Green City, Clean Waters
Comprehensive Monitoring Plan

Consent Order & Agreement
Deliverable III

City of Philadelphia Combined Sewer Overflow Long Term Control Plan Update

Submitted to
The Commonwealth of Pennsylvania
Department of Environmental Protection

By The Philadelphia Water Department
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Appendices

Glossary of Acronyms

ADDWF	Average Daily Dry Weather Flow
ANOVA	Analysis of Variance
BLS	Bureau of Laboratory Services
BMP	Best Management Practice
BOD	Biological Oxygen Demand
CBOD	Carbonaceous Biochemical Oxygen Demand
CCR	Comprehensive Characterization Report
CFD	Cumulative Frequency Distribution
CMP	Comprehensive Monitoring Plan
COA	Consent Order and Agreement
CSO	Combined Sewer Overflow
CSS	Combined Sewer System
CSV	Comma Separated Value
DCIA	Directly Connected Impervious Area
DNREC	Delaware Department of Natural Resources and Environmental Control
DO	Dissolved Oxygen
DRBC	Delaware River Basin Commission
EAP	Evaluation and Adaptation Plan
EXTRAN	Extended Transport
GSI	Green Stormwater Infrastructure
H&H	Hydrologic and Hydraulic
HSI	Habitat Suitability Index
IBI	Index of Biological Integrity
ICE	Instream Comprehensive Evaluation
IDF	Intensity-Duration-Frequency
IWMP	Integrated Watershed Management Plan
LTCPU	Long Term Control Plan Update
NBOD	Nitrogenous Biochemical Oxygen Demand
NEXRAD	Next-Generation Radar
NJDEP	New Jersey Department of Environmental Protection
NOAA	National Oceanographic and Atmospheric Agency
NPDES	National Pollutant Discharge Elimination System
NWIS	National Water Information System
NWS	National Weather Service
OOW	Office of Watersheds
PADEP	Pennsylvania Department of Environmental Protection
PAR	Photosynthetically-Active Radiation
PIA	Philadelphia International Airport
PWD	Philadelphia Water Department
QA/QC	Quality Assurance and Control
RBP	Rapid Bioassessment Protocol
RDI/I	Rainfall Dependant Infiltration and Inflow
SDWA	Safe Drinking Water Act
SFR	Storm Flood Relief Program
SMP	Stormwater Management Practices
SOD	Sediment Oxygen Demand

SOP	Standard Operating Procedure
SRT	Simulated Runoff Testing
SSES	Sewer System Evaluation Survey
SSOAP	Sanitary Sewer Overflow Analysis and Planning
STORM	Storage Treatment Overflow Runoff Model
SWMM	Storm Water Management Model
TTF	Tookany-Tacony/Frankford
US EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WASP	Water Quality Analysis Simulation Program
WPCP	Water Pollution Control Plant
WQBEL	Water Quality Based Effluent Limit

1.0 Introduction

On June, 1, 2011, the Commonwealth of Pennsylvania Department of Environmental Protection and the City of Philadelphia entered into a Consent Order and Agreement that included approval of the City's Combined Sewer Overflow Long Term Control Plan Update and its supplements, as amended through negotiations. The approved Long Term Control Plan Update and its supplements, called the *Green City, Clean Waters* program, represent the City of Philadelphia's commitment towards meeting regulatory obligations while helping to revitalize the City. This Comprehensive Monitoring Plan describes how the Philadelphia Water Department (Water Department) will assess the program effectiveness through monitoring of the green stormwater infrastructure controls and program implementation efforts, and modeling of hydrologic and hydraulic performance of these controls, the sewer system and the effect on the receiving waters. The framework for the Comprehensive Monitoring Plan was established during negotiations and is included in Appendix G of the Consent Order and Agreement.

This Comprehensive Monitoring Plan contains a description of the Water Department's plan for the ongoing practices of monitoring of natural and engineered systems that are associated with the *Green City, Clean Waters* program. The plan reviews previous monitoring associated with the program before and during development of the Long Term Control Plan Update and its supplements. It describes the locations, monitoring tasks, and goals to assess surface waters, groundwater, rainfall, combined sewer discharges, sewer flows, and green stormwater infrastructure performance. Monitoring tasks include methods for site selection, quality assurance and quality control procedures, and additional analysis and processing procedures to assist in developing valuable data sets.

In addition to monitoring, the Comprehensive Monitoring Plan also addresses hydrologic, hydraulic, and hydrodynamic and water quality modeling. The models apply data for characterizing green stormwater infrastructure functions, runoff reductions, combined sewer overflow volume reductions, pollutant loads, and receiving water quality improvements resulting from the implementation of the *Green City, Clean Waters* program.

Comprehensive Monitoring Plan monitoring data and modeling will be used to verify the functions and conditions of stormwater controls, the sewer system, and receiving waters. Monitoring individual green stormwater infrastructure projects will provide data to assess performance and validate assumed hydrologic and hydraulic functions. This data will be used to simulate green stormwater infrastructure on larger scales to assess the hydraulic influence the controls have on the combined sewer system. Specific stormwater runoff control functions, such as infiltration or retention, will impact expected control effectiveness. Monitoring data will be able to determine effectiveness and will provide information for inclusion in hydrologic, hydraulic, and water quality models to determine combined sewer overflow volume reduction effectiveness and improvements in area water quality conditions resulting from the implementation of the *Green City, Clean Waters* program.

1.1 Assessment of Regulatory Compliance

Green City, Clean Waters is based on the National Combined Sewer Overflow Control Policy for a presumption approach to meeting the water quality requirements of the Federal Clean Water Act. The City will construct and place into operation, the controls described as the selected alternative in the Long Term Control Plan Update and its supplements, to achieve the elimination of the mass of pollutants that would otherwise be removed by the capture of 85% by volume of the combined sewage collected in the combined sewer system during precipitation events on a system-wide annual average basis.

The Water Quality Based Effluent Limit in the Consent Order and Agreement includes quantitative performance standards, which will be achieved by specific interim dates, or by the end of the Program (Table 1-1).

Table 1-1: Water Quality Based Effluent Limit Performance Standards

Metric	Units	Base line value	Cumulative amount as of Year 5 (2016)	Cumulative amount as of Year 10 (2021)	Cumulative amount as of Year 15 (2026)	Cumulative amount as of Year 20 (2031)	Cumulative amount as of Year 25 (2036)
NE / SW / SE WPCP upgrade: Design	percent complete	0	TBD June 2013	TBD June 2013	TBD June 2013	100%	100%
NE / SW / SE WPCP upgrade: Construction	percent complete	0	TBD June 2013	TBD June 2013	TBD June 2013	100%	100%
Miles of interceptor lined	miles	0	2	6	14.5	14.5	14.5
Overflow Reduction Volume	million gallons per year	0	600	2,044	3,619	5,985	7,960
Equivalent Mass Capture (TSS)	percent	62%	Report value	Report value	Report value	Report value	85%
Equivalent Mass Capture (BOD)	percent	62%	Report value	Report value	Report value	Report value	85%
Equivalent Mass Capture (Fecal Coliform)	percent	62%	Report value	Report value	Report value	Report value	85%
Total Greened Acres	Greened Acres	0	744	2,148	3,812	6,424	9,564

The *Green City, Clean Waters* program is includes an adaptive approach. The Comprehensive Monitoring Plan describes how the Water Department will assess and test new types of green stormwater infrastructure projects to select techniques that best achieve program goals, while continually working towards the Water Quality Based Effluent Limit targets and water quality standards. In addition to understanding and evaluating green stormwater infrastructure the objective of the Comprehensive Monitoring Plan includes creating models that simulate these green stormwater infrastructure practices and assessment of conditions and processes that effect simulations of the sewer and receiving water systems for the ultimate goal of assessing progress towards the Water Quality Based Effluent Limit targets and water quality standards.

1.1.1 Assessment of Progress towards Water Quality Based Effluent Limit Targets

The Comprehensive Monitoring Plan provides the approach for assessing progress towards the Water Quality Based Effluent Limit targets for Overflow Reduction Volume, Equivalent Mass Capture for Total Suspended Solids, Biochemical Oxygen Demand, and Fecal Coliform, and Total Greened Acres. The Comprehensive Monitoring Plan provides the methods for progress tracking and reporting for these targets for the Evaluation and Adaptive Management Plans submitted to Pennsylvania Department of Environmental Protection every 5 years. Actual progress compared to expected progress at each 5-year decision point will be used to implement adaptive management approaches for potential program modifications for achieving program goals.

The *Green City, Clean Waters* program is an adaptive implementation approach and the Comprehensive Monitoring Plan describes how the Water Department will evaluate new types of green stormwater infrastructure to select practices that attain program objectives, assess inputs and processes for modeling, and determine progress towards the Water Quality Based Effluent Limit targets.

1.1.2 Assessment of Attainment of Water Quality Goals

The Water Department's *Green City, Clean Waters* program is not just aimed at meeting Water Quality Based Effluent Limit targets, but also at the attainment of water quality standards and the achievement of the City's goals: to have healthy streams for aquatic resources; to make these streams accessible and safe when people are recreating around them; to protect, preserve, and maintain these streams against the challenges of sedimentation, erosion, and the disposal of trash; to improve the riparian habitat and to make stream corridors a great asset for everyone to enjoy.

The watershed approach, recommended by the National Combined Sewer Overflow Control Policy, addresses all of these issues confronting urban streams - in dry and wet weather - whether they fall within or outside the direct control of the Clean Water Act. The approach allows the Water Department to consider all of the societal and environmental benefits and impacts. Therefore, the Water Department has viewed the implementation of its combined sewer overflow mitigation program as an element within the context of a far broader approach. The Long Term Control Plan Update and its supplements were crafted based on extensive input from the community and numerous stakeholders. The goals of *Green City, Clean Waters*, and the strategies proposed to achieve them, go well beyond nominal achievement of water quality standards, and look to achieve a broad array of environmental and societal goals that the community values and respects.

The National Combined Sewer Overflow Control Policy recognizes the site specific nature of combined sewer overflows and their impacts and provides the necessary flexibility to adapt controls to local situations. The Water Department believes that the implementation of *Green City, Clean Waters* will achieve not only the broader endpoints of the ambitious goals contained in the Long Term Control Plan Update and its supplements, but also the health risk-based goals of the water quality standards.

The receiving waters of Philadelphia are subject to water quality standards as regulated by two entities. The water quality conditions of the tributary Cobbs and Tacony-Frankford Creeks are assessed against the criteria defined by the Commonwealth of Pennsylvania, while the conditions in the tidal Delaware and Schuylkill Rivers have criteria defined by the Delaware River Basin Commission. The numeric criteria vary by location for both dissolved oxygen and for fecal coliform contamination. For fecal coliform, the criteria of both regulating agencies is expressed as a geometric mean over time of in-stream concentrations. The Comprehensive Monitoring Plan provides the framework for developing assessment techniques for evaluating the attainment of both dissolved oxygen and fecal coliform control goals.

The Comprehensive Monitoring Plan provides the approach for assessing program effectiveness and progress towards Water Quality Based Effluent Limit targets through comprehensive monitoring and modeling programs. These efforts will lead to the development of additional assessment techniques utilizing the hydrologic and hydraulic models to evaluate compliance with the Water Quality Based Effluent Limits.

1.2 Comprehensive Monitoring Plan Related to First Five Years of Deliverables to Pennsylvania Department of Environmental Protection

The implementation of this Comprehensive Monitoring Plan will support the development of 5 future deliverables required by the Consent Order and Agreement, including:

- **Bacteria Tributary Water Quality Model – June 1, 2013**
  This report will describe the methods, and provide the results, of the development of the model of the receiving water quality in the Tacony/Frankford Creek and the Cobbs Creek. The work will include the collection of field data for model development and validation. The model will be used to assess the projected impact of the Combined Sewer Overflow Program in future years, and to evaluate alternative implementation options within the context of the evaluation and adaption planning process.

- **Dissolved Oxygen Tributary Water Quality Model – June 1, 2014**
  This report will describe the methods, and provide the results, of the development of the model of the receiving water quality in the Tacony/Frankford Creek and the Cobbs Creek. The work will include the collection of field data for model development and validation. The model will be used to assess the projected impact of the Combined Sewer Overflow Program in future years, and to evaluate alternative implementation options within the context of the evaluation and adaption planning process.
- **Bacteria Tidal Water Quality Model – June 1, 2015**
  This report will describe the methods, and provide the results, of the development of the model of the receiving water quality in the tidal Delaware River and the tidal Schuylkill River. The work will include the collection of field data for model development and validation. The model will be used to assess the projected impact of the Combined Sewer Overflow Program in future years, and to evaluate alternative implementation options within the context of the evaluation and adaption planning process.
- **Dissolved Oxygen Tidal Water Quality Model – June 1, 2015**
  This report will describe the methods, and provide the results, of the development of the model of the receiving water quality in the tidal Delaware River and the tidal Schuylkill River. The work will include the collection of field data for model development and validation. The model will be used to assess the projected impact of the Combined Sewer Overflow Program in future years, and to evaluate alternative implementation options within the context of the evaluation and adaption planning process.
- **Green Stormwater Infrastructure Maintenance Manual – June 1, 2014**
  Results of green stormwater infrastructure monitoring and assessment will assist the Water Department in development of the green stormwater infrastructure Maintenance Manual. For example, monitoring and assessment of the performance of green stormwater infrastructure controls may lead to adjustments in maintenance frequency if measured performance varies from assumed based on construction drawings. The Manual will address the operation and maintenance of the full range of types of green stormwater infrastructure projects that have been, and that are proposed to be, implemented by the City as part of the program. The Manual will be designed to be used by City agencies and other entities that have responsibility for performing maintenance of green stormwater infrastructure.

1.3 Contents of the Comprehensive Monitoring Plan

Section 1 provides an introduction to the plan contents, regulatory assessment framework, and associated deliverables.

Section 2 describes the objectives of each monitoring and modeling section of the plan. This section provides introductory context to how monitoring assists in the development of models that provide both adaptive management support and assessment of program implementation effectiveness.

Section 3 describes the Comprehensive Monitoring Plan basis and objectives, describing how it will be used by the Water Department for assessing program effectiveness at achieving Water Quality Based Effluent Limit targets and water quality standards. The section includes a description of programmatic assumptions that assure a successful program and explains the approach for each 5 year assessment milestone.

Section 4 describes the approach for monitoring green stormwater infrastructure based on current assessment techniques. This section describes the data acquisition methods, monitoring procedures, quality control and assurance, and analysis techniques for green stormwater infrastructure practices. It is understood that as new types of practices are implemented the monitoring methodologies will be adapted to suit assessment of each practice.

Section 5 describes the approach for sewer system monitoring program. This section describes the data acquisition methods, monitoring procedures, quality control and assurance, and analysis techniques for sewer system monitoring. The section also addresses previous monitoring efforts completed as part of the development of the Water Department's Long Term Control Plan Update and its supplements.

Section 6 describes the approach for the receiving water monitoring program, including physical, chemical and biological monitoring of the four receiving waters: Cobbs and Tacony-Frankford Creeks and the tidal Delaware and Schuylkill Rivers.

Section 7 describes the meteorological monitoring program. The section also addresses and references previous monitoring and assessment efforts completed as part of the development of the Water Department's Long Term Control Plan Update and its supplements.

Section 8 describes the methods and assessment techniques for the monitoring of groundwater levels. Monitoring of groundwater levels is necessary to assess the impacts of the increased recharge of stormwater to supplement groundwater resources

Section 9 describes the hydrologic and hydraulic modeling program and addresses the approach for modeling green stormwater infrastructure.

Section 10 describes the receiving water modeling program. The section introduces the receiving water modeling approach, additional detail of the development and capabilities of these models will be provided in the modeling reports in the next 3 years.

2.0 Summary of Data Collection and Analysis Objectives

As described in the Consent Order and Agreement, this Plan is intended to determine the tasks and analyses associated with monitoring and modeling of natural and engineered systems associated with the *Green City, Clean Waters* program. The monitoring and assessment of green stormwater infrastructure performance, sewer system response to precipitation, receiving water quality, meteorological conditions, and groundwater are integral parts of the program's implementation and adaptive management approach. In addition to the ongoing monitoring and assessments of the sewer system, receiving waters, meteorological, and groundwater conditions, the Water Department's efforts for the Comprehensive Monitoring Plan also will be focused on developing, testing, and refining monitoring protocols and improving design concepts for green stormwater infrastructure. The Comprehensive Monitoring Plan will utilize and build upon the existing monitoring and assessment data types, applications, analyses, and quality management procedures established for its past and current monitoring programs. It will continue and expand these monitoring programs as required to characterize the implementation of the *Green City, Clean Waters* program. In addition, the plan addresses ongoing needs for the monitoring program including potential monitoring locations and standard practices for measurement and evaluation. This plan also addresses the continuing use of hydrologic, hydraulic, and hydrodynamic models for characterizing green stormwater infrastructure, combined sewer overflow reductions and receiving water quality improvements resulting from the implementation of the *Green City, Clean Waters* program.

This section is a summary of the contents and objectives of each of the Comprehensive Monitoring Plan sections, addressing the types of monitoring, analysis, and modeling needed to assess program effectiveness.

2.1 Green Stormwater Infrastructure Monitoring

The Water Department continues to evaluate the effectiveness of green stormwater infrastructure through monitoring hydrologic conditions, sewer hydraulics, groundwater levels, and individual control performance. The experience gained through conducting these initial efforts assisted in the development of the Comprehensive Monitoring Plan. The initial objectives of the Water Department's green stormwater infrastructure monitoring from here forward are:

- Develop monitoring methods for each green stormwater infrastructure control type and identify the best combination of monitoring methods for program efficiency
- Evaluate the performance of green stormwater infrastructure to ensure controls are providing stormwater management as designed
- Evaluate the effectiveness of green stormwater infrastructure through monitoring hydrologic conditions, sewer hydraulics, groundwater levels, and individual control performance

- Analyze green stormwater infrastructure performance monitoring information to refine control measure designs and maintenance procedures
- Evaluate green stormwater infrastructure function and performance to enhance the predictive capabilities of the hydrologic and hydraulic models to ensure progress towards water quality goals
- Verify the effectiveness of the maintenance program, and use monitoring data to make adaptive improvements to the maintenance program over time.

Section 4 describes the data acquisition methods, monitoring procedures, quality control and assurance, and analysis techniques that will determine green stormwater infrastructure effectiveness at reducing combined sewer overflows.

2.2 Sewer System Monitoring

Monitoring of the combined sewer system response to precipitation will provide information for continuing the process of validating the hydrologic and hydraulic models of the sewer system and later in the program, provide a direct measure of the cumulative performance of controls at the sewershed level. The objectives of sewer system monitoring are:

- Continue monitoring at predefined, hydraulically significant, long term monitoring locations
- Identify new monitoring locations
- Monitor the sewer system to assess conditions
- Obtain data to assist in the continued calibration and validation of the hydrologic and hydraulic models.

Section 5 describes the sewer system monitoring program components including types of monitoring, monitoring locations, future tasks, quality control and assurance, and analysis techniques.

2.3 Receiving Water Monitoring

Receiving water monitoring and sampling for the Comprehensive Monitoring Plan will be conducted by the Water Department and through various partnerships with the United States Environmental Protection Agency, the Delaware River Basin Commission, the National Oceanic and Atmospheric Administration, and the United States Geological Survey. The hydrologic and water quality data collected under the Comprehensive Monitoring Plan will be used in the ongoing development of the hydrodynamic and water quality models of the Tacony-Frankford Creek, the Cobbs Creek, and the tidal Schuylkill and tidal Delaware Rivers. The objective of receiving water monitoring is to characterize the receiving waters physical, chemical and biological conditions, and support the development of the water quality models by obtaining reliable data. Section 6 describes the receiving water monitoring locations, methods, and data processing an analysis.

2.4 Meteorological Monitoring

Precipitation information is a fundamental component of a combined sewer system monitoring program, especially in the validation of hydrologic and hydraulic models and the characterization and estimation of combined sewer overflow statistics. Both long-term temporal precipitation data and event based precipitation data, collected synoptically with sewer system flow data, are required to appropriately characterize the combined sewer system. The objective of meteorological monitoring is to assess meteorological conditions and obtain reliable data to assist the characterization of the sewer system via the hydrologic and hydraulic models. The information regarding meteorological monitoring sources and data analysis is discussed in Section 7.

2.5 Groundwater Monitoring

The Water Department contracted the United States Geological Survey to instrument a network of groundwater level recording wells throughout the City, intended to establish a baseline of groundwater levels and to inform groundwater models to simulate changes over time. In addition, groundwater levels will be recorded at selected stormwater management control locations to validate model assessments of short-term groundwater effects in response to precipitation. The objective of groundwater monitoring is to accurately measure groundwater levels and calibrate the existing groundwater models. This will allow the groundwater models to assist in assessing any effects the *Green City, Clean Waters* program implementation may have on groundwater levels at localized and larger scales. A complete description of these data collection and analysis efforts are included in Section 8.

2.6 Hydrologic and Hydraulic Modeling

Over the past 18 years, the Water Department has developed United States Environmental Protection Agency Storm Water Management Models to serve sewer system planning and design needs, to explore storm flood relief options, to characterize the combined sewer system for overflow control planning, and for evaluations related to permit related requirements. The hydrologic and hydraulic models are continually updated as additional data on the sewer system and its operating characteristics are measured or verified, and this practice will continue under the Comprehensive Monitoring Plan. Much of the monitoring described in this Comprehensive Monitoring Plan will be utilized to further refine the hydrologic and hydraulic models to assess the projected impact of the *Green City, Clean Waters* program. The objectives of hydrologic and hydraulic modeling, within the context of *Green City, Clean Waters*, are to:

- Continue to characterize the combined sewer system hydraulics and performance
- Simulate the performance of green stormwater infrastructure and other combined sewer overflow controls
- Determine the long-term effects of the implementation of green stormwater infrastructure and other control elements on combined sewer overflows.

More specifically, the hydrologic and hydraulic models will be used to simulate the response of green stormwater infrastructure at the site scale and validate functions of individual controls compared to green stormwater infrastructure monitoring data to validate the effectiveness of the controls. This will enhance techniques to assess green stormwater infrastructure at the subsewershed scale, to validate the functions of several controls, and create reliable tools to validate performance and ensure adequate representations of stormwater runoff routing through many structures and conduits. The subsewershed models will lead to simulations of green stormwater infrastructure on sewershed scales to evaluate performance of the program's progress towards combined sewer system Water Quality Based Effluent Limit targets. This stepwise approach leads to model simulations that reliably quantify long-term combined sewer overflow statistics for overflow volume and pollutant mass, and validates the amount of greened acres implemented.

Hydrologic and hydraulic modeling will also be used as a tool to assist in developing inputs for the water quality models, discussed in Section 10, and assist in the development of the water quality model deliverables. A summary of the methods and application of the hydrologic and hydraulic models are documented in Section 9.

2.7 Water Quality Modeling

The Consent Order and Agreement requires the development of receiving water hydrodynamic and water quality models for the tidal Delaware and Schuylkill Rivers and water quality models for the Tacony-Frankford and Cobbs Creeks. The development of the water quality models, in conjunction with additional monitoring will lead to better definition of the expected water quality conditions in the receiving waters. The water quality models will be used to assess the *Green City, Clean Waters* program's progress towards achieving attainment of water quality standards.

The objective of the water quality modeling section is to describe the tasks and analyses necessary to develop models to adequately simulate receiving water conditions. The production of the water quality models will lead to the development of tools to predict improvements in water quality conditions resulting from the implementation of the *Green City, Clean Waters* program. The ultimate objective of the tasks completed under the Comprehensive Monitoring Plan associated with the water quality models is the completion of these related deliverables discussed in Section 1:

- Bacteria Tributary Water Quality Model – June 1, 2013
- Dissolved Oxygen Tributary Water Quality Model – June 1, 2014
- Bacteria Tidal Water Quality Model – June 1, 2015
- Dissolved Oxygen Tidal Water Quality Model – June 1, 2015.

These deliverables will document model capabilities and validation procedures. Summaries of receiving water quality model development and methodology are documented in Section 10.

3.0 Assessment of Program Effectiveness

The Comprehensive Monitoring Plan describes the data acquisition and analyses needed to validate the assumptions and the effectiveness of the *Green City, Clean Waters* program to control combined sewer overflows. Data collected during the implementation of this plan will be used to refine the baseline characterization of the existing Water Department combined sewer system, the starting point for *Green City, Clean Waters*. The objective of the Comprehensive Monitoring Plan is to verify the efficacy of the green stormwater infrastructure and to prove the effectiveness of the plan elements in controlling sewer overflows and meeting the requirements of the Water Quality Based Effluent Limit included in the Water Department's National Pollutant Discharge Elimination System permits.

Assessment of program effectiveness in reducing combined sewer overflow discharges will include a variety of monitoring methods, scales, control types and models. The success of *Green City, Clean Waters* depends on: the flexibility needed to assess program components, the flexibility inherent in the adaptive management approach, and the need for a uniform, system wide approach to the implementation of green stormwater infrastructure (Figure 3-1). This comprehensive and flexible approach is necessary to address the complexity and uncertainty involved in measuring, monitoring and modeling the operation of green stormwater infrastructure, and traditional sewer infrastructure, ensuring that the Water Quality Based Effluent Limit and the other goals of *Green City, Clean Waters* are met.

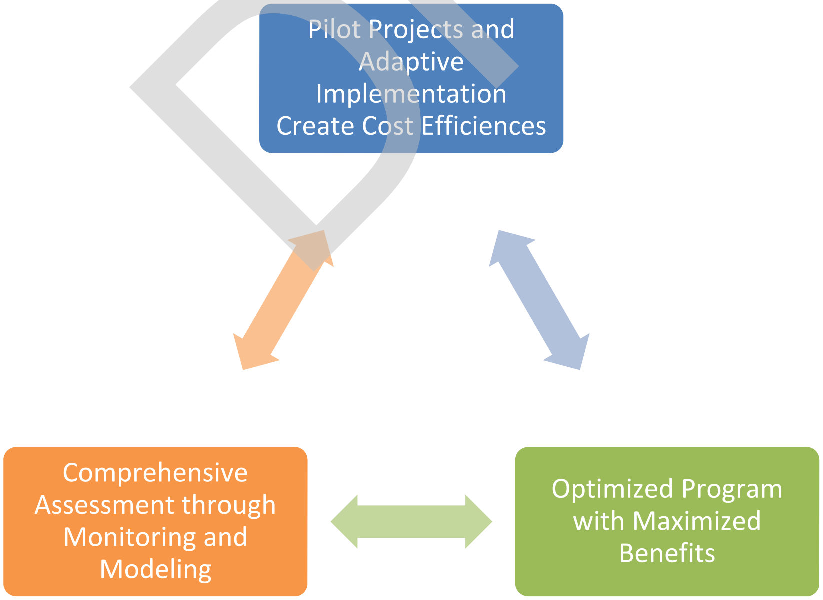

Figure 3-1: Visualization of Program Approach, Assessment, and Equal Priority for Ensuring Success

3.1 Rationale for Comprehensive Assessment of Program Effectiveness

3.1.1 Proof of Concept and Adaptive Management

Implementation of the requirements within the approved Consent Order and Agreement will rely upon an adaptive management process throughout the 25 year implementation period. The adaptive management approach relies upon flexibility and periodic program assessments throughout the implementation period of *Green City, Clean Waters*. Adaptations in assessment methods and management approaches are expected, to ensure that the Water Quality Based Effluent Limit goals are met, that the implementation of program elements is optimized and enhanced, and that benefits are maximized and costs are minimized.

To most effectively implement the adaptive management approach, the first five years of the program will be dedicated to proving the fundamental concepts of *Green City, Clean Waters* by designing and constructing pilot projects. Pilot projects are defined as green stormwater infrastructure projects designed, constructed, and monitored under controlled conditions to provide information for optimal design and program development. Information from pilot projects will be collected to develop a cost effective green stormwater infrastructure program by testing a variety of projects and evaluating them for a number of factors. Green stormwater infrastructure pilot projects can take many forms. They will be located in a variety of settings, will include the entire range of stormwater management practices currently in use, and will include a number of different technologies. As described in Section 4, the intent of the pilot program is to design, construct, monitor and verify the effectiveness of the projects chosen to encompass the entire range of green stormwater technologies in current use, leading up to the development of the first Evaluation and Adaptation Plan in 2016. Monitoring and assessment of the projects included in the pilot program, conducted through the implementation of the Comprehensive Monitoring Plan, are intended to provide information that will lead to more effective and cost efficient technical designs, site locations, and maintenance procedures for stormwater management practices. Information derived from implementation of the Comprehensive Monitoring Plan will lead to the continual enhancement and effective corrective adaptations needed to insure the success of *Green City, Clean Waters*.

Achieving the Water Quality Based Effluent Limits quantitative targets will require the development of innovative policy and infrastructure improvement tools in the first five years, and throughout the implementation of *Green City, Clean Waters*. As stated in Appendix I of the Consent Order and Agreement, “the green stormwater infrastructure component of the Long Term Control Plan Update is intended to provide for the gradual and continual conversion of the hydrologic characteristics of the Philadelphia combined sewer area, and consequently to reduce the frequency and volume of overflows from the combined sewer system.” *Green City, Clean Waters* is intended to implement a green stormwater infrastructure approach to overflow control in the most cost effective and efficient manner. Identifying and implementing management practice improvements that manage stormwater to meet program control requirements, verified by site scale monitoring under varying conditions throughout the combined sewer system, will be critical to achieving those effectiveness and efficiency goals. The monitoring and analyses conducted in implementing the Comprehensive Monitoring Plan are intended to provide the data and information that will be needed for the success of those technology assessments.

The diagram shown in Figure 3-2 depicts the pilot program implementation and evaluation process. The process started with the identification of management practice elements and characteristics, identified in the diagram as variables, such as location, hydraulic controls, settings, materials, etc. The variables have been compiled into tracking lists. Existing management control facilities that provide a basis for evaluating management practice elements and characteristics on the list were identified. The process continues to identify new projects that will need to be designed and constructed to investigate the remaining management practice elements and characteristics on the list. It is anticipated that this list of investigatory needs will continually undergo a process of reevaluation, that it will evolve over time, and that Pilot projects continually will be identified, designed and constructed to provide the answers needed for program success.

3.1.2 Equal Distribution of Green Stormwater Infrastructure Implementation in all Neighborhoods

The proposed system-wide distribution of green stormwater infrastructure will yield water quality benefits and improvements uniformly to the aquatic habitat and living resources of the City's waterways, restoring resources long forsaken as assets by most residents. The uniform investment of green stormwater infrastructure will ensure equal access for all to the expected environmental, social and economic benefits derived from green infrastructure.

As described in the Supplemental Documentation to the Consent Order and Agreement, the program is designed to maximize return on investment to benefit the residents across all neighborhoods, to achieve a fair and equitable distribution of those benefits, and to garner maximum popular support. This keystone socioeconomic aspect of the *Green City, Clean Waters* plan lays the groundwork for the revitalization of the City in areas of public health, recreation, housing and neighborhood values.

From the developmental stages of the program, the preservation of a fair and just basis for the implementation of the *Green City, Clean Waters* program was based on an equal investment of greening efforts throughout the combined sewered areas such that there is an equitable spatial distribution of burdens and benefits. The data gathered and analyzed under the Comprehensive Monitoring Plan will provide the information needed to verify the spatial distribution of benefits. Identifying a location for intensive investment of the Water Department resources for the sole purpose of measuring large scale implementation effectiveness disproportionately favors a single area and reduces the Water Department's ability to implement uniformly and provide equal access to the expected benefits from green stormwater infrastructure. An independent full-scale implementation pilot area would assume 100% of the cost-burden on the Water Department, thereby decreasing cost efficiency and impacting the ability to meet later program performance targets within budget.

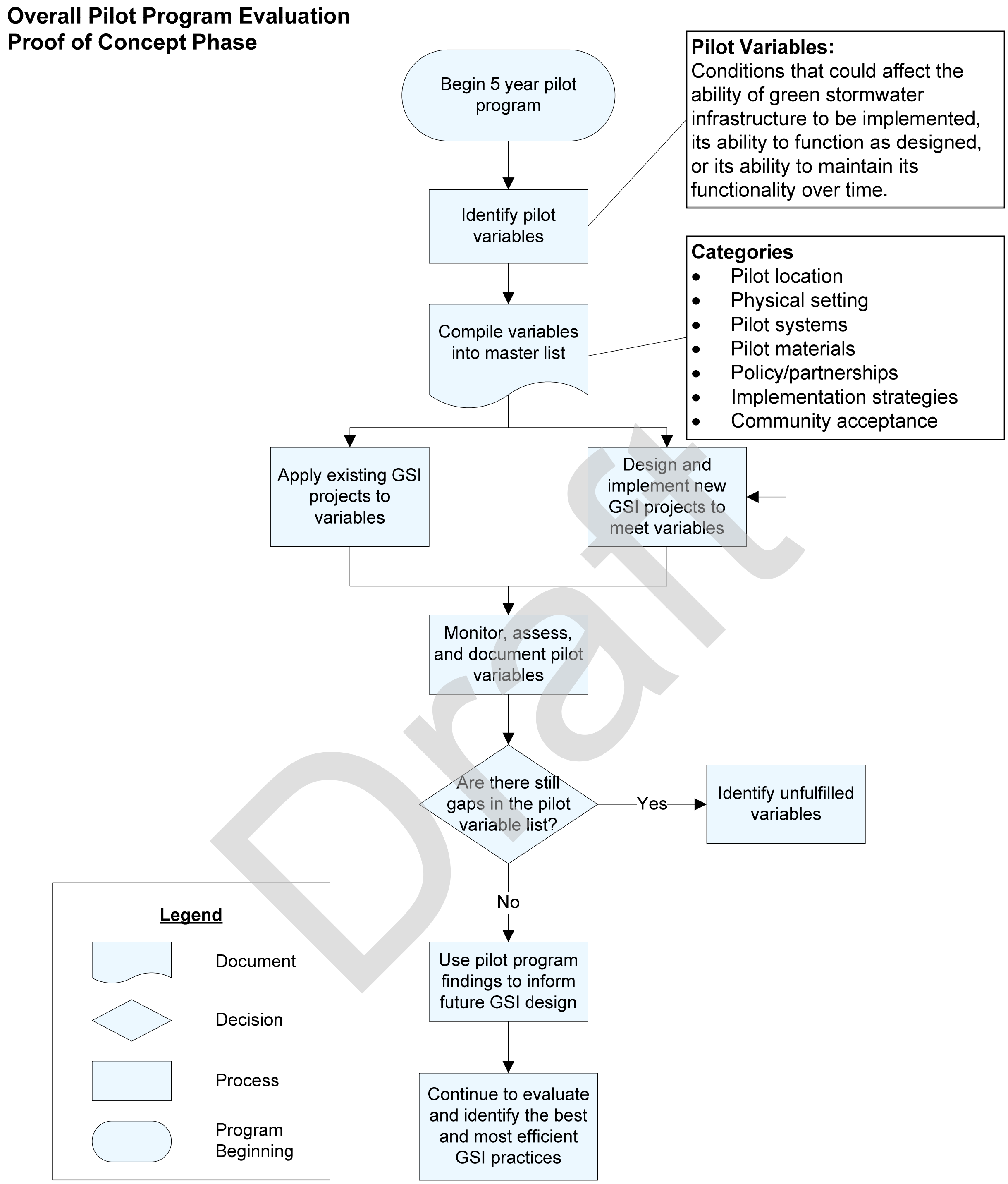

Figure 3-2: Pilot Program Process and Evaluation

Figure 3-3 shows the anticipated results of the equitable distribution of green stormwater infrastructure investment among economic levels, as envisioned in the *Green City, Clean Waters* program. The figure shows how investment (represented as impervious drainage area based planning level capital implementation cost) will be equal in all combined sewer areas of the city, regardless of household income. It is clear that deviations from this distribution of investment likely would result in unfair, and environmentally and socially unjust, accumulations of investment and benefits in some areas of the City over others. Additionally, disproportionate investment of green stormwater infrastructure would reduce the expected environmental, social and economic benefits derived from the spatially equitable implementation. These triple bottom line benefits are dependent upon widespread uniform applications of green infrastructure.

Figure 3-3: Distribution of Census Block Group Median Household Incomes and *Green City, Clean Waters* Area Weighted Investment in Green Stormwater Infrastructure

3.1.3 Comprehensive Monitoring and Modeling Approach to Reduce Uncertainty

The monitoring and modeling proposed in the Comprehensive Monitoring Plan will be utilized to assess the effectiveness of green stormwater infrastructure at reducing the frequency and volume of combined sewer overflow discharges. Stormwater management practice and other stormwater infrastructure, sewer system, meteorological, and receiving water monitoring each will provide data and information essential to the refinements of the hydrologic, hydraulic and hydrodynamic models and to the validate the results of modeling efforts.

Monitoring data and the modeling results both will be used to assess the effectiveness of *Green City, Clean Waters* in meeting environmental targets. Inherent in all assessment programs, monitoring and modeling uncertainty must be considered as part of the data analysis and assessment of combined sewer overflow reductions. Various factors may affect both monitoring data and modeling results. Individual control and sewer system monitoring uncertainties include two basic categories. One is physical system uncertainties in hydrologic factors or hydraulic controls, such as constrictions creating backflow conditions or unknown inflows or discharges to the sewer system. The other is equipment uncertainties resulting from the precision and accuracy ranges associated with monitoring equipment, and the inherent limitations of the monitoring process under varying and often difficult hydraulic conditions at monitoring sites. The Comprehensive Monitoring Plan includes techniques and measures to identify and quantify these uncertainties and their potential effect on the assessment of the efficacy of the green stormwater infrastructure controls and other remedial measures in meeting *Green City, Clean Waters* goals.

Sewer flow monitoring relies upon equipment and estimation techniques to estimate flows consistently. Monitoring equipment relies on indirect surrogate measurements to quantify wastewater depth and flow and engineering hydraulic calculations to quantify wastewater flow. It has been shown that, even at monitoring sites under ideal conditions, sewer monitoring equipment provides estimates of flows with a typical expected uncertainty of about 15% (U.S. Bureau of Reclamation, 2001). The uncertainty can be even greater at monitoring locations with unfavorable conditions. In addition, after obtaining site investigation results, the Water Department constantly finds conditions in sewer systems from site investigations that are different than assumed from sewer plans and drawings. Discrepancies are often discovered when sewer flow monitoring data is evaluated and compared with sewer modeling data. Sewer condition and sewer flow estimation uncertainties make it impractical to rely solely on monitoring data to quantify the effectiveness of implemented green stormwater infrastructure controls at a sewershed scale, at least until sufficient progress has been made in implementing controls throughout the combined sewer system to a degree that significantly exceeds those expected estimation uncertainties (Figure 3-4). As shown by Figure 3-4, achieving a level of implementation above 15% of a given area would be needed to statistically measure reductions in combined sewer flows and this level of implementation will not be reached for 15-20 years in a large enough area.

The role of sewer system and green stormwater infrastructure monitoring is to validate the theoretical structure of the hydrologic and hydraulic models under existing conditions, and to support model refinement and adaptive management in the future. The Comprehensive Monitoring Plan describes the use of monitoring information collected both at the sewershed scale and at smaller than sewershed scales, to validate hydrologic and hydraulic models of green stormwater infrastructure and the hydraulic response of the City's combined sewer system. These efforts rely and further build upon the work performed by the Water Department over the past 18 years to develop the validated hydrologic and hydraulic models of the City's combined sewer system that have been used successfully over that time to guide the design of hydraulic structures, to plan for storm flood relief, to investigate sewer system developmental needs, and to plan for and assess the success of the City's compliance with environmental regulatory requirements. The Comprehensive Monitoring Plan describes the intended use of monitoring data and associated information in further validation efforts for the hydrologic and hydraulic models, and for the building of and validation of the water quality models currently under development (Figure 3-5).

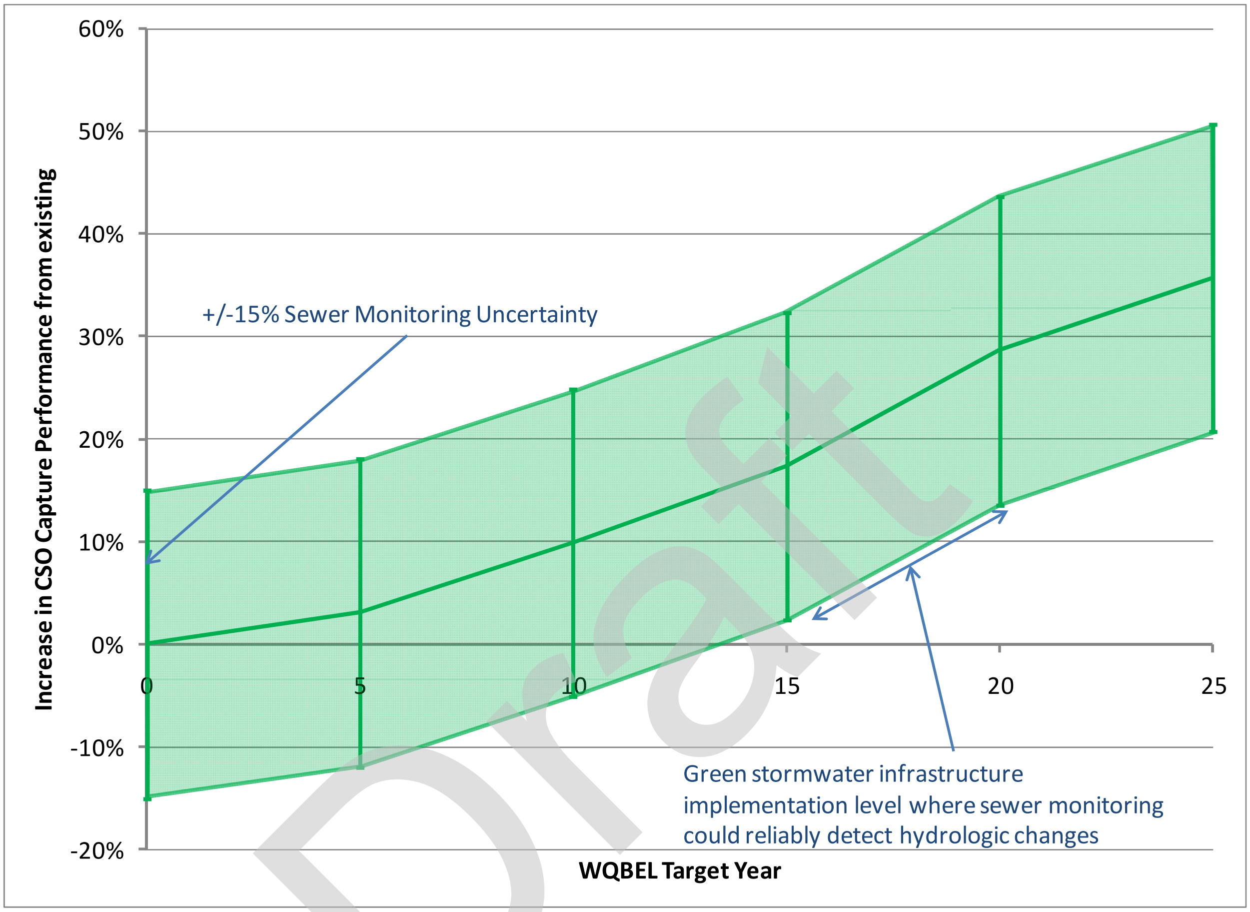

Figure 3-4: Representation of Sewer Monitoring Uncertainty during Program Implementation

The approaches incorporated into the Comprehensive Monitoring Plan to assess program success are largely drawn from national combined sewer overflow control guidance. The United States Environmental Protection Agency Combined Sewer Overflow Control Policy (1994) requires the characterization of the combined sewer system area and evaluation of the control measure performance in terms of system-wide average annual hydrologic conditions for Combined Sewer Overflow Long Term Control Plan Update planning purposes. More recently the United States Environmental Protection Agency Combined Sewer Overflow Post Construction Compliance Monitoring Guidance (2012) suggests modeling of the combined sewer system to estimate outflows "because it allows the permittee to be more confident in evaluating different circumstances and scenarios after calibration and validation of the model." And more specific to the Water Departments' selected approach, Criterion iii of the Presumption Approach, validated models are used to determine drainage district and system wide annual average capture volumes and to assess achieving mass removal targets. The annual average period was selected in the Long Term Control Plan Update development and the characterization and monitoring described in this Comprehensive Monitoring Plan are intended to provide additional data and information to further validate modeling assumptions, further refine the performance of the hydrologic and hydraulic models, and to validate the choice and performance of receiving water quality models. The use of system-wide average annual rainfall and validated models allows understanding of performance improvements without the difficulty of distinguishing performance changes in monitoring data from hydrologic fluctuations from year to year.

Figure 3-4 is a representation of the typical sewer monitoring uncertainty that could be expected as green stormwater infrastructure is implemented. The graphic indicates that, while direct monitoring evidence of the effectiveness of stormwater management practices at the sewershed scale is not feasible in the early implementation years of *Green City, Clean Waters*, the green stormwater infrastructure benefits to the urban water budget likely can be measured through sewer flow monitoring in the later periods of the program. Until that time, program effectiveness will be assessed as described previously, using a combination of monitoring data and model simulation science.

This is in fact an approach that directly is analogous to how this process is conducted in American cities that rely largely upon traditional infrastructure techniques for combined sewer overflow control. For instance, a storage tunnel option is selected and designed using hydrologic and hydraulic simulations, and environmental protection performance is determined through simulations, until much later in the life of the control program. In such a traditional control program, it is only when the tunnel and all of its appurtenances are constructed and stabilized, and sufficient time has passed after a post-construction monitoring program has been implemented, that the efficacy of the tunnel in meeting environmental goals can directly be measured. It is not unusual for that entire process, from facility planning to proof of concept, to occur over a 10-20 year time frame. And even in that case, since compliance with combined sewer overflow control goals most often are determined based on performance under typical year conditions, it still requires reliance upon hydrologic, hydraulic and water quality models to properly assess control compliance with the regulatory requirements.

Figure 3-5 shows representations of the Comprehensive Monitoring Plan's process to construct and validate hydrologic and hydraulic models of increasing scales to prove the efficacy of green stormwater infrastructure from single controls to subsewersheds of several controls to combined sewer overflow sewersheds and eventually entire collection systems. The Comprehensive Monitoring Plan approach allows for broad, cost efficient implementation of green stormwater infrastructure by monitoring and assessing individual and clusters of stormwater management practices to identify the best and most efficient practices (Figures 3-2 and 3-3). The approach also allows additional time to assess the sewer system for existing conditions to validate models at the sub-sewershed and sewershed scale. This establishes a baseline to assess the efficacy of improvements in reducing combined sewer flows when green stormwater infrastructure implementation levels have reached adequate levels distributed throughout the City (Figures 3-3 and 3-4).

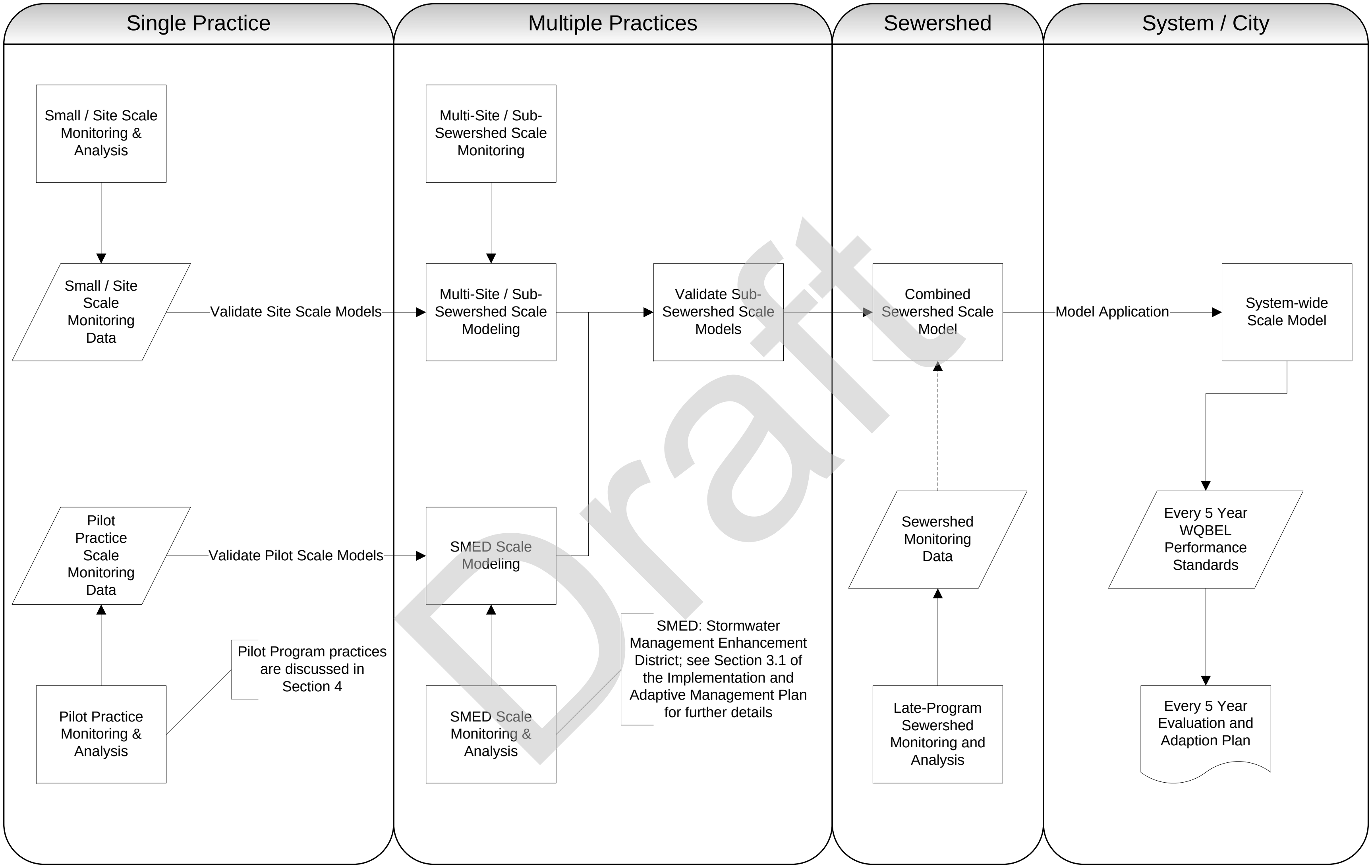

Figure 3-5: Representation of Green Stormwater Infrastructure and Hydrologic and Hydraulic Monitoring and Modeling Scales and Processes

3.2 Comprehensive Assessment to Validate Program Approach

When implemented on a large scale, green stormwater infrastructure alters the urban water budget to a state more similar to a natural system such as a forest or meadow. Monitoring is the key to verifying that green stormwater infrastructure management practices are performing as expected. Ensuring program goals and efficiencies relies upon a focus during the earlier period of the program on monitoring at smaller, individual or multi-management practices to provide information to validate hydrologic and hydraulic models of practice and sub-sewershed scale models, that then can be used at both the smaller and the larger scales to inform investigators and managers on overall program performance.

At the individual and multiple practice scales, measured stormwater volumes are compared to those predicted by the Water Department's hydrologic and hydraulic models. The validation process for those models is described Section 9 of this Plan. The validated models initially are used to estimate runoff volumes for the uncontrolled conditions for a site's drainage area and monitored rainfall depths (specifics of this process are described in Section 4). Flows at the stormwater management practices are monitored on site, within the control element or at its outlet control structure. These level or flow measurements are used to obtain flow estimates and compared against the simulated runoff volumes. The models are run using the same measured precipitation for the same period covered by the monitoring data. A simulation is run with a condition that mimics the green stormwater infrastructure control characteristics, including dimensions, infiltration rates, outlet controls, etc. To determine the effectiveness of the controls, measured runoff is compared to runoff predicted by the models. Controls are performing as expected when the measured water budget is similar to the water budget predicted by the model, within a reasonable range of uncertainty inherent in both the measured and modeled results. These results will then be used to validate the green stormwater infrastructure modeling approach of the larger sewershed and drainage district models.

These validated models will be used to assess actual progress compared to expected progress at each 5-year Evaluation and Adaptation Plan submission. As described in the Integrated Adaptive Management Plan, the hydrologic and hydraulic models will be used as part of the process to assist in a comprehensive assessment of the City's progress towards full implementation of *Green City, Clean Waters*.

As previously described, when the degree of green stormwater infrastructure implementation increases and encompasses more of the combined sewer area, it will become possible to monitor and assess the effects of implementation on the scale of sewer system flows. In the future, when a level of green stormwater infrastructure is achieved where this is possible, the process for verification of performance would commence within the context of post-construction monitoring as described in national guidance. This would involve comparing measured stormwater volumes to those predicted by the Water Department's calibrated hydrologic and hydraulic model of the pre-implementation, existing condition land use, as defined by the Long Term Control Plan Update and Consent Order and Agreement. The Comprehensive Monitoring Plan will be revised in the future as those conditions are achieved, and any changes will be submitted to regulatory agencies within the context of a scheduled Evaluation and Adaption Plan.

As described in Section 1, the Comprehensive Monitoring Plan provides the approach for assessing program effectiveness and provides the framework for attainment of the water quality goals described in the Water Quality Based Effluent Limit included in the Water Department's National Pollutant Discharge Elimination System permits. The Water Department currently is developing the receiving water quality models as described in this Plan and the deliverables related to these models are due in the coming years. The methods and assessment techniques developed will lead to the creation of additional tools for evaluating the attainment of the water quality goals by utilizing the receiving water quality models.

4.0 Green Stormwater Infrastructure Monitoring

4.1. Introduction

The Water Department's *Green City, Clean Waters* program aims to address stormwater runoff problems in heavily urbanized areas with a combination of traditional infrastructure and green stormwater infrastructure. Green stormwater infrastructure projects vary in size, complexity, and the degree to which the project is connected to the existing drainage system, but in general, the objective is to infiltrate or detain stormwater rather than convey it directly to the sewer system. Numerous green stormwater infrastructure projects have been constructed or are in the design phase. Monitoring the overall effectiveness of green stormwater infrastructure at the combined sewer system or sewershed level is difficult at present, because although many projects have been implemented, they still serve only a small fraction of the drainage area. The impact of individual green infrastructure projects is generally too small to detect due to monitoring uncertainty and rainfall variability at downstream monitoring points within the larger drainage system. Currently there are no sub-basins within which a large enough number of projects have been constructed to definitively identify the effect of green stormwater infrastructure implementation. Therefore, the Water Department has elected to monitor at the individual stormwater management practice level and not the sewershed or sewer system level until an appropriate level of green stormwater infrastructure has been implemented system-wide.

The focus of the Water Department's monitoring program during the first five years of the *Green City, Clean Waters* program is post-construction performance monitoring of individual green stormwater infrastructure practices. As the portion of the drainage system served by green stormwater infrastructure increases, it will be increasingly possible to distinguish the green infrastructure "signal" from the monitoring uncertainty and climate variability "noise".

4.2 Monitoring Objectives

The feasibility of implementing green stormwater infrastructure will be monitored by tracking the progress of identifying, designing, and constructing projects during the first five years. For each green stormwater infrastructure project, the amount of impervious area draining to the control will be determined. The impervious drainage area for all green stormwater infrastructure projects will be summed to track the total area managed by green stormwater infrastructure. The impervious acreage being controlled by green stormwater infrastructure will be referred to as greened acres. Therefore progress will be tracked as greened acres over time.

The effectiveness of green stormwater infrastructure will be determined by monitoring the performance of individual green stormwater infrastructure practices after construction. The first five years of the *Green City, Clean Waters* green stormwater infrastructure monitoring program is focused on developing appropriate methods and identifying the best combination of monitoring methods for the sites available such that the most important questions are addressed. The need for clearly defined monitoring objectives cannot be understated. Individual green stormwater infrastructure monitoring activities must be planned and carried out knowing the research questions to be answered, parameters to be estimated, hypotheses to be tested, monitoring constraints, reporting deadlines and available resources. The primary goal of green stormwater infrastructure monitoring is measuring performance, (i.e., determining the green stormwater infrastructure system stormwater management function). Secondary goals include providing information for improvements to design and maintenance of green stormwater infrastructure practices.

4.3 Green Stormwater Infrastructure Performance Monitoring

Green stormwater infrastructure performance monitoring is conducted at the individual stormwater management practice level. This monitoring is being conducted concurrently with, and intended to complement, other Water Department monitoring activities. As described in subsequent sections, the Water Department proposes to monitor the overall effectiveness of green stormwater infrastructure in reducing combined sewer overflows via sewer system (Section 5), receiving water (Section 6), meteorological (Section 7), and groundwater monitoring (Section 8), as well as hydrologic and hydraulic modeling (Section 9). The Water Department will use long-term post-construction monitoring and post-construction testing, such as simulated runoff tests, to evaluate the performance of individual stormwater management practices.

Performance monitoring at an individual green stormwater infrastructure practice level will require a combination of monitoring locations, direct measurement, and calculated values. Performance can be categorized by the functional components of the green stormwater infrastructure. Sections 4.3.1 through 4.3.8 describe performance monitoring of each of these functional categories, including stormwater inflow, soil moisture storage, storage, evapotranspiration, surface infiltration, subsurface infiltration, underdrain return flow, and bypass flow.

4.3.1 Stormwater Inflow

Stormwater inflow into an individual green stormwater infrastructure practice is difficult to monitor, but it is critical information required to effectively evaluate performance of an individual system. Green stormwater infrastructure practices will be linked to a nearby rain gage from which runoff estimates can be generated for the project's contributing drainage area. This approach will be the minimum level of monitoring to determine the volume and flow rate of inflow. In addition, where practical the inflow to the green stormwater infrastructure practice will be measured using flow measurement devices such as flumes, weirs, and pipes. Measured flow and volumes will be compared to calculated values based on drainage area and rainfall data. This comparison data will then be used to validate the accuracy of using calculated inflow data versus measured data.

4.3.2 Soil Moisture Storage

Soil moisture monitoring throughout the growing season will be critical to determine the long term sustainability of vegetated green stormwater infrastructure practices in a highly urbanized area. Soil moisture measurement devices will be tested during the first five years of the *Green City, Clean Waters* program to determine the best method to monitor soil moisture. Monitoring the soil moisture will provide insight into the frequency and amount of irrigation required to supplement rainfall events to maintain vegetation. In addition, measuring the amount of water stored within the soil profile between rain events will be important to accurately simulate green stormwater infrastructure performance over time.

4.3.3 Storage

Designed storage for green stormwater infrastructure may include surface detention or retention storage and/or underground storage. Storage volume can be monitored fairly easily by developing depth-volume curves based on the physical measurements of the storage and then monitoring the depth of water in the green stormwater infrastructure practice. Underground storage is the most difficult to monitor but if properly considered during design a monitoring well or access point can be constructed that allows for monitoring the depth of water within the underground storage. The critical performance data for storage is the dewatering time (recession rate) after the rainfall event. Monitoring the change in storage over time will be critical in evaluating the performance of storage and to effectively simulate storage using historical rainfall data.

4.3.4 Evapotranspiration

Recession rate, or the change in storage volume over time, is actually a combination of infiltration, evapotranspiration, and also slow release if the project is equipped with an outflow orifice. The degree to which evapotranspiration contributes to the observed recession rates is assumed to vary according to project type. For example, some subsurface projects may not provide much vegetation or soil surface area, factors which are required for water to evapotranspire from the storage area. Conversely, bioretention and bioinfiltration practices generally have vegetation, soil surfaces, and other conditions that provide higher potential evapotranspiration rates. Furthermore, evapotranspiration rates at a given site may vary considerably from precipitation event to precipitation event based on meteorological and soil conditions.

The Water Department's green stormwater infrastructure monitoring plan is designed to be as practical as possible, and is thus focused on categorization of measurable performance parameters where evapotranspiration can rationally be assumed to be a certain value or negligible. Evapotranspiration can provide a significant pathway for stormwater removal and it will be considered in monitoring and design activities. The quantification and categorization of actual *in situ* evapotranspiration rates will be supported in research opportunities developed from the Water Department's ongoing academic and/or professional relationships.

4.3.5 Infiltration Rate

Although green stormwater infrastructure monitoring encompasses a large number of methods and project attributes that can be tested, measured, or verified, infiltration rate measurements are of great importance to the ultimate success of the Water Department's *Green City, Clean Waters* program. Infiltration contributes the greatest reduction in runoff volume, mimicking more closely the natural hydrologic conditions. Furthermore, when stormwater is infiltrated, water quality-related goals can be supported as well. Generally, green stormwater infrastructure projects are designed for infiltration, unless infiltration is considered inadvisable due to contaminated soils or the presence of sensitive structures nearby. Infiltration results from pre-construction site investigations have been found to be highly variable, particularly in urban fill soils. Actual infiltration rates are measured to quantify the runoff volume reduction that can be applied to hydraulic and hydrologic model simulations.

Two infiltration rate types are currently categorized by monitoring green stormwater infrastructure. Subsurface infiltration rates are calculated as the decrease in storage volume over time, excluding slow release where present. Surface infiltration rates are measured with permeameters and ring infiltrometers where applicable (permeable pavement, bioretention cells, etc.). The distinction between surface and subsurface infiltration rates is necessary due to monitoring constraints.

Infiltration, as traditionally defined, is a depth per unit time over the area in question. Pre-construction testing can allow for the determination of surface infiltration rates at the excavated depth of the green stormwater infrastructure practice and at the finished grade (where applicable). However, some specific green stormwater infrastructure designs do not utilize surface infiltration as the primary inflow pathway nor allow for the surface infiltration rate to be determined in a practical and applicable manner. The typical tree trench design is an excellent example. While some water can infiltrate through exposed tree pit soil and enter the subsurface storage area, the majority of flow will enter the storage area through an inlet and be distributed through a perforated pipe where the primary flow path will become lateral and vertical percolation through the substrate (unless it is lined with an impermeable barrier). The subsurface infiltration rate is reported as a volume over unit time to encompass the composite lateral and vertical flow (percolation) out of the storage volume and should not be confused with traditional reporting of infiltration rates as these rates have similar but different limiting factors. Using the "storage footprint" as the area of infiltration can allow for rudimentary comparison between the surface infiltration rate as determined at the excavated depth and the *in situ* subsurface infiltration rate. However, this simplification should be avoided when reporting observed values as it does not accurately describe the hydrologic processes occurring.

During the first five years of the *Green City, Clean Waters* program, the Water Department will continuously monitor as many sites as possible in order to refine infiltration rate estimates (both surface and subsurface). As the number of constructed projects exceeds monitoring manpower and data processing capabilities, a probabilistic study design may be implemented. Preliminary work can inform the statistical study design by providing an initial estimate of the expected variability in infiltration rate estimates.

4.3.6 Lateral Groundwater Mounding

The Water Department will conduct lateral groundwater monitoring studies at a limited number of infiltration stormwater management practices to understand the effects of groundwater mounding. Numerical computer modeling simulations may be useful to aid understanding of the likelihood of problems due to groundwater mounding, such as basement flooding, especially with respect to seasonal groundwater level fluctuations.

4.3.7 Return Flow

Typically, in cases where a green stormwater infrastructure practice is designed for slow release, return flow back to the existing combined sewer system will either be through an underdrain or from a detention control structure orifice designed to slowly release captured stormwater volume back to the combined sewer system. Monitoring return flows to the combined sewer system will be important information to collect to evaluate the individual green stormwater infrastructure practice performance. Special consideration during design and implementation of slow release practices is necessary to accurately measure these small flows. For monitoring purposes it may be necessary to construct a monitoring point where the return flow is routed through a flow measurement device.

4.3.8 Bypass Flow

Likely the most challenging flow measurement on an individual green stormwater infrastructure practice monitoring scale is quantifying the bypass flow. This is stormwater runoff from the contributing drainage area that cannot enter the green stormwater infrastructure practice. This can be caused by a number of different scenarios including rainfall intensity greater than the green inlet can accommodate, blocked inlet/inflow, backwater within the green stormwater infrastructure practice, clogged outlet pipe, or loss of stormwater storage. Monitoring the bypass flow can provide valuable information about green stormwater infrastructure performance.

4.4 Post-Construction Performance Testing

Verification that projects are constructed according to design plans is can be completed through both construction oversight and inspection, and monitoring and basic water balance calculations. Monitoring may be useful to confirm project characteristics such as contributing drainage area, storage volume, inlet capture efficiency, and (when present) slow release discharge parameters. Green stormwater infrastructure practices are associated with a nearby rain gage from which runoff estimates can be generated for the project's contributing drainage area. Combined with a stage to storage relation, water level observations can generally indicate whether the green stormwater infrastructure system fills with water to the expected storage volume for a given runoff magnitude. For example, if the stormwater management practice exhibits a tendency to fill more slowly than would be expected given the design parameters, clogging of the distribution pipe might be suspected. It might also be the case that the contributing drainage area assumption is wrong and the practice is actually receiving runoff from a smaller area. Another, less likely explanation could be that the stormwater management practice was not built to specifications and dimensions in the construction records are incorrect. Interpretation of these data requires sound application of engineering principles.

Simulated runoff testing with flow from a fire hydrant and surface level infiltration testing with permeameters are more direct and precise methods for metering an exact volume of water into a stormwater management practice for making these basic measurements. The Water Department is evaluating the operational efficiency of post-construction performance monitoring and testing when the goal is a rapid assessment of the project's function for confirmation of design parameters. Given that there may be a tendency for some systems to lose efficiency over time, and the City has the ability to request remedial action during the warranty period for new construction, there is an advantage to conducting performance testing soon after the project is constructed. Post construction performance testing will establish a baseline for infiltration performance in order to judge whether infiltration rate decreases over time.

4.5 Performance Monitoring and Testing Outcomes

Green stormwater infrastructure performance monitoring and testing will have multiple outcomes during the first five years of the *Green City, Clean Waters* program. Monitoring results will assist the Water Department in simulating the effect of green stormwater infrastructure in reducing overflows from the combined sewer system, making informed decisions regarding the design standards of green stormwater infrastructure, determining appropriateness of maintenance activities and frequency of maintenance, as well as optimizing the location of different types of practices.

4.5.1 Hydrologic and Hydraulic Modeling

Infiltration rate estimates used for simulating green stormwater infrastructure in the Long Term Control Plan Update hydrologic and hydraulic modeling were based on soil properties obtained from the United States Department of Agriculture Natural Resources Conservation Service. Initial infiltration parameters were assigned to areas based on soil texture classification. Conducting infiltration testing at a variety of green stormwater infrastructure practices throughout the City will allow the Water Department to determine whether this infiltration rate is appropriate or whether different infiltration rates or correction factors should be used for different project types, soils, geographic areas, etc. If monitoring indicates that infiltration rates begin to increase over time where designers have incorporated deep-rooted vegetation, or that some percentage of sites become clogged or "short circuited," that information may also be used to adjust infiltration rates used in modeling. In addition to model parameterization, infiltration performance tracking over time will also provide valuable information for design of future projects and project maintenance.

4.5.2 Design Improvements

It is anticipated that there will be frequent communication between the green stormwater infrastructure monitoring, planning, and design coordination staff, as monitoring activities will provide valuable feedback on green stormwater infrastructure performance characteristics. For example, green stormwater infrastructure performance monitoring provides an opportunity to evaluate factors of safety, including area loading ratio and the designed storage volume. Generally, the Water Department design guidelines are very conservative, and safety factors are incorporated into designs to increase the project's useful service life and decrease the likelihood of premature failure. These safety factor protections come at an increased cost in terms of project efficiency or cost per greened acre. Performance monitoring may provide helpful quantitative information to be used as the basis for evaluating the relative merits of these factors of safety or whether they can potentially be relaxed based on local data from projects implemented in Philadelphia.

As described in Section 2 of the Implementation and Adaptive Management Plan, the Water Department's *Green City, Clean Waters* program Tracking System is currently in development in order to track greened acres. The Tracking System development is being designed to record the managed impervious area and to conservatively determine which portions of the storage volume are considered for each green stormwater infrastructure practice. Performance testing or other forms of monitoring may be useful to determine under what conditions additional storage contributes to stormwater management and suggest more accurate accounting methods for these systems.

4.5.3 Maintenance Requirements

It is anticipated that there will be frequent communication between the green stormwater infrastructure maintenance and monitoring staff, as monitoring activities will provide valuable information to the maintenance group. For example, performance testing might show a much slower rate of storage volume increase than expected during runoff events, perhaps indicative of a clogged distribution pipe. Findings of this nature should be reported to the maintenance group so that appropriate maintenance activities can be scheduled. The degree to which storage volume response is restored after cleaning the pipe by flushing could then be determined by additional monitoring. In addition to this reactive model of monitoring and maintenance, alternative maintenance methods and maintenance frequency schedules could potentially be evaluated with long-term monitoring data.

4.6 Early Program Monitoring

4.6.1 Early Action Pilot Program

The first five years of the *Green City, Clean Waters* program implementation is identified as the proof of concept phase, representing a period of growth, evolution, and experimentation. During the proof of concept phase, many of the green stormwater infrastructure projects that will be constructed and monitored will be selected to fit into a carefully designed pilot program. The pilot program is intended to test the feasibility and measure the effectiveness of green stormwater infrastructure under the full range of potential conditions. Six goals were identified for the pilot program:

1. Demonstrate the feasibility of green stormwater infrastructure
2. Assess green stormwater infrastructure opportunity

3. Assess green stormwater infrastructure cost effectiveness
4. Confirm green stormwater infrastructure functions
5. Define maintenance requirements
6. Support design standard development

As described in Section 3.1.1.2 of the Implementation and Adaptive Management Plan, pilot projects are defined as green stormwater infrastructure projects designed, constructed, and monitored to provide information for optimal design and program implementation. Information from pilot projects will be collected to develop a cost effective green stormwater infrastructure program by testing a variety of projects and evaluating them for a number of factors, including:

- Ability to meet performance requirements
- Ease of implementation for on-street and off-street settings
- Cost and effectiveness under a variety of physical conditions
- Efficiency in controlling stormwater
- Effectiveness of various materials
- Ease of maintenance
- Community acceptance

Lessons learned from pilot projects will support efforts to improve design; estimate total stormwater management area potential; develop design, construction, and maintenance procedures; and refine program cost estimates.

Potential green stormwater infrastructure projects will take many forms, be located in a variety of settings, and consist of different technologies and materials. To assess the range of potential conditions and variability of green stormwater infrastructure projects, 112 descriptive variables have been identified. Variables are conditions that could affect the ability of green stormwater infrastructure to be implemented, its ability to function as designed, or its ability to maintain its functionality over time. These variables have been organized into the following categories:

- Pilot Locations
- Physical Settings
- Pilot Systems
- Pilot Materials
- Policy/Partnerships
- Implementation Strategies
- Community Acceptance

The full list of pilot variables and descriptions is located in Appendix A (Pilot Program Details). Applicable variables are assigned to every pilot project. It is the intent to design and construct one or more projects to cover each of the variables. Although there are 112 variables, each pilot project is likely to be useful in testing multiple variables.

Not every green stormwater infrastructure project to be built is selected as a pilot project. Pilot projects are identified for their applicability to pilot program variables and for other factors such as quality of available information, reducing unnecessary redundancy, and availability of monitoring locations. After all of the existing constructed and designed pilot projects are assessed for pilot variables, gaps in the variable list will be used to guide new designs to ensure that each variable is evaluated in the proof of concept phase.

Ten tasks were formulated to carry out the pilot program. The implementation of these tasks is intended to collect the full range of information needed to assess the variables applied to each pilot project, and are described in detail in Appendix A (Pilot Program Details). The identified tasks are:

- Task 1: Create a matrix of variables and applied existing projects
- Task 2: Select potential projects and new sites to fill in variable gaps (location, physical setting, policy/partnerships)
- Task 3: Develop site visit checklists and perform site visits to fill in all observable variables for new projects
- Task 4: Decide on pilot project design to fill in variable gaps (pilot systems, pilot materials)
- Task 5: Develop a monitoring plan for each pilot project
- Task 6: Develop a maintenance plan for each pilot project
- Task 7: Develop a survey and/or questionnaire for Community Acceptance variables and gather community and owner response
- Task 8: Calculate a water budget for a variety of storms for monitored projects
- Task 9: Compile design, inspection, construction, maintenance, and monitoring costs
- Task 10: Prepare pilot program final report

One of the most important objectives of the pilot program is to confirm and understand the performance and function of the various types of green stormwater infrastructure. Monitoring is necessary to support this goal of the pilot program. In order to assess the performance of the variety of pilot projects, 13 research questions and potential monitoring tasks were identified (Table 4-1). The research questions will be applied to each monitored project to help guide monitoring plans.

Table 4-1: Pilot Program Research Questions Addressed by Green Stormwater Infrastructure Post-Construction Monitoring Program

Monitoring Subject	No.	Question	Potential Tasks
Storage	1	How does measured storage relate to designed storage?	• Simulated Runoff Testing • Continuous Water Level Monitoring.
Infiltration	2	What are the in situ surface and subsurface infiltration rates versus the designed parameters?	• Continuous Water Level Monitoring • Simulated Runoff Testing. • Determination of surface level infiltration rates via Permeameter where applicable.
	3	Does performance change over time (2-5+ years post-construction)?	• Continuous water level monitoring. • Simulated Runoff Testing. • Determination of surface level infiltration rates via Permeameter where applicable.
	4	What is the subsurface infiltration rate through the Stormwater Management Practices?	• Soil moisture sensors where applicable to categorize the wetting front in the engineered media.
	5	Is the subsurface infiltration rate for the storage volume below the slow release orifice adequate to consider this storage volume available for a statistically significant number of precipitation events?	• Continuous water level monitoring of storage area. • Inflow and outflow monitoring via continuous water level monitoring. • Perform simulated runoff test with orifice plugged and observe changes in storage area.
	6	What impact, if any, does the Stormwater Management Practices contribute to groundwater mounding?	• Continuous water level monitoring in piezometer wells
	7	Does the porous pavement surface maintain infiltration capacity and structural strength over time?	• Perform surface infiltration rate testing using ASTM C1701/C1701M-09 Standard Test method for Infiltration Rate of in Place Pervious Concrete. • Inspection of surfaces for structural degradation based on photo documentation and field inspection logs.
Slow Release	8	What is the draindown time of the slow release system?	• Continuous water level monitoring • Simulated Runoff Testing.
	9	Does the slow release orifice lose efficiency over time?	• Continuous water level monitoring. Compare results over time to estimate if orifice efficiency has changed.
Vegetation	10	What is the optimal growing media depth for bioretention/bioinfiltration for plant health?	• Photo logs and written observations from routine site visits. • Periodically examine rooting depth of vegetation, comparing observed rooting depth over time to the designed growing media depth.

Monitoring Subject	No.	Question	Potential Tasks
Vegetation	11	What are rates of evapotranspiration associated with specific Stormwater Management Practices?	• Utilize soil moisture data (where practical and applicable) to calculate evapotranspiration rates via the soil moisture depletion method. • Where applicable a water balance can be used to estimate evapotranspiration if remaining components of water budget can rationally or observationally be accounted for. • Where applicable and practical heat dissipation sap flux sensors can be used to estimate transpiration rates in vegetation.
Inlets/Pipe Sizing	12	What, if any, change to inlet efficiency occurs over time given the Water Department's existing inlet cleaning program?	• Regular inspections of sediment and debris buildup in the inlet, ponding area, and subsurface distribution pipes • Continuous water level monitoring. • Simulated runoff testing.
	13	Are the specific infrastructure components of the Stormwater Management Practices providing the anticipated design function?	• Continuous water level monitoring. • Simulated Runoff Testing. • Videoing cleanout and distribution pipe to visually identify component efficiency loss. • Photo documentation and written observations from field reports.

4.6.2 Example of Preliminary Post-Construction Performance Monitoring Results

A stormwater tree trench on Montgomery Ave. from Blair St. to Frankford Ave. in the Fishtown neighborhood of Philadelphia was chosen as a demonstration monitoring site. Continuous water level monitoring is being conducted in an observation well located in the center of the tree trench using a pressure transducer. More information about the continuous water level monitoring methods and data analysis procedures is presented in Sections 4.8 (Methods) and 4.9 (Data Evaluation).

Like most green stormwater infrastructure projects being constructed for the *Green City, Clean Waters* program, this site was investigated for infiltrative properties of the soil. As part of the project planning and design phase, soil borings and percolation test(s) were performed, including one percolation test on Montgomery Ave. for which the observed infiltration rate was 0.29 in/hr. Infiltration rate estimates on adjacent streets ranged between 0.06 and 0.59 in/hr. The stormwater tree trench on Montgomery Ave. was designed to accept runoff from 34,090 ft^2 of impervious area. For seven storm events monitored, infiltration rates ranging from 7 to 30 ft^3/hr were observed based on the recession rate of water within the observation well and calculated change in storage volume (as described in Section 4.3.5, subsurface infiltration rates are expressed as ft^3/hr rather than in/hr). The results from continuous monitoring have confirmed that infiltration is occurring at this site as expected.

It is expected that the infiltration (recession) rates measured at each green stormwater infrastructure practice will vary based on physical and chemical characteristics of the surrounding soil profile, efficiency of individual components within the practice, local climatic conditions, and the presence of unknown influencing factors.

4.7 Monitoring Locations

As described in Section 4.6 (Early Action Pilot Program), a pilot program is being implemented during the first five years of the *Green City, Clean Waters* program to test the feasibility and measure the effectiveness of green stormwater infrastructure under the full range of potential conditions. The pilot program will be used to select which projects and locations will be high priority for green stormwater infrastructure performance monitoring.

Currently, monitoring is only conducted at the individual stormwater management practice level. The development of the *Green City, Clean Waters* Tracking System has defined a hierarchy for green stormwater infrastructure components. In increasing order of complexity, multiple stormwater management practices may be hydraulically connected within a "System", multiple systems may be located on a given "Project", and multiple projects may be combined in a single "Work number" bid package (Figure 4-1). Fourteen constructed pilot projects were identified and categorized by stormwater management practice type and the number of potential monitoring locations (i.e., observation wells or hydraulic control structures) was determined (Table 4-2). Constructed projects were also categorized according to primary stormwater management function (i.e., detention and slow release or infiltration) (Table 4-3).

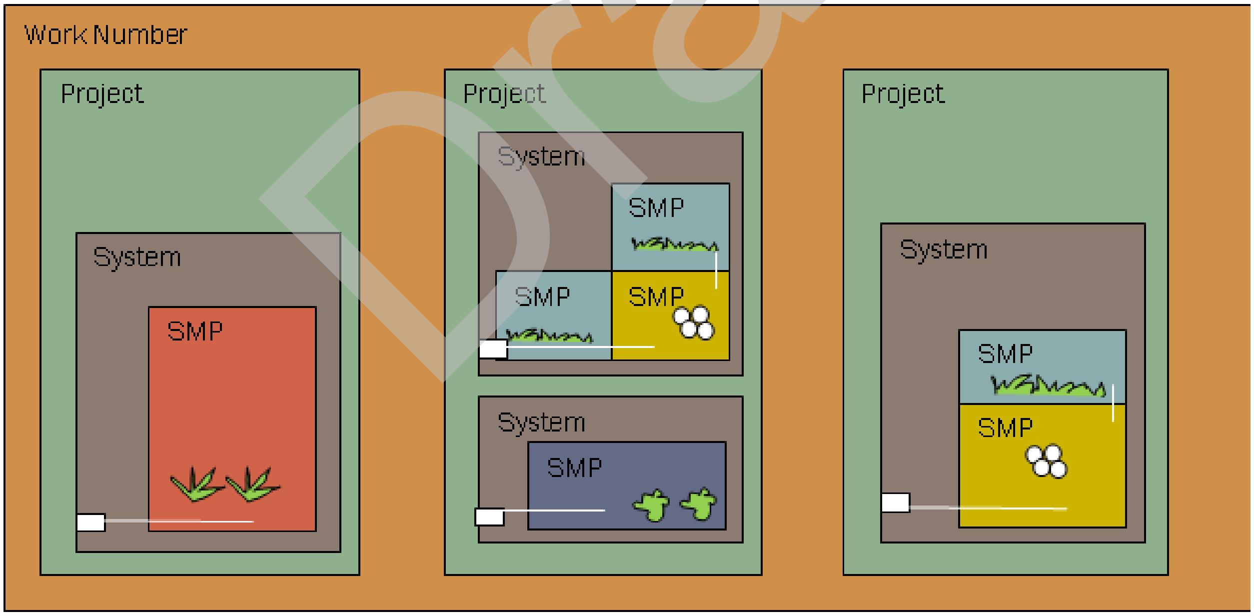

Figure 4-1: Conceptual Diagram of Green Stormwater Infrastructure Project Hierarchy

Table 4-2: Constructed Green Stormwater Infrastructure Pilot Projects by Project Type and Monitoring Locations Present

Constructed Pilot Project Stormwater Management Practices by Type	Number of Individual Stormwater Management Practices	Number of Sites	Number of Stormwater Management Practices with Monitoring Equipment*
Bumpouts	6	1	6
Infiltration trench	3	3	2
Tree trench	15	5	15
Street planters	9	2	8
Planter trench	1	1	1
Roof leader planters	2	1	-
Porous asphalt	2	2	2
Pervious concrete	1	1	1
Pervious pavers	2	2	1
Porous play surface	2	1	-
Swales	1	1	-
Single stormwater tree	17	1	-
Bioretention	1	1	1
Bioinfiltration	9	3	-

*Monitoring locations includes observation wells, outlet control structures with a weir and orifice, piezometer wells, etc.

Table 4-3: Constructed Green Stormwater Infrastructure Pilot Projects by Primary Stormwater Function Type

Stormwater Function Type	Number of Individual Stormwater Management Practices	Number of Sites	Number of Stormwater Management Practices with Monitoring Equipment*
Infiltration	64	13	33
Slow Release Only	5	4	5

*Monitoring locations include observation wells, outlet control structures with a weir and orifice, piezometer wells, etc.

In addition to the 14 constructed pilot projects which are identified for potential monitoring, 29 projects currently in the construction or design complete phase are expected to be completed by the end of 2014 and eligible for inclusion in pilot program monitoring activities (Figure 4-2, Table 4-4). A complete listing of constructed and design complete pilot project sites identified for potential monitoring can be seen in Table 4-4, with a map of locations shown in Figure 4-2.

Table 4-4: Projects in Construction or Design Phase Eligible for Inclusion in Pilot Program Monitoring

Project	Status	Stormwater Management Practice Type
Greenfield Elementary School	Complete	Rain Garden
Percy St from Catharine St to Christian St	Complete	Pervious Paving
Sepviva St from Susquehanna Ave to Dauphin St	Complete	Infiltration/Storage Trench
Waterview Recreation Center	Complete	Stormwater Planter
Belfield Ave from Chew Ave to Walnut Ln	Complete	Stormwater Tree Trench
Columbus Square	Complete	Stormwater Planter
Bureau of Laboratory Services	Complete	Stormwater Planter
Queen Lane from Henry St to Fox St	Complete	Stormwater Bumpout
Liberty Lands	Complete	Rain Garden
West Mill Creek Recreation Center	Complete	Stormwater Tree Trench
47th & Grays Ferry	Complete	Rain Garden
Herron Playground Basketball Court	Complete	Pervious Paving
Shissler Playground	Complete	Stormwater Tree Trench
Eadom Parking Lot	Complete	Rain Garden
12th St and Reed St	Design Complete	Rain Garden
Chew Playground	Design Complete	Stormwater Bumpout
Passyunk Ave from Dickinson St To Reed St	Design Complete	Stormwater Planter
3rd St and Fairmount Ave Intersection	Design Complete	Stormwater Bumpout
Bodine High School	Design Complete	Stormwater Planter
Blue Bell Inn Triangle	Design Complete	Rain Garden
Dickinson Square	Design Complete	Stormwater Bumpout
A.S. Jenks School	Design Complete	Stormwater Tree Trench
Andrew Hamilton School	Design Complete	Stormwater Planter
Daroff School	Design Complete	Stormwater Bumpout
Shepard Recreation Center	Design Complete	Stormwater Bumpout
Bryant Elementary School	Design Complete	Stormwater Tree Trench
Christy Recreation Center	Design Complete	Stormwater Tree Trench
William Harrity School	Design Complete	Stormwater Tree Trench
Philadelphia Military Academy	Design Complete	Stormwater Tree Trench
Morris Leeds Middle School	Design Complete	Stormwater Tree Trench
Simons Recreation Center	Design Complete	Stormwater Tree Trench
Thompson St and Columbia Ave	Design Complete	Stormwater Bumpout
29th and Chalmers Playground	Design Complete	Stormwater Tree Trench
Mastery Charter School	Design Complete	Stormwater Tree Trench
Muhammed Square	Design Complete	Stormwater Tree Trench
Sister Clara Muhammad School	Design Complete	Stormwater Tree Trench
Yorktown Parks	Design Complete	Stormwater Planter

Project	Status	Stormwater Management Practice Type
Longstreth School	Design Complete	Stormwater Planter
Springfield Ave and Cobbs Creek Island	Design Complete	Rain Garden
Bridesburg Recreation Center and Bridesburg School	Design Complete	Rain Garden
Harpers Hollow Park	Design Complete	Stormwater Basin
Wakefield Park	Design Complete	Rain Garden
Womrath Park	Design Complete	Rain Garden

4.8 Methods

The Water Department will use long-term hydrologic and hydraulic monitoring and simulated runoff tests to evaluate post-construction performance of individual stormwater management practices. Project sites with observation wells and other structural elements that lend themselves to water level monitoring will be subjected to post-construction performance tests with simulated runoff from a fire hydrant in order to verify that water flows through the system as designed and establish a baseline measurement for infiltration performance. Other stormwater management practice types, such as porous surfaces may also be tested as appropriate on a project-by-project basis. In addition to this post-construction simulated runoff testing, continuous water level monitoring will be used to evaluate performance of selected sites over longer periods of time and observe system response to a broader range of natural storm events.

Details of monitoring equipment, such as observation wells, are available in the design drawings for each project, and are necessary to develop monitoring plans. Detail information is extracted from the plans and organized into simple and concise monitoring schematics for each stormwater management practice to be monitored. These schematics clearly indicate the locations of monitoring equipment that are available for the monitoring methods described in this section. Examples of green stormwater infrastructure monitoring schematics are located in Appendix B.

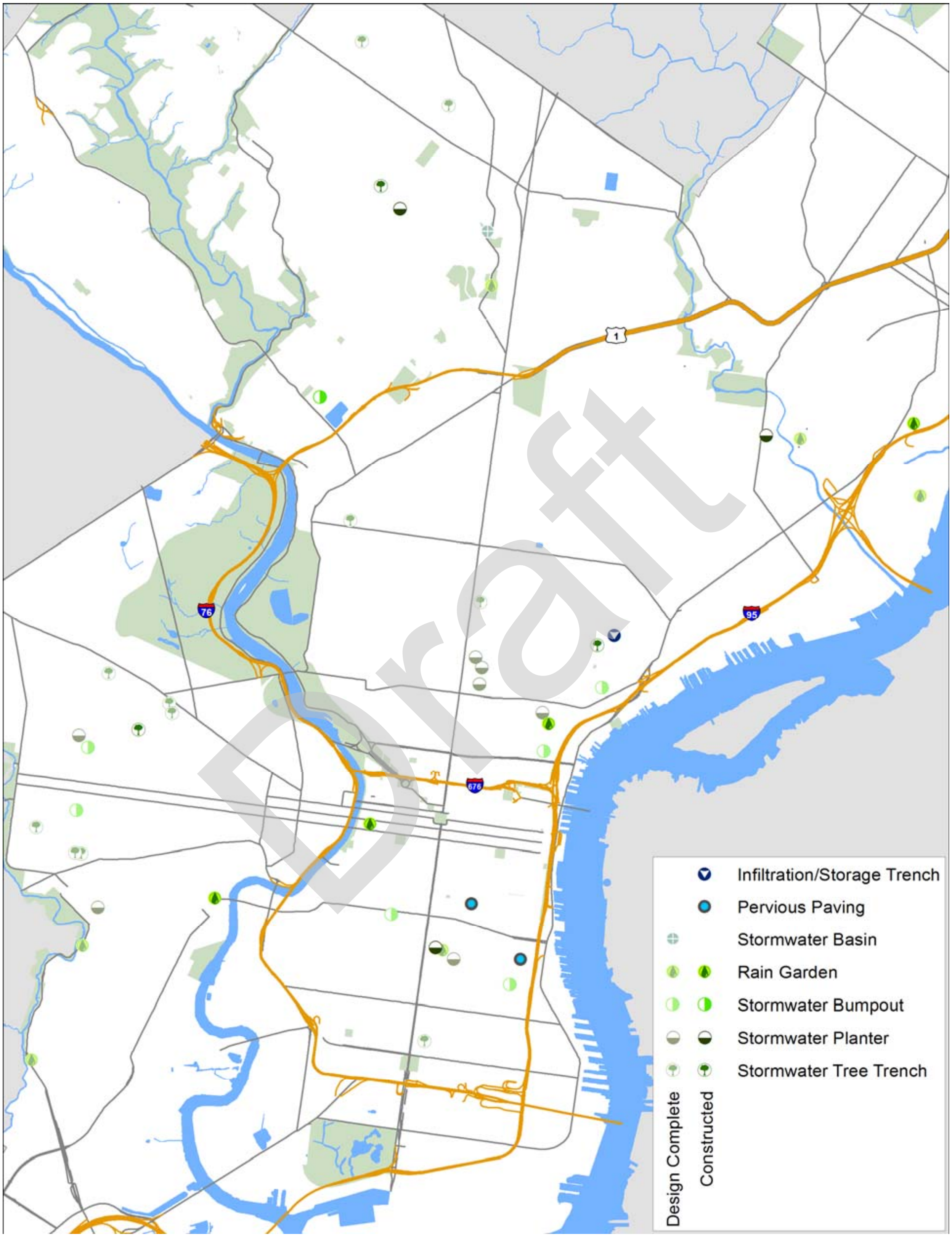

Figure 4-2: Green Stormwater Infrastructure Pilot Project Monitoring Locations with Stormwater Management Practice Type and Project Status

4.8.1 Continuous Hydrologic and Hydraulic Monitoring Methods

The Water Department performs continuous monitoring using water level loggers (HOBO U-20-004, Onset Computer Co., Bourne, MA) installed in observation wells or other stationary locations where water elevation information can be obtained. Long-term hydrologic and hydraulic monitoring, including post-construction performance monitoring, will be used for calculating long-term reduction in stormwater runoff volume over a range of naturally occurring storm events. Compared to simulated runoff testing, continuous monitoring has the advantage of collecting data over a broader range of storm hyetograph patterns, and under different conditions of antecedent soil moisture, temperature, etc.

Sensors are suspended in observation wells via braided stainless steel cable such that they are elevated off the bottom surface of the well (Figure 4-3). Sensors are programmed to record pressure and temperature at 5 minute intervals. The five minute interval has been shown to be an appropriate balance between storm event response and data capacity, allowing for deployments of approximately 75 days. Water level readings are made manually at the time of deployment with an electric tape (Watermark 75 ft electric water level meter) in order to establish the vertical correction offset between sensor water level readings and the elevation reference datum, typically the top of the well. Pressure and temperature data are downloaded at regular intervals via a laptop computer. Manual water level readings are taken when downloading data and re-deploying sensors in order to calibrate water level readings and determine whether sensor drift occurred during the deployment. Infiltration rate is calculated as the change in storage volume over time as described in Section 4.8 (Data Evaluation).

Based on previous monitoring experience, the water level sensors selected for continuous water level monitoring are absolute pressure transducers that require a source of barometric pressure data for barometric pressure compensation. The barometric pressure sensor is an additional sensor of the same model (HOBO U-20-004) installed within the same observation well as the water level sensor, or in a nearby location that will not be exposed to submersion. Currently all monitored green stormwater infrastructure sites have a local barometric pressure correction sensor. However, as the number of monitored sites grows, the Water Department will explore the possibility of regional barometric pressure compensation data networks rather than having a local barometric pressure compensation device at each site. More information about long term continuous monitoring methods is available in Appendix C (The Water Department's Standard Operating Procedures for Continuous Water Level Monitoring of Green Stormwater Infrastructure Practices).

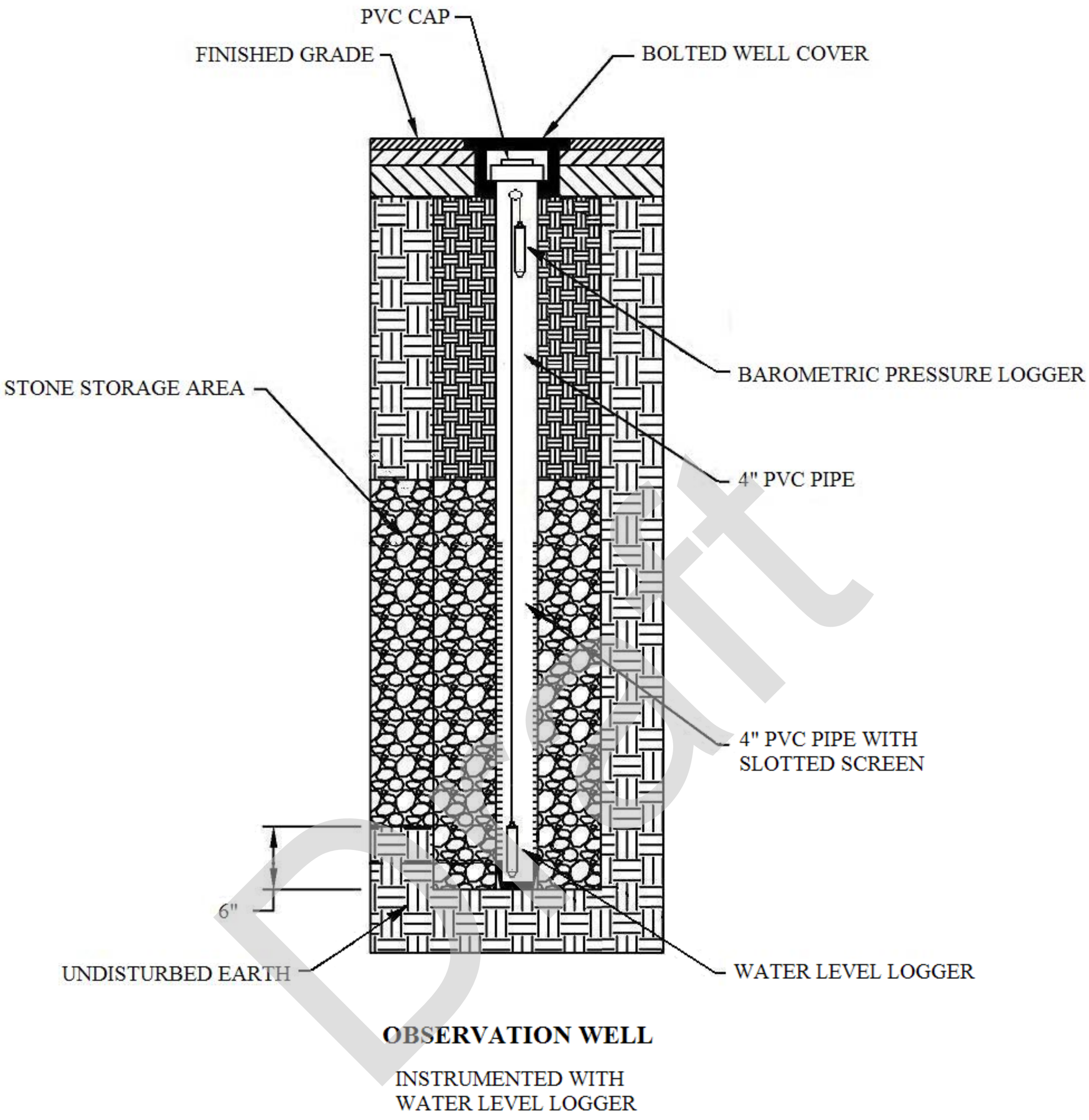

Figure 4-3: Water level and Barometric Pressure Sensors Installed in Observation Well (typical)

4.8.2 Simulated Runoff Testing Methods

Simulated runoff testing (also known as hydrant testing) will be the primary means of testing a newly-constructed green stormwater infrastructure project site to verify that water flows through the project as designed and to measure infiltration rate. This method has the distinct advantage of introducing a controlled rate and volume of water, which increases the accuracy of infiltration rate measurements. Simulated runoff tests will be performed after a project has been completed and vegetation has been established, as appropriate for individual site conditions. Hydrants will be used to deliver a metered volume of water, while datalogging water level sensors installed in observation wells and/or hydraulic control structures are used to record water depth. Water level data are collected using the same equipment and methods as described in Section 4.8.1 (Continuous Hydrologic and Hydraulic Monitoring Methods), except that manual water level observations are taken more frequently during the test procedure.

Infiltration rate testing is performed by filling a stormwater management practice with controlled flow from a fire hydrant or other source of water. Flow rate is calculated based on measured hydraulic pressure and standard hydraulic loss equations for the fixtures and hose(s) in use. When feasible, the flow rate is also checked by directing flow to a vessel such as a bucket or barrel and recording the time required to fill it to a known volume. The Water Department is currently evaluating portable metering equipment that will provide more accurate measurements of the flow into the stormwater management practice. Standard operating procedures will be adjusted as necessary once this equipment is obtained.

The Water Department is also developing guidelines for how quickly the stormwater management practice storage volume should be filled, and how to proceed when certain conditions are encountered during the simulated runoff test. Guidelines for runoff simulation are being developed based on design specifications and observed meteorological data but also incorporate measures to avoid damage to structures or vegetation, as well as general safety considerations. For example, the test can be terminated or scaled down if inlet bypass occurs and cannot be corrected with sandbags. Tests are terminated immediately if it appears that damage to structures will occur or safety concerns arise that cannot be abated with appropriate measures.

Guidelines currently state that the rate of simulated runoff should not exceed the equivalent of 1” of runoff in one hour (rectangular hyetograph). Modified meteorological data from 2005 is used by the Water Department as a “typical year” of rainfall for hydrologic modeling. In this “typical year,” 12 storm events exceeded this event volume and 8 events exceeded this rate (rainfall measured at 15 min intervals). It should be noted that the simulated runoff test depends upon hydrant water pressure and hydraulic losses associated with fixtures and hoses required to perform the test. It may not be feasible to simulate the 1 in/hr runoff event for large stormwater management practices, in areas of the City with low water pressure, where long hose runs are required to deliver water to the site, or where combinations of these factors apply. Current guidelines for conducting simulated runoff tests are available in Appendix D (The Water Department’s Standard Operating Procedures for Simulated Runoff Testing of Green Stormwater Infrastructure Practices).

Depending on the design of the stormwater management practice in question, individual structures may be isolated during the simulated runoff test in order to verify that they are within design specifications or evaluate their performance individually. For example, stormwater management practices constructed at sites where pre-construction infiltration testing indicates infiltration rates less than 0.25 in/hr (or if the storage bed will not drain within 72 hours) are required to have underdrains connected to control structures or orifices. Temporarily blocking this orifice allows calculation of infiltration rate independent of orifice flow rate. If a particular stormwater management practice was designed for slow release only, temporarily blocking the orifice will allow for an assessment of whether the site experiences infiltration or other losses that might indicate leaks or failure of the liner. As an extension of this test, if no appreciable losses are detected, the orifice can be opened and the resultant change in storage volume can be used to estimate the orifice coefficient.

As described above, it may not be feasible to fill a given stormwater management practice to its designed static storage volume. Fortunately it is not necessary to do so in order to perform the simulated runoff test and measure recession rate. It is desirable, however, to test all functions of a stormwater management practice when and where it is feasible to do so. If water is constantly delivered to the stormwater management practice at a rate exceeding the effective infiltration rate, an overflow condition will be created at the overflow to the sewer system, allowing field staff to verify that structures are working properly and as designed. Furthermore, construction defects or unanticipated site characteristics may be more readily observed while the stormwater management practice is being loaded with water under controlled conditions during dry weather.

4.8.3 Lateral Groundwater Mounding Methods

Many green stormwater infrastructure practices are designed to reduce stormwater runoff volume by allowing an amount of runoff to infiltrate into the local substrate, which mimics natural processes and enhances groundwater recharge and stream baseflow. As urban development often utilizes all available space both at the surface and in the subsurface, a more informed understanding of the groundwater table and how the decentralized nature of green stormwater infrastructure can impact local groundwater characteristics is needed. Where applicable and practical, according to the constraints of installing specific green stormwater infrastructure practices, piezometer wells will be used to characterize the groundwater table and groundwater response to green stormwater infrastructure on a localized basis for select Stormwater Management Practices.

Shallow piezometer wells are installed in the soil profile along a transect extending laterally from the stormwater management practice infiltration structure footprint area at distances of 1, 5 and 10 feet. Water level data are collected from piezometer wells using methods similar to those described in Section 4.8.1 (Continuous Hydrologic and Hydraulic Monitoring Methods). More detailed information is available in Appendix C (The Water Department's Standard Operating Procedures for Continuous Water Level Monitoring of Green Stormwater Infrastructure Practices). Lateral groundwater mounding profile data are collected for several months and results are compared to estimates computed with groundwater numerical computer model simulations as described in Section 4.8 (Data Evaluation).

4.8.4 Pervious Paving Infiltration Testing Methods

Pervious paving is a generalized project category that includes porous asphalt and pervious concrete, as well as projects containing a combination of materials. The primary means of monitoring these types of projects is routine visual and photographic monitoring, documenting whether areas of the project have accumulated fine sediment or appear to have reduced permeability as determined by the presence of ponded water. Annual infiltration testing is conducted at selected projects at the same location over a number of years to track infiltration rates over time. Infiltration testing may also be conducted to verify whether gross infiltration estimates used for modeling stormwater runoff from pervious pavement are appropriate, or to test infiltration at a specific location within the project to determine whether corrective maintenance (cleaning, pavement replacement) is required.

Infiltration rate is measured using a modified version of ASTM Test Method C1701. Infiltration rate is determined by temporarily sealing a graduated ring to the pervious pavement surface, pre-wetting the surface, then introducing a known quantity of water to the ring and recording the time it takes for the water to seep into the surface (Figure 4-4). In general, this type of infiltration testing is only performed at projects that have homogenous surfaces (slab-poured pervious concrete or large contiguous areas of porous asphalt). As infiltration rates calculated by this method are only applicable to a small area where the test was performed, multiple infiltration tests should be conducted at the same site if the purpose of the testing is to determine an appropriate average infiltration rate to apply to the entire area. For areas up to 25,000 ft^2, a minimum of three test locations are measured. At least one additional test location is added for each additional 10,000 ft^2 of area or fraction thereof. After the test is completed, sealant residue is removed from the surface but a sufficient amount of residue remains within the surface to ensure that subsequent tests, if conducted, will occur at the same area. For more detailed information about pervious paving infiltration testing methods, refer to ASTM Test Method C1701.

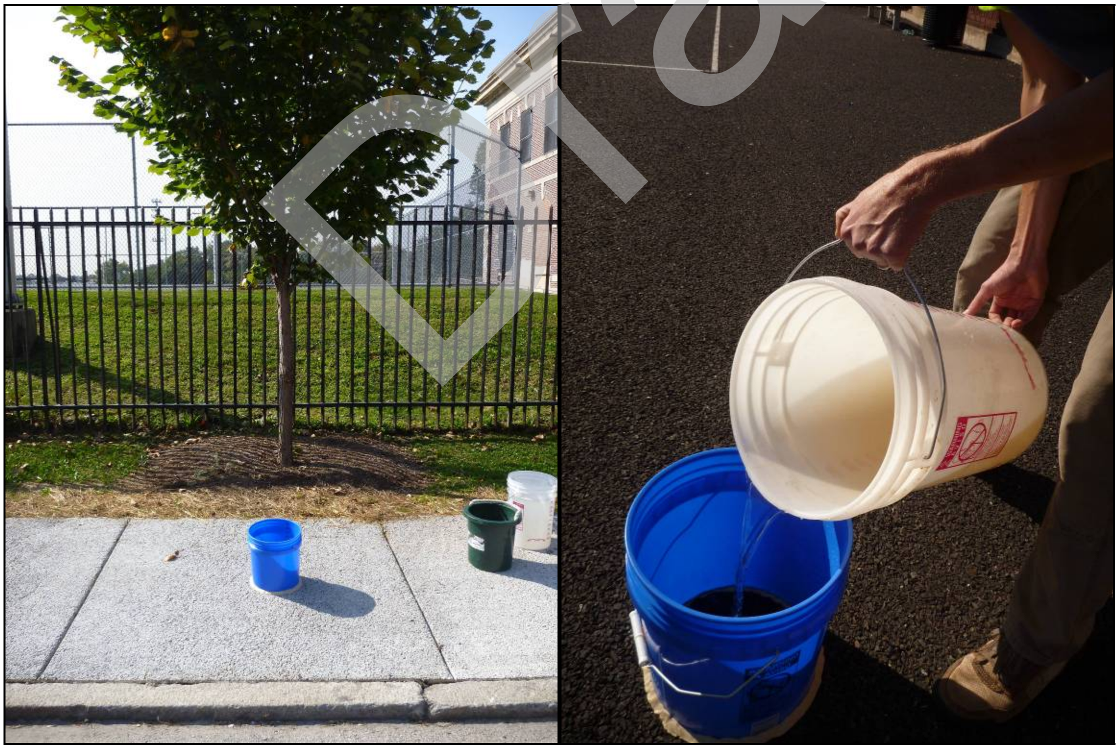

Figure 4-4: Pervious Paving Infiltration Testing Procedure

When infiltration test results or qualitative observations made during the test procedure indicate poor infiltration at one or more monitoring locations, or a marked decrease in infiltration performance overall compared to previous tests at that location, this information will be shared with the green stormwater infrastructure maintenance group in order to schedule maintenance activities and follow up monitoring. Follow up monitoring will be conducted after maintenance procedures such as power washing and vacuuming to provide quantitative estimates of the effectiveness of maintenance procedures.

4.8.5 Soil Moisture Testing and Monitoring Methods

Proper soil moisture conditions are critical for the survival of vegetation within green stormwater infrastructure practices. Although it might be assumed that too frequent inundation and saturated root zone conditions might be a problem for vegetation, it may actually be the case that soil moisture conditions are often too dry. Other conditions present in the urban environment such as excessive heat and road salts can exacerbate the effects of dry soil conditions, further stressing vegetation. Soil moisture monitoring techniques are being researched in collaboration with the green stormwater infrastructure maintenance staff to determine what kind of soil moisture information is most useful. Over time, soil moisture information may help better inform the choice of vegetation or establish guidelines for when supplemental watering is required.

The Water Department has acquired dielectric soil moisture sensors and begun testing them in the laboratory and on a pilot scale at Columbus Square stormwater planter. The first sensors tested (Vegetronix model VG400) were chosen for their low cost, but found to be difficult to calibrate due to their large measurement volume. Three of six sensors deployed within the stormwater planter failed during the initial pilot period. The Water Department is presently testing high frequency sensors (Decagon model 10HS, Decagon Devices, Pullman WA; Vegetronix VH400) under laboratory bench-top conditions before any additional sensors are acquired or field studies are conducted.

4.8.6 Additional Research

Some green stormwater infrastructure project types (e.g., green roofs, small planters, swales and conveyance systems, etc.) are not conducive to the types of monitoring described above and require specific monitoring strategies. The Water Department proposes to monitor selected projects from these project types that require specific monitoring techniques in order to build the local knowledge base regarding these techniques and help inform the design process for projects incorporating these techniques. The Water Department will continue to partner with local universities and research institutions to monitor project characteristics (infiltration and evapotranspiration rates, temperature, etc.) and other measures of success at various green stormwater infrastructure project sites.

4.9 Data Evaluation

4.9.1 Continuous Hydrologic and Hydraulic Monitoring Data Evaluation

Water level and barometric pressure compensation data from sensors are formatted, processed, and used to plot figures created for data quality assurance and control procedures. Corrected water level data are plotted and visually evaluated for expected patterns, such as rates of change and inflection points relative to known elevations (e.g., inflections in stage-storage relation, overflow; control structures and/or invert of slow release orifice, if present). Manual water level measurements are imported and plotted along with the data. Final accepted water level data, corrected for atmospheric pressure and sensor drift, if observed, are imported into a database for long-term storage of water level data.

Several other types of information are required in order to interpret the results of water level monitoring and perform infiltration rate calculations. A conceptual workflow diagram was created to illustrate the data collection and processing steps (Figure 4-5). Stormwater management practice characteristics such as contributing drainage area and the total designed storage volume are extracted from a database application developed for green stormwater infrastructure implementation planning. If a low flow orifice is present, the invert and diameter are recorded from design plans. A stage-storage relation is required to determine storage volume given water surface elevation. If this is not available, such as a hydrologic model report or other documentation provided by the design engineer, it is developed based on as-built drawings or the best available final design plan sets. The stage storage relation is formatted as a comma separated value look up table of water surface elevation and corresponding storage volume.

In addition to site characteristics, meteorological data are required to determine when precipitation events occurred and estimate stormwater runoff volume. Each stormwater management practice monitoring site is associated with a rain gage in the Water Department rain gage network for volume input data. Usually the nearest gage is used, however a different gage may be used in the event that the analyst believes another gage may provide better results. The Water Department rain gage data base is queried for rainfall data for the rain gage of interest for the time period concurrent with the water level sensor deployment. (More information about data collection, processing and quality assurance procedures for meteorological data, including the Water Department rain gage network, is available in Section 7 Meteorological Monitoring). Site characteristics and rainfall data are formatted as a series of comma separated value text files and stored in the same location as the corrected water level data.

Data analysis procedures are scripted using a statistical programming language. Based on the observed data and site characteristics, maximum and minimum water level elevations are chosen to define an interval of change in storage volume that will be the subject of infiltration rate calculations. The interval is chosen such that the system fills up enough to support the assumption that soils are relatively wet and the falling water surface is a good representation of the infiltration rate during the recession (drain down) period (Figure 4-6). Choosing a maximum elevation value that is too high will result in few events being identified from the data record. If the storage volume measurement interval is changed, then the entire period of record should be subsequently re-analyzed to keep the assumption that hydraulic head is consistent among events, eliminating hydraulic head variability as a confounding factor.

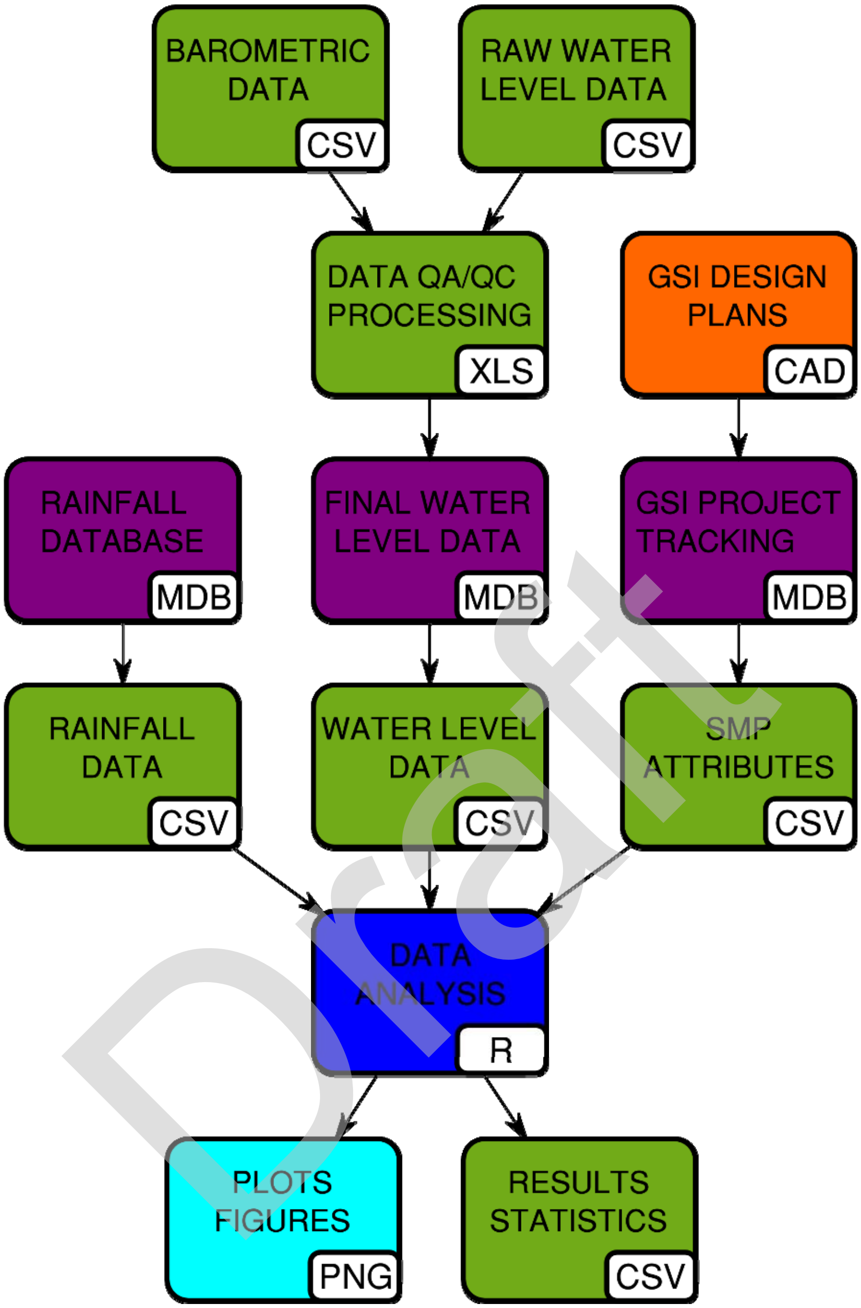

Figure 4-5: Conceptual Workflow Diagram of Continuous Water Level Data Monitoring and Infiltration Rate Calculations

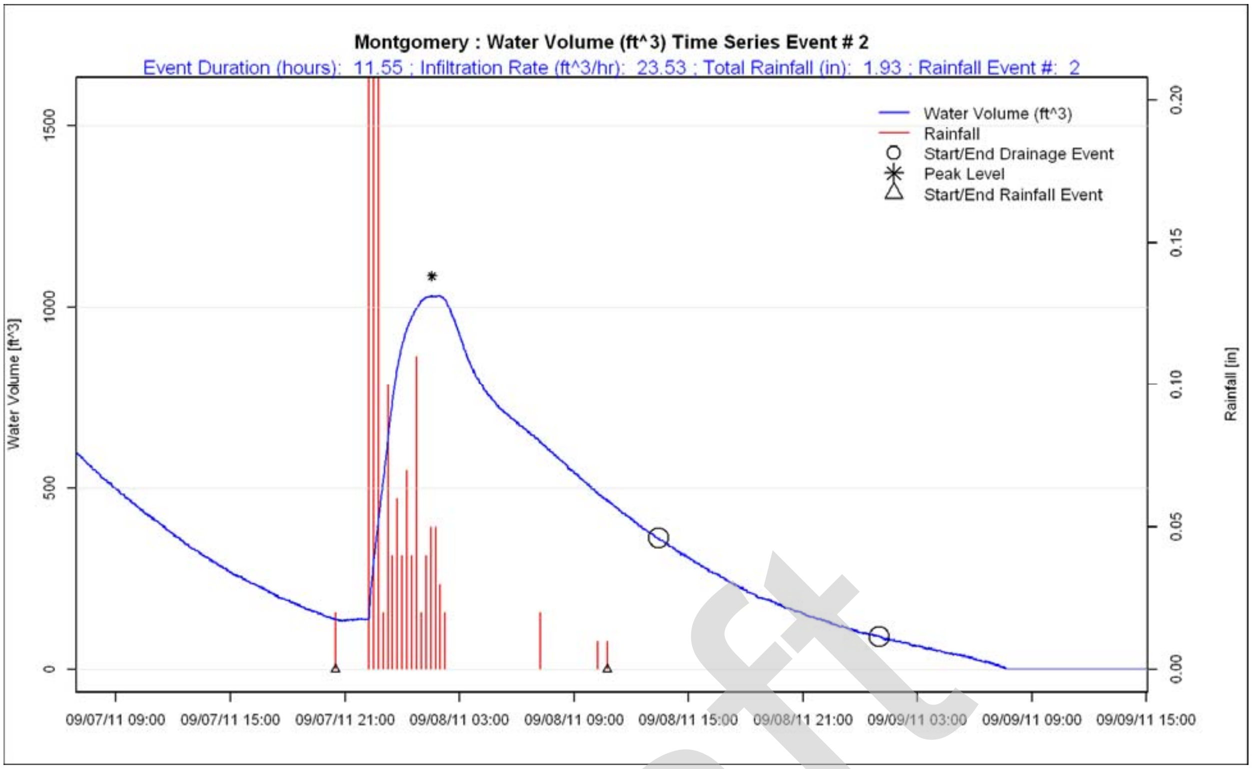

Figure 4-6: Plot of Storage Volume and Precipitation for Storm Event September 7, 2011 – September 9, 2011 at Montgomery Stormwater Tree Trench

In addition to infiltration rate calculations, the cumulative frequency distribution of water surface elevation is calculated. This analysis may provide valuable information about how frequently the practice has been observed to fill up completely and also potentially information about soil moisture conditions for plants. A comparison between observed storage volume and calculated runoff volume from rain gage data can be used to check assumptions about stormwater management practice characteristics and a basic check of inlet efficiency. When a major divergence from the 1:1 ratio between the calculated runoff volume and observed volume is detected, further investigation is needed to determine the cause. More detailed information about data analysis procedures and preliminary results from approximately three months of continuous water level monitoring at a representative tree trench stormwater management practice (Montgomery St.) are available in Appendix C (The Water Department's Standard Operating Procedures for Continuous Water Level Monitoring of Green Stormwater Infrastructure).

Results of continuous water level monitoring and accompanying infiltration rate estimates will be summarized in an annual green stormwater infrastructure monitoring report. When continuous monitoring data is used to evaluate the effectiveness of maintenance procedures (i.e., separate analysis of infiltration rate estimates before and after cleaning or other maintenance procedures) results will also be presented in narrative form in collaboration with the green stormwater infrastructure maintenance team.

4.9.2 Simulated Runoff Testing Data Evaluation

Data processing and analysis procedures for simulated runoff testing are generally similar to those described in Section 4.8.1. Following the simulated runoff test, water level and barometric pressure compensation data are formatted, processed, and plotting figures created for data quality assurance and control procedures. Corrected water level data are plotted and visually evaluated for expected patterns, such as rates of change and inflection points relative to known elevations (e.g., inflections in stage-storage relation, overflow; control structures and/or invert of slow release orifice, if present). Manual water level measurements are imported and plotted along with the data. Final accepted water level data, corrected for atmospheric pressure and sensor drift, if observed, are imported into a database for long-term storage of water level data.

Data analysis procedures are a subset of those described above in Section 4.8.1. Infiltration rate is calculated as the change in storage volume over time as the system drains down, accounting for slow release orifice discharge if one is present (infiltration rate measured by this test is actually made up of infiltration and evapotranspiration components). More detailed information is available in Appendix D (The Water Department's Standard Operating Procedures for Simulated Runoff Testing of Green Stormwater Infrastructure Practices).

For each test conducted, a test report will be prepared summarizing the test parameters along with a brief narrative of any observations or unusual conditions encountered during the test. Recommendations for maintenance, changes to project design, or future monitoring activities will also be included as necessary in the test report. Results of all simulated runoff tests and accompanying infiltration rate estimates will be summarized in an annual green stormwater infrastructure monitoring report. When simulated runoff testing is used to evaluate the effectiveness of maintenance procedures (i.e., performing simulated runoff tests before and after cleaning or other maintenance procedures) results will also be presented in narrative form in collaboration with the green stormwater infrastructure maintenance team.

4.9.3 Lateral Groundwater Mounding Data Evaluation

Data processing procedures for water level data collected in piezometer wells are generally similar to those described in Section 4.8.1. Water level and barometric pressure compensation data are formatted, processed, and plotting figures created for data quality assurance and control procedures. Corrected water level data are plotted and visually evaluated for expected patterns, such as whether evidence of mounding is present and whether water levels generally decrease with distance from the infiltration practice. Data are also screened for water level fluctuations or other unusual patterns. Manual water level measurements are imported and plotted along with the data. Final accepted water level data, corrected for atmospheric pressure and sensor drift, if observed, are imported into a database for long-term storage of water level data. Groundwater levels may not fluctuate as rapidly as water levels in stormwater management practices and thus the data may be resampled at a lower frequency in order to match time series input requirements of numerical groundwater computer model simulations.

For each site monitored with piezometer wells, the groundwater mounding effect will be described in terms of average and maximum observed mounding above the nearby water table as well as how closely observed mounding data match results of numeric groundwater computer simulations (Figure 4-7). Once a sufficient amount of lateral groundwater mounding data have been collected, results will be shared with the Water Department green stormwater infrastructure design coordination staff in order to make changes as necessary if observed data suggest that design guidelines should be changed.

4.9.4 Pervious Paving Infiltration Testing Data Evaluation

Pervious paving infiltration test data are entered into a table of infiltration test results in a database, and average infiltration rate is calculated for each monitoring event at each stormwater management practice as the simple arithmetic average of all individual infiltration tests conducted on that date. Results from all pervious paving infiltration tests will be summarized in an annual report. When infiltration testing is used to evaluate the effectiveness of maintenance procedures (i.e., infiltration rate testing before and after cleaning the pervious surface) results will also be presented in narrative form in collaboration with the green stormwater infrastructure maintenance team in an annual report.

4.10 Data Quality Management and Standard Operating Procedures

Water level data collected in green stormwater infrastructure practices are subjected to a rigorous quality assurance and control procedure, drawing on experience gained through the Water Department's temporary flow monitoring program. Spreadsheets are used to ensure that the water level data meets the data quality objectives of the green stormwater infrastructure monitoring program. Similarly, precipitation data used to determine stormwater runoff input and time of cessation of rainfall is processed according to the Water Department quality assurance and control procedures for meteorological data. More information about these procedures is available in Sections 5 and 7, respectively.

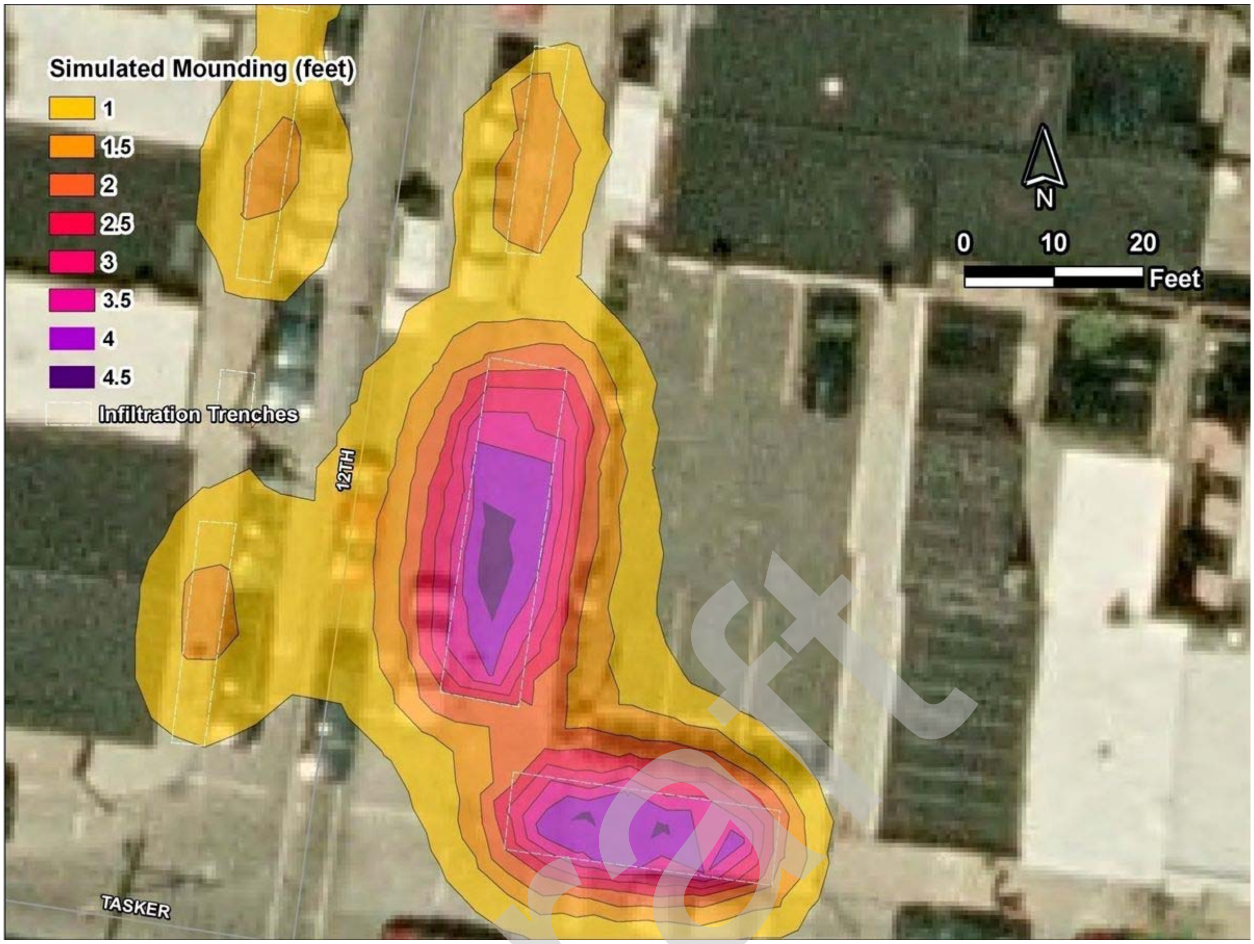

Figure 4-7: Preliminary Groundwater Mounding Results from Computer Model Simulation of Stormwater Tree Trenches at 12th and Tasker Streets

5.0 Sewer System Monitoring

Monitoring of a combined sewer system's response to precipitation can provide two categories of information: information supporting the process of validating hydrologic and hydraulic models of the sewer system and information providing a direct measure of the cumulative performance of constructed controls and other mitigation measures at the sewershed level. The sewer system monitoring activities associated with this Comprehensive Monitoring Plan would provide both. During approximately the first five years of implementing the Long Term Control Plan Update, while initial green stormwater infrastructure pilot programs and the associated green stormwater infrastructure monitoring (Section 4) are being implemented, Comprehensive Monitoring Plan data would provide additional information in support of the continuing process of refining the validation process for the hydrologic and hydraulic models that have been developed for the Water Department system. Observations of flow and precipitation that will be obtained under this phase of the Comprehensive Monitoring Plan will be critical to refining the established baseline for the existing condition urban water budget, against which future progress from constructed *Green City, Clean Waters* program activities and facilities can be measured.

During the remaining years of the program, while selected larger scale green stormwater infrastructure projects and other mitigation measures are being implemented, the Comprehensive Monitoring Plan sewer system monitoring data would help quantify the performance benefits and other measures of success that the constructed green stormwater infrastructure controls were able to provide. The Comprehensive Monitoring Plan data would also inform the adaptive management process (described in Section 3) and provide the necessary information to refine the Evaluation and Adaptation Plan recommendations to optimize the program, maximize benefits, and minimize cost.

The Water Department has existing permanent and temporary monitoring programs in place to develop a comprehensive and accurate dataset. Section 5.1 describes how the Comprehensive Monitoring Plan will build upon and adapt these existing Water Department monitoring programs and describes the criteria and processes by which future monitoring sites will be selected. Section 5.2 summarizes the existing data quality assurance protocols and procedures that will be implemented and the analyses that will be conducted on the collected monitoring data. To maximize utilization of the monitoring data, measured flows will be separated into their components—base wastewater flow, groundwater inflow, and stormwater.

5.1 Summary of Monitoring Data Sources

The existing Water Department sewer system monitoring network, on which the Comprehensive Monitoring Plan will be based, includes multiple categories of monitoring locations and equipment:

- Permanent location depth only monitoring sites

- Permanent location depth, velocity, and flow monitoring sites
- Portable location depth, velocity, and flow monitoring sites
- Tide gate monitoring locations

These existing monitoring site and equipment categories will be maintained for the Comprehensive Monitoring Plan. They include a network of permanent location monitors maintained for a long duration, a network of portable depth and velocity monitors that can be deployed for shorter durations and relocated in multiple locations, and Water Pollution Control Plant influent flow meters. Additional Comprehensive Monitoring Plan data will be obtained from the existing network of outlying community billing meters, the Sewer Assessment Program, pumping data, and tide gate monitoring.

5.1.1 Permanent Location, Long Duration Flow Monitoring

The continued monitoring of fixed long-term monitoring locations within the combined sewer system will provide broad-brush data for larger sewershed areas. The data obtained from the earlier years of Comprehensive Monitoring Plan monitoring will augment previously collected monitoring data and is important for the continuing refinement of the hydrologic and hydraulic model validation process, and continuing refinement of the characterization of system performance over time in terms of dry and wet weather flow and pollutant loadings. The data from the later years of Comprehensive Monitoring Plan monitoring will be important for large scale quantification of the effectiveness of the constructed green stormwater infrastructure facilities and other mitigation measures, and will inform the adaptive management process. The primary sources for continued monitoring under this Comprehensive Monitoring Plan at fixed long-term locations, described in the subsequent subsections, are as follows:

- Water Pollution Control Plant influent flow data including hourly flow rates at major interceptor connection points
- Outlying community metering chamber flow data
- Collection System Pumping Station wet-well level records
- Permanent metering of water levels at Combined Sewer Overflow (CSO) regulators, along interceptors, and in key locations that control the hydraulic grade line in the system

Maintaining long-term continuous flow monitoring stations in ideal representative priority locations is desirable to track the Combined Sewer System performance improvement over time because the Combined Sewer System response to wet weather conditions is generally greater over the range of events experienced at a single location than it is between locations across the Combined Sewer System at any given time. Long-term continuous monitoring is also valuable for estimating inter-annual base groundwater inflow and infiltration rates as well as relating short-term monitoring results with long-term average hydrologic conditions. The Comprehensive Monitoring Plan approach of continued monitoring at existing permanent long-term monitoring locations will maximize the utility of the collected data.

5.1.1.1 Water Pollution Control Plant Influent Flow Data

Permanent location monitoring stations have been established at all three Water Pollution Control Plants and record influent level/depth, velocity, and flow data in daily and hourly time increments. Monitoring activities and data collection at these three sites will be maintained under the Comprehensive Monitoring Plan. Water Pollution Control Plant daily qualitative data—such as unusual color or odors of influent flow—and quantitative data—flow level, pH, total suspended solids, fecal coliform, biological oxygen demand, and chlorine residual—are reported to regulatory agencies in monthly Discharge Monitoring Reports. A map of the three Water Pollution Control Plant locations and drainage areas can be seen in Figure 5-1.

5.1.1.2 Outlying Community Billing Meters

Permanent location flow meters have been installed at major points of connection for many of the municipalities contributing sanitary sewage to the Water Department system. At some of the outlying community meter locations, portable meters have been installed which are discussed in Section 5.1.2. A list of the permanent location outlying community billing meters that will be incorporated into the Comprehensive Monitoring Plan is provided in Table 5-1. A map of these outlying meter locations with contributing areas is shown in Figure 5-2.

5.1.1.3 Collection System Pumping Station Monitoring Data

The Water Department owns and operates two combined sewer collection system pump stations, one stormwater pump station, and 13 sanitary sewer pump stations. Monitoring activities and data collection at each of these locations will be continued under the Comprehensive Monitoring Plan. The combined and storm water pump stations are identified in Table 5-2.

The Central Schuylkill Pumping Station is the Water Department's largest combined sewer system pump station. Pump flow rates are recorded for each of the six pumps and level data are recorded for the North and South shafts of the Central Schuylkill Siphon.

The 42nd Street pump station is the other combined sewer system pump station owned and operated by the Water Department. It serves a small combined sewer area of approximately 6 acres of institutional land use with an estimated design capacity of 6,000 gpm. Pump run times are recorded along with wet-well water level data. Flows can be estimated using mass balance methods based on wet-well water level volume changes, manufacturer pump performance curves, and estimated force main system head losses.

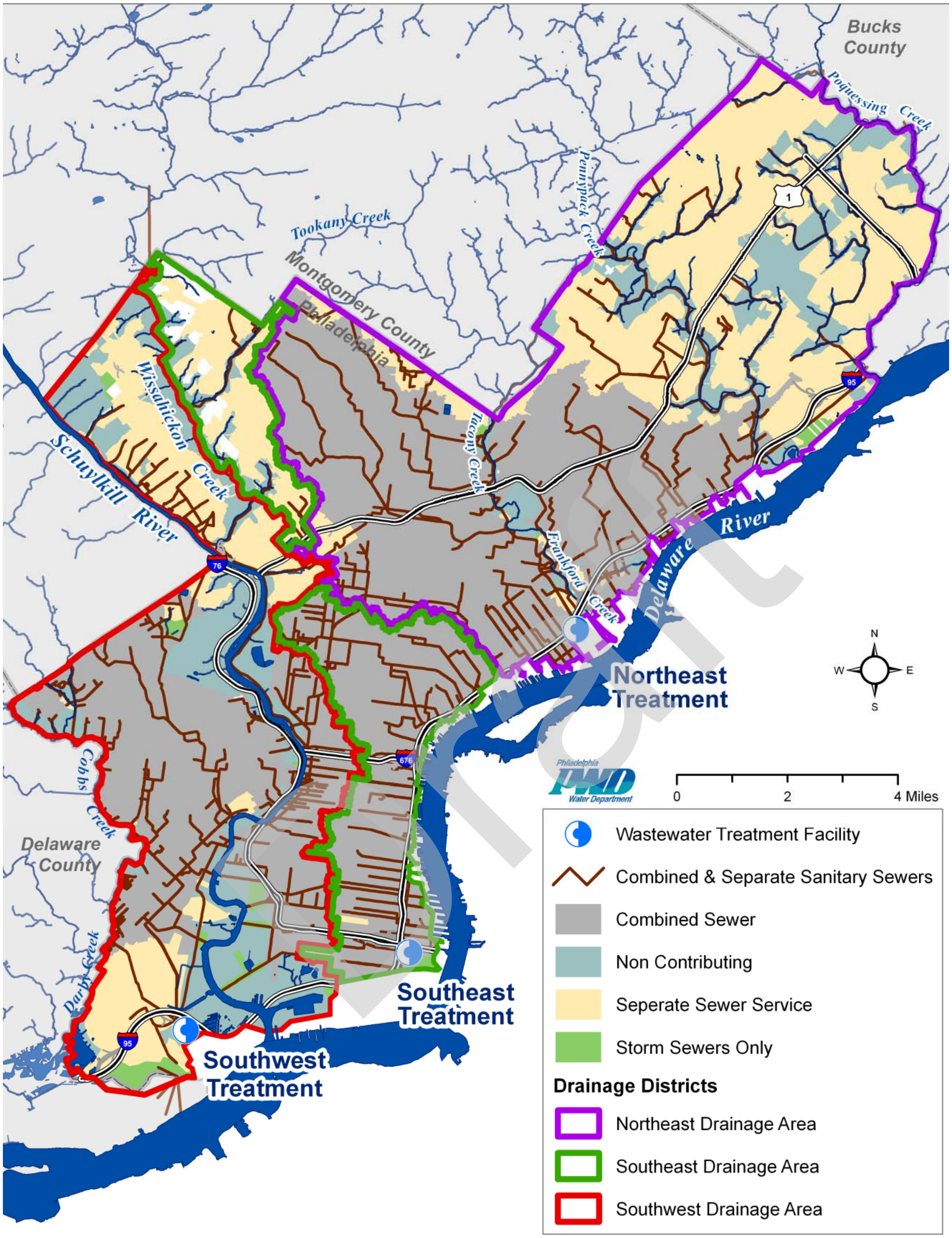

Figure 5-1: Water Pollution Control Plant Locations and Drainage Area Districts

Table 5-1: Permanent Outlying Community Flow Meters

Permanent Meter Deployments for Outlying Community Connections			
Site ID	Township	Drainage District	Location
MA2	Abington	NE	Pine Road & Pennypack Creek
MB1	Bucks Co.	NE	Totem Rd. & Neshaminy Cr.
MBE1	Bensalem	NE	Byberry Grounds
MBE2	Bensalem	NE	Dunks Ferry Road
MBE3	Bensalem	NE	Emerson & Evelyn
MBE4	Bensalem	NE	Red Lion & Frankford
MBE5	Bensalem	NE	Grant & James
MBE6	Bensalem	NE	Gravel Pike @ Poquessing Creek
MBE7	Bensalem	NE	Townsend Road @ Poquessing Creek
MBE8	Bensalem	NE	Bensalem Shopping Ctr.
MBE9	Bensalem	NE	Elmwood Apartments
MBE10	Bensalem	NE	Colonial Ave
MBE11	Bensalem	NE	Betz Laboratories
MBE12	Bensalem	NE	Creekside Apartments North
MBE13	Bensalem	NE	Rt 1 West Side of Highway
MBE14	Bensalem	NE	Old Lincoln Hwy & Old Trevose Rd
MBE15	Bensalem	NE	Knights Rd & Poquessing Creek
MBE16	Bensalem	NE	Creekside Apartments South
MC1	Cheltenham	NE	Bouvier & Cheltenham
MC2	Cheltenham	NE	Tookany Creek & Cheltenham
MC3	Abington	NE	Fillmore & Shelmire (Abington flow)
MCx1	Cheltenham	NE	Cottman (Out)
MCx2	Cheltenham	NE	County Line & Franklin (Out)
MCx3	Cheltenham	NE	County Line & Washington (Out)
MCx4	Cheltenham	NE	Kerper (Out)
MCx5	Cheltenham	NE	Passmore (Out)
MCx6	Cheltenham	NE	Devereaux (Out)
MCx7	Cheltenham	NE	Comly (Out)
MD1	Delaware Co.	SW	DELCORA
ML1	Lower Merion	SW	51st Street & City Line
ML3	Lower Merion	SW	63rd Street & City Line
ML4	Lower Merion	SW	66th Street & City Line
ML5	Lower Merion	SW	73rd Street & City Line
ML6	Lower Merion	SW	Conshohocken & City Line

Permanent Meter Deployments for Outlying Community Connections			
Site ID	Township	Drainage District	Location
ML7	Lower Merion	SW	Presidential & City Line
MLM1	Lower Moreland	NE	Philmont & Byberry
MLM2	Lower Moreland	NE	Lower Moreland PS @ Welsh & Huntington Pk
MS2	Springfield	SW	Northwestern & Wissahickon Cr.
MS3	Springfield	SW	Erdenheim & Stenton
MS6	Springfield	SE	Woodbrook & Stenton
MSH1	Southampton	NE	Trevose Rd. & Poquessing Creek E side
MUD1-N	Upper Darby	SW	60Th & Cobbs Creek
MUD1-S	Upper Darby	SW	60Th & Cobbs Creek
MUD1-O	Upper Darby	SW	60Th & Cobbs Creek Overflow
MP796	PIDC - PNBC	SE	Phila. Naval Business Ctr. @ PS 796

Table 5-2: Combined Sewer Pump Stations

Pump Station Name	Pump Station Number	Drainage District
Central Schuylkill	PS-03	SW
42nd Street	PS-13	SW

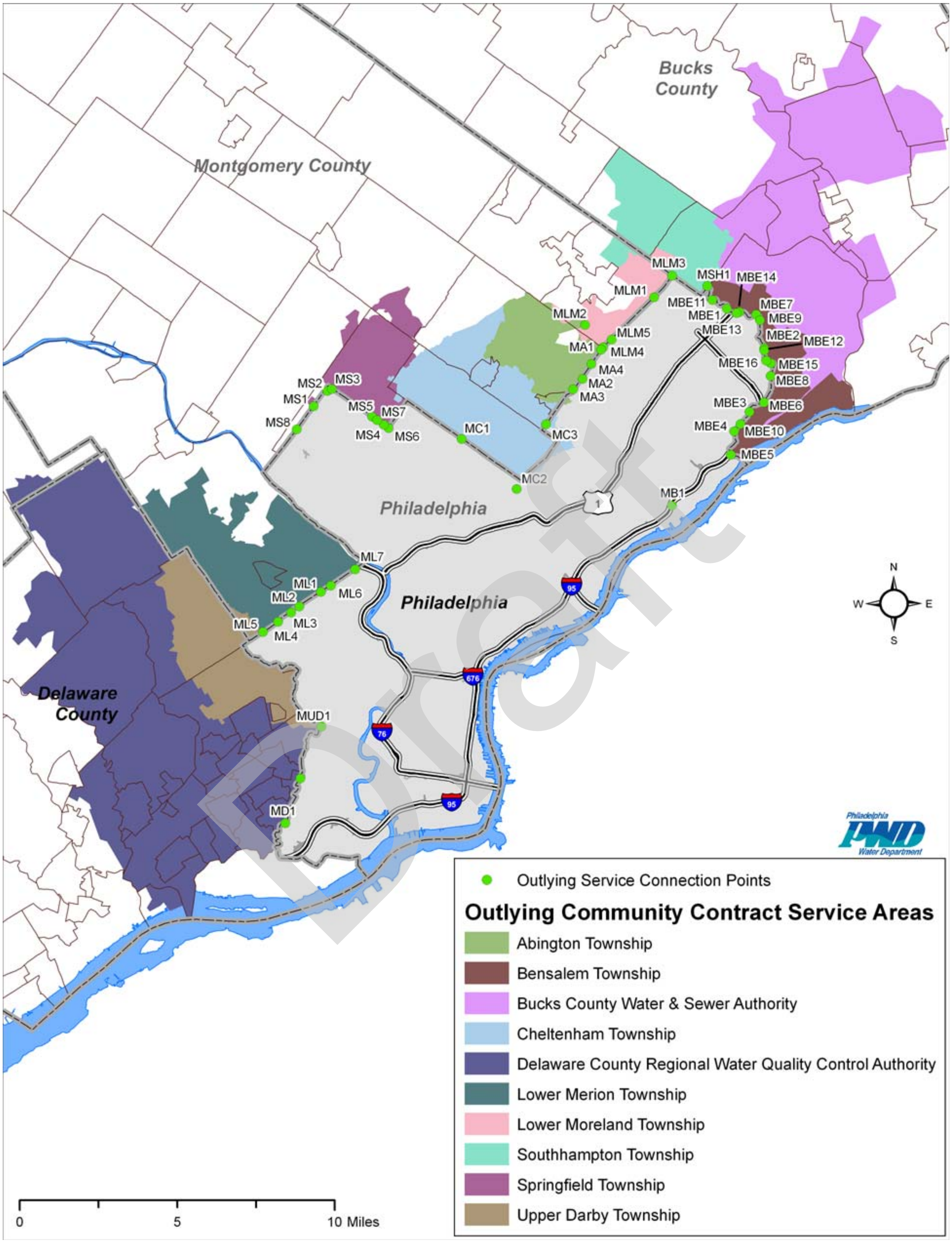

Figure 5-2: Outlying Community Sewer Flow Meter Locations and Drainage Areas

The Comprehensive Monitoring Plan will continue monitoring activities at the 13 sanitary sewer pump stations located within the Water Department system and identified in Table 5-3. A map depicting the locations of the combined sewer, stormwater, and sanitary sewer pump stations is provided in Figure 5-3. The collected data will support the ongoing refinement of the hydrologic and hydraulic model models and the characterization and quantification of dry and wet weather flow from the sanitary sewer collection systems tributary to the pump stations. The Comprehensive Monitoring Plan data will also support a second purpose. As part of the City's Capacity Management Operation and Maintenance program for the sanitary sewage collection system, evaluation of the firm capacity of sanitary sewage pump stations is being performed to determine if they have sufficient capacity to handle the typical peak wet weather inflows. Each of the City's sanitary sewage pump stations has been designed with multiple pumps (usually of the same size and type). The firm capacity of a sanitary sewage pump station is defined as the peak pump station capacity with the equivalent of the largest pump out of service and the wet well water level just below the overflow level. To evaluate the station performance for peak wet weather flows, measured wet well level data is used to estimate station inflow and discharge rates from recorded wet well level time series data, wet well geometry, and estimated pump discharge rates. In addition to wet-well level and pump run time monitoring at the PNBC-796 sanitary sewage pump station, pump discharge flow rates are monitored directly at this site through billing meter MP-796. Wet and dry weather flow analyses are performed on the data to characterize the pump station inflow rates and discharge capacity.

Table 5-3: Sanitary Sewer Pump Stations

Pump Station Name	Pump Station Number	Drainage District
Bank Street	PS-01	SE
Belfry Drive	PS-02	SW
Ford Road	PS-04	SW
Hog Island	PS-06	SW
Linden Avenue	PS-07	NE
Lockart Street	PS-08	NE
Milnor Street	PS-09	NE
Neil Drive	PS-10	SW
Rennard Street	PS-12	NE
Spring Lane	PS-19	SW
PNBC-796 *	PS-20	SE
PNBC-603	PS-21	SE
PNBC-648	PS-24	SE

*metered pump discharge

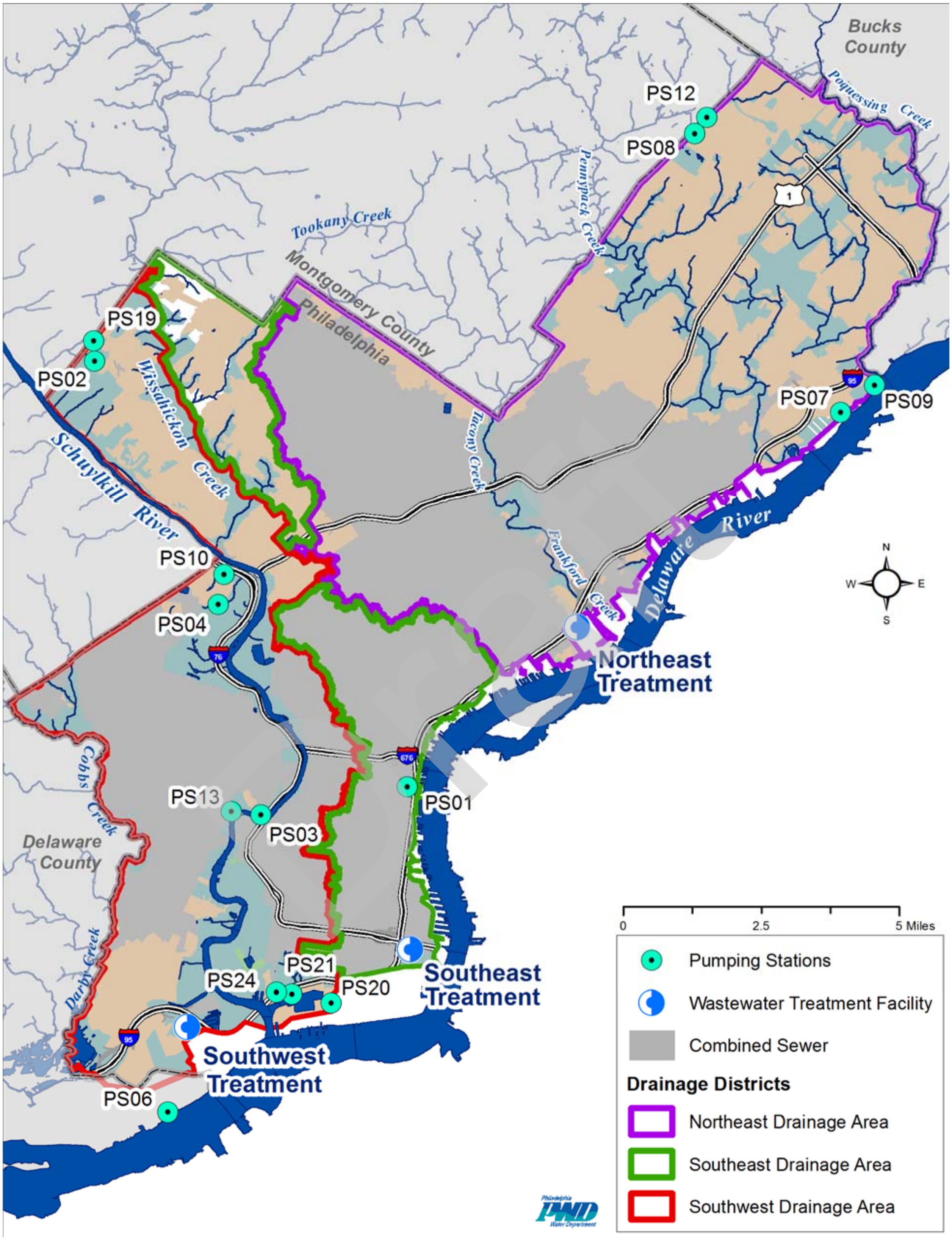

Figure 5-3: Location Map of Pumping Stations

5.1.1.4 Permanent Location Depth Monitoring

The Water Department maintains real-time sewer flow depth monitors in the combined sewer system at regulator locations and system hydraulic control points. The regulator chamber level monitors are typically located in the trunk sewer just above the regulator and in the outfall pipe itself. Hydraulic control point level monitors are generally located in interceptor sewers upstream of confluence points and in trunk sewers at diversion structures. Monitoring activities and data collection at each of these locations will be continued under the Comprehensive Monitoring Plan. These level monitors are used for system operation and control, identification of CSOs, and for determining head losses and hydraulic grade lines used for calibration and validation of system hydraulic models. Table 5-4 is a list of the permanent depth monitor locations, which can also be seen in the map in Figure 5-4.

Table 5-4: Permanent Depth Monitoring Locations

Site Name	Location	Measurement Name	Measurement Type
C_01	City Line Ave. & 73rd St.	SWO LEVEL	LEVEL
C_02	City Line Ave. 100' S of Creek	SWO LEVEL	LEVEL
C_04	Malvern Ave. & 68th St.	SWO LEVEL	LEVEL
C_04A	Malvern Ave. NW of 68th St.	SWO LEVEL	LEVEL
C_05	Lebanon Ave. SW of 73rd St.	SWO LEVEL	LEVEL
C_06	Lebanon Ave. & 68th St.	SWO LEVEL	LEVEL
C_07	Lansdowne Ave. & 69th St.	SWO LEVEL	LEVEL
C_09	64th St. & Cobbs Creek.	SWO LEVEL	LEVEL
C_10	Gross St. & Cobbs Creek.	SWO LEVEL	LEVEL
C_11	63rd St. S of Market St.	SWO LEVEL	LEVEL
C_12	Spruce St. @ Cobbs Creek.	SWO LEVEL	LEVEL
C_13	62nd St. @ Cobbs Creek.	SWO LEVEL	LEVEL
C_14	Baltimore Ave. & Cobbs Creek.	SWO LEVEL	LEVEL
C_15	59th St. & Cobbs Creek. Parkway	SWO LEVEL	LEVEL
C_16	Thomas Ave. & Cobbs Creek.	SWO LEVEL	LEVEL
C_17	Beaumont St. & Cobbs Creek.	SWO LEVEL	LEVEL
C_18	60th St. @ Cobbs Creek. Parkway	SWO LEVEL	LEVEL
C_19	Mount Moriah Cemetery & 62nd St.	SWO LEVEL	LEVEL
C_20	65th St. & Cobbs Creek. Parkway	SWO LEVEL	LEVEL
C_21	68th St. & Cobbs Creek. Parkway	SWO LEVEL	LEVEL
C_22	70th St. & Cobbs Creek. Parkway	SWO LEVEL	LEVEL
C_23	Upland St. Cobbs Creek. Parkway	SWO LEVEL	LEVEL
C_24	Greenway Ave. & Cobbs Creek. Parkway	SWO LEVEL	LEVEL
C_25	Woodland Ave. E of Island Ave.	SWO LEVEL	LEVEL
C_26	Saybrook Ave. & Island Ave.	SWO LEVEL	LEVEL
C_27	Paschall Ave. & Island Ave.	SWO LEVEL	LEVEL
C_28A	Island & Grays Aves.	SWO LEVEL	LEVEL

Site Name	Location	Measurement Name	Measurement Type
C_29	Claymount St. & Grays Ave.	SWO LEVEL	LEVEL
C_30	77th St. W of Elmwood Ave.	SWO LEVEL	LEVEL
C_31	Cobbs Creek. Park S of City Line Ave.	SWO LEVEL	LEVEL
C_32	Cobbs Creek. Park & 77th St.	SWO LEVEL	LEVEL
C_33	S of Brockton Rd. & Farrington Rd.	SWO LEVEL	LEVEL
C_34	Woodcrest Ave & Morris Park	SWO LEVEL	LEVEL
C_35	Morris Park W of 72nd St. & Sherwood R.	SWO LEVEL	LEVEL
C_36	69th St. & Woodbine Ave S of Brentwood	SWO LEVEL	LEVEL
C_37	Cobbs Creek. Park S of 67th St & Callowhill S.	SWO LEVEL	LEVEL
CSPS	University Ave. & 34th St Bridge	INTERCEPTOR LEVEL N	LEVEL
CSPS	University Ave. & 34th St Bridge	INTERCEPTOR LEVEL S	LEVEL
D_02	Cottman St. SE of Milnor St.	DWO LEVEL	LEVEL
D_02	Cottman St. SE of Milnor St.	SWO LEVEL	LEVEL
D_03	Princeton Ave SE of Milnor St.	DWO LEVEL	LEVEL
D_03	Princeton Ave SE of Milnor St.	SWO LEVEL	LEVEL
D_04	Disston St. SE of Wissinoming St.	DWO LEVEL	LEVEL
D_04	Disston St. SE of Wissinoming St.	SWO LEVEL	LEVEL
D_05	Magee St. SE of Milnor St.	DWO LEVEL	LEVEL
D_05	Magee St. SE of Milnor St.	SWO LEVEL	LEVEL
D_06	Levick St. SE of Milnor St.	DWO LEVEL	LEVEL
D_06	Levick St. SE of Milnor St.	SWO LEVEL	LEVEL
D_07	Lardner St. SE of Milnor St.	DWO LEVEL	LEVEL
D_07	Lardner St. SE of Milnor St.	SWO LEVEL	LEVEL
D_08	Comly St. SE of Milnor St.	SWO LEVEL	LEVEL
D_09	Dark Run La. & Milnor St.	DWO LEVEL	LEVEL
D_09	Dark Run La. & Milnor St.	SWO LEVEL	LEVEL
D_11	Sanger St. SE of Milnor St.	DWO LEVEL	LEVEL
D_11	Sanger St. SE of Milnor St.	SWO LEVEL	LEVEL
D_12	Bridge St. SE of Garden St.	SWO LEVEL	LEVEL
D_13	Kirkbridge St/ & Delaware Ave.	SWO LEVEL	LEVEL
D_15	Orthodox St. & Delaware Ave.	DWO LEVEL	LEVEL
D_15	Orthodox St. & Delaware Ave.	SWO LEVEL	LEVEL
D_17	Castor Ave. & Balfour St.	SWO LEVEL	LEVEL
D_18	Venango St. W of Casper St.	SWO LEVEL	LEVEL
D_19	Tioga St. W of Casper St.	SWO LEVEL	LEVEL
D_20	Ontario St. W of Casper St.	SWO LEVEL	LEVEL
D_21	Westmoreland St. W of Balfour St.	SWO LEVEL	LEVEL
D_22	Allegheny Ave. SE of Bath St.	SWO LEVEL	LEVEL
D_23	Indiana Ave. SE of Allen St.	SWO LEVEL	LEVEL
D_24	Cambria St. E of Melvale St.	SWO LEVEL	LEVEL

Site Name	Location	Measurement Name	Measurement Type
D_25	Somerset St. E of Richmond St.	SWO LEVEL	LEVEL
D_37	Cumberland St. & Richmond St.	SWO LEVEL	LEVEL
D_38	Dyott St. & Delaware Ave.	SWO LEVEL	LEVEL
D_39	Susquehanna Ave. E of Beach St.	SWO LEVEL	LEVEL
D_40	Berks St. E of Beach St.	SWO LEVEL	LEVEL
D_41	Palmer St. E of Beach St.	SWO LEVEL	LEVEL
D_42	Columbia Ave.E of Beach St.	SWO LEVEL	LEVEL
D_43	Marlborough St. & Delaware Ave.	SWO LEVEL	LEVEL
D_44	Shackamaxon St. E of Delaware Ave.	SWO LEVEL	LEVEL
D_45	Laurel St. & Delaware Ave.	SWO LEVEL	LEVEL
D_46	Penn St. & Delaware Ave.	SWO LEVEL	LEVEL
D_47	Fairmount Ave. W of Delaware Ave.	SWO LEVEL	LEVEL
D_48	Willow St. W of Delaware Ave.	SWO LEVEL	LEVEL
D_49	Callowhill St. & Delaware Ave.	SWO LEVEL	LEVEL
D_50	Delaware Ave. N of Vine St.	SWO LEVEL	LEVEL
D_51	Race St. W of Delaware Ave.	SWO LEVEL	LEVEL
D_51A	Race Street West of Delaware Avenue	TRUNK LEVEL	LEVEL
D_52	Delaware Ave. & Arch St. (inside I-95 fence)	SWO LEVEL	LEVEL
D_53	Market St. & Front St.	SWO LEVEL	LEVEL
D_54	Front St. S of Chestnut St.	SWO LEVEL	LEVEL
D_58	South St. & Delaware Ave.	SWO LEVEL	LEVEL
D_61	Catherine St. E of Swanson St.	SWO LEVEL	LEVEL
D_62	Queen St. E of Swanson St.	SWO LEVEL	LEVEL
D_63	Christian St. W of Delaware Ave.	SWO LEVEL	LEVEL
D_64	Washington Ave. E of Delaware Ave.	SWO LEVEL	LEVEL
D_65	Reed St. E of Delaware Ave.	SWO LEVEL	LEVEL
D_66	Tasker St. E of Delaware Ave.	SWO LEVEL	LEVEL
D_67	Moore St. E of Delaware Ave.	SWO LEVEL	LEVEL
D_68	Snyder Ave. & Delaware Ave.	SWO LEVEL	LEVEL
D_69	Delaware Ave. N of Porter St.	SWO LEVEL	LEVEL
D_70	Oregon Ave. & Delaware Ave.	SWO LEVEL	LEVEL
D_71	Bigler St. & Delaware Ave.	SWO LEVEL	LEVEL
D_72	Packer St. E of Delaware Ave.	SWO LEVEL	LEVEL
D_73	Pattison Ave. & Swanson St.	SWO LEVEL	LEVEL
F_03	Castor Ave. & Unity St.	SWO LEVEL	LEVEL
F_04	Wingohocking St. E of Adams Ave.	SWO LEVEL	LEVEL
F_05	Bristol St. W of Adams Ave.	SWO LEVEL	LEVEL
F_06	Worrell St. E of Frankford Creek.	SWO LEVEL	LEVEL
F_07	Worrell St. W of Frankford Creek.	SWO LEVEL	LEVEL
F_08	Erie Ave. & Hunting Park Ave.	SWO LEVEL	LEVEL

Site Name	Location	Measurement Name	Measurement Type
F_09	Frankford Ave. N or Frankford Creek.	SWO LEVEL	LEVEL
F_10	Frankford Ave. S of Frankford Creek.	SWO LEVEL	LEVEL
F_11	Paul St. S of Vandyke St.	SWO LEVEL	LEVEL
F_12	Sepviva St. N of Butler St.	SWO LEVEL	LEVEL
F_13	Duncan St. Under I-95	DWO LEVEL	LEVEL
F_13	Duncan St. Under I-95	SWO LEVEL	LEVEL
F_14	Bristol St. in Cemetery	SWO LEVEL	LEVEL
F_21	Wakling St. NW of Creek Basin	SWO LEVEL	LEVEL
F_23	Bridge St. NW of Creek Basin	SWO LEVEL	LEVEL
F_24	Bridge St. SE of Creek Basin	SWO LEVEL	LEVEL
F_25	Ash St. W of Creek Basin	SWO LEVEL	LEVEL
H_29	Main Relief Inflatable Dam Storage	DWO LEVEL	LEVEL
H_29	Main Relief Inflatable Dam Storage	SWO LEVEL	LEVEL
H_29	Main Relief Inflatable Dam Storage	TRUNK LEVEL	LEVEL
H_35	Rock Run Relief Inflatable Dam Storage	SWO LEVEL	LEVEL
R_01	56th St. & Locust St.	SWO LEVEL	LEVEL
R_01A	56th St. & Locust	SWO LEVEL	LEVEL
R_02	56th St. & Spruce St. (North)	SWO LEVEL	LEVEL
R_03	56th St. & Spruce St. (South)	SWO LEVEL	LEVEL
R_04	56th St. & Pine St.	SWO LEVEL	LEVEL
R_05	56th St. & Cedar Ave.	SWO LEVEL	LEVEL
R_06	56th St. & Webster St.	SWO LEVEL	LEVEL
R_07	16th St. & Clearfield St.	SWO LEVEL	LEVEL
R_08	22nd St. & Dauphin St.	SWO LEVEL	LEVEL
R_09	22nd St. & Berks St.	SWO LEVEL	LEVEL
R_10	22nd St. & Montgomery Ave.	SWO LEVEL	LEVEL
R_11	24th St. & North College Ave.	SWO LEVEL	LEVEL
R_11A	23th St. & North College Ave.	SWO LEVEL	LEVEL
R_12	Pennsylvania Ave. & Fairmount Ave.	SWO LEVEL	LEVEL
R_13	Levick East of Everett	SWO LEVEL	LEVEL
R_13A	Levick St. & Frontenac St.	SWO LEVEL	LEVEL
R_14	Benner East of Oakland	SWO LEVEL	LEVEL
R_15	7th St. & Nedro Ave	SWO LEVEL	LEVEL
R_16	Oregon Ave. Relief: Diversion Chamber	SWO LEVEL	LEVEL
R_17	Oregon Ave. Relief: Tide Gate Chamber	SWO LEVEL	LEVEL
R_18	Frankford Grit (FHL Relief Sewer)	SWO LEVEL	LEVEL
R_19	32nd St. & Thompson Relief Sewer	SWO LEVEL	LEVEL
R_20	Main St. & Shurs La.	SWO LEVEL	LEVEL
R_24	62nd & Arch St.	SWO LEVEL	LEVEL
R_25	16th & Snyder	SWO LEVEL	LEVEL

Site Name	Location	Measurement Name	Measurement Type
S_01	Mantua Ave. & West River Dr.	SWO LEVEL	LEVEL
S_02	Haverford Ave. & West River Dr.	SWO LEVEL	LEVEL
S_03	Spring Garden St. W of Schuylkill Exp.	SWO LEVEL	LEVEL
S_04	Powelton Ave. W of Schuylkill Exp.	SWO LEVEL	LEVEL
S_05	24th St. 155 S of Park Towne Place	SWO LEVEL	LEVEL
S_06	24th St. 350' S of Park Towne Place	SWO LEVEL	LEVEL
S_07	24th St. E of Schuylkill R. (Vine St.)	SWO LEVEL	LEVEL
S_08	Race St. & Bonsall St.	SWO LEVEL	LEVEL
S_09	Arch St. W of 23rd St.	SWO LEVEL	LEVEL
S_10	Market St. 25' E of 24th St.	SWO LEVEL	LEVEL
S_11	Market St. (in PRR Baggage Room)	SWO LEVEL	LEVEL
S_12	24th St. N of Chestnut St. Bridge	SWO LEVEL	LEVEL
S_12A	24th St. under Chestnut St. Bridge	SWO LEVEL	LEVEL
S_13	Samson St. W of 24th St.	SWO LEVEL	LEVEL
S_14	Schuylkill Expressway Under Walnut St.B	SWO LEVEL	LEVEL
S_15	Walnut St. W of 24th St.	SWO LEVEL	LEVEL
S_16	Locust St. & 25th St.l;	SWO LEVEL	LEVEL
S_17	Spruce St. & 25th St.	SWO LEVEL	LEVEL
S_18	Pine St. W of Taney St.	SWO LEVEL	LEVEL
S_19	Lombard St. W of 27th St.	SWO LEVEL	LEVEL
S_20	NNW of South St. (Behind Penn Stad.)	SWO LEVEL	LEVEL
S_21	South St. E of 27th St.	SWO LEVEL	LEVEL
S_22	660' S of South St E of Penn Field	SWO LEVEL	LEVEL
S_23	Schuylkill Ave. & Bainbridge St.	SWO LEVEL	LEVEL
S_24	1060' S of South St. E of Penn Field	SWO LEVEL	LEVEL
S_25	Schuylkill Ave. & Christian St.	SWO LEVEL	LEVEL
S_26	Ellsworth St. E of Schuylkill R.	SWO LEVEL	LEVEL
S_27	43rd & Locust St.	DWO LEVEL	LEVEL
S_27	43rd & Locust St.	SWO LEVEL	LEVEL
S_28	Chester Ave. W of 43rd St.	SWO LEVEL	LEVEL
S_30	46th St. & Paschall Ave.	SWO LEVEL	LEVEL
S_31	Reed St. & Schuylkill Ave.	SWO LEVEL	LEVEL
S_32	49th St. S of Botanic St.	SWO LEVEL	LEVEL
S_33	51st St. & Botanic Ave.	SWO LEVEL	LEVEL
S_34	52nd St. & Paschall Ave.	SWO LEVEL	LEVEL
S_35	35th St. & Mifflin St.	SWO LEVEL	LEVEL
S_36	36th St. & Mifflin St.	SWO LEVEL	LEVEL
S_36A	34th St. & Mifflin St.	SWO LEVEL	LEVEL
S_37	Vare Ave. & Jackson St.	SWO LEVEL	LEVEL
S_38	56th St. E of P&R RR	SWO LEVEL	LEVEL

Site Name	Location	Measurement Name	Measurement Type
S_39	57th St. & Grays Ave.	SWO LEVEL	LEVEL
S_40	59th St. & Grays Ave.	SWO LEVEL	LEVEL
S_42	Passyunk Ave. & 29th St.	SWO LEVEL	LEVEL
S_42A	Passyunk Ave. & 28th St.	SWO LEVEL	LEVEL
S_43	64th St. & Buist Ave.	SWO LEVEL	LEVEL
S_44	26th St. 700' off Hartranft St.	SWO LEVEL	LEVEL
S_45	67th St. E of P&R RR	DWO LEVEL	LEVEL
S_45	67th St. E of P&R RR	SWO LEVEL	LEVEL
S_46	Penrose Ave. & 26th St.	SWO LEVEL	LEVEL
S_47	69th St. & Buist Ave.	SWO LEVEL	LEVEL
S_50	43rd St. E of Woodland Ave.	SWO LEVEL	LEVEL
S_51	42nd St. SE of Woodland Ave.	SWO LEVEL	LEVEL
T_01	Williams Ave. SE of Sedgwick St	SWO LEVEL	LEVEL
T_03	Champlost Ave. W of Tacony Creek.	SWO LEVEL	LEVEL
T_04	Rising Sun Ave. E of Tacony Creek.	SWO LEVEL	LEVEL
T_05	Rising Sun Ave. W of Tacony Creek.	SWO LEVEL	LEVEL
T_06	Bingham St. E of Tacony Creek.	SWO LEVEL	LEVEL
T_07	Tabor Rd. W of Tacony Creek.	SWO LEVEL	LEVEL
T_08	Ashdale St. W of Tacony Creek.	SWO LEVEL	LEVEL
T_09	Roosevelt Blvd. W of Tacony Creek.	SWO LEVEL	LEVEL
T_10	Roosevelt Blvd. E of Tacony Creek.	SWO LEVEL	LEVEL
T_11	Ruscomb St. E of Tacony Creek.	SWO LEVEL	LEVEL
T_12	Whitaker Ave. E of Tacony Creek.	SWO LEVEL	LEVEL
T_13	Whitaker Ave. W of Tacony Creek.	SWO LEVEL	LEVEL
T_14	I St. & Ramona St.	SWO LEVEL	LEVEL
T_15	J St. & Juniata Park	SWO LEVEL	LEVEL

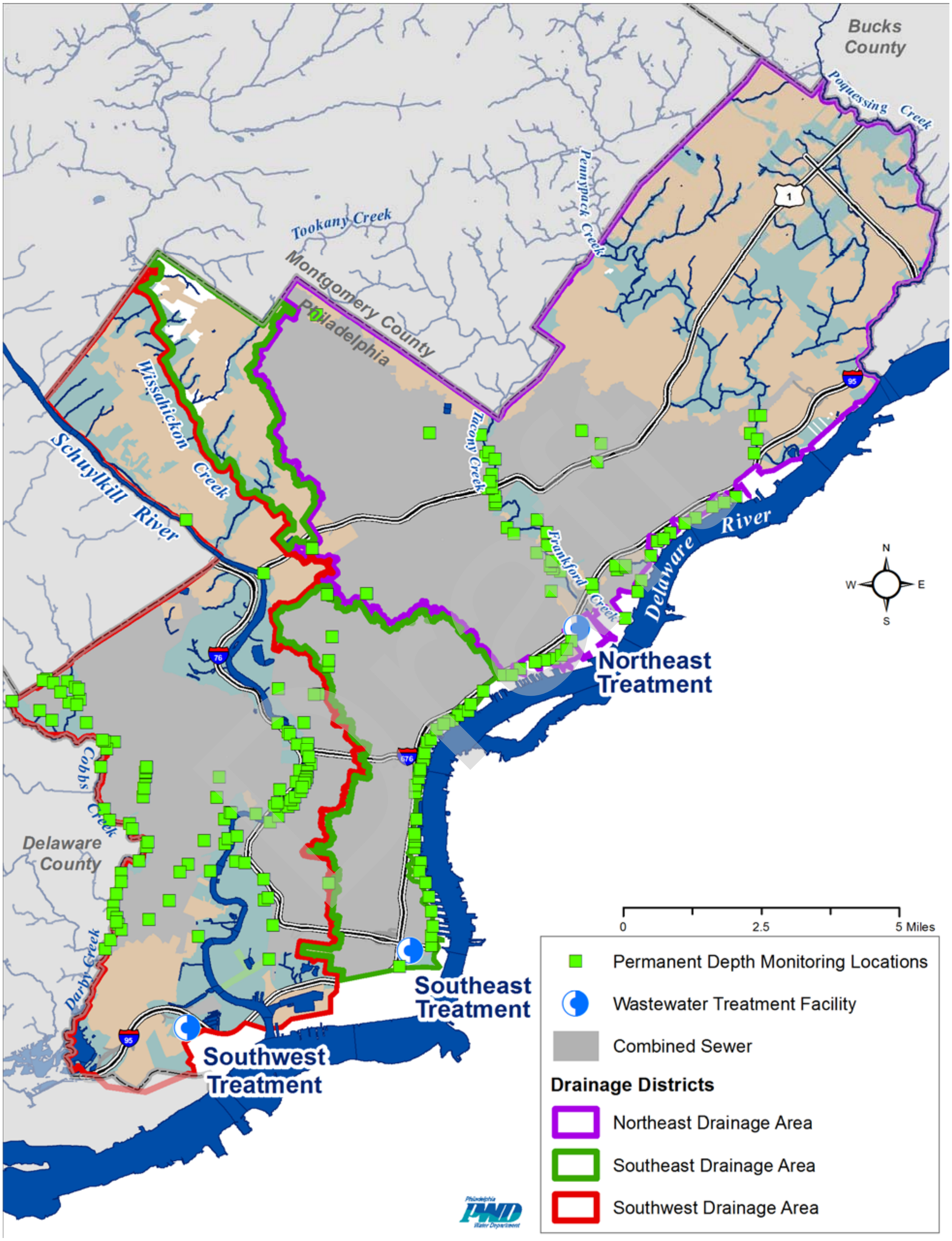

Figure 5-4: Permanent Depth Monitoring Locations

5.1.2 Portable Flow and Level Monitoring

The Water Department portable flow and level monitoring program will be continued as part of the Comprehensive Monitoring Plan. The primary categories of portable monitoring sites under this Comprehensive Monitoring Plan are as follows:

- Sanitary sewershed characterization monitoring sites
- Combined sewer storm relief area monitoring sites
- Outlying community point of connection monitoring sites
- Other targeted monitoring sites at selected sewershed areas

Sanitary sewershed monitoring, initiated in July 1999, deployed flow meters throughout targeted Philadelphia sewershed areas to quantify wastewater flow through sanitary sewers and characterize the tributary sewersheds. This work continued through 2004 with a primary focus on flow monitoring of sanitary sewersheds in order to characterize rainfall dependent inflow and infiltration rates as well as base wastewater and ground water infiltration rates from service areas both within and outside the City. Approximately 56 locations were monitored over this period (1999-2004) with deployment durations ranging from two months to over three years. After the desired monitoring duration and quantity of data was achieved, the portable monitoring equipment was relocated to new sites to maximize the coverage of the Water Department service area. Under the Comprehensive Monitoring Plan, selected sanitary sewersheds will be monitored on a temporary basis to continue the process of refining the characterization and quantification of dry and wet weather flow from separate sewershed areas as the *Green City, Clean Waters* program is implemented.

Combined sewer storm relief monitoring was initiated in 2005. Sixteen flow and nine level-only monitoring locations were selected in targeted combined sewer storm flood relief areas that were experiencing basement flooding caused by sewer backups. The deployment dates and locations of the storm flood relief meters are shown in Table 5-5 and Figures 5-5 and 5-6. Combined sewer storm flood relief monitoring will be continued as needed to better characterize areas that experience sewer backups into basements.

Table 5-5: Fall 2005 and Spring 2006 Deployment Dates, Locations, and Meter IDs for Targeted Storm Flood Relief Areas

Meter ID	Measurement Type	Location	Date Installed	Deployment Phase
D39-110	Level and Flow	Northern Liberties	4/21/2006	Spring 2006
D39-110	Level and Flow	Northern Liberties	11/21/2007	Fall 2007
D44-75	Level Only	Northern Liberties	4/20/2006	Spring 2006
D44-75	Level and Flow	Northern Liberties	9/20/2005	Fall 2005
D45-000080	Level Only	Northern Liberties	9/20/2005	Fall 2005
D45-1425	Level Only	Northern Liberties	4/20/2006	Spring 2006
D45-165	Level Only	Northern Liberties	11/1/2005	Fall 2005
D45-1660	Level and Flow	Northern Liberties	9/19/2005	Fall 2005
D45-3620	Level Only	Northern Liberties	9/22/2005	Fall 2005

Meter ID	Measurement Type	Location	Date Installed	Deployment Phase
D45-3705	Level and Flow	Northern Liberties	4/21/2006	Spring 2006
D45-445	Level Only	Northern Liberties	9/21/2005	Fall 2005
D45-45	Level and Flow	Northern Liberties	5/5/2006	Spring 2006
D45-450	Level and Flow	Northern Liberties	5/19/2006	Spring 2006
D45-490	Level and Flow	Northern Liberties	4/20/2006	Spring 2006
D45-510	Level and Flow	Northern Liberties	4/20/2006	Spring 2006
D45-610	Level and Flow	Northern Liberties	4/21/2006	Spring 2006
D45-70	Level and Flow	Northern Liberties	4/20/2006	Spring 2006
D54-000080	Level Only	Germantown	9/20/2005	Fall 2005
D54-15	Level and Flow	Washington West	5/18/2006	Spring 2006
D54-3320	Level and Flow	Washington West	9/19/2005	Fall 2005
D54-3653	Level and Flow	Washington West	4/24/2006	Spring 2006
D54-3890	Level and Flow	Washington West	9/19/2005	Fall 2005
D54-3890	Level and Flow	Washington West	4/24/2006	Spring 2006
D54-70	Level Only	Washington West	9/19/2005	Fall 2005
D54-70	Level and Flow	Washington West	4/21/2006	Spring 2006
D54-95	Level and Flow	Washington West	10/10/2005	Fall 2005
D66-001595	Level and Flow	Germantown	6/10/2011	Spring 2011
D66-125	Level and Flow	Tasker Street	10/18/2005	Fall 2005
D66-140	Level and Flow	Tasker Street	4/25/2006	Spring 2006
D66-1585	Level and Flow	Tasker Street	4/25/2006	Spring 2006
D66-1625	Level and Flow	Tasker Street	10/10/2005	Fall 2005
D68-135	Level and Flow	Passyunk Avenue	11/2/2005	Fall 2005
D68-1505	Level and Flow	Passyunk Avenue	11/7/2005	Fall 2005
D68-430	Level Only	Passyunk Avenue	9/20/2005	Fall 2005
D68-85	Level and Flow	Passyunk Avenue	9/22/2005	Fall 2005
S42-130	Level and Flow	Passyunk Avenue	11/1/2005	Spring 2006
S42-130	Level and Flow	Passyunk Avenue	11/21/2007	Fall 2007
T14-000140	Level and Flow	Germantown	10/14/2011	Fall 2010
T14-000330	Level and Flow	Germantown	1/30/2012	Winter 2012
T14-000345	Level and Flow	Germantown	9/29/2010	Fall 2010
T14-000490	Level and Flow	Germantown	2/1/2011	Winter 2011
T14-010220	Level and Flow	Germantown	4/27/2012	Spring 2012
T14-013795	Level and Flow	Germantown	1/27/2012	Winter 2012
T14-013875	Level and Flow	Germantown	2/28/2012	Winter 2012
T14-013940	Level and Flow	Germantown	2/18/2011	Winter 2011
T14-013985	Level and Flow	Germantown	9/14/2011	Fall 2010
T14-014030	Level and Flow	Germantown	2/11/2011	Winter 2011
T14-023480	Level and Flow	Germantown	5/26/2011	Spring 2011
T14-029300	Level and Flow	Germantown	6/15/2011	Spring 2011

The Water Department also performs portable flow monitoring of outlying community points of connection with the City of Philadelphia that serve small areas without existing permanent flow meters. In a monitoring program that commenced in 2004, 24 sanitary sewer locations were monitored at a time for three month durations. The following year, the portable monitoring equipment was relocated to 24 different points of connection sites and monitoring was conducted for three months. In this way, data from the temporary outlying community monitoring sites was updated every three years. The flow data are evaluated and the primary use is for updating billing estimates. The outlying community point of collection monitoring program with its three year cycles will be continued under the Comprehensive Monitoring Plan. The data will be used to further refine the characterization and quantification of dry and wet weather flow discharged from customer municipalities. The locations for these meters can be listed in Table 5-6 and shown in Figure 5-7.

Additional flow monitoring at targeted sewershed areas has continued through present day for calibration and verification of detailed combined sewer system models used for characterizing the response of the sewer system to wet weather under current conditions and for the evaluation of the performance benefit of proposed the Long Term Control Plan Update projects. A list of all portable monitoring deployments within the City since 1999 is located in Appendix E. Currently, temporary flow monitoring is performed through a contract to provide sewer monitoring. Depth and velocity data are monitored continuously and recorded at intervals of no more than 15-minutes. Monitors are generally left in place until a sufficient duration of dry weather days and a sufficient number and range of smaller and larger rain events are captured. The monitors are then removed and reinstalled at other selected sewer sites to maximize the coverage of the Water Department service area. The Water Department portable flow monitoring program will continue under the Comprehensive Monitoring Plan. The selection of new monitoring sites is discussed in Section 5.1.2.1.

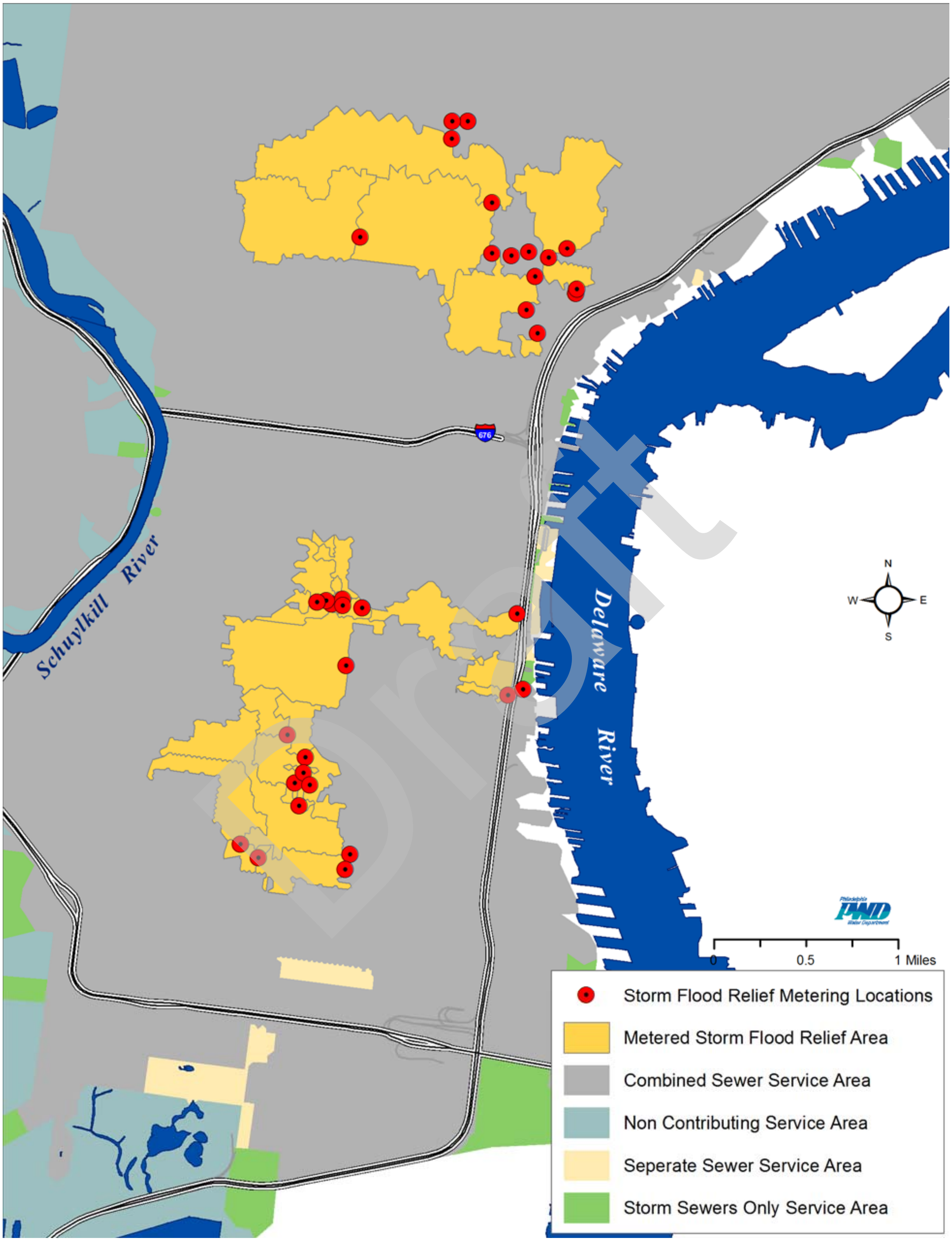

Figure 5-5: Targeted Storm Flood Relief Monitoring Program Meter Locations for the South Philadelphia Area

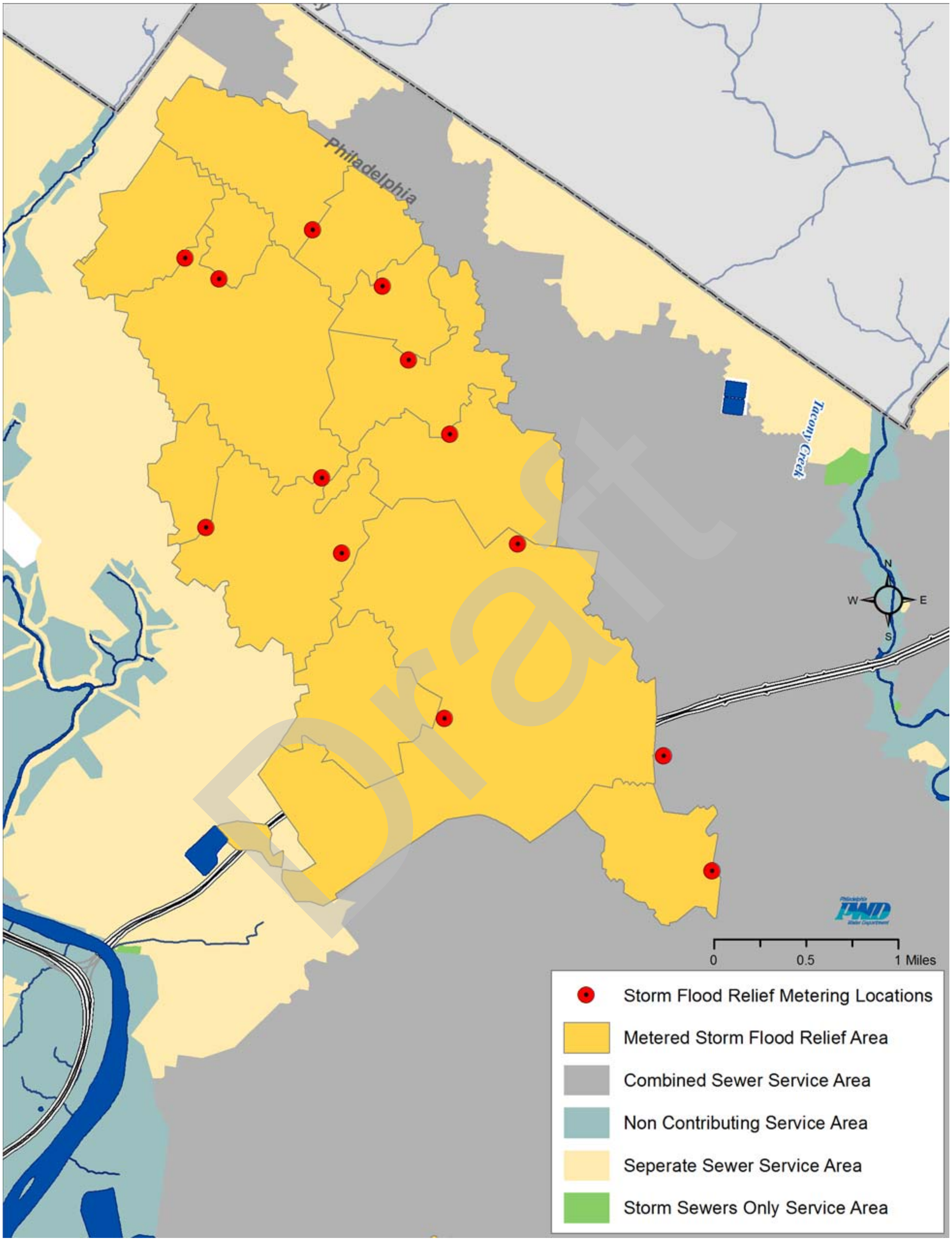

Figure 5-6: Targeted Storm Flood Relief Monitoring Program Meter Locations for the Germantown Area

Table 5-6: Outlying Community Temporary Meter Locations

Temporary Meter Deployments for Outlying Community Connections			
Site ID	Township	Drainage District	Location
MA1	Abington	NE	Buckly Drive & Pine Rd
MA3	Abington	NE	Shady Lane & Pine Road
MA4	Abington	NE	Pine Road & Lee Lynn La.
MCx1	Cheltenham	NE	Cottman (Out)
MCx2	Cheltenham	NE	County Line & Franklin (Out)
MCx3	Cheltenham	NE	County Line & Washington (Out)
MCx4	Cheltenham	NE	Kerper (Out)
MCx5	Cheltenham	NE	Passmore (Out)
MCx6	Cheltenham	NE	Devereaux (Out)
MCx7	Cheltenham	NE	Comly (Out)
ML2	Lower Merion	SW	59th Street & City Line
ML3	Lower Merion	SW	63rd Street
MLM3	Lower Moreland	NE	Ramage Run & City Boundry
MLM4	Lower Moreland	NE	Moreland Rd. & Pine Rd.
MLM5	Lower Moreland	NE	Jonathan place
MLM6	Lower Moreland	NE	Pine & Radburn Rd
MLM7	Lower Moreland	NE	Welsh Road and City Line
MS1	Springfield	SW	Thomas & Northwestern
MS4	Springfield	SE	Mermaid La. & Stenton
MS5	Springfield	SE	Winston & Stenton
MS7	Springfield	SE	Willow Grove & Stenton
MS8	Springfield	SW	Ridge Ave Connections
MSH1	Southampton	NE	Trevose Rd
MSH2	Southampton	NE	Thomas & Northwestern
MSHX_1	Southampton	NE	Mermaid La. & Stenton
MSHX_2	Southhampton	NE	Winston & Stenton

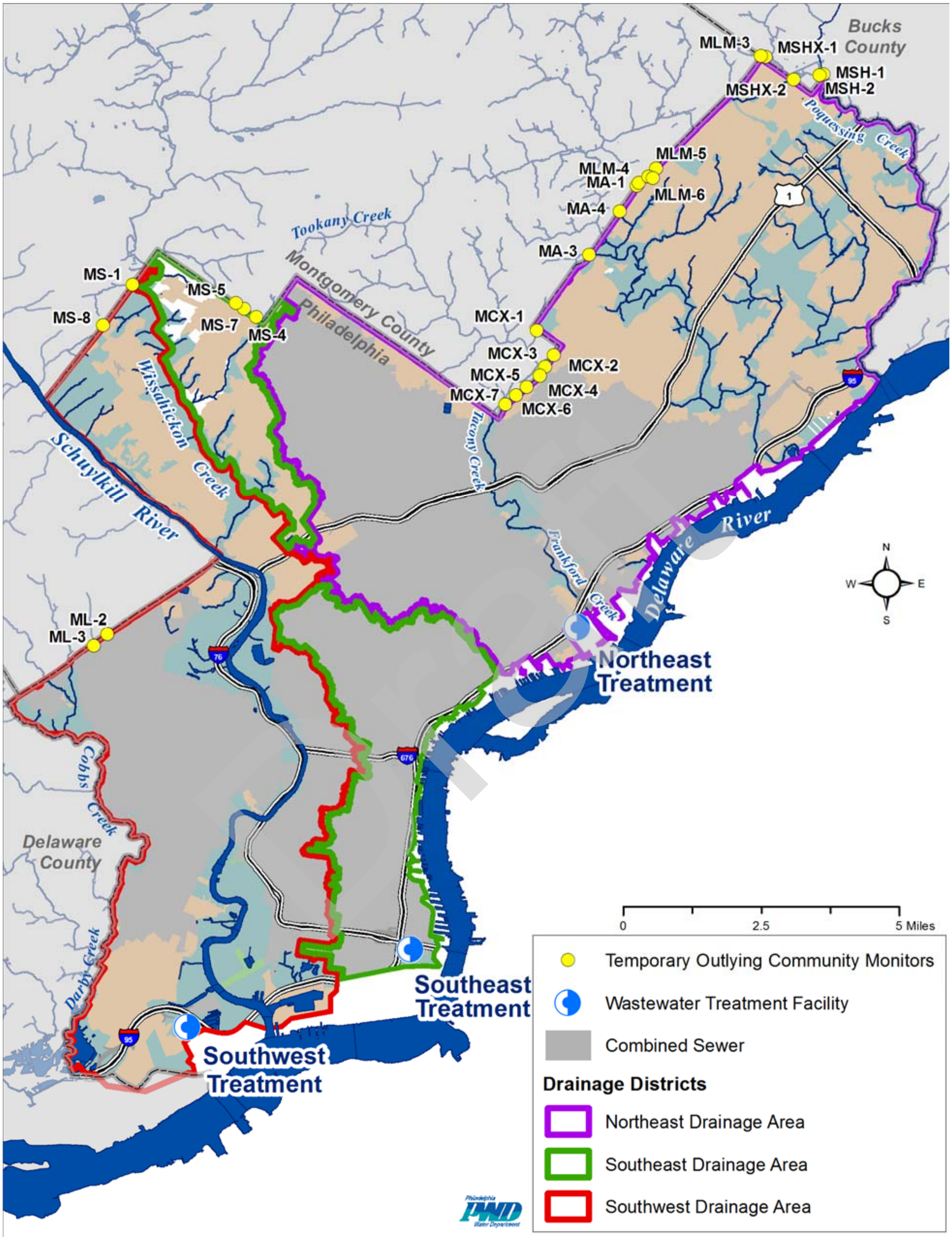

Figure 5-7: Location Map of Temporary Outlying Community Monitors

5.1.2.1 Temporary Flow Monitoring Site Selection

Under the Comprehensive Monitoring Plan, temporary monitoring locations will be distributed among different sewer system types in order to more accurately characterize the entire sewer system. At any given time, temporary flow monitoring deployments will be distributed among different areas with the following percent ranges:

- Combined Sewers – 50 to 60%
- Sanitary Sewers – 30 to 40%
- Project Specific – 0 to 10%

Under the Comprehensive Monitoring Plan, a project specific monitoring site would include a specifically targeted piece of infrastructure, a targeted priority location (e.g., Storm Flood Relief), monitoring of a constructed project connected to the Combined Sewer System, or a hydraulic control point that needs special evaluation. Combined and sanitary sewer locations are typically installed in manholes with access to the sewer. Primary flow monitoring locations should target priority locations coordinated with permanent metering programs as part of automated and real time Combined Sewer System operation decision support systems.

A site investigation rating system was developed to assess the feasibility of new sites for portable sewer system monitoring. Criteria were developed for a range of scores from A to F; with A being the most easily feasible and F being completely infeasible. This existing site investigation rating system will be utilized to implement the Comprehensive Monitoring Plan. The rating system helps to differentiate between ideal, average, and marginal monitoring sites and adjust expectations in regard to data quality and the uncertainty range associated with the monitored data from specific monitoring sites. The criteria are outlined in Table 5-7. Monitors are typically only installed at sites that receive a rating of A, B, or C. The field notes from each monitor site investigation provide information that assists with site selection. The site installation includes photos, video, and a detailed description of the conditions at each monitoring location. An example set of field notes for a site investigation is provided Appendix F.

Table 5-7: Portable Monitoring Site Selection Criteria and Score System

Site Conditions		
Initial	Access	yes/no
	Safety	yes/no
	Adequate space to install sensors	yes/no
Pipe	Pipe Shape	irregular / uniform
	Rectangular Pipe Bottom	flat / v bottom
	Pipe Material	concrete/brick/steel/etc.
	Proximity to Bend	distance (ft)
Flow	Depth Measurement	depth (in)
	Velocity Measurement	velocity (ft/s)
	Silt	depth of silt (in)
	Flow Regime	amplitude of inst. dry weather flow variation

Site Score Card		Action
A	Ability to access site	Install Flow Meter
	No safety Concerns (traffic, depth, sewer gas, etc.)	
	Adequate sensor placement	
	Rectangular Pipe not flat bottom box (where applicable)	
	Site more than 10 diameters from pipe attribute change	
	No silt present at site	
	Field measured flow depth > 4"	
	Field measured velocity > 2 ft/s and < 5 ft/s	
	Turbulence amplitude <= 0.25"	
B	Ability to access site	Install Flow Meter
	No safety Concerns (traffic, depth, sewer gas, etc.)	
	Adequate sensor placement	
	Rectangular Pipe not flat bottom box (where applicable)	
	Site more than 5 diameters from pipe attribute change	
	No silt present at site	
	Field measured flow depth > 3"	
	Field measured velocity > 1.5 ft/s and < 5 ft/s	
	Turbulence amplitude <= 0.75"	
C	Ability to access site	Investigate nearby alternate sites. Install if no better option is found
	No safety Concerns (traffic, depth, sewer gas, etc.)	
	Adequate sensor placement	
	Rectangular Pipe not flat bottom box (where applicable)	
	Site more than 5 diameters from pipe attribute change	
	Minimal silt present at site	
	Field measured flow depth > 2"	
	Field measured velocity > 1 ft/s and < 7 ft/s	
	Turbulence amplitude <= 1.5"	
D	Ability to access site	Confirm with the Water Department before installation
	No safety Concerns (traffic, depth, sewer gas, etc.)	
	Adequate sensor placement	
	Rectangular Pipe not flat bottom box (where applicable)	
	Site more than 5 diameters from pipe attribute change	
	Silt present at site	
	Field measured flow depth > 1.5"	
	Field measured velocity > 0.5 ft/s and < 10 ft/s	
	Turbulence amplitude <= 3"	
F	Criteria for D not met	Do not install Flow Meter

5.1.2.2 Anticipated Temporary Flow Monitoring

In addition to the existing sources of data from fixed long-term monitoring locations, the Water Department's Comprehensive Monitoring Plan will continue the portable flow monitoring program to collect combined and sanitary sewer system data from a greater number of locations.

Each interceptor system drainage area will be individually targeted for flow monitoring investigations aimed at identifying representative locations highly suitable for flow monitoring. Some of the larger CSO basins may call for monitoring of multiple smaller sub-sewershed basins or warrant investigating alternative portable high-rate metering technology or permanent meter installation.

Secondary monitoring locations will be deployed on a rotating basis in continued support of Combined Sewer System remediation projects and investigations. Installed monitors are generally left in place until a sufficient number of dry weather days and rainfall events are captured, including storms of varying intensity, total volume, and antecedent dry periods. Many sites with acceptable quality data are left in place for a complete year in order to characterize the seasonal variability in dry-weather and wet-weather inflow and infiltration rates. These monitors are then removed and reinstalled at other selected sewer sites to maximize the coverage of the Water Department service area. Selected representative locations that are determined to be highly suitable for flow monitoring using portable velocity-depth recording technology are planned to be deployed and maintained as long-term monitoring sites. This will enable correlation of results from all monitoring periods while accounting for inter-annual variations.

5.1.2.3 Considerations for Future Monitoring Site Selections

CSO Control Capital Project Design and Evaluation

Achieving the quantitative performance standards of the Water Quality Based Effluent Limit may require implementation of controls and combined sewer system improvements beyond green stormwater infrastructure. Projects that are implemented as part of other Water Department priorities, such as storm flood relief, may also provide CSO reductions. The Water Department updates the hydrologic and hydraulic models as projects move from planning to design and from design to construction, adjusting model parameters with design changes and final construction status. As part of this process additional sewer system monitoring targeted in or near new infrastructure may be necessary under the Comprehensive Monitoring Plan to characterize its effect from design to completed construction.

Flood Relief Studies

In order to address and reduce flooding in areas of the City—including South Philadelphia, Northern Liberties, and Germantown— study area specific sewer system modeling and alternatives analyses were conducted using hydrologic and hydraulic models developed as part of the storm flood relief program. In order to calibrate and validate the storm flood relief program models, portable sewer monitors were deployed in targeted storm flood relief program areas. The data that is collected from storm flood relief program monitoring is also used to supplement the data for the CSO models. Future storm flood relief program monitoring stations, installed under the Comprehensive Monitoring Plan, can be used to provide flow data for both storm flood relief program efforts and to improve the overall City hydrologic and hydraulic model.

5.2 Sewer System Monitoring Analysis

The Comprehensive Monitoring Plan not only encompasses flow monitoring activities and collecting data, but also includes the associated quality assurance programs and data analysis efforts. This section presents an overview of the methods and processes that have been developed and used in conducting sewer system flow monitoring data quality assurance and control procedures as well as primary data reduction and analysis methods. The collected data is organized, assessed for errors, and analyzed using a variety of tools and methods for use in models and other assessment programs. These quality assurance procedures and data analysis methods will be applied to Comprehensive Monitoring Plan activities and data.

5.2.1 Flow Data Quality Assurance and Control Procedures for the Comprehensive Monitoring Plan

Flow monitoring field personnel install and maintain depth and velocity recording monitors and upload hydraulic data, via a laptop computer, on a bi-weekly basis throughout the monitoring period. All deployed monitors have data uploaded in a period of 2 to 14 days. Obtaining and recording field-measured depth, velocity, and flow points are vital in verifying that the monitoring equipment is properly calibrated and providing reliable results. During site visits, field calibration measurements are taken at various times of the day and under various ranges of depths and flows to check and verify the equipment is functioning correctly. Wastewater depths are measured from the crown of the pipe using a ruler. Average velocities through the pipe are measured using a hand-held portable velocity meter. Several of the field calibration events for each meter location take place in high flow periods during wet weather at locations where a measurement may be safely obtained by the crew. The calibration data and observed discrepancies are documented by field crews in a field log and submitted along with interrogated data from every deployed site. After several site visits, the field-measured flow points are used to establish depth versus flow relationships and rating curves when appropriate to be used in quality assurance procedures.

The monitored data are transferred from the field to the Water Department Server on a bi-weekly basis where they undergo a comprehensive quality assurance and quality control review process. Standard procedures for reviewing the portable flow monitoring data, assessing its accuracy, and making any required adjustments are in development.

Flow meter data are imported into template quality assurance and quality control spreadsheets where missing, errant, or otherwise unusable data can be identified and either flagged for removal or filled using averaging techniques. The spreadsheet is a useful tool facilitating the evaluation, documentation, and organization of monthly flow data. The spreadsheets are used to create time-series plots and scatter-plots of raw monitored data which are qualitatively assessed (alongside quantitative analyses) for anomalies that may have otherwise gone unnoticed.

Two types of data errors are detected: random errors and systematic errors. Random errors are typically caused by temporary hydraulic conditions or sensor problems that usually last for a few time-steps. Since randomly errant data points usually are surrounded by reliable data points, both depth and velocity errors can be corrected by matching the adjacent data. The corrections are made by observing the reliable depths, velocities, and flows from the adjacent monitored data, observing the trends, and applying linear interpolations between the adjacent data points to determine the appropriate value for the incorrect data point(s).

Systematic errors are typically caused by long-term hydraulic conditions, sensor fouling, improper calibrations, and/or equipment failures that can last several hours, several days, or even several weeks in extreme cases. These errors in depth measurements usually cannot be corrected. When depth sensors are fouled or fail for long durations, there are usually not reliable means by which to recover or correct the lost or errant data. Detected errant data are flagged for unacceptable quality, regarded as data gaps, and are not used in the subsequent data analyses. However, errors in velocity measurements usually can be corrected as long as the corresponding depth measurements are reliable. Systematic errors may be corrected by using the envelope curve(s) from the scatter-plots to mathematically define the typical depth-flow relationships (rating curves) at the monitoring site. The rating curve can then be applied to the level data to obtain an estimate of the flow. These relationships are generally reliable only during dry weather conditions. Recurring systematic error can be an indication of hydraulic conditions unsuitable for depth velocity monitoring or of a sensor or meter that requires maintenance.

5.2.2 Flow Monitoring Data Analysis for the Comprehensive Monitoring Plan

Once the Comprehensive Monitoring Plan flow and rainfall monitoring data have been quality assured and processed, they are imported into databases that contain all data used in the analyses needed to characterize the wet weather flow response in either the sanitary or combined sewer being monitored. The data are imported along with rainfall data into the United States Environmental Protection Agency (US EPA) Sanitary Sewer Overflow Analysis and Planning software package designed to analyze sewer flow monitoring data.

The software assists in performing dry weather flow evaluations to determine average daily weekend and weekday dry weather flow patterns from the period of record. The weekend and weekday dry weather flow patterns are different and require individual evaluation. The software facilitates the selection of days with normal dry weather flows to be used to determine the average daily dry weather flow patterns for a monitoring location. The dry weather flow includes groundwater infiltration and base wastewater flows. Groundwater adjustment points are added to represent seasonal changes in groundwater infiltration rates by graphically aligning computed average daily dry weather flow patterns and observed flow time series. The US EPA Sanitary Sewer Overflow Analysis and Planning software then subtracts the average daily dry weather flow hydrographs from observed flow time series during rainfall events to determine the wet weather flow hydrograph, including rainfall dependent infiltration and inflow in sanitary sewers and stormwater runoff in combined sewers.

Wet weather flow evaluations lead to the determination of rainfall dependent infiltration and inflow and runoff peak flow rates and volumes for individual events. US EPA Sanitary Sewer Overflow Analysis and Planning computes the percentage of rainfall over the sewered area that enters the sewer system, or the total R-value. It also allows the fitting of triangular unit hydrograph parameters to simulate rainfall dependent infiltration and inflow flows from observed rainfall using the RTK methodology (US EPA, 2007).

Unwanted rainfall enters the sanitary sewer system as rainfall dependent infiltration and inflow as inflows from directly connected downspout pipes, sump pumps, foundation drains, manhole openings, and large defects along streams and as infiltration through saturated soils and an elevated groundwater table into small leaks in degraded sewer pipes and joints. Excessive rainfall dependent infiltration and inflow reduces the available sewer capacity available to convey sanitary and combined sewage through the interceptors for treatment. The hydrologic and hydraulic model uses the RTK values to represent the shape of the rainfall dependent infiltration and inflow hydrograph response to the input precipitation hyetograph.

Specific rainfall event boundaries are defined with rain gage data as input for each flow meter site. The initial selection criterion includes a minimum rainfall depth of 0.1 inch. Quality assurance of the events is completed after event boundary delineation to remove events affected by errant data, snow, or malfunctioning rain gages. These selected rainfall event boundaries are used along with the basin average rainfall time series throughout the model calibration process.

RTK shape analysis is performed for selected sanitary sewer system monitoring locations using US EPA Sanitary Sewer Overflow Analysis and Planning or an iterative spreadsheet tool developed by the Water Department. RTK shape analysis fits three triangular unit hydrographs to an actual rainfall dependent infiltration and inflow 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. The analysis determines RTK values to characterize rainfall dependent infiltration and inflow response for the sanitary sewer system, which are defined as the following:

- R – The fraction of rainfall volume that enters the sewer system and equals the volume under the hydrograph
- T – The time from the onset of rainfall to the peak of the unit hydrograph in hours
- K – The ratio of time to recession of the unit hydrograph to the time to peak.

The first unit hydrograph represents the most rapidly responding inflow component and has a T of one to three hours. The second unit hydrograph includes both rainfall-derived inflow and infiltration and has a longer T value. The third unit hydrograph includes infiltration that may continue long after the storm has ended and has the longest T value. The RTK parameters for each of the three triangles are defined for each unit rainfall over one unit time frame. The sum of the R values for each of the three unit hydrographs (*i.e.*, R1, R2, R3) must equal the total R value for the rainfall event. A flowchart of rainfall dependent infiltration and inflow and RTK parameter analysis can be seen in Figure 5-8. A more detailed decomposition of the rainfall dependent infiltration and inflow hydrograph into three unit hydrographs is shown in Figure 5-9.

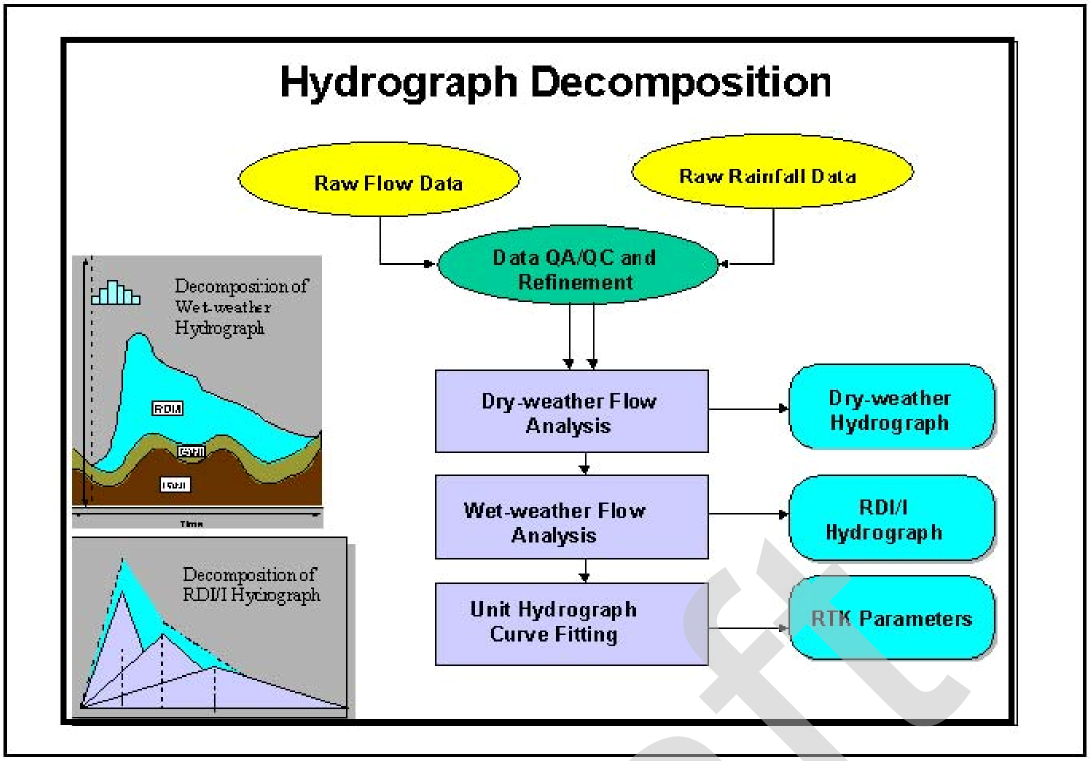

Figure 5-8: Processing Steps and Outputs from the SHAPE Software

Rainfall dependent infiltration and inflow analysis is performed on separate sanitary sewersheds to more accurately account for the rate of excess rain water entering the sanitary sewer system and quantify its effects in reducing wet weather treatment capacity available in the combined sewer collection and treatment system. The quantification of rainfall dependent infiltration and inflow in the sanitary sewer collection system is also important for sewer condition assessment as part of a maintenance and capacity management program.

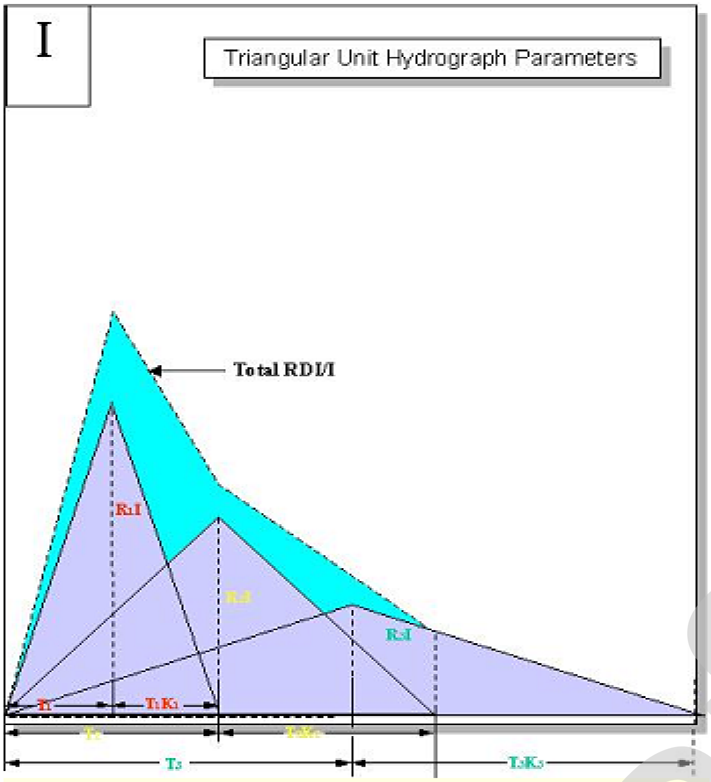

Figure 5-9: Deconstruction of Rainfall Dependent Infiltration and Inflow Hydrograph into Three Unit Hydrographs with SHAPE Software

6.0 Receiving Water Monitoring

6.1 Background

This section describes receiving waters monitoring activities proposed for the Combined Sewer Overflow (CSO) Long Term Control Plan Update (LTCPU) *Green City, Clean Waters* Program. Receiving waters under the City of Philadelphia's Consent Order and Agreement (COA) with the Pennsylvania Department of Environmental Protection include tidal portions of the Delaware and Schuylkill Rivers as well as major areas of the Cobbs Creek and Tookany/Tacony-Frankford Watersheds within the City of Philadelphia. The proposed activities described in this section build upon physical, chemical, and biological monitoring conducted by the Water Department since the 1997 Long Term Control Plan. These previous efforts are documented in Comprehensive Characterization Reports that were completed for the Cobbs Creek and Tookany/Tacony-Frankford watersheds in 2004 and 2005, respectively, as well as annual CSO and National Pollutant Discharge Elimination System Stormwater Municipal Separate Storm Sewer System permits.

6.2 Program Overview

Based on extensive monitoring, the Cobbs and Tookany/Tacony-Frankford Comprehensive Characterization Reports characterized watershed conditions, identified major stressors, and listed problem parameters and watershed indicators. Subsequent monitoring activities have focused on collecting additional data for these parameters, particularly bacteria and dissolved oxygen. Bacteria and dissolved oxygen are also the primary parameters of concern for tidal receiving waters in the Schuylkill and Delaware Rivers, and the Water Department is collecting data for these parameters—as well as related parameters such as nutrients—to support development of water quality models, as described in Section 10.

Monitoring activities carried out in the Cobbs and Tookany/Tacony-Frankford watersheds have been described extensively in the Comprehensive Characterization Reports as well as in LTCPU Section 3 (Characterization of Current Conditions). The Water Department monitoring activities described in this section are organized into three programs, or groups of similar monitoring techniques, specifically to highlight new programs or programs which have changed significantly following monitoring activities conducted for the Cobbs and Tookany/Tacony-Frankford Comprehensive Characterization Reports. Three primary programs are described in the following section:

- The Water Department/United States Geologic Survey (USGS) Cooperative Water Quality Monitoring Program
- The Water Department Wadeable Streams Biological Assessment Program
- The Water Department Tidal Water Quality Monitoring Program

The Water Department/USGS Cooperative Water Quality Monitoring Program is a City-wide initiative. The wadeable streams biological assessment program is applied sequentially to targeted watersheds, which may contain both combined and separate sewered areas. Although the majority of land area within Cobbs Creek and Tookany/Tacony-Frankford watersheds is served by combined sewer systems, some areas drain to separate sewer systems as well as non-contributing, or direct drainage areas. Monitoring programs are described in their entirety for the sake of clarity and to convey the scope of the programs. Although not directly related to the CSO LTCPU, monitoring conducted in separate sewered areas generally provides complementary information.

6.2.1 The Water Department/USGS Cooperative Water Quality Monitoring Program

The Water Department/USGS Cooperative Water Quality Monitoring Program is the primary means of tracking spatial and temporal surface water quality throughout Philadelphia's watersheds. Long-term operation and maintenance of these ambient monitoring stations will generally allow the Water Department to measure water quality entering and leaving the City of Philadelphia. Moreover, measurements of key parameters such as dissolved oxygen at these gage stations will serve as indicators to track water quality improvements related to implementation of the City's CSO LTCPU as well as Integrated Watershed Management Plans. The gage network currently consists of 11 gages at which water quality instrumentation is operated and maintained by the Water Department. USGS staff performs periodic discharge measurements and operates stream gaging instrumentation and data transmission equipment.

In 2009, the Water Department initiated a dry weather water quality sampling program designed to work in tandem with the continuous data collection efforts of the Water Department/USGS Cooperative Program. Grab samples are collected from 10 sites covering all six of Philadelphia County's watersheds on a quarterly basis by the staff of the Water Department's Bureau of Laboratory Services. Data collected through this program are most pertinent to Target A (Dry Weather Water Quality & Aesthetics) of the Water Department's Integrated Watershed Management Plan Strategy, whereas continuous water quality monitoring is most pertinent to Targets B (Healthy Living Resources) and C (Wet Weather Water Quality and Aesthetics).

The Water Department is implementing a City-wide approach to dry weather water quality monitoring, rather than focusing on individual watersheds. Because green stormwater infrastructure is in the early stages of implementation, water quality benefits will only be observable over a period of several years. Gaging the effectiveness of such projects on a more immediate scale is best accomplished by hydrologic and hydraulic analysis at the site level (Section 4). Therefore, the strategic value of the widespread sampling approach is that as more green stormwater infrastructure projects are completed over the coming years, water quality data should gradually begin to reflect positive environmental impacts.

6.2.2 The Water Department Wadeable Streams Biological Assessment Program

Biological assessment is a key component of the monitoring strategy for the CSO LTCPU as well as the integrated watershed management plan process being implemented in all of Philadelphia's watersheds. Biological monitoring of aquatic invertebrate, fish, and algae communities is a means of characterizing biological community structure, identifying potential physical impairments or chemical stressors, and as a "baseline" for measuring the effects of future restoration projects. Water Department biological monitoring protocols are based on methods developed by the Pennsylvania Department of Environmental Protection and United States Environmental Protection Agency (US EPA). These procedures are as follows:

- The Pennsylvania Department of Environmental Protection instream comprehensive evaluation protocol (benthic macroinvertebrate and physical habitat assessments)
- US EPA Rapid Bioassessment Protocol V (fish assessment)
- US EPA Periphyton Assessment (benthic algae assessment)

6.2.2.1 Macroinvertebrate Assessments

From 1999-2006, The Water Department employed US EPA Rapid Bioassessment Protocols (Barbour et al. 1999) for benthic macroinvertebrate and physical habitat assessments. In 2007, the Pennsylvania Department of Environmental Protection published new protocols for Benthic Macroinvertebrate Assessments, with significant changes to field sampling, laboratory, and data analysis techniques (Pennsylvania Department of Environmental Protection 2007, 2009a). The Water Department adopted the Pennsylvania Department of Environmental Protection Riffle-Run Freestone sampling and data analysis techniques for 2007 and 2008 monitoring activities in Pennypack Creek and Poquessing-Byberry Creek Watersheds. With the Instream Comprehensive Evaluation method, sample results are compared to an index of biotic integrity that is intended to be used statewide, without regard for regional or climatic influences. The index of biotic integrity is sensitive to effects of season and drainage area, as index scores generally tend to decline in larger streams and during the warmer months. In both cases, these effects are more pronounced at high quality sites.

The instream comprehensive evaluation method requires a sample size of 200±20% individuals, while macroinvertebrate samples processed by the Water Department from 1999-2006 were subsampled with minimum 100 individual sample size. Due to this discrepancy, re-sampling or other normalization procedures may need to be used with the data collected with the Pennsylvania Department of Environmental Protection instream comprehensive evaluation protocols to maintain compatibility with pre-established integrated watershed management plan indicators for Indicator Status Update reports. Preliminary work with the instream comprehensive evaluation metrics shows streams used by the Water Department as reference sites (e.g., French Creek and tributaries to French Creek) are narrowly meeting their designated aquatic life use or in some cases are classified as "impaired" when assessed with the instream comprehensive evaluation index of biotic integrity.

The integrated watershed management plans for the Cobbs and Tookany/Tacony-Frankford Creek Watersheds were completed in 2004 and 2005. Watershed Management Implementation

Plans were completed for both watersheds in 2006. Integrated watershed management plans initially recommended a five-year interval for re-assessments and integrated watershed management plan indicator status updates, but that interval was determined to be too aggressive, at least for the initial status updates. The initial re-assessment monitoring interval recommendation was changed to 10 years, in recognition of the fact that watershed-scale assessments are best suited to characterize larger-scale water quality and biological community health.

Allowing 10 years before re-assessment will potentially allow for a greater number of integrated watershed management plan and CSO LTCPU projects to be completed. Re-assessment and subsequent indicator status update reports should complement the “adaptive management approach” and allow for the locations and methods of assessment to be changed, depending upon the number of projects implemented and their spatial distribution.

In recent years, agencies tasked with evaluating water quality have attempted to incorporate statistical sampling designs, or a “probabilistic” approach, to selecting sampling sites (Paulsen 2008) rather than relying on fixed sites. Statistical sampling design is particularly important when the goal of monitoring is to make an estimate of the percentage of waters impaired by pollution. When monitoring efforts are directed at individual watersheds (e.g., on a rotating basis, as was formerly the case with the Water Department’s macroinvertebrate assessment program), the possibility arises that larger-scale patterns may be missed. For example, the effects of floods or drought conditions are widespread, but only the watershed that is being monitored within the same time period will have data reflecting these effects. An advantage of probabilistic study design is that the assessment units may be distributed over a larger geographic area. Disadvantages of a probabilistic approach include the technical demands of establishing and randomly selecting from geographic data sets containing all possible sampling locations as well as additional field reconnaissance work when conducting the actual monitoring.

The Water Department’s wadeable streams assessment strategy is intended to be a compromise, recognizing the benefits of collecting data from randomly selected sites but also the importance of maintaining a consistent monitoring effort at fixed locations over time. This plan is based on a similar monitoring program implemented in Chester County, Pennsylvania by the USGS (Reif 2002, Reif 2004). The plan also reflects the manpower constraints of collecting and processing samples with the Pennsylvania Department of Environmental Protection instream comprehensive evaluation protocol. It is hoped that this semi-randomized approach will achieve some of the benefits of a randomized approach while providing periodic re-evaluation of our watersheds required for informing the watershed planning process and updating integrated watershed management plan indicators.

6.2.2.2 Physical Habitat Assessments

The Water Department conducted physical habitat assessments from 1999 to 2007 using the US EPA Rapid Bioassessment Protocols (Barbour et al., 1999). Reference conditions were used to normalize the assessment to the “best attainable” situation. In 2007, the Pennsylvania Department of Environmental Protection published new protocols for physical habitat assessments that differ slightly from those in the US EPA Rapid Bioassessment Protocols. Some individual habitat metrics were split into separate categories, while others had slight changes to the condition description text. The Water Department adopted these new assessment techniques for 2008 monitoring activities in the Poquessing-Byberry Creek Watershed. Normalization procedures may be used with the data collected with the Pennsylvania Department of Environmental Protection assessment protocol to maintain compatibility with pre-established integrated watershed management plan indicators for indicator status update reports. As physical habitat assessment is conducted concurrently with benthic macroinvertebrate assessments, the study design incorporating semi-randomized and fixed stations in addition to targeted watershed monitoring applies to physical habitat assessment activities as well.

6.2.2.3 Habitat Suitability Index Modeling

In addition to habitat assessments, Habitat Suitability Index models developed by the U.S. Fish and Wildlife Service were incorporated into the monitoring program from 2003 to 2007. Based on empirical data and supported by years of research and comprehensive review of scientific literature, these models present numerical relationships between various habitat parameters and biological resources, particularly gamefish species and species of special environmental concern. Habitat Suitability Index studies were completed in the Darby-Cobbs, Tookany/Tacony-Frankford, Wissahickon, and Pennypack Creek watersheds. The Poquessing-Byberry Watershed Comprehensive Characterization Report approach attempted to simplify the application of fish habitat suitability analysis to generalized guilds, as described below.

6.2.2.4 Physical Habitat Survey and Integrated Flow Modeling

The Water Department began performing detailed surveys of fish sampling sites with a total station in 2007, replacing the previous cross-sectional transect technique. The increased level of spatial data quality has enabled development of two-dimensional finite element flow models for these locations using River 2D software. These models allow us to examine habitat suitability across a range of flows and better determine the spatial and temporal extents of suitable combinations of water depth, velocity, and substrate. It is expected that these models will be particularly useful in evaluating the effectiveness of instream fish habitat enhancement structures and instream structural Best Management Practices. Additional research is needed in order to parameterize physical habitat suitability models for various aquatic life groups of concern, but the Water Department is presently applying generalized “guild” characteristics that are intended to represent the habitat requirements of groups of similar species.

6.2.2.5 Fish Assessments

From 1999 through 2009, the Water Department sampled fish communities in wadeable segments of each of Philadelphia’s watersheds using US EPA Rapid Bioassessment Protocol V (Barbour *et al*. 1999). Assessment results were presented in Comprehensive Characterization Reports, including the Darby-Cobbs and Tookany/Tacony-Frankford Comprehensive Characterization Reports (Water Department 2004, 2005, respectively). The Water Department has conducted additional non-quantitative fish assessments in tidal areas of the Delaware and Schuylkill Rivers, as well as quantitative monitoring of fish utilization of the Fairmount Fishway.

Consistent with the rationale of an extended interval for macroinvertebrate re-assessments, as described above in Section 6.2.2.1, fish re-assessments will also be conducted within targeted watersheds on approximately a 10-year interval. Other projects where Rapid Bioassessment Protocol fish surveys may be helpful in assessing best management practice performance include streambank restoration projects along Tookany/Tacony-Frankford and Cobbs Creeks, as well as fish habitat and passage improvements. Fish assessments are generally not appropriate for monitoring of very small (and particularly of small, high-gradient) stream segments, so the primary means of evaluating biological health and success of stream restoration projects in small streams is macroinvertebrate assessment.

6.2.2.6 Algae Assessments

From 2002 through 2009, the Water Department collected algal periphyton samples from a small number of sites in selected watersheds using components of US EPA Rapid Bioassessment Protocol 6.1 (laboratory-based approach) (Barbour et al. 1999). Algal periphyton is collected from natural substrates and biomass is estimated based on quantitative chlorophyll-*a* and total chlorophyll analysis. Periphyton sampling is performed primarily to address the question of whether anthropogenic nutrient sources are causing eutrophication, which adversely affects aquatic food webs and may result in violations of water quality criteria for dissolved oxygen and pH. High concentrations of chlorophyll indicate excessively dense algal growth, which may help explain observed aquatic life impairments.

Beginning in 2005, the Water Department began providing samples of algal periphyton to the Patrick Center of the Academy of Natural Sciences of Philadelphia, phycology section, for taxonomic identification of diatoms and soft algae, as well as the determination of intracellular nutrient (C, N, P) concentrations of algal periphyton. Algal biomass and nutrient ratio data may be used to provide information for the parameterization of water quality models (Section 10, Water Quality Modeling). Algal taxonomic data are analyzed for standard measures of community structure and also compared to autecological information and indices developed through USGS National Water Quality Assessments (Porter 2008).

6.2.3 The Water Department Tidal Water Quality Monitoring Program

The Delaware River has a long history of water quality monitoring by the Delaware River Basin Commission and academic researchers from the University of Delaware, among others. However, the Water Department recognizes the need to collect additional modern water quality data for the tidal Schuylkill and Delaware Rivers in the vicinity of Philadelphia.

6.2.3.1 Boat Run Water Quality Grab Sampling

The Water Department collects water quality grab samples from the Delaware River at seven stations on a monthly basis. The sampling schedule is not designed to specifically target wet or dry periods. The primary objective of this work is to collect modern water quality data as precisely as possible at similar tidal conditions in order to obtain spatially discrete data. Spatial trends would tend to be obfuscated if samples were collected at varying tidal conditions. Water quality monitoring results will be useful to characterize current conditions and to provide needed information for the parameterization and calibration of water quality models of the Tidal

Delaware and Schuylkill Rivers. Additional information about specific studies such as substrate classification and sediment oxygen demand are described in Section 10 (Water Quality Modeling).

6.2.3.2 Water Quality Transect Measurements

Based on data collected by researchers from the University of Delaware (Sharp 1984, Sharp 2010), the Water Department is reasonably confident that the Delaware River in the vicinity of Philadelphia is well-mixed, lacking major vertical or lateral gradients, and that center channel measurements are generally representative of the river as a whole for most parameters. While it is impractical to make accurate instantaneous measurements of water chemistry over entire river cross-sections vertically and horizontally, the Water Department has elected to perform spot check measurements at transects located at boat run monitoring stations in order to verify that no major lateral or vertical water quality gradients are present.

6.3 Methods

6.3.1 Water Quality Monitoring

6.3.1.1 Discrete Water Chemistry Assessment

During the 2002-2007 assessment cycles, a series of four weekly surface water grab samples were manually collected during winter, spring, and summer at several locations in each watershed (n=12 sampling events at each location). This sampling program represented the finest watershed-wide spatial resolution of all of the Water Department's water quality monitoring activities. Parameters were chosen because state water quality criteria apply to them or because they are known or suspected to be important in urban watersheds. These discrete interval water chemistry assessment data represent the most complete modern water chemistry "grab sample" dataset for the majority of Philadelphia's watersheds.

Of 39 water quality parameters regularly sampled during the Water Department's Comprehensive assessments 1999-2009 (Table 6-1), several were identified as water quality problems. However, many parameters were not found to be present in concentrations that would cause concern. Furthermore, changes to analytical methods and regulatory requirements and the desire to remain up-to-date with best practices encourage frequent re-evaluation of the suite of chemical parameters to be sampled during various monitoring activities. By tailoring the group of chemical parameters monitored to project goals, the Water Department hopes to increase sampling efficiency. When fewer parameters are sampled, a smaller volume is required for each sample, increasing the number of samples that can be collected and/or decreasing the amount of time between individual samples. This philosophy is especially beneficial in automated wet weather sampling programs.

Table 6-1: Water Chemistry Parameters Analyzed in the Water Department's Monitoring Programs, 2002-2012

Parameter	Units	Discrete	Wet Weather	Continuous	Quarterly Grab
Alkalinity	mg/L	X			
Aluminum	mg/L	X	X		
Dissolved Aluminum	mg/L	X			
Ammonia	mg/L as N	X	X		X
Arsenic	mg/L	X	X		
Dissolved Arsenic	mg/L	X			
BOD5	mg/L	X	X		
Cadmium	mg/L	X	X		
Dissolved Cadmium	mg/L	X			
Calcium	mg/L	X	X		
Chromium	mg/L	X	X		
Dissolved Chromium	mg/L	X			
Specific Conductance	µS/cm	X		X	X
Copper	mg/L	X	X		
Dissolved Copper	mg/L	X			
E. coli	CFU/100mL	X	X		X
Enterococcus	CFU/100mL	X			X
Fecal Coliform	CFU/100mL	X	X		X
Hardness	mg/L CaCO3	X	X		
Iron	mg/L	X	X		
Dissolved Iron	mg/L	X			
Lead	mg/L	X	X		
Dissolved Lead	mg/L	X			
Magnesium	mg/L	X			
Manganese	mg/L	X	X		
Dissolved Manganese	mg/L	X			
Nitrate	mg/L	X	X		X
Nitrite	mg/L	X	X		
Orthophosphate	mg/L	X	X		X
Dissolved Oxygen	mg/L	X		X	X
pH	pH units	X		X	X
Total Phosphorus	mg/L	X	X		
Sodium	mg/L	X			
Suspended Solids	mg/L	X	X		X
Total Solids	mg/L	X	X		
Temperature	°C	X		X	X
TKN	mg/L	X	X		
Turbidity	NTU	X	X	X	X
Zinc	mg/L	X	X		
Dissolved Zinc	mg/L	X			

As described in Section 6.2.1, the Water Department will continue quarterly baseflow water chemistry assessment at 10 USGS gages in the Philadelphia area. It is hoped that these data will be useful as a long-term record of water quality changes in the region and more appropriate for assessing the goals of the City-wide green stormwater infrastructure implementation program than an approach that focuses on individual watersheds. Field standard operating procedures for discrete water quality grab sampling are kept on file and are available from the Water Department's Bureau of Laboratory Services.

6.3.1.2 Boat Run Grab Sampling

Samples are collected from approximately 5 feet below the water surface near center channel using a horizontal sampler (Wildco Instruments). The collected samples are then transferred into plastic sample bottles and delivered to the Bureau of Laboratory Services for chemical analysis of parameters listed in Table 6-2. Dissolved oxygen (mg/l), specific conductance (µS/cm^2), pH, turbidity (NTU), and temperature (°C) are measured at the site using a YSI multiparameter sonde weighted and suspended by a calibrated rope to a depth of 5 feet. Field Standard Operating Procedures for grab sampling and operation of YSI multiparameter sondes are kept on file and are available from Bureau of Laboratory Services.

Table 6-2: Water Chemistry Parameters Analyzed from Delaware River Surface Water Samples

Physicochemical Analytes	Units
Alkalinity	mg/L $CaCO_3$
Ammonia	mg/L
Bromide	mg/L
Calcium	mg/L
Chloride	mg/L
Conductivity	µSiemens/cm @ 25°C
Magnesium	mg/L
Nitrate	mg/L
Nitrite	mg/L
Total Nitrogen*	mg/L
Orthophosphate	mg/L
Dissolved Oxygen	mg/L
Total Phosphorus	mg/L
pH	pH units
Potassium	mg/L
Silica	mg/L
Sodium	mg/L
Total Suspended Solids	mg/L
Total Dissolved Solids	mg/L
Sulfate	mg/L
Temperature	°C

Physicochemical Analytes	Units
TKN	mg/L
Turbidity	NTU
BOD5	mg/L
CBOD5	mg/L
CBOD20	mg/L
Fecal coliform	CFU/100mL
E. coli	CFU/100mL
Enterococci	CFU/100mL
Chlorophyll a	µg/L
Chlorophyll, Total	µg/L
Diatom/soft algae taxonomy**	Organisms/mL
Seston C:N:P mass ratio**	Dimensionless

*Calculated water quality parameter

**Samples processed by the Patrick Center of the Academy of Natural Sciences of Philadelphia

6.3.1.3 Water Quality Transect Measurements

In order to determine whether lateral or vertical gradients exist at water quality monitoring stations in the Delaware River, water quality measurements are made across the transects using a YSI model 6600 multiparameter sonde lowered to predetermined depth via a weighted graduated line, including a minimum of three sampling locations laterally across the channel, three sampling depths vertically (where depth allows) at each lateral location, and some measurements collected at high and low tide such that the water quality transect measurements span an entire tide cycle. Data are reviewed constantly by the field staff throughout the water quality transect measurement procedure in order to achieve a balance between the number of sample point locations and the degree to which different measurements are affected by changing tidal conditions.

6.3.1.4 Wet Weather Water Quality Assessment

The Water Department's data collection effort for the Cobbs and Tookany/Tacony-Frankford Comprehensive Characterization Reports included collecting water samples during wet weather flows. Automated samplers (Isco, Inc. models 6712, 6700) were deployed throughout the targeted watersheds and used to collect samples during runoff-producing rain events. This automated system obviated the need for staff to manually collect samples, thereby greatly increasing sampling efficiency. Automated samplers were programmed to commence sampling with a small (~0.1 ft.) increase in stage. Once sampling was initiated, a computer-controlled peristaltic pump and distribution system collected grab samples at 30 min. to 1 hr. intervals, the actual interval being adjusted on a site-by-site basis according to "flashiness." Adjustment of the rising-limb hydrograph sampling interval allows optimum characterization of water quality responses to stormwater runoff and wet weather sewer overflows. Due to sample volume restrictions and inability to filter, fewer chemical analyses were performed on samples collected in wet weather (Table 6-2).

6.3.1.5 Continuous Streamflow Measurement

The Water Department provides, in whole or in part, the local cooperator funding portion of the costs for USGS to operate and maintain 11 stream gaging stations in the Philadelphia area. USGS staff follow the techniques described in USGS Techniques and Methods Book 3 for stage measurements and discharge measurements at gaging stations (Sauer & Turnipseed 2010, Turnipseed & Sauer 2010, respectively), briefly summarized herein. Streamflow is computed by the velocity-area method using a stage measurement device and a stage discharge relation developed for each gage station. The stage (depth) measurement device is usually a "bubbler" type gage consisting of submerged orifice pressurized with a gas and a pressure transducer connected to an electronic data recorder. The pressure exerted on the gas within the bubbler tube is proportional to the depth of water over the orifice. USGS staff visits each site on a periodic basis, approximately every six to eight weeks, in order to perform discharge measurements, establishing and/or maintaining the stage discharge relation. Discharge measurements are made by Acoustic Doppler Velocimeter or Acoustic Doppler Current Profiler equipment. Stream velocity is measured at approximately 25 points across a stream transect, with individual measurements distributed along the transect such that cross-sectional polygons of approximately equal discharge are represented. In addition to regular visits, USGS staff attempts to visit each gage to make discharge measurements during various higher flow events to continually refine the stage discharge relation. More information about USGS stream gaging methods is available in USGS Techniques and Methods Book 3.

6.3.1.6 Continuous Water Quality Assessment

In addition to discrete chemical sampling, the Water Department incorporated *in situ* continuous water quality monitoring at strategic locations within each watershed as part of the 1999-2009 comprehensive monitoring strategy. Using submerged instruments (YSI 6600, 6600 EDS and 600 XLM Sonde), dissolved oxygen, temperature, pH, conductivity, depth, and turbidity were logged at 15-minute intervals. The instruments were deployed for approximately two weeks, retrieved, and replaced with fresh calibrated instruments in order to produce nearly seamless temporal data. Continuous *in situ* water quality monitoring was completed for the Darby-Cobbs, Tookany/Tacony-Frankford, Wissahickon, Pennypack, and Poquessing-Byberry Watershed Comprehensive Characterization Reports.

Long-term continuous monitoring for building a long-term water quality data record for the Cobbs and Tookany/Tacony-Frankford watersheds will be accomplished in partnership with the USGS, as described in Section 6.2.1 and 6.1.3.5. Water Department staff have been trained to use standard USGS protocols (Wagner, et al 2006) when calibrating YSI multiparameter sondes co-located at USGS gage stations. Water quality data are transmitted to USGS National Water Information System, where the current status of water quality instruments may be viewed in a web browser. When data indicate that water quality probes are fouled (due to storms, failure of pump through apparatus, etc.), the Water Department staff visit the gage in order to re-calibrate the instruments and replace any components as necessary. Continuous water quality monitoring will also be utilized in evaluating the performance of certain stormwater Best Management Practices and assessing conditions in tidal portions of the Schuylkill and Delaware Rivers as well as Frankford Creek.

6.3.1.7 Tide Level Measurement

The National Oceanographic and Atmospheric Agency publishes hourly tidal data for the Delaware River stations 8545240 (United States Coast Guard station at Washington Avenue, Philadelphia, PA), 8538886 (Tacony-Palmyra Bridge, NJ), 8540433 (Marcus Hook, PA), and 8539094 (Burlington-Bristol Bridge). Data is available in a preliminary form (most recent) and a verified form after the National Oceanographic and Atmospheric Agency performs quality assurance measures to ensure data integrity. National Oceanographic and Atmospheric Agency verified hourly water level data are downloaded, converted to City datum, and interpolated to 15-minute intervals. Three sets of data are created from this to estimate three different tidal zones accounting for shifting tidal boundaries using a water-level offset and the time it takes the tide to affect the various zones based on distance upstream from the gage station.

Tidal boundary conditions are needed because many of the CSO regulator outfalls are located in tidal waters and are equipped with flap gates to prevent tidal inflows to the collection system. The tidal boundary condition in turn determines the effective overflow elevation for these regulators. These tidal effects need to be taken into account when implementing the program to accurately quantify and characterize existing baseline conditions and to accurately quantify and assess the benefits of implemented green stormwater infrastructure controls and other remedial measures.

6.3.2 Wadeable Streams Assessment Program

6.3.2.1 Benthic Macroinvertebrates and Physical Habitat Assessment

The Water Department employs the Pennsylvania Department of Environmental Protection instream comprehensive evaluation field and laboratory protocols for benthic macroinvertebrate and physical habitat assessments. All Philadelphia sites are considered appropriate for the Freestone Riffle-Run sampling method (Pennsylvania Department of Environmental Protection, 2009a). More detailed information about the Pennsylvania Department of Environmental Protection assessment methods is available at the following URL:

http://files.dep.state.pa.us/Water/Drinking%20Water%20and%20Facility%20Regulation/WaterQualityPortalFiles/Methodology/rifflerubfreestone_2009am.pdf

6.3.2.2 Fish Assessment

Fish are collected by electrofishing as described in the US EPA's Rapid Bioassessment Protocol V (Barbour et al. 1999). Depending on stream conditions, Smith-Root backpack or tote barge electrofishers are used to stun fish. A 100-meter reach of stream is blocked at the upstream and downstream limits with nets to prevent immigration or emigration from the study site. Each reach is uniformly sampled, and all fish captured are placed in buckets for identification and counting. An additional pass without replacement is completed along the reach to ensure maximum likelihood population and biomass estimates.

Fish are identified to species, weighed (± 0.01 g) with a digital scale (Model Ohaus Scout II) and measured to the nearest 0.1 cm using a Wildco fish measuring board. Large fish that exceed the digital scale's capacity are weighed using spring scales (Pesola). Any external deformations, lesions, tumors, cysts, or disease are noted during processing. Species that cannot be identified in the field (e.g., small or juvenile cyprinids) are preserved with 10% formalin solution and stored in polyethylene bottles for laboratory identification.

To facilitate the process of acquiring total fish biomass and to reduce field time, a log-log regression was developed between weight (g) and length (cm). Approximately 20 individuals of each species were weighed, and total lengths were measured. Once 20 individuals of each species were measured (both weight and length), biomass (g) for each fish was calculated using the regression analysis. Similar procedures were conducted at the reference locations (i.e., French Creek and Rock Run) to obtain a discrete measure of the condition of the fish assemblages at each assessment location.

6.3.2.3 Algae Assessments

Periphyton is collected from natural substrate particles in shallow (~20 cm) run habitats. Substrate particles for periphyton analysis are collected by walking transects through the stream along a randomly selected angle until appropriate depth of flow is reached. Biologists then walk heel to toe and select the first substrate particle encountered by reaching down at the very tip of the wading shoe. Very large and very small substrate particles are rejected, as are substrate particles that appear to have been recently moved. Manmade substrate particles such as bricks, concrete and other debris are also rejected.

Substrate particles are placed in white plastic lab trays in the same orientation they were found and debris such as gravel, leaves, and large macroinvertebrates are removed. Substrate particles (particularly sides and undersides of rocks) typically contain caddisfly nets that are removed as part of the periphyton sampling procedure. If the substrate particle has extensive coverage of macroalgae, filaments are trimmed to the profile of the substrate particle as viewed from above and portions of filaments that extend beyond the substrate particle are removed. Three replicate samples are collected at each site. Depending on the size of the substrate particles collected, one to three particles are used for each replicate sample at each site. Each member of the three-person sampling team is assigned a different replicate letter ("A," "B," or "C") and sample containers are pre-labeled with site and replicate information. Periphyton is removed from the upper surface of each substrate particle using firm bristle toothbrushes with half the brush length trimmed away. Substrate particles are irrigated with stream water and scraped to remove periphyton until the rock surface becomes noticeably rough and not slimy. All scraped material for each replicate sample is composited into 250 mL Nalgene sample bottles by rinsing the plastic tray with stream water. (Throughout the CCR data collection period, stream water in Philadelphia streams has been characterized as having very low phytoplankton density, with water column chlorophyll-a <5µg/L.) Samples are stored on ice in a darkened cooler and exposure to sunlight is minimized throughout the sample handling procedure.

All substrate particles used for a given replicate are wrapped with aluminum foil, which is folded, trimmed, and/or notched, as appropriate, to carefully match the surface of the substrate particle that was scraped to collect periphyton. All substrate particle foil molds for each replicate are stored in pre-labeled Ziploc bags.

Foil molds are scanned and digitized using a Microtek Scanmaker 4900 scanner. The scanner is modified with a dense black light-absorbing background to increase contrast in the resulting images, which are saved as 8-bit (256 levels of greyscale) TIFF files. Surface area is measured using ImageJ version 1.46 (Rasband 2012). Differences in color between the foil and background are used to select and count the number of foil pixels, which is converted to square meters based on a calibration to the scanned image. For replicates in which more than one substrate particle is scraped to obtain the periphyton sample, the total surface area of all substrate particles sampled for each replicate is calculated by summing the individual areas of each particle used for the sample.

Periphyton samples are brought to the Water Department Bureau of Laboratory Services and processed using a modified version of US EPA Method 445.0. Each replicate sample is homogenized using a laboratory blender (Waring, Inc.). The sample is transferred to a large beaker and the blender is rinsed with deionized water multiple times. Deionized water is added to the sample to make volume up to 1 L for ease of filtration and to simplify volumetric calculation of algal density.

5-mL aliquots of diluted sample are vacuum-filtered through a 1.2 µm glass fiber filter (Whatman, Inc. GF/C) to concentrate filterable periphyton material. Depending on the density of algal periphyton in the sample, several 5 mL aliquots may be filtered to ensure that enough material is collected by the filter. A laboratory vacuum manifold is used to process multiple samples simultaneously. Total volume filtered is recorded on a data sheet and the sample label. Filters are individually wrapped in aluminum foil and stored for up to 21 days in a laboratory freezer at -20°C.

Filters are placed in a test tube with 90% acetone extraction solution and homogenized using a counter-rotating tissue grinder (Omni EZ Connect Homogenizer model TH115), and the chlorophyll-a pigments are extracted from the phytoplankton in 90% acetone overnight in a refrigerator at 4°C. A volume of 5 mL of extract is placed in a cuvette and analyzed by the fluorometer before and after acidification to 0.003 N HCl with 0.1 N HCl to convert chlorophyll-*a* to pheophytin-*a*. The ratio of chlorophyll-*a* to pheophytin-*a* is then used to determine the initial chlorophyll-*a* concentration.

6.4 Monitoring Locations

6.4.1 The Water Department/USGS Cooperative Water Quality Monitoring

The Water Department/USGS Cooperative Water Quality Monitoring network currently consists of 11 USGS gages at which water quality instrumentation is operated and maintained by the Water Department Bureau of Laboratory Services staff (Table 6-3, Figure 6-1). The Water Department also funds the operation and maintenance of water quality instrumentation at USGS gage 01473500 Schuylkill River at Norristown. The Delaware River Basin Commission funds the acquisition of water quality data at numerous USGS gages along the Delaware River, including USGS gage 01467200 Delaware River at the Ben Franklin Bridge (Figure 6-1).

Table 6-3: Monitoring Locations in the Water Department/USGS Cooperative Water Quality Monitoring Program with Location IDs Used by the Water Department Bureau of Laboratory Services and River Mile-Based Site IDs

Description	USGS Gage #	Bureau of Laboratory Services Location ID	Site ID
Cobbs Creek at US Rte. 1 (City Line Ave.)	01475530	COBB700	DCC770
Cobbs Creek at Mt. Moriah Cemetery	01475548	COBB355	DCC251
Schuylkill River at Fairmount Dam	01474500	SCHU154	SC825
Wissahickon Creek at Ft Washington (Rte. 73)	01473900	WISS500	WS1075
Wissahickon Creek at Ridge Ave.	01474000	WISS130	WS076
Tacony Creek at Castor Ave.	01467087	TACO250	TF280
Tacony Creek at Adams Ave.	01467086	TACO435	TF597
Pennypack Creek at Pine Rd.	01467042	PENN407	PP993
Pennypack Creek at Rhawn St.	01467048	PENN175	PP340
Poquessing Creek at Grant Ave.	01465798	POQU150	PQ050
Delaware River nr Pennypack Woods	014670261	DR11011	DR11011

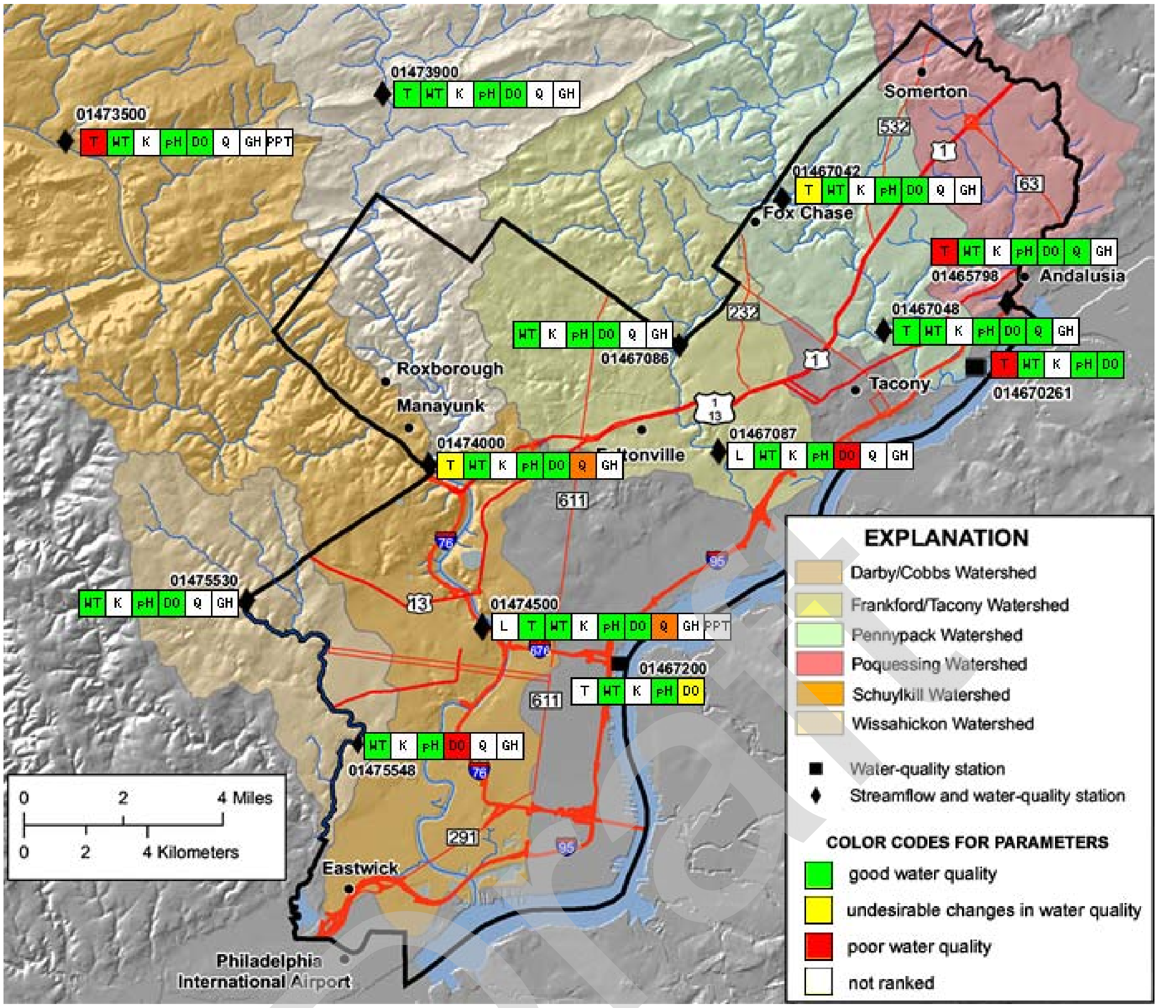

Figure 6-1: The Water Department/USGS Cooperative Water Quality Monitoring Program Locations

6.4.2 Non-Tidal Receiving Waters Assessment

Monitoring locations in the Cobbs and Tookany/Tacony-Frankford watersheds generally remain similar to those sampled during the data collection efforts for the Cobbs and Tookany/Tacony-Frankford Comprehensive Characterization Reports (2004 and 2005, respectively) (Figures 6-2 through 6-5). As described in Section 6.2.2 and 6.3.3, the Water Department has developed a wadeable streams assessment program to include fixed monitoring locations at USGS gage stations and randomly chosen sites along with targeted watershed sampling locations.

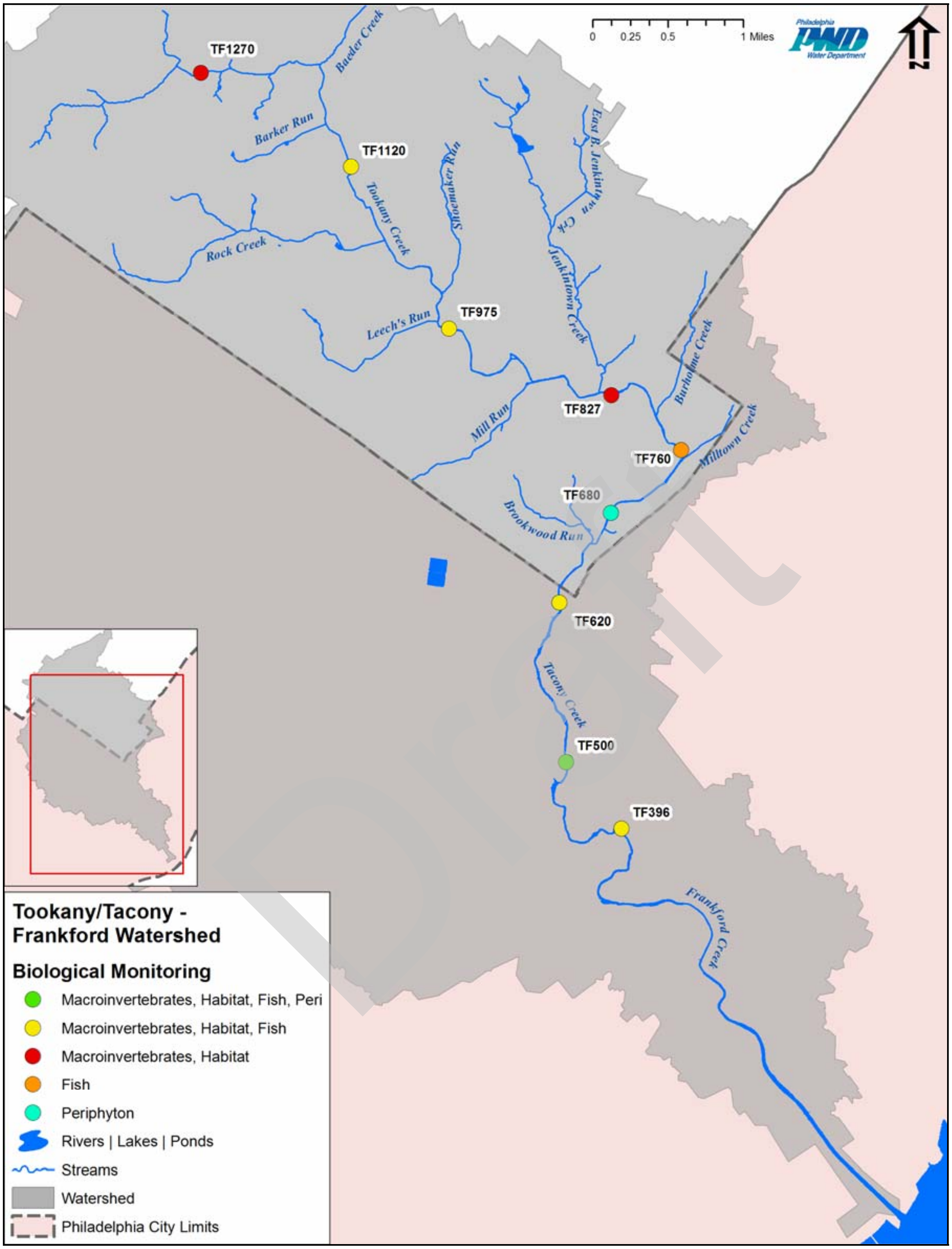

Figure 6-2: Biological and Physical Habitat Monitoring Locations in Tookany/Tacony-Frankford Watershed

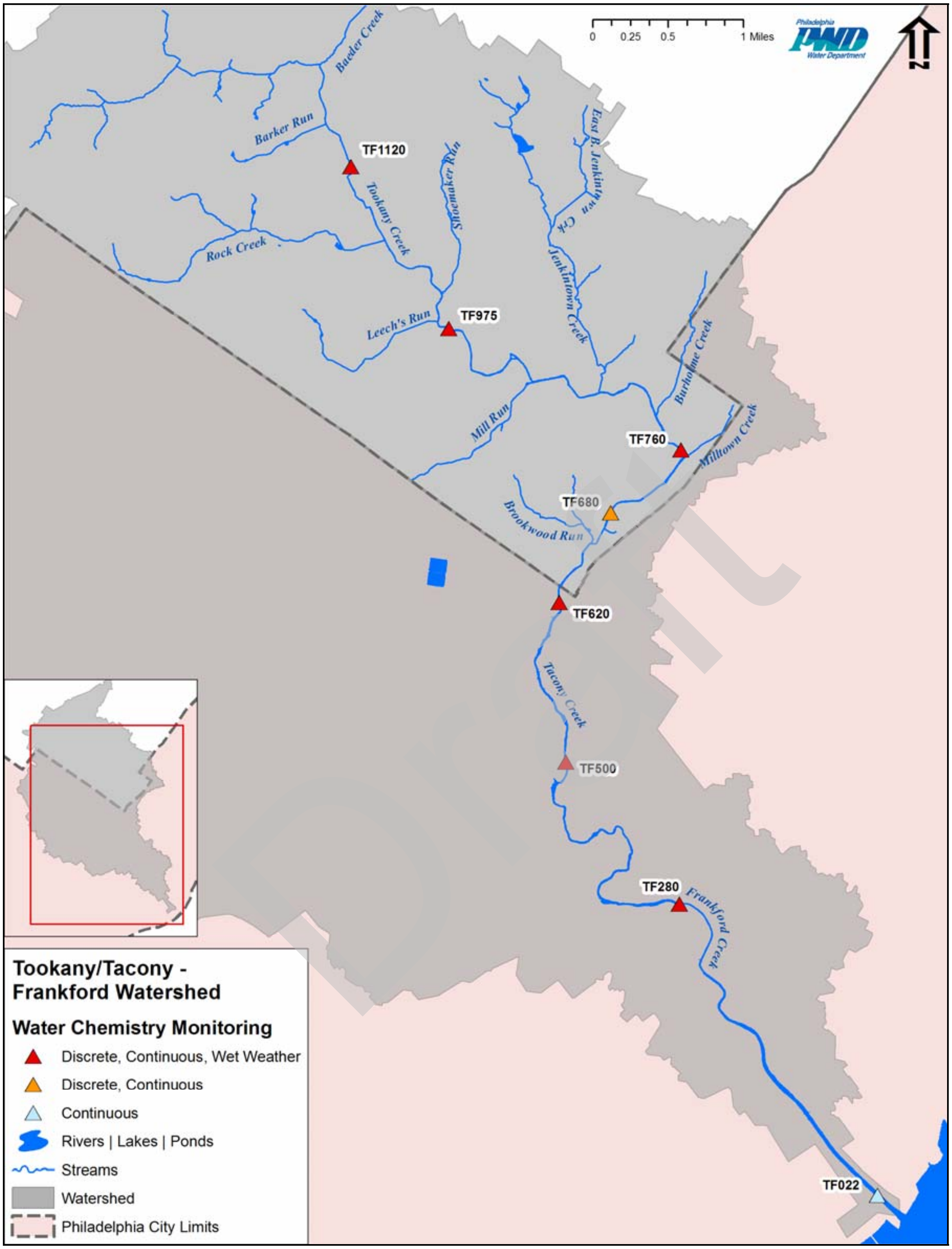

Figure 6-3: Water Chemistry Monitoring Locations in Tookany/Tacony-Frankford Watershed

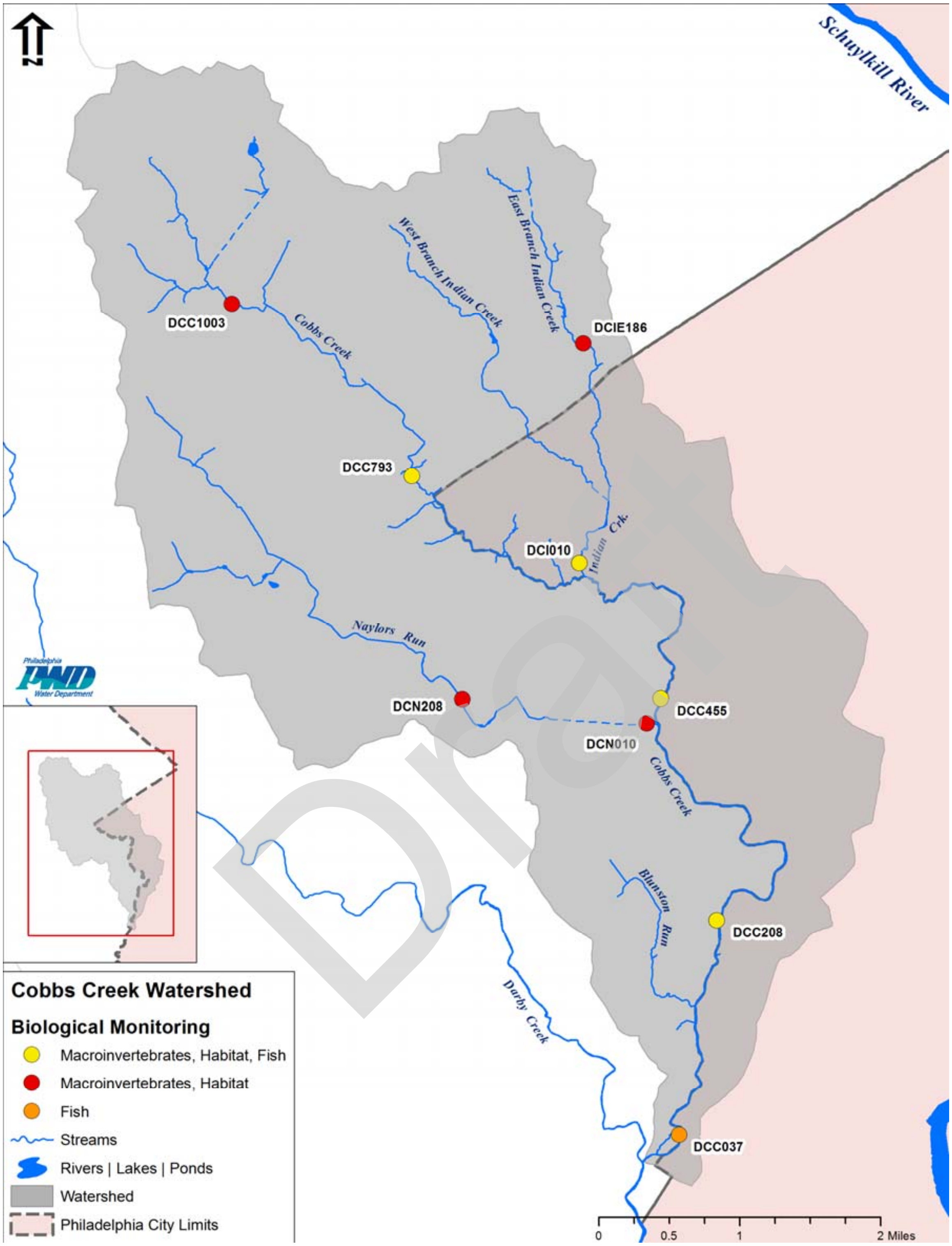

Figure 6-4: Biological and Physical Habitat Monitoring Locations in Cobbs Creek Watershed

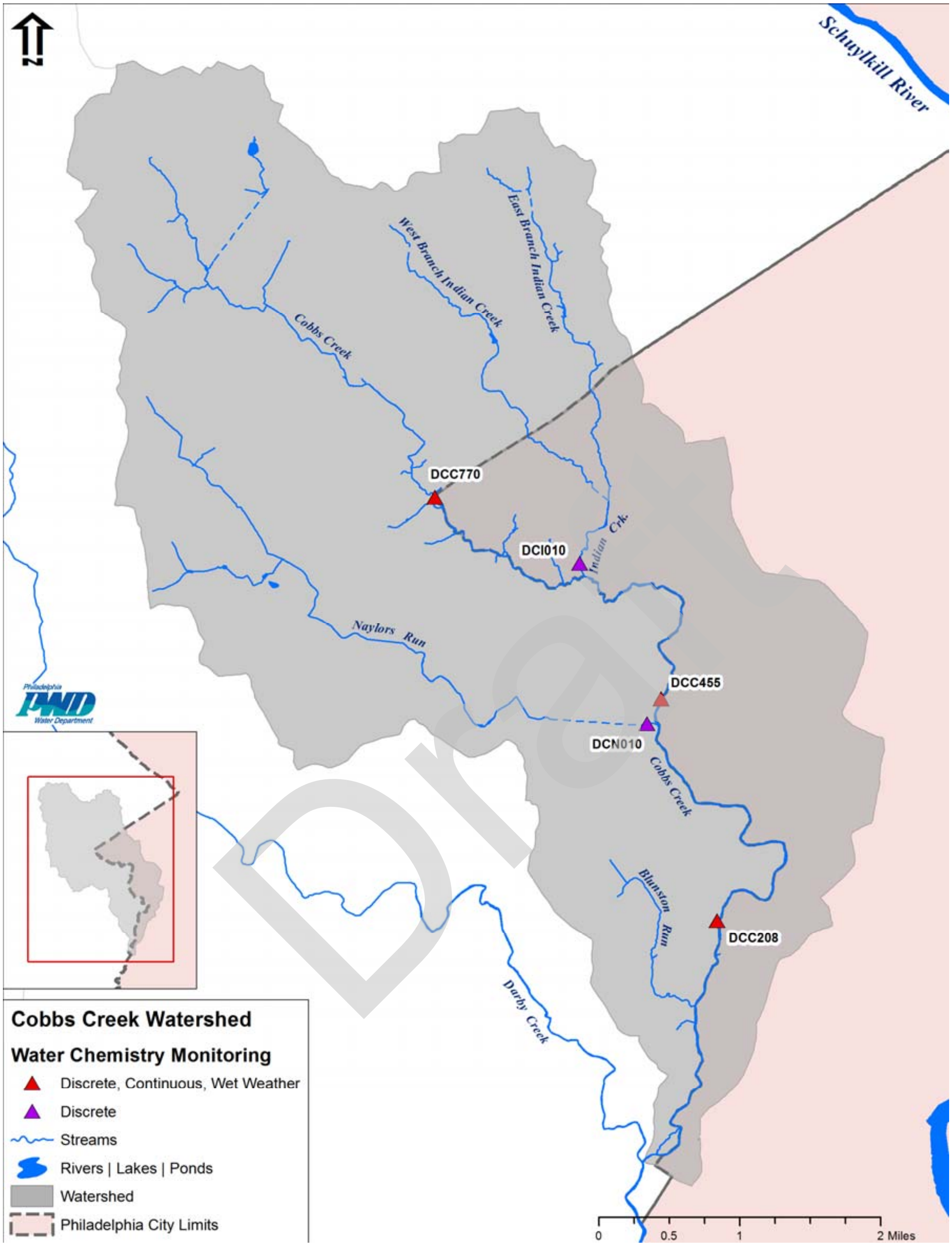

Figure 6-5: Water Chemistry Monitoring Locations in Cobbs Creek Watershed

6.4.3 Tidal Receiving Waters Assessment

6.4.3.1 Tidal Receiving Waters Monitoring Stations

As described in Section 6.2.3.1, samples are collected monthly from seven stations in the tidal Delaware River (Table 6-4, Figure 6-6). The locations of monitoring stations were chosen based on existing Delaware River Basin Commission boat run sampling stations and navigational landmarks (primarily bridges), as well as their proximity to discharges. For the purposes of naming monitoring stations, the Water Department adopted a river mile measurement system originally developed by the Delaware River Basin Commission, in which the Ben Franklin Bridge is identified as river mile 100.16. A geographic information system was used to measure longitudinal distance to other monitoring stations along the main shipping channel (Table 6-4). Note that some station descriptions refer to landmarks on shore, but all sampling locations indicate center channel samples.

Table 6-4: Delaware Estuary and Schuylkill River Water Quality Grab Sampling Monitoring Stations, the National Oceanic and Atmospheric Administration Tide Observation Stations, and USGS Stations

Station Name	Station Description	River Mile Distance
Water Department Water Quality Boat Run Grab Sampling Stations		
DR8190	Delaware River at Commodore Barry Bridge	81.90
DR8575	Delaware River at Darby Creek Confluence	85.75
DR9147	Delaware River at Fort Mifflin	91.47
DR9472	Delaware River at Horseshoe bend	94.72
DR10016	Delaware River at Ben Franklin Bridge	100.16
DR10475	Delaware River at Betsy Ross Bridge	104.75
DR11011	Delaware River at the Water Department Baxter Drinking Water Intake	110.11
SC048	Schuylkill River at USCG Buoy RB	0.48
SC470	Schuylkill River at USCG Buoy 13	4.70
Water Department Water Quality Transect Sampling Stations		
DR9681	Delaware River at Walt Whitman Bridge	96.81
DR11171	Delaware River at Poquessing Creek confluence	111.71
USGS/The National Oceanographic and Atmospheric Agency Monitoring Stations		
01482800	USGS gage Delaware River at Reedy Island Jetty, DE	66.78
01477050	USGS gage Delaware River at Chester, PA	83.10
01474703	USGS gage Delaware River at Ft. Mifflin	91.95
01467200	USGS gage Delaware River at Ben Franklin Bridge	100.16
01467029	USGS gage Delaware River div at Delran, NJ	110.16

Station Name	Station Description	River Mile Distance
USGS/the National Oceanographic and Atmospheric Agency Monitoring Stations		
014670261	USGS gage Delaware River nr Pennypack Woods, PA	110.48
01463500	USGS gage Delaware River at Trenton, NJ	134.50
01474500	USGS gage Schuylkill River at Fairmount Dam (SC825)	8.25
8540433	National Oceanographic and Atmospheric Agency Tide gage Marcus Hook	79.25
8545240	National Oceanographic and Atmospheric Agency Tide gage Philadelphia	98.73
8538886	National Oceanographic and Atmospheric Agency Tide gage Tacony-Palmyra Bridge	107.00
8539094	National Oceanographic and Atmospheric Agency Tide gage Burlington-Bristol Bridge	117.49

6.5 Monitoring Schedules

6.5.1 Continuous Water Quality Monitoring Schedule

Continuous water quality monitoring instruments will be deployed at 11 USGS gages in the Philadelphia area, including two USGS gages in the Tookany/Tacony-Frankford Watershed and two USGS gages in the Cobbs Creek Watershed. Water quality instrumentation is operated each year from March through November. Results will be summarized by permit reporting periods, currently July 1 through June 30.

6.5.2 Quarterly Dry Weather Water Quality Grab Sampling

The Water Department will collect baseflow water chemistry samples quarterly at 10 USGS gages in the Philadelphia area, including two stations in Cobbs Creek and two stations in the Tookany/Tacony-Frankford Watershed. It is hoped that these data will be useful as a long-term record of water quality changes in the region, more appropriate for assessing the goals of a City-wide distributed green infrastructure program than an approach that focuses on individual watersheds. Quarterly sampling was initiated in June 2009, and cumulative results will be summarized each year by permit reporting periods, currently July 1 through June 30.

6.5.3 Wadeable Streams Assessment Schedule

As described in Section 6.2.2 and 6.3.3, the Water Department conducts macroinvertebrate and physical habitat assessments at wadeable streams with a semi-randomized site selection design. This program meets watershed assessment requirements for watersheds served by combined and separate sewer systems, with sampling efforts allocated roughly according to watershed size and number of river miles in each watershed. Each year, sites in targeted watersheds are sampled along with fixed USGS gage stations and randomly chosen sites (Tables 6-5 and 6-6). In April 2012, the Water Department performed macroinvertebrate and physical habitat assessments at 8 sites in Cobbs Creek Watershed, 7 USGS gage stations, and 10 randomly chosen wadeable sites. In spring 2013, the Water Department will perform macroinvertebrate and physical habitat assessments at 12 sites in Tookany/Tacony-Frankford Watershed, 7 USGS gage stations and 6 randomly chosen wadeable sites.

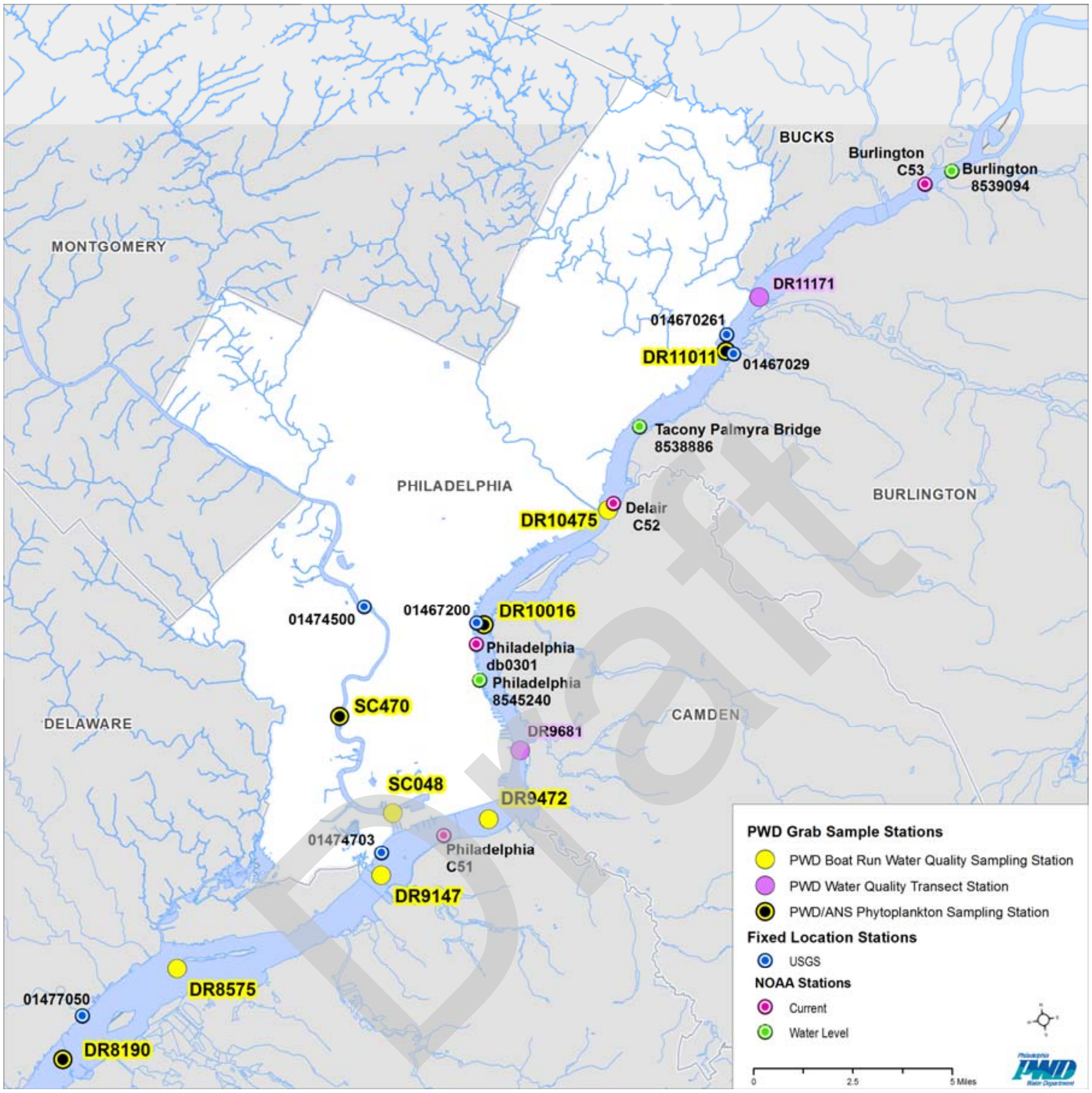

Figure 6-6: Delaware Estuary and Schuylkill River Water Quality Grab Sampling Monitoring Stations, National Oceanographic and Atmospheric Agency Tide Observation Stations, and USGS Stations

Fish assessment is generally limited to larger reaches, so fewer sites are monitored for fish than macroinvertebrates in a given year (Table 6-7). It is expected that the Water Department will continue to employ this semi-randomized study design for macroinvertebrate and physical habitat assessments and rotate through targeted river basins, making changes as needed to address specific assessment requirements.

Table 6-5: The Water Department Benthic Macroinvertebrate and Physical Habitat Assessment Program Targeted Watershed Assessment Schedule by Year 2011-2018

Year	Targeted Watershed	Target sites*	USGS	Random
2011	None	none	9	16
2012	Cobbs Creek	6	9	10
2013	Tookany/Tacony-Frankford	10	9	6
2014	Wissahickon Creek Tributaries	15	9	1
2015	Wissahickon Creek	12	9	4
2016	Pennypack Creek Tributaries	11	9	5
2017	Pennypack Creek	12	9	4
2018	Poquessing Creek	12	9	4

* Number of monitoring sites excludes USGS gage site(s) in target watershed

Table 6-6: The Water Department Wadeable Streams Macroinvertebrate and Physical Habitat Assessment Program Number of Samples by Watershed 2011-2018

Watershed	2011	2012	2013	2014	2015	2016	2017	2018
Cobbs	5	8	3	2	2	4	2	3
Tacony	4	6	12	3	2	3	2	3
Wissahickon	7	6	2	17	16	3	6	2
Pennypack	4	3	5	2	4	13	14	4
Poquessing	5	2	3	1	1	2	1	13
Total:	25	25	25	25	25	25	25	25

Table 6-7: The Water Department Wadeable Streams Fish Assessment Program Number of Samples in Targeted Watershed 2012-2018

Year	Target Watershed	Number of sites
2012	Cobbs	4
2013	Tookany/Tacony	7
2015	Wissahickon	10
2017	Pennypack	6
2018	Poquessing	6

The Water Department is conducting algae assessments in the Cobbs and Tookany/Tacony-Frankford watersheds in order to better characterize algal biomass, nutrient composition, and scouring dynamics. Sampling is storm dependent. Each sampling event consists of a pre-storm sample collected after several days of dry weather, a post-storm sample collected as closely after the storm event as possible, and two to three post-storm accrual samples intended to measure the rate at which algae re-establish densities similar to pre-storm conditions.

6.5.4 Tidal Receiving Waters Monitoring Schedule

The Water Department began collecting grab samples from the Delaware River at seven stations via boat in June 2011. Due to the logistics and safety considerations for sampling in the Philadelphia area, the Water Department entered into a data collection partnership with US EPA Region 3. Subsequent Delaware River boat run samples have been collected from a US EPA vessel. Samples are collected at low tide from tidal Schuylkill River stations as part of the Fairmount fish ladder migratory assessment program. It is expected that this data collection effort will continue for at least two years, or a period sufficient to collect adequate data for parameterization of water quality models of the Schuylkill and Delaware Rivers as required by the COA (Section 10 Water Quality Modeling).

The Water Department has conducted four water quality transect measurements at water quality monitoring stations and plans to continue with water quality monitoring along Delaware River transects through fall 2012. If results from water quality transect measurements indicate lateral or vertical gradients in water quality, the Water Department will make appropriate adjustments to the sampling schedule in order to most appropriately characterize water quality in the Delaware Estuary.

6.6 Quality Assurance and Quality Control

6.6.1 Water Chemistry Assessments

6.6.1.1 Continuous Water Quality Monitoring and Field Measurements

The Water Department has been trained to use standard USGS protocols (Wagner, et al. 2006) when calibrating water quality instrumentation such as YSI multiparameter sondes co-located at USGS gage stations. Furthermore, all field measurements accompanying quarterly dry weather grab sampling, boat run grab sampling, and those made during water quality cross-sectional transects are performed with pre-calibrated sondes that undergo post-measurement checks similar to post-deployment checks used in the continuous water quality monitoring.

6.6.1.2 Discrete Water Chemistry

The Water Department staff follows Standard Operating Procedures when collecting grab samples for water chemistry analysis. The Standard Operating Procedure includes chain-of-custody tracking as well as health and safety provisions. Water chemistry analyses are carried out at the Water Department Bureau of Laboratory Services, which is a Pennsylvania Department of Environmental Protection certified laboratory for Clean Water Act National Pollutant Discharge Elimination System program and Safe Drinking Water Act samples. Discrete water chemistry samples are analyzed using the same laboratory methods and analytical techniques as National Pollutant Discharge Elimination System and System program and Safe Drinking Water Act samples. In the event that samples are analyzed by contract laboratories, proper chain-of-custody and certification procedures are adhered to such that the same data quality objectives are met. The Water Department’s Standard Operating Procedures for grab sampling, as well as more information about analytical techniques and laboratory quality assurance and control procedures, are available from the Water Department Bureau of Laboratory Services.

6.6.2 Hydrologic Data

6.6.2.1 Continuous Streamflow Measurement

USGS staff follow the techniques described in USGS Techniques and Methods Book 3 for stage measurements and discharge measurements at gaging stations (Sauer & Turnipseed 2010, Turnipseed & Sauer 2010, respectively), including quality assurance and control procedures. Individual discharge measurements are assigned quality ratings according to streamflow characteristics and other factors observed during the measurement interval. More information about USGS stream gaging methods is available in USGS Techniques and Methods Book 3.

6.6.2.2 Continuous Tide Level Measurement

The National Oceanic and Atmospheric Administration releases real time and recent tide level data as provisional, and then applies quality assurance procedures to the tide level data internally prior to its release as accepted data. Therefore, no quality assurance protocols are conducted or proposed for the National Oceanic and Atmospheric Administration tide level data under this Comprehensive Monitoring Plan.

6.7 Data Processing and Analysis

6.7.1 Water Chemistry Data Comparison to Water Quality Standards

The Water Department performs water chemistry assessments by comparing results to appropriate water quality criteria published by the Pennsylvania Department of Environmental Protection (and in the case of Delaware River samples, Delaware River Basin Commission criteria). Some water quality parameters for which the Pennsylvania Department of Environmental Protection does not have water quality criteria (e.g., nutrients, *E. coli*, enterococci) are compared against US EPA recommended water quality criteria (US EPA 2000, US EPA 1986). In 2006, the Pennsylvania Department of Environmental Protection published a review of statistical techniques and provided guidelines for water chemistry statistical analysis when the goal is determining whether or not a site is meeting its designated use (Pennsylvania Department of Environmental Protection 2006). This document described attainment and non-attainment of water quality criteria as mutually exclusive cases, and presented a statistical framework for evaluation of the hypothesis that a stream is or is not attaining its designated use. The Pennsylvania Bacteriological Sampling Protocol (Pennsylvania Department of Environmental Protection 2008) is used for recreational use assessments.

6.7.2 Continuous Water Quality Data Processing

With 12 USGS gages collecting data for multiple water quality parameters at half-hour intervals, a large amount of data are produced. The Water Department staff has developed procedures for processing and analyzing these data using Microsoft Excel and Access software, as well as R, a free software environment for statistical computing and graphics (R Core Team 2012). Most aspects of the data processing and analysis have been automated with custom Visual Basic and R code.

The Water Department independently maintains databases of water quality and streamflow via automated regular retrievals of these data from USGS National Water Information System. Each month, the databases are queried and results for each gage are imported into MS Excel workbooks. Any available field data collected during that period (e.g., hand meter readings from field maintenance checks, water quality grab samples, etc.) are also imported. Once all required data have been entered, separate plots are produced for each parameter (dissolved oxygen, turbidity, pH, specific conductance, and temperature) to enable a subjective review of data quality (Figure 6-7).

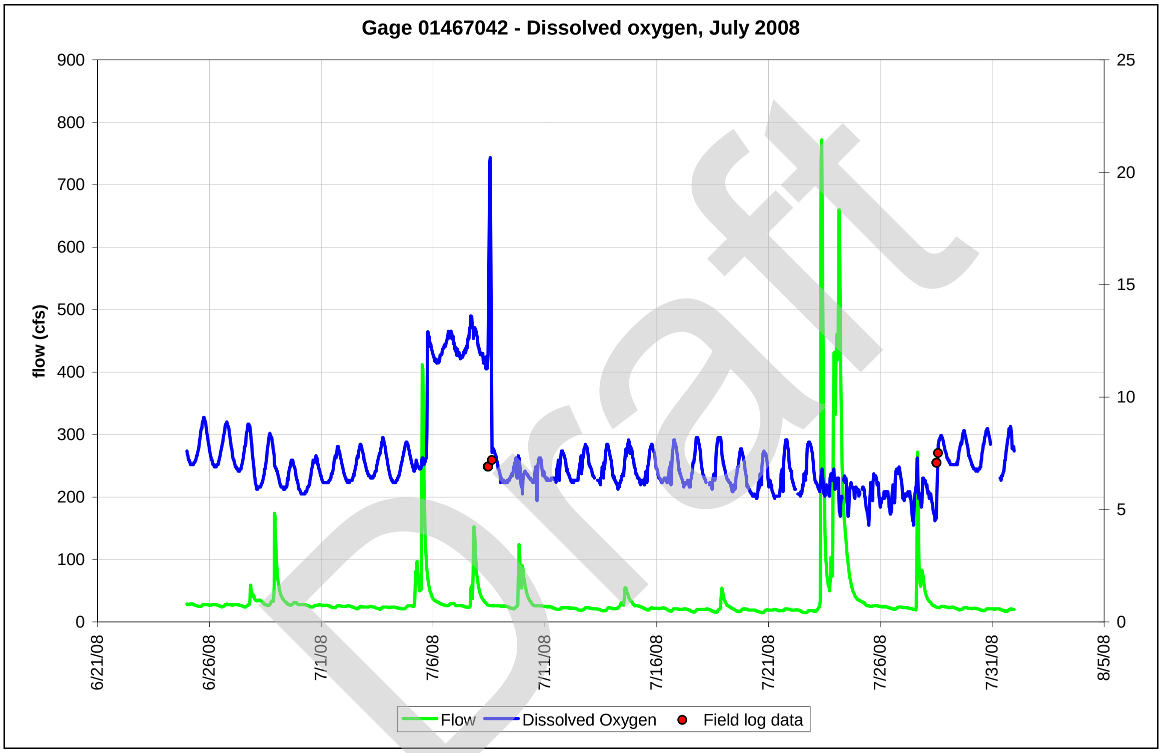

Figure 6-7: Example of an Excel-generated Data Processing/Analysis Plot; Gage 01467042, Dissolved Oxygen, July 2008

These plots are examined and are the primary basis for the selection of good vs. questionable data for a given month. Intervals of questionable data are located and added to a table of “flagged” data for that particular parameter, which is then used to update the water quality database.

The final step of the procedure utilizes R, a statistical programming language and software environment. The R software code developed by the Water Department staff analyzes all of the water quality data in a database, as well as the good and questionable flags, and generates statistical and graphic results in a variety of forms. These include monthly plots for all data parameters for each site, showing accepted and questionable data, water quality criteria, grab sample data, and streamflow (Figure 6-8); assorted statistics including accepted and questionable data comparisons, monthly exceedance percentages, and comparisons of wet and dry weather periods; and additional plots, including average dissolved oxygen, percent dissolved oxygen saturation, and pH/percent dissolved oxygen saturation.

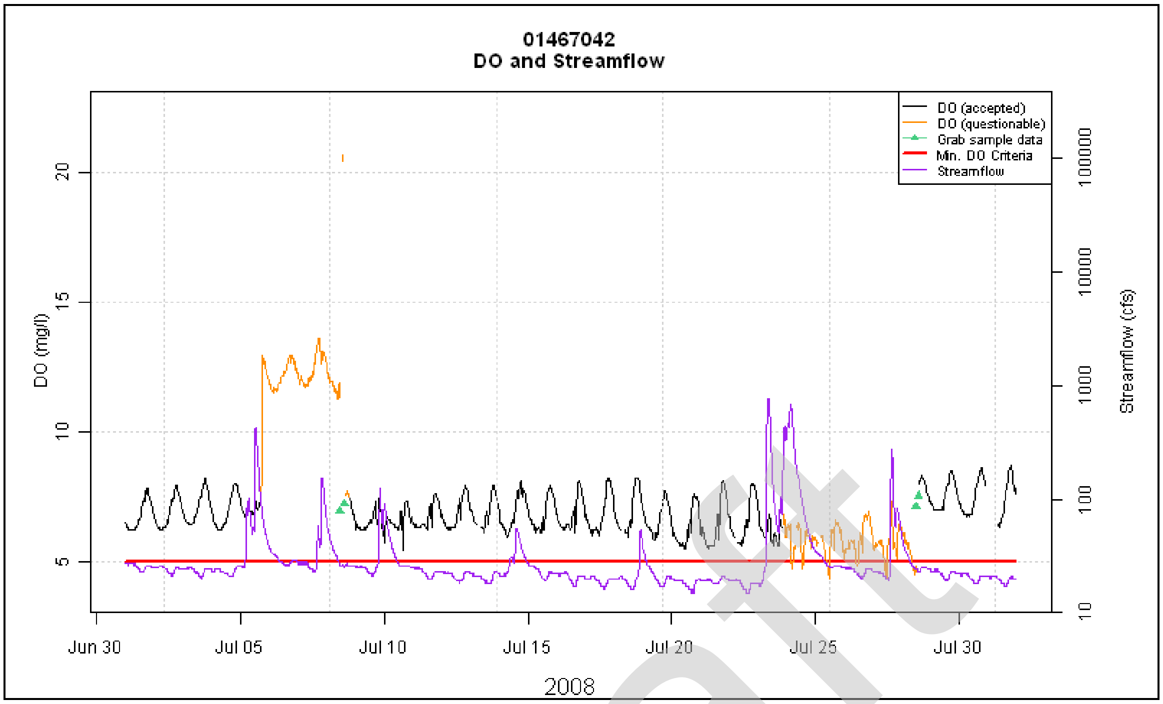

Figure 6-8: Example of an R-generated Plot Showing Accepted and Questionable Data, and Minimum Water Quality Criteria; Gage 01467042, Dissolved Oxygen, July 2008

6.7.3 Wadeable Streams Assessment Data Processing and Analysis

6.7.3.1 Benthic Macroinvertebrate Assessment

The Water Department benthic macroinvertebrate and physical habitat assessments are performed using the field and laboratory methods described in the Pennsylvania Department of Environmental Protection Freestone Riffle-Run Index of Biotic Integrity (Pennsylvania Department of Environmental Protection 2009a) and instream comprehensive evaluation protocol (Pennsylvania Department of Environmental Protection 2009b). The Pennsylvania Department of Environmental Protection index of biotic integrity is a multimetric index consisting of six individual metrics (Table 6-8). Individual site scores for these metrics are compared to standardization values. Earlier assessments conducted for integrated watershed management plans used different methods (Table 6-9), so the Water Department will perform normalization and/or compare to local reference sites when applicable to provide further information about integrated watershed management plan indicators. These results will be presented alongside the Pennsylvania Department of Environmental Protection instream comprehensive evaluation metrics for comparison purposes.

Table 6-8: The Pennsylvania Department of Environmental Protection Instream Comprehensive Evaluation Protocol Index of Biotic Integrity Macroinvertebrate Metrics

Metric	Standardization Value
Taxa Richness	33
EPT Taxa Richness (PTV 0-4 only)	19
Beck's Index	38
Shannon Diversity Index	2.86
Hilsenhoff Biotic Index	1.89
Percent Sensitive Taxa (PTV 0-3 only)	84.5

Table 6-9: Rapid Bioassessment Protocol III Macroinvertebrate Community Metrics used in the Water Department Comprehensive Characterization Reports for Cobbs and Tookany/Tacony-Frankford Watersheds

Metric (*)	Biological Condition Scoring Criteria			
	6	4	2	0
Taxa Richness [(a)]	>80%	79-70%	69-60%	<60%
Hilsenhoff Biotic Index (Modified) [(a)]	<0.71	0.72-1.11	1.12-1.31	>1.31
Modified EPT Index [(a)]	>80%	79-60%	59-50%	<50%
Percent Contribution of Dominant Taxon [(a)]	<10%	11-16%	17-22%	>22%
Percent Modified Mayflies [(a)]	<12%	13-20%	21-40%	>40%
Ratio of Scrapers/Filter [(b)] Collectors	>50%	35-50%	20-35%	<20%
Community Loss Index [(b)]	<0.5%	0.5-1.5	1.5-4.0	>4.0
Ratio of Shredders/Total [(b)]	>50%	35-50%	20-35%	<20%

[a] Metrics used to quantify scoring criteria (Pennsylvania Department of Environmental Protection)

[b] Additional metrics used for qualitative descriptions of sampling locations (US EPA)

(*) Percentage values obtained that are intermediate to the above ranges will require subjective judgment as to the correct placement. Use of the habitat assessment and chemical data may be necessary to aid in the decision process.

6.7.3.2 Physical Habitat Assessment

Water Department physical habitat assessments are performed using the methods described in the Pennsylvania Department of Environmental Protection Riffle-Run Freestone Index of Biotic Integrity (Pennsylvania Department of Environmental Protection 2009a) and instream comprehensive evaluation protocol (Pennsylvania Department of Environmental Protection 2009b). Physical habitat assessment forms are completed along with benthic macroinvertebrate sampling. Aquatic biologists rank 12 habitat condition parameters at the monitoring site on a scale of 0-20 (Table 6-10). The site total score is computed as the sum of all the individual condition parameter scores.

Table 6-10: The Pennsylvania Department of Environmental Protection Instream Comprehensive Evaluation Protocol Habitat Assessment Parameters

Condition Parameter	Condition			
	Optimal	Suboptimal	Marginal	Poor
Instream Fish Cover	16-20	11-15	6-10	0-5
Epifaunal Substrate	16-20	11-15	6-10	0-5
Embeddedness	16-20	11-15	6-10	0-5
Velocity/Depth Regime	16-20	11-15	6-10	0-5
Channel Alteration	16-20	11-15	6-10	0-5
Sediment Deposition	16-20	11-15	6-10	0-5
Frequency of Riffles	16-20	11-15	6-10	0-5
Channel Flow Status	16-20	11-15	6-10	0-5
Condition of Banks	16-20	11-15	6-10	0-5
Bank Vegetative Protection	16-20	11-15	6-10	0-5
Grazing or Other Disruptive Pressure	16-20	11-15	6-10	0-5
Riparian Vegetative Zone Width	16-20	11-15	6-10	0-5

6.7.3.3 Fish Assessment

The Water Department assesses the health of fish communities based on the technical framework of the index of biotic integrity developed by Karr (1981). The analysis entailed the definition of “ecoregional-specific” metrics pertinent to the fish assemblages located in the lower Schuylkill River drainage. Standardized metrics (i.e., indices) were then integrated to provide an overall indication of the condition of fish assemblages at each assessment location. Individual metrics within the fish index of biotic integrity framework were also used to provide quantitative information regarding a specific attribute of the respective assessment location (e.g., pollution tolerance values). In addition to index of biotic integrity metrics, other metrics were incorporated into the design to evaluate the overall ecological health of fish assemblages and as a means of comparison of each assessment site. Tables 6-11 and 6-12 describe the various indices and scoring criteria used for the index of biotic integrity metrics. Additional metrics used in the analysis are displayed in Table 6-13.

Table 6-11: Metrics Used to Evaluate Fish Community Index of Biological Integrity*

Metric	Scoring Criteria		
	5	3	1
1. Number Of Native Species	>67%	33-67%	<33%
2. Number Of Benthic Insectivore Species	>67%	33-67%	<33%
3. Number Of Water Column Species	>67%	33-67%	<33%

Metric	Scoring Criteria		
	5	3	1
4. Percent white sucker	<3%	3-15%	>15%
5. Number Of Sensitive Species	>67%	33-67%	<33%
6. Percent Generalists	<20%	20-45%	>45%
7. Percent Insectivores	>50%	25-50%	<25%
8. Percent Top Carnivores	>5%	1-5%	<1%
9. Proportion of diseased/anomalies	0%	0-1%	>1%
10. Percent Dominant Species[a]	<40%	40-55%	>55%

* Metrics used are based on modifications as described in Barbour et al., 1999.

[a] Metric based on USGS NAWQA study (2002).

Table 6-12: Index of Biological Integrity Score Interpretation*

Index of Biological Integrity	Integrity Class	Characteristics
45-50	Excellent	Comparable to pristine conditions, exceptional assemblage of species
37-44	Good	Decreased species richness, intolerant species in particular
29-36	Fair	Intolerant and sensitive species absent; skewed trophic structure
10-28	Poor	Top carnivores absent or rare; omnivores and tolerant species dominant
<10	Very Poor	Few species and individuals present; tolerant species dominant; diseased fish frequent

* Index of biotic integrity score interpretation based on Halliwell et al., 1999.

Table 6-13: Additional Metrics Used to Evaluate Fish Assemblage Condition

Metric	Assessment Type
Species Diversity	Shannon (H') Diversity Index
Trophic Composition	Percentage of Functional Feeding Groups
Tolerance Designations	Percentage of Pollution Tolerant, Moderate And Intolerant Species
Modified Index Of Well-Being	MIwb Index

7.0 Meteorological Monitoring

Precipitation data are a fundamental component of a combined sewer system monitoring program and are required to calibrate and validate combined sewer system models and develop design conditions needed for characterizing the combined sewer system and estimating combined sewer overflow statistics. Long-term historic record precipitation data are used to establish average or typical year precipitation. Precipitation data are also necessary for assessing the effectiveness of green stormwater infrastructure practices at reducing stormwater inflows to the combined sewer system and determining the effects that reduced combined sewer overflow volumes and pollutant loads have on the receiving water bodies. Both long-term temporal rainfall data and spatially distributed event based rainfall data synchronized with combined sewer system, receiving water, and green stormwater infrastructure monitoring are needed to appropriately calibrate models and characterize the green stormwater infrastructure effects on the combined sewer system and receiving waters.

Hydrologic models depend upon the reliability of precipitation and flow monitoring datasets used for calibration and simulation. Consistent precipitation and flow monitoring measurements are very important when attempting to characterize rainfall runoff relationships over time. Hydrologic models require rain gage networks to monitor and represent the volume, intensity, and spatial distribution of precipitation across a drainage basin.

The Water Department currently collects precipitation data from its network of 23 rain gages throughout the City and from publicly available meteorological data from the Philadelphia International Airport. The Philadelphia International Airport gage has over 110 years of historic precipitation data reported in hourly increments. In addition to precipitation data retrieved from the Philadelphia International Airport station, the National Weather Service provides other climatological data at this location useful for monitoring and hydrologic and hydraulic modeling.

The Water Department plans to improve the quality and resolution of the precipitation data by installing additional rain gages and contracting work for performing both historic and ongoing gage-adjusted radar-rainfall analyses.

7.1 Summary of Data Sources

Data sources for meteorological monitoring include the following categories:

- The Water Department rain gage network
- The Water Department radar-rainfall data
- National Weather Service operated Philadelphia International Airport precipitation data
- National Weather Service Philadelphia International Airport surface observation station climate data
- Various locations where temperature, evaporation, wind and solar radiation data are collected

7.1.1 The Water Department Precipitation Gage Network

The Water Department maintains a network consisting of 23 tipping-bucket rain gages located throughout the City that record rainfall depths (number of 0.01 inch "tips") at 2.5-minute intervals. Monitoring activities and data collection at these gage sites will be maintained under the Comprehensive Monitoring Plan. The Water Department rain gage network was established in 1990, and the data is reliable from 1990 – present. The raw 2.5-minute tipping-bucket rain gage data are extracted from a link to the Water Department Collector System's recording telemetry unit database which collects data directly via automatic telephone polling of the gages. This system was updated in 2010 to a TELOG system which uses cellular-based telemetry and improved enterprise data management software.

The total number of Water Department rain gages in each watershed is shown in Table 7-1 and in each drainage district in Table 7-2. Approximate rain gage locations are presented in Figure 7-1. New Water Department gage locations recommended under a proposed expansion of the current gage network are documented in Section 7.2.1.

Table 7-1: Number of Water Department Rain Gages within each Watershed

Watershed	Total Number of Rain Gages
Delaware River	10
Schuylkill River	7
Darby-Cobbs Creek	2
Tookany/Tacony-Frankford Creek	4

Table 7-2: Number of Water Department Rain Gages within Drainage District

Drainage District	Total Number of Rain Gages
Northeast	12
Southeast	4
Southwest	8

7.1.1.1 Improved Rain Gage Coverage

As required in the Consent Order and Agreement, the Water Department will conduct a Sewer System Evaluation Survey. The primary goal of the Sewer System Evaluation plan is to address infiltration and inflow in the separate sewer area tributary to the City's Water Pollution Control Plants by identifying critical sewers with excessive infiltration and inflow. The study will identify outlying community sanitary sewer connections that contribute excessive wet weather flows and suggest possible further investigatory needs, including additional rainfall records for areas outside the City. These data will assist in improving the rain gage coverage of outlying communities to support rainfall dependent infiltration and inflow analyses of their sanitary sewers that are tributary to the City's water pollution control plants. Historic local rainfall data will be inventoried and assessed for reliability for use in performing hydraulic evaluations of wet weather flows in sanitary sewers. The assessment of historical and existing data will identify critical gaps or deficiencies in the availability or reliability of data needed to complete the Sewer

System Evaluation Plan. Areas with unreliable or non-existent data will be assessed for additional rain gages or radar-rainfall data to improve rainfall monitoring coverage of outlying communities.

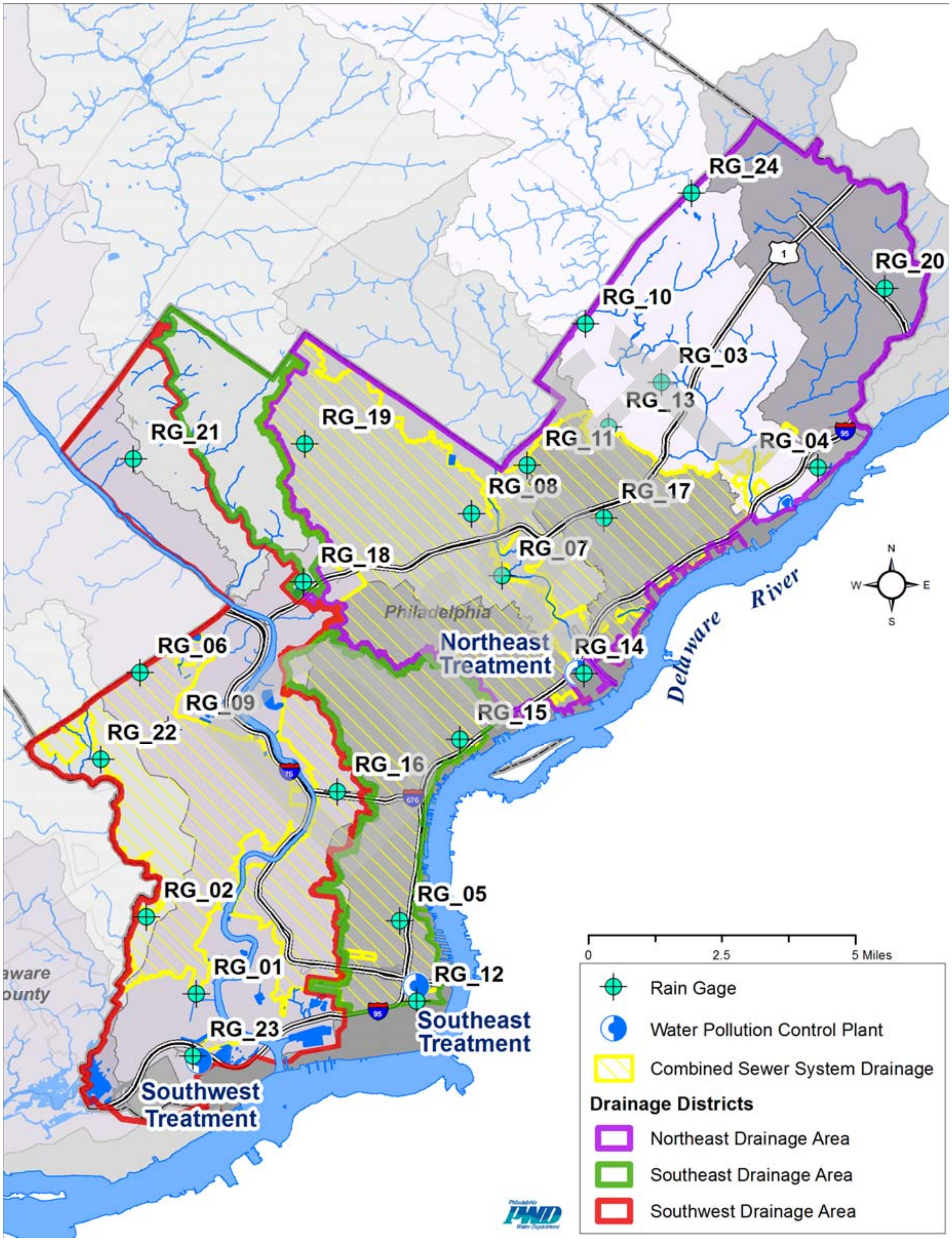

Figure 7-1: The Water Department Rain Gage Locations, Watersheds, and Combined Sewer Drainage Areas

Assessment of the rain gage network by the Water Department has identified 11 potential new rain gage sites in addition to the existing network to improve resolution along the perimeter limits of the Water Department service area. Under the Comprehensive Monitoring Plan, detailed site installation investigations will be conducted at these proposed sites, and gages will be installed where it is feasible to do so. Data from these new rain gage sites will be used in conjunction with the existing rain gage network and radar reflectivity data to produce a higher resolution spatially distributed precipitation dataset for sewer service areas outside the City.

These 11 potential rain gages are proposed under the Comprehensive Monitoring Plan in order to further refine the precipitation monitoring coverage. Four of the gages are located within Philadelphia, while the remaining gages are all in surrounding communities. The increased coverage serves several purposes:

- Outlying community sanitary sewer service areas will now have precipitation monitoring, which is not currently available with the existing rain gage network
- Combined Sewer Overflow (CSO) watersheds including the Cobbs Creek and Tookany/Tacony-Frankford Creek will have increased precipitation monitoring capability
- More detailed coverage is needed to calibrate the radar-rainfall grid outside the City

A list of the proposed new rain gages that will be investigated, and where feasible implemented, under the Comprehensive Monitoring Plan is presented in Table 7-3. A map with the locations of the gages is given in Figure 7-2.

Table 7-3: Locations of Proposed Additional Rain Gages

Site	Location	County	Municipality
25	24th and Jackson St – 3 Story School Building	Philadelphia County	Philadelphia
26	Fairhill High Pressure P.S. Lehigh and 7th St	Philadelphia County	Philadelphia
27	Northeast Airport 2901 Grant Ave	Philadelphia County	Philadelphia
28	Possible Mounting on Utility Pole	Philadelphia County	Philadelphia
29	Springfield Township High School	Montgomery County	Springfield Township
30	Myers Elementary School	Montgomery County	Cheltenham Township
31	Meadowbrook Train Station, Old Valley Rd	Montgomery County	Abington Township
32	US Post Office 1050 Street Rd Southampton	Bucks County	Southampton Township
33	Gladstone Train Station, Walsh Rd	Delaware County	Clifton Heights Borough
34	Lynnewood Elementary School	Delaware County	Haverford Township
35	Welsh Valley Middle School	Montgomery County	Lower Merion Township

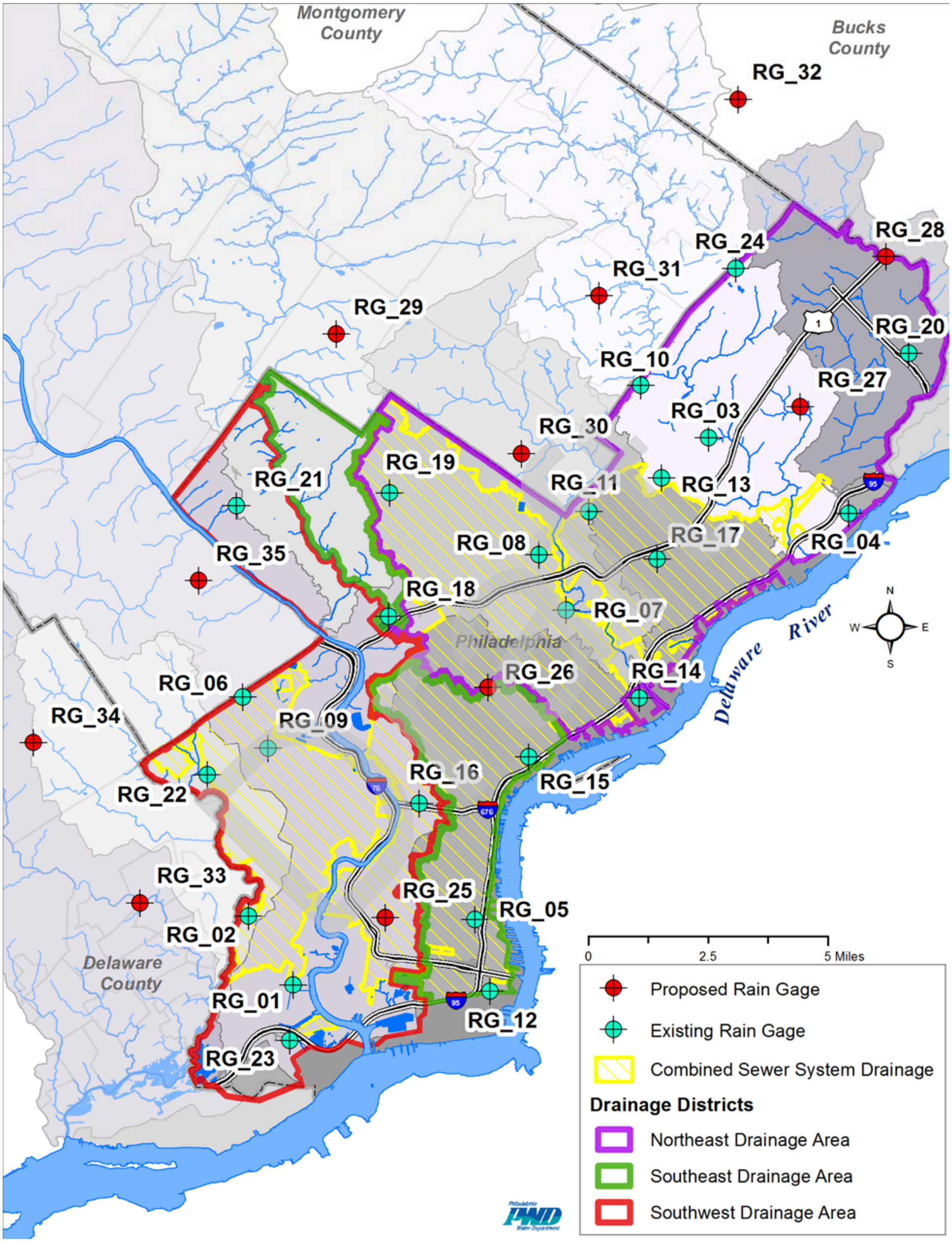

Figure 7-2: Proposed Rain Gage Locations

7.1.2 Water Department Radar-Rainfall Data Sources

To augment the information provided by the gage network and improve the spatial and temporal distribution and resolution of precipitation data, the Comprehensive Monitoring Plan will include the use of a regional radar-rainfall system. The Water Department has previously contracted work to collect, analyze, and report high-resolution, spatially-distributed, gage-adjusted radar-rainfall data for specific time periods that was used to further calibrate its hydrologic and hydraulic models. Data were obtained from the Next-Generation Radar Doppler weather radar network operated by the National Weather Service, specifically the KDIX radar site located near Mt. Holly, New Jersey, approximately 75 km from the City of Philadelphia. Level II data was obtained, which are the digital radial base data (reflectivity, mean radial velocity, and spectrum width) and dual polarization variables (differential reflectivity, correlation coefficient, and differential phase) output from the signal processor in the Radar Data Acquisition unit. These data are used to determine spatially-distributed precipitation type, intensity, and volume information. Proposed future uses of radar-rainfall data under the Comprehensive Monitoring Plan are described in Section 7.1.2.1. The Water Department's previous acquisition of calibrated radar-rainfall data includes:

- 18 months of 15-minute, 2 x 2 km grid, gage calibrated radar-rainfall data covering 399 square miles including the Water Department service area plus all surrounding contributory watershed areas. These data were acquired for use in calibration of CSO sewershed, Cobbs Creek restoration, and Main and Shurs sewershed models. The time periods covered include:
    - 2 month period containing historic rainfall events: July 1994 and October 1996
    - 12-month period from September 1, 1999 through August 31, 2001
    - 4-month period from March 1, 2002 through June 30, 2002
- 21 months of continuous 1-hour, 4 x 4 km, gage calibrated radar-rainfall data covering the Lower Delaware River Basin for the period of July 1, 2001 through March 31, 2003. These data were acquired for calibration of the Delaware River Basin PCB loading model.
- Four seasons of event based 15-minute 1 x 1 km gage calibrated radar-rainfall data covering the Water Department service area plus the Tookany/Tacony-Frankford and the Darby-Cobbs Watersheds. These data were acquired for the wet weather water quality monitoring program and the calibration of open channel flow models and as part of the Tookany/Tacony-Frankford and Darby-Cobbs Watershed management plans. The time periods covered include:
    - Spring 2003 (4 events): May 2, 5, 7, and 16
    - Summer 2003 (5 events): July 10, 23, and 24; September 13 and 23
    - Fall 2003 (1 event): October 14
    - Summer 2004 (2 events): July 7 and August 30

7.1.2.1 Gage-Adjusted Radar-Rainfall Monitoring

The Water Department has contracted work to collect, analyze, and report high-resolution, spatially-distributed, gage-adjusted radar-rainfall data that will be used to further calibrate its hydrologic and hydraulic models.

The radar-rainfall data also includes the analysis and assessment of precipitation data from the network of tipping-bucket rain gages that are owned and operated by the Water Department. The precipitation data will be compared to the next-generation radar data for each storm event to identify gages that appear to perform poorly or exhibit suspect behavior. Gages exhibiting synchronization issues, clogging, mechanical problems, or other suspicious behavior will need to be identified and excluded from further analysis.

The radar-estimated rainfall data will be compared with gaged rainfall to identify and quantify any bias, defined as the varying differences between the average gage values and the average radar pixel estimates. The historic and monthly next-generation radar data will be gage and bias adjusted. The resulting precipitation data will be a combination of measured precipitation gage data and weather radar data accumulated to 15-minute intervals, geo-referenced, gage and bias corrected, and merged into a single and consistent dataset. The dataset will provide an accurate estimate of the quantity, timing, and distribution of rainfall precipitation over the Water Department service area.

7.1.3 Philadelphia International Airport Precipitation Data

The National Weather Service rain gage at the Philadelphia International Airport, located in southwestern Philadelphia, has over 110 years of hourly precipitation data. The period of record runs from January 3, 1902 through the present. An annual online subscription is maintained by the Water Department for the Philadelphia International Airport station that allows the download of monthly edited local climatological data published by the National Oceanic and Atmospheric Administration National Climatic Data Center. The reports are downloaded on a monthly basis when made available, which is typically four to six weeks behind the end of the current month. The collection and analysis of Philadelphia International Airport data will continue under the Comprehensive Monitoring Plan.

The historical record data were previously analyzed and typical year precipitation was characterized and determined for the Water Department service area. The average spatial distribution of precipitation over the combined sewer system areas is characterized using the 17-year rainfall record for the Water Department 23-raingage network collected over the period 1990-2006, along with 15 months of gage calibrated radar-rainfall data. Extensive analyses of non-climatic gage biases based on inter-gage comparison and radar-rainfall data are performed leading to the creation of a bias adjusted rainfall dataset for the Water Department 23-raingage network over the 17-year period of record (1990- 2006). The detailed analyses are presented in the Long Term Control Plan Update (LTCPU) Supplemental Documentation Volume 5 – Precipitation Analysis.

7.1.4 Philadelphia International Airport Meteorological Data

In addition to precipitation data, the National Weather Service weather station at the Philadelphia International Airport provides other relevant and useful climatological data including wind speed, weather conditions, temperature, relative humidity, and air pressure. The collection and analysis of Philadelphia International Airport meteorological data will continue under the Comprehensive Monitoring Plan.

7.1.4.1 Temperature Data

Temperature data are used as input for water quality modeling of the receiving waters. Temperature statistics developed for the LTPCU are shown below in Table 7-4 and were obtained from the National Oceanographic and Atmospheric Agency. The air temperature statistics that are shown below come from a period of record from 1947 to 2008. The dry-bulb temperature which is commonly referred to as the ambient air temperature is the temperature of the air that is measured by a thermometer that is freely exposed to the air but is shielded from radiation and moisture. Table 7-4 shows that the highest mean dry-bulb air temperature occurs during the month of July and is 77.3^{o}F, while the lowest mean dry-bulb air temperature occurs during the month of January and is 32.3^{o}F.

Time series of temperature data in conjunction with other input datasets will be used for receiving water quality modeling.

Table 7-4: Temperature Statistics

Element	Period of Record (years)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Mean Daily Maximum Air Temperature (^{o}F)	61	39.7	42.5	51.5	63.4	73.3	82.0	86.6	84.8	77.7	66.7	55.3	44.0
Mean Dry Bulb Air Temperature (^{o}F)	61	32.3	34.5	42.5	53.3	63.2	72.4	77.3	75.8	68.5	57.1	46.7	36.6
Mean Daily Minimum Air Temperature (^{o}F)	61	24.9	26.4	33.6	43.1	53.1	62.3	68.0	66.8	59.3	47.6	38.1	29.1

7.1.4.2 Snowfall Data

Snowfall statistics developed for the LTCPU are shown below in Table 7-5 and were obtained from the National Oceanographic and Atmospheric Agency from a period of record of 1978 to 2008. The table shows that the average yearly snowfall for this period was 19.3 inches with the highest monthly average snowfall occurring during the month of February and accounted for 6.6 inches. The table also shows that for the period of record the average total days with a snowfall amount greater than or equal to 1 inch is only 5.1 days. The table shows that Philadelphia does not normally receive large snow events.

Table 7-5: Snowfall Statistics

Element	Average Monthly Snowfall (in)	No. of Days with Snowfall >= 1.0 in
Period of Record (years)	30	30
JAN	6.4	1.9
FEB	6.6	1.5
MAR	3.2	0.8
APR	0.6	0.2
MAY	0	0
JUN	0	0
JUL	0	0
AUG	0	0
SEP	0	0
OCT	0.1	0
NOV	0.4	0.2
DEC	2	0.5
Total Annual	19.3	5.1

7.1.5 Evaporation Data

Limited long-term daily evaporation data exists for the Philadelphia area. Neither the Philadelphia Airport nor the Wilmington Airport records evaporation data. For the development of the LTPCU one site in New Castle County, Delaware was located with recorded daily evaporation data from 1956 through 1994. Average evaporation rates (inches per day) determined from this site are given in Table 7-6.

Table 7-6: Evaporation Statistics

Month	Average Evaporation Rate (in/day)
Jan	0.07
Feb	0.07
Mar	0.07
Apr	0.15
May	0.18
Jun	0.21
Jul	0.22
Aug	0.19
Sep	0.14
Oct	0.09
Nov	0.07
Dec	0.07

Evaporation and transpiration are critical components of the hydrologic cycle of green stormwater infrastructure. Understanding the amount and variation of these processes could lead to enhanced performance of green stormwater infrastructure and its effect on the combined sewer system. Microcosms of green stormwater infrastructure (vegetation, soil, and/or gravel components) have been studied by other entities such as research universities. The Water Department will investigate opportunities for development of evaporation and transpiration monitoring as part of the Comprehensive Monitoring Plan.

7.1.6 Wind Data Sources

Wind field measurements are necessary for incorporating driving equations of fluid motion into hydrodynamic models that ultimately affect estimates of water quality conditions in the receiving waters. Wind measurements are recorded at the local National Weather Service stations and provide a source for historical and ongoing data for development of the hydrodynamic models under the Comprehensive Monitoring Plan. Station locations identified as wind data sources for application in hydrodynamic modeling include the Philadelphia International Airport and Burlington, NJ.

In addition, as part of the data acquisition for the hydrodynamic modeling effort and a component of the Comprehensive Monitoring Plan, a surface-buoy will be deployed with capabilities to measure meteorological conditions including wind speed and direction. The proposed location is in the Delaware River near Marcus Hook, Chester, PA.

7.1.7 Solar Radiation Data Sources

Photosynthetically-active radiation is an important input for water quality modeling, particularly in estimating the growth of benthic algae. Photosynthetically-active radiation is recorded at 15-minute intervals at two United States Geological Survey (USGS) stations located in Philadelphia: station 01467087 Frankford Creek at Castor Avenue and station 01474500 Schuylkill River upstream from Fairmount Dam. Photosynthetically-active radiation data will be utilized for water quality model development and validation and documentation of its use will be included as part of associated deliverables for the water quality models.

7.2 Meteorological Data Analysis

This section presents the methods and processes used in conducting quality assurance and control, numerical analyses, and data processing for meteorological monitoring data. The collected data are organized, assessed for errors, and analyzed using a variety of tools and methods for use in models and other assessment programs. Quality assurance and quality control and analytical methods have been established and implemented as part of the ongoing Water Department monitoring programs. These procedures and methods will be continued under the Comprehensive Monitoring Plan and compiled into standard procedure documents. There are six categories of meteorological data analyses that are addressed in this data analysis section of the Comprehensive Monitoring Plan:

- Water Department precipitation data quality assurance and quality control and data analysis procedures
- The National Weather Service Philadelphia International Airport precipitation data quality assurance and quality control and data analysis procedures
- Water Department radar-rainfall data quality assurance and quality control and data analysis procedures
- Temperature data quality assurance and quality control and data analysis procedures
- Wind data quality assurance and quality control and data analysis procedures
- Solar radiation quality assurance and quality control and data analysis procedures

7.2.1 Precipitation Data Analysis

The main goal in acquiring precipitation data under the Comprehensive Monitoring Plan is to get the most detailed and consistent—temporally and spatially—data available for the periods in which hydraulic data are available for the Philadelphia Combined Sewer System service area. Quality assurance and quality control of this data is necessary to identify missing and questionable data. Additional analyses may be required to integrate with hydrologic and hydraulic models and other assessment tools.

7.2.1.1 Water Department Precipitation Data Quality Assurance and Control Procedures

The Water Department rain gage data are analyzed through extensive quality assurance and control procedures to identify bad or missing data, which are filled or replaced with accurate nearby gage data, and to perform bias adjustment using a combination of software tools developed by the Water Department.

Quality Assurance and Control Procedures

Existing quality assurance and quality control procedures will continue to be implemented under the Comprehensive Monitoring Plan. Documentation of these analyses into a standard procedure will be completed as part of this plan. The Water Department raw 2.5-minute data are summed to fixed 15-minute intervals. Quality assurance and quality control of these data is performed on a monthly basis by visual inspection using comparison of data across the network in order to identify and flag missing or questionable data. Flagged data are then filled with coincident data from the six nearest gages using inverse distance squared weighting.

Daily rainfall totals for each gage are compared to the network mean using double mass and cumulative residual time series plots in order to identify historical changes in non-climatic biases at the gages. In this way, gage malfunctions not readily apparent from initial visual inspection of the raw gage data can be identified. Furthermore, gage-adjusted radar-rainfