size of the plant and consolidation sewers for each level of land-based control. The spreadsheet determines the most appropriate regulator outfall to place at the satellite treatment plant, based on the volume of overflow, and then routes the remaining overflow collected from the other regulator overflows to that chosen location.

In some cases, satellite treatment locations are manually overridden to place facilities at locations where PWD has known space availability for such construction. In this situation, the conveyance pipes are routed to the user designated treatment location and sized according to cumulative flow.

Figure 5-36 shows a visual representation of a potential parallel conveyance system routed to various locations of satellite treatment facilities for the Delaware Watershed located with the spreadsheet analysis.

Areas available for satellite treatment construction are:

- Frankford Arsenal (Delaware Direct Watershed) near Regulator D12
- Near Eagle Creek (Schuylkill Watershed) at Regulator S45
- Oregon Avenue (Delaware Direct Watershed) at Regulator D70

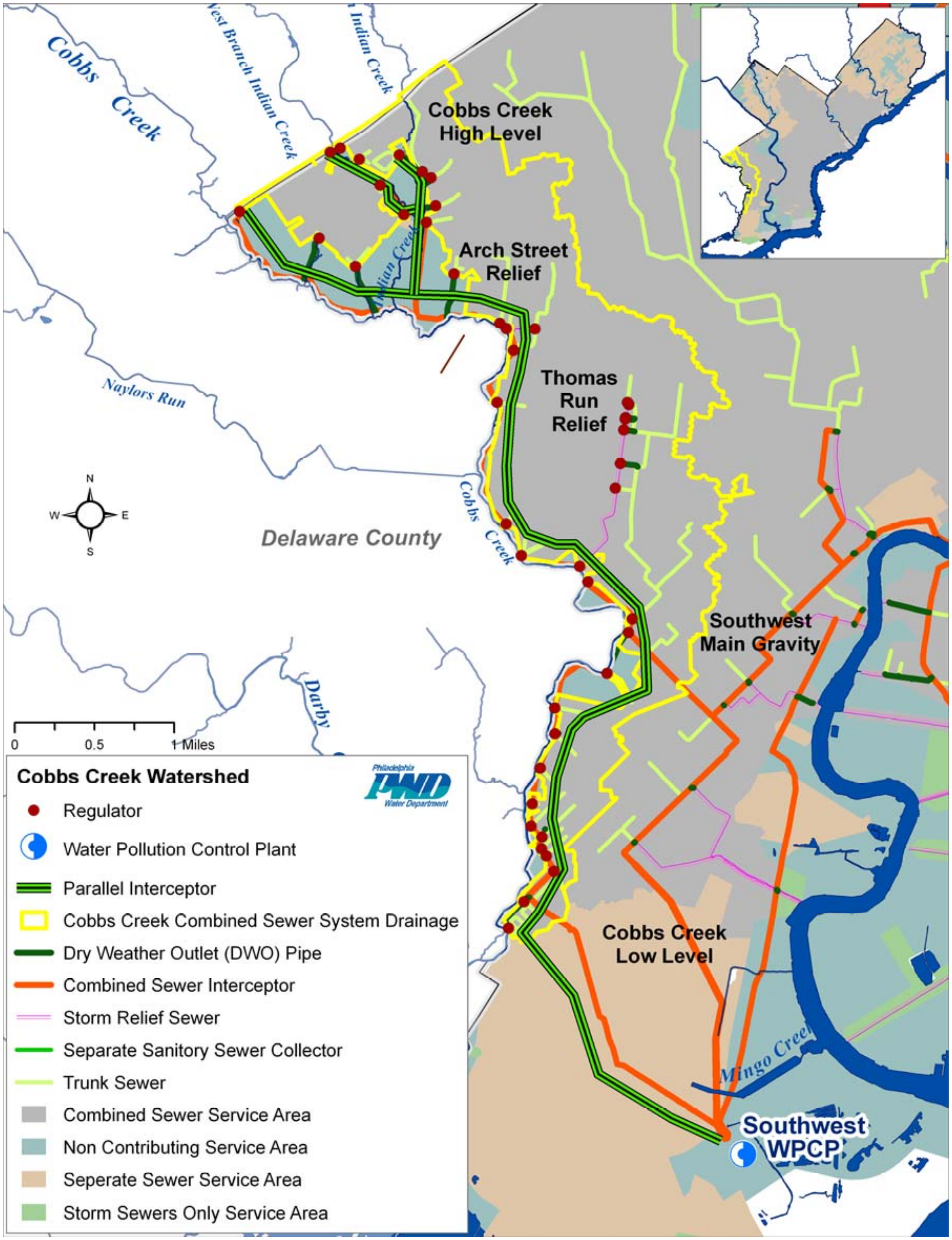


Figure 5-35 Potential Layout for an All Transmission Parallel Interceptor System to Capture Overflow from the Cobbs Creek Watershed CSO Regulators

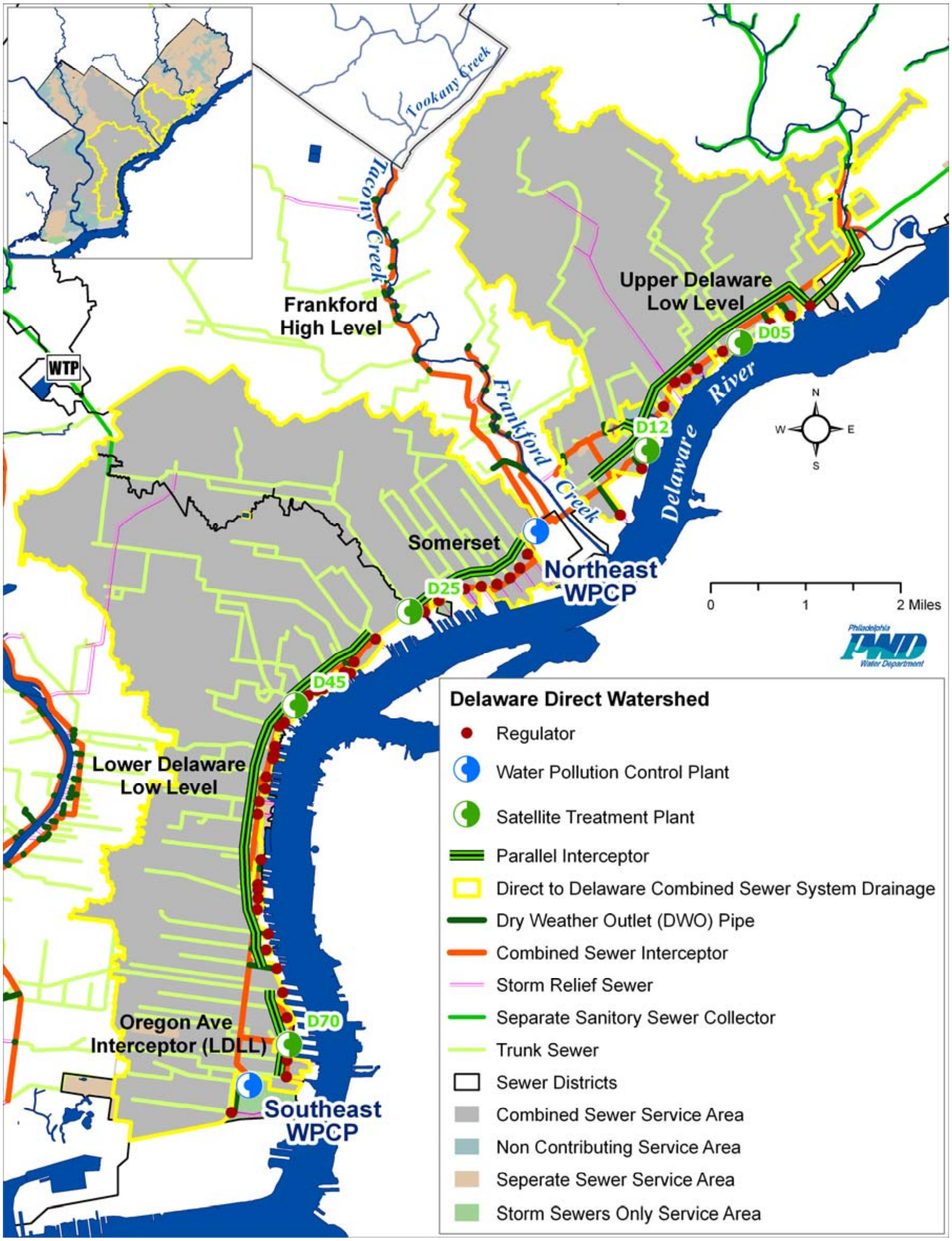


Figure 5-36 Example of a Parallel Interceptor System with Strategically Placed Satellite Treatment Facilities for the Delaware Watershed

5.4.2.5 Retention Treatment Basins (RTBs)

RTBs are satellite high rate treatment facilities designed to provide screening, settling, skimming (with a fixed baffle) and disinfection of combined sewer flows before discharge to a receiving water. Since RTBs are empty between wet weather events, they also provide storage, which can completely capture combined sewer flows from small wet weather events for later dewatering and conveyance to the WWTP for treatment. RTBs can be designed with a variety of screen types, disinfection methods and basin geometries. The surface loading rates can also vary but are typically higher than rates used for design of primary clarifiers. RTBs can be constructed above or below grade but typically require at least an above grade process/control building. If pumping of the combined sewer flow is required, the pump station may be integral to the RTB facility or constructed as a separate structure.

The RTB facilities are assumed to include:

- Coarse, mechanically cleaned bar screens located at the headworks of the facility
- Disinfection via chlorine using sodium hypochlorite- disinfectant contact time is achieved in the basin, which is sized to achieve the design contact time at the design flow rate
- A basin divided into two parallel compartments just below grade, with an effluent weir and geometry based on a design surface overflow rate of 6,000 gal per day/ft^2. If pumping is required, it will be provided in a separate structure

A preliminary method of analysis is employed for evaluation of the effectiveness of RTB facilities in the reduction of CSO volume and frequency. This method is based on the development of peak flow reduction factors that can be used with existing high-rate treatment tools used for sizing high-rate treatment facilities designed without a significant storage component.

For this study, a simplified representation of an RTB was created in NetSTORM (see Figure 5-37 below). The system operates as follows:

- During small storms that do not exceed the treatment rate of the RTB, flow in the model continues through the RTB uninterrupted and is considered treated. In the real system, flow is detained in the storage element for settling and disinfection. When the storage element reaches capacity, treated effluent is discharged to a receiving water. When interceptor capacity is again available after the storm, the storage element is slowly drained back to the interceptor
- During large storms that exceed the treatment rate of the RTB, excess flow is discharged untreated to a receiving water
- Storage in the RTB is assumed to be 0.20 in over the drainage area
- Simulations were run with hourly rainfall records from the representative year used in LTCPU simulations
- Simulations were run for three regulator structures and their drainage areas: D65, C19 and S02. These were chosen because they represent a range of treatment rate to drainage area ratio
- Effects of low-impact development were approximated by reducing runoff coefficients by 25%, 50% and 75%

Compared to the treatment systems without storage, systems represented in the satellite treatment spreadsheet reduce design flows by the following amounts:

The recommendations after evaluating the conclusions above are as follows:

- Compared to the treatment systems without storage represented in the satellite treatment spreadsheet, reduce design flows by the following amounts:
  - 10 overflows per year: 55%
  - 4 overflows per year: 50%
  - 1 overflow per year: 30%

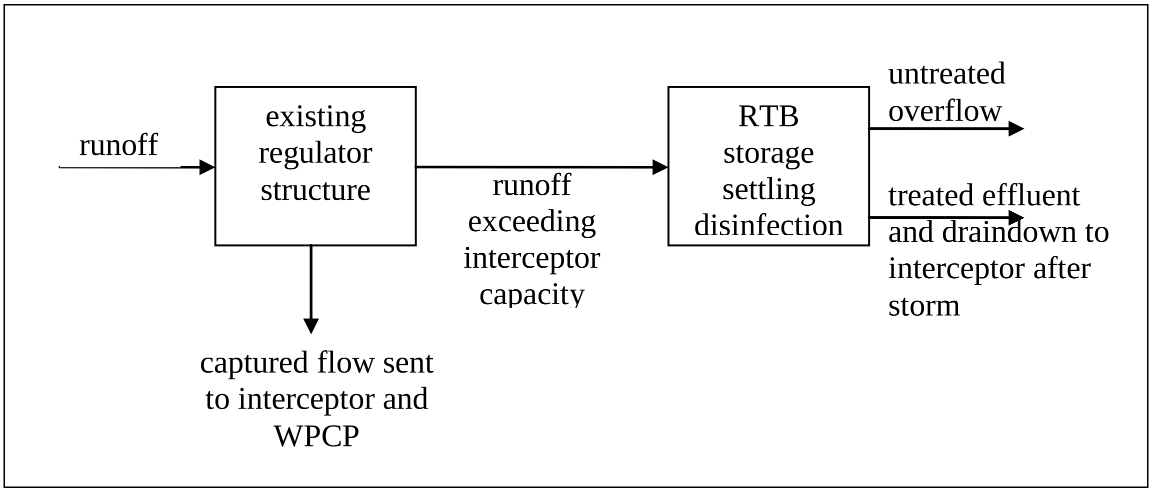


Figure 5-37 Schematic Diagram of RTB Model

Table 5-10 Results

	Regulator Treatment Rate (cfs/ac)	Treatment Rate Percentile (percentile)	Reduction in Design Flow Compared to a No-Storage System: ≤ 10 overflows per year	≤ 4 overflows per year	≤ 1 overflow per year
D65	0.017	17th	50 - 66%	43 - 60%	25 - 33%
S02	0.065	51st	N/A	N/A	22 - 77% (median 40%)
C19	0.173	76th	N/A	N/A	22 - 36%

N/A: This regulator generated less than this number of overflows during the typical year.
Ranges given are for a range of reduction in runoff coefficient.

5.4.2.6 Off-Line Storage

Off-line storage facilities are designed, whenever possible, to be fed by gravity during wet weather surcharge conditions through overflow weirs in the trunk sewer and drained by gravity to a downstream location using a head dependant sluice gate orifice. Off-line storage projects that have been modeled for evaluation of CSO performance benefit as part of the LTCPU include:

- State Road Relief Sewer (Delaware Direct Watershed)

Off-line storage projects that are planned or have been completed as part of the 1997 LTCP have been incorporated into all baseline models for LTCPU evaluations. These include:

- Venice Island Storage Tank (Schuylkill River Watershed)

5.4.2.7 In-Line Storage

In-line storage facilities are modeled as either conduits or storage nodes with both downstream dry weather outlets modeled as wet weather overflow weirs and orifices with either head dependant or static orifices. The wet weather overflow weirs can be either static structures or head dependant dynamically controlled structures such as inflatable dams or crest gates. These structures allow for the maximum use of in-line storage capacity while providing maximum flood protection.

In-line storage projects that have been modeled for evaluation of CSO performance benefit as part of the LTCPU include:

- T14 Crest Gate (Tacony Creek Watershed)
- Rock Run Relief Inflatable Dam (Tacony Creek Watershed)
- Indian Creek Day lighting (Cobbs Creek Watershed)

In-line storage projects that are planned or have been completed as part of the 1997 LTCP have been incorporated into all baseline models for LTCPU evaluations. These include:

- Main Relief Inflatable Dam (Schuylkill River Watershed)

5.5 Overview of the Alternatives Analysis Process

In order to appropriately determine and select an alternative, it is necessary to develop a thorough and comprehensive analysis procedure. For the PWD LTCPU, this process followed the following outline:

- Problem identification and goal setting
- Development and screening of management options
- Development and initial screening of alternatives
- Detailed evaluation of alternatives
- Selection of a recommended alternative
- Refinement of the recommended alternative

These tasks are briefly discussed in the following sections.

5.5.1 Overview

The LTCPU alternatives analysis process follows the following steps:

- Watershed-specific characterization and problem identification
- Watershed-specific goal setting
- Development and screening of management options
- Development and initial screening of alternatives by watershed

- Detailed evaluation of alternatives by watershed
- Selection of a recommended alternative by watershed
- Refinement of the selected alternative, integration of watershed-specific alternatives into a single plan and implementation planning

5.5.2 Problem Identification and Goal Setting

The characterization, problem statement and goal setting process, presented in Sections 3 and 4, form the foundation for the alternatives development and evaluation process. Through the extensive field studies, modeling and data analysis, the highest priority problems in each watershed are identified and goals are set to address each of these problems. Goals set by the Integrated Watershed Management Plans (IWMP) incorporate the needs expressed by stakeholders in each watershed. The goals also include applicable regulatory requirements.

5.5.3 Development and Screening of Management Options

The IWMP process defines a management option as an individual project, technology, or practice intended to address some aspect of watershed management. Bioretention basins, street sweeping and public notification are examples of options. An individual option is not intended to address all watershed management or combined sewer overflow control goals. Watershed management and combined sewer overflow control options to be considered are compiled from many sources including the following:

- Options recommended for implementation in IWMPs
- Continuing implementation of the Nine Minimum Controls
- Continuing options from PWD's 1997 Long Term CSO Control Plan
- Options required by an NPDES permit or consent order agreement
- A wide range of additional combined sewer overflow controls from the National CSO Policy and EPA guidance documents, professional literature, other cities' experiences and best professional judgment, including:
  - Green infrastructure and other stormwater source controls
  - Modification and optimization of existing infrastructure
  - Storage
  - Increased collection system capacity
  - Satellite treatment facilities
  - Bypass of secondary treatment at existing WPCPs
  - Expansion of wet weather treatment capacity at WPCPs

A screening process is applied to these potential options to identify those that should be incorporated into all alternatives, those that should be considered for incorporation into some alternatives and those that should be dropped from further consideration. This process results in one of the following outcomes for each option:

1. An option is recommended for inclusion in all alternatives if the option is a regulatory requirement or if its implementation has already been ensured by a related planning process, such as an IWMP. Many non-structural options fall into this category.

2. An option is dropped from further consideration if it does not address at least one goal and is not a regulatory requirement.

3. Options that do not fall into categories 1 or 2 are recommended for consideration in the alternatives development process. Most green infrastructure and traditional infrastructure controls fall into this category.

Options from category 3 above are subjected to an initial, qualitative cost-effectiveness screen. Options are dismissed at this point if their cost is expected to be approximately an order of magnitude or more greater per unit of combined sewer overflow eliminated. In this initial step, care is taken to eliminate only those options that are clearly much less cost-effective than the body of options as a whole.

5.5.4 Development and Initial Screening of Alternatives

Alternatives are formulated as packages of options that meet the following criteria:

- An alternative must include options to address all goals of the LTCPU over the course of the planning period
- An alternative must meet these goals in a cost-effective manner relative to other alternatives. Options are dismissed at this point if their cost is expected to be approximately an order of magnitude or more greater per unit of combined sewer overflow eliminated relative to the body of alternatives as a whole. This determination is made graphically

5.5.5 Detailed Evaluation of Alternatives

Alternatives are evaluated using several measures, ranging from cost and performance to ancillary benefits and qualitative criteria.

5.5.5.1 Performance (CSO Control Level)

Performance of the urban hydrologic system is quantified in terms of stormwater runoff generated and loaded to the CSS.

5.5.5.2 Cost

Cost opinions include capital cost, operation and maintenance cost and, where appropriate, replacement and residual costs. Cost opinions were developed using ACT described previously. To allow direct comparison of multiple alternatives, costs are expressed as present value over the course of the planning period. However, present value can be misleading or inappropriate when trying to predict cash flows and staffing needs at specific points in the future. For this reason, annual cost and current dollar cost projections are also given where appropriate.

5.5.5.3 Affordability and Financial Capability

For initial alternatives analysis, quantitative measures of affordability include percent of median household income spent on wastewater and stormwater management and average annual increase in wastewater and stormwater bills for residential households.

5.5.5.4 Triple Bottom Line: Quantifiable Benefits and External Costs

The methods in determining the costs and benefits associated with the sustainability and environmental, social and economic benefits produced from implementing green infrastructure versus the traditional grey technologies are discussed below. Please refer to Supplemental Documentation Volume 2: Triple Bottom Line Analysis for more details.

Water Quality and Ecosystem Improvement

Green infrastructure improves ecosystems in two ways. First, by restoring a water cycle more similar to a natural watershed, green infrastructure allows rain to soak into the ground and return to streams slowly. Second, PWD's green infrastructure approach includes physical restoration of stream channels and streamside lands, including wetlands, to restore habitat needed for healthy ecosystems. Water quality and ecosystem health are difficult to value economically. However, human beings clearly value clean water and healthy ecosystems both for themselves and for future generations. Environmental economists refer to this as a "non-use" or "non-market" value and have a number of tools for estimating these values in monetary terms. For this study, these values were monetized based on a large body of academic literature where households were surveyed to determine how much they would be willing to pay to improve water quality or habitat by a defined amount. Values also were derived from a large body of literature on the economic value of wetlands.

Selected References: Van Houtven *et al.*, 2007; Woodward and Wui, 2001; Borisova-Kidder, 2006

Recreation Benefits

Improved access, appearance, and opportunities in these areas will make them more desirable destinations for the public. Recreation also will be more desirable along newly greened neighborhood streets and public places. The team established a baseline for the number of visitors to Philadelphia's parks today, based on reports prepared for the Philadelphia Parks Alliance and the Fairmount Park Commission, and input from park staff. With improvements to underused areas along stream corridors and riverfronts, the team estimated that these areas could be brought up to a level of use more similar to the park system as a whole. Recreation along newly greened streets and public places was linked to the area greened in each watershed. Environmental economists are able to estimate monetary values for recreation activities using "direct use" values from the academic literature and government agencies. These values estimate what a typical user pays or would be willing to pay to take part in that activity. For this study, the team was able to draw upon Philadelphia-specific direct-use values for different recreational activities, as published in a report prepared by the Trust for Public Lands (2008): *How Much Value Does the City of Philadelphia Receive from its Park and Recreation System?*.

Selected References: Trust for Public Lands, 2008; Tidal Schuykill River Master Plan, 2003

Reduction in Heat Stress Mortality

Green infrastructure (for example, trees, green roofs, and bioretention sidewalks) reduces the severity of extreme heat events in three ways - by creating shade, by reducing the amount of heat absorbing pavement and rooftops, and by emitting water vapor – all of which cool hot air. This cooling effect will be sufficient to actually reduce heat stress-related fatalities in the City during extreme heat wave events. Extreme heat events in Philadelphia have been studied extensively by the Philadelphia Health Department, the federal Centers for Disease Control, the US EPA and others. The study team used results of several of these studies that quantified the reduction in temperature that results from significant increases in urban vegetated acreage. The study team incorporated these results into the City's existing methodology for quantifying excess heat mortality to evaluate human deaths avoided under the different green CSO options. The value of avoided heat-related deaths was then monetized based on standard methods routinely used by US EPA in regulatory impact assessments.

Selected References: CDC, 1994; Hudischewskyj *et al.*, 2001; Kalkstein and Sheridan, 2003

Air Quality Improvement from Trees

Like many major cities in the United States, US EPA currently classifies the Philadelphia metropolitan area as exceeding federal air quality standards for both ozone (smog) and fine particles (soot). Once in the air, some ozone and particles are taken into the leaves of trees as they "breathe." Leaves also trap additional fine particulates, which then wash off in the rain or fall with the autumn leaf drop. The U.S. Forest Service estimated air concentration removal rates associated with the urban forest in Philadelphia. The study team combined these pollutant removal rates with the projected number of new trees under the various green infrastructure scenarios. The study team then used BenMAP, US EPA's air quality benefits model, to estimate corresponding health impacts using current and projected Philadelphia air quality levels. US EPA also provides the standard methods used to value the economic impact of these avoided health effects. Additional air pollution related impacts associated with changes in emissions from energy production and vehicles are discussed in more detail in the energy and carbon section.

Selected References: USDA, 2007; US EPA, 2008a; US EPA, 2008b

Green Infrastructure Jobs Reduce the Social Cost of Poverty

Green infrastructure creates jobs which require no prior experience and are therefore suitable for individuals who might be otherwise unemployed and living in poverty. Green infrastructure is not by itself the solution to poverty, but it is a valuable tool in the toolbox of poverty reduction. Based on a number of local and national studies, economists have estimated that the cost of poverty related outlays in Philadelphia divided by the number of adults living in poverty ranges from about $15,000 to $45,000 per year. These studies are based on estimates of spending by all levels of government on assistance programs and avoidable crime and health impacts (*e.g.*, it costs $30,000 per year to keep a person in jail in Philadelphia). Many of the study estimates include documented increased costs of seemingly unrelated City services due to poverty. Some of the lower estimates of total social cost are missing a number of these cost elements, thus, the higher estimates seem more plausible.
Based on these various studies, this study assumes an avoided social cost of $10,000 per new green infrastructure job created. This study also assumes that three-quarters of these new jobs would require no experience and thus provide the benefits of hiring unemployed adults living in poverty, and reducing poverty expenditures.

Selected References: Schwartz, 1993; Summers and Jakubowski 1996; Pack, 1998; Oppenheim and MacGregor, 2006; Holzer *et al.*, 2007; Glaster *et al.*, 2007; Laurie *et al.*, 2008

Energy Savings

Green infrastructure reduces energy use, fuel use, and carbon emissions in two ways. First, the cooling effects of trees and plants shade and insulate buildings from wide temperature swings, decreasing the energy needed for heating and cooling. Second, rain is managed where it falls in systems of soil and plants, reducing the energy needed for traditional systems to store, pipe, and treat it. The team estimated energy savings, pollutant emission reductions, and carbon emission reductions from trees and plants using a study published by the U.S. Forest Service. Emissions related to energy production in Pennsylvania are published by the Energy Information Administration. The cost of carbon emissions to society is an area of active debate, but in the study the team used an estimate provided by the Intergovernmental Panel on Climate Change (IPCC).

Estimates of carbon emissions and sinks also considered construction, traffic delays caused by construction, and the manufacturing and transport of concrete.

Selected References: EIA, 2007; IPCC, 2007; USDA, 2007

Improved Property Values

One way to estimate a value is to study property values in areas that are close to parks and greenery. There is a rich body of academic literature showing that property values are higher when trees and other vegetation are present in urban neighborhoods, including some Philadelphia-specific studies. The study team combined estimates from this literature, data on current Philadelphia home values, and proposed increases in "greened area" to estimate these benefits under the greened area CSO options. It is important to note that the study team evaluated increases in the value of residential properties only. However, commercial, industrial and institutional property values would also likely increase.

Selected References: Braden and Johnston, 2003; Shultz and Schmitz, 2008; Wachter and Wong, 2006

5.5.5.5 Qualitative Factors

The following are the qualitative factors that are used to screen the alternatives:

Public Support

- High: The majority of public feedback received has been positive
- Medium: About half of public feedback received has been positive and half negative
- Low: Less than half of public feedback received has been positive

Construction Feasibility

- High: Construction is seen as routine and low-risk. Many local contractors will have experience with the technology
- Medium: Construction is moderately difficult or risky
- Low: The technology is new or perceived as high risk. A limited number of specialty contractors have experience with the technology

Operation Feasibility

- High: The technology is familiar. Either skill required is low or skilled labor is readily available
- Medium: The technology is familiar but significant new staff and training are required
- Low: The technology is unfamiliar. New staff, skills and training are required

Reliability and Past Performance of Technology

- This measure is derived from a matrix comparing the risk of failure to the consequences of a particular alternative failing to perform as expected

Complexity and Difficulty of Solution

- High: The alternative requires difficult coordination of many phases, technologies, sites, or contracts

- Low: The alternative requires one or a small number of phases, technologies, sites, or contractors

Coordination and Consistency with other PWD and City Programs

- High: The alternative supports and benefits from other programs taking place in PWD and the City. Examples include basement flooding abatement and waterfront revitalization
- Low: The alternative solves only CSO-related problems and does not support or benefit from other programs

Table 5-11 Risk of Failure Matrix

Likelihood of Failure	Consequences of Failure		
	Low	Medium	High
Low	High	High	Medium
Medium	High	Medium	Low
High	Medium	Low	Low

5.5.6 Selection of a Recommended Alternative

For each watershed, a recommended alternative is selected for implementation that achieves the best balance between the criteria listed in the previous section:

- The alternative meets all goals of the IWMP, including improved dry weather water quality, aesthetics and recreational opportunities; restoration of living resources; improved wet weather water quality and minimal adverse impact on people who choose to engage in wet weather recreation
- The alternative achieves a level of stormwater management and CSO control acceptable to PWD, regulatory agencies and the public
- The alternative is cost-effective relative to the body of alternatives studied
- The cost is within the financial capability of the PWD and its ratepayers
- The alternative is sustainable, adaptable and resilient under uncertain long-term conditions. The alternative achieves a net benefit to the public, considered both quantitatively and qualitatively. Net benefit is the difference between the total cost of an alternative to the public and private sectors and the total value to society. Considering net benefit may give a different picture than considering cost to the utility alone
- The public expresses support for the alternative relative to other alternatives
- Controls chosen are constructible, operable, reliable and not overly complex
- The alternative is reasonable in a larger context of other water resources and urban planning-related programs taking place in Philadelphia

5.5.7 Refinement of the Recommended Alternative

The alternative selected in each watershed will be further refined and optimized. Interactions and dependencies between alternatives selected in the different watersheds will be evaluated. Sensitivity analyses were performed to evaluate the response of the system under a range of economic and climatic conditions. Institutional, programmatic and legal changes needed to operationalize the program will be identified. Steps will be taken to reduce uncertainty in site constraints and cost, which will be further refined during a subsequent facilities planning stage. Affordability and financial capability analysis are further refined for the selected alternative at this stage and a detailed financing plan is developed.

5.6 IMPLEMENTATION

5.6.1 Adaptive Management

Adaptive management is a management approach that assumes management policies and actions, once implemented, are not static but must be adjusted based on the combination of practical experience, new scientific and technical advances, and socio-economic changes. This adaptability is needed to improve management of uncertain systems by learning from the system being affected. Given the inherent environmental, technical, financial, and social uncertainty in LTCP implementation, adaptive management recognizes that it is not possible, a priori, to identify the "best" management alternative. Therefore, an incremental approach is warranted, and learning about the system becomes an integral part of achieving the economic, social, and environmental goals.

Adaptive management includes:

- Taking near term actions to improve water quality
- Experimenting with a variety of approaches toward implementing the program
- Data collection and analysis on initial projects
- Reassessment of appropriate actions and adaptation of the program to improve effectiveness

5.6.2 Adaptive Management Strategy Requirements

An adaptive management strategy as part of the LTCPU should include a number of elements to provide sufficient and timely feedback to adjust the program during the implementation phase. In general, these elements include:

- Rationale for choosing the adaptive management approach
- Interim milestones - related to the targets over a specific time frame, *i.e.*, the expected outcome of the above actions
- Monitoring plan - to gather sufficient information to assess progress towards expected milestones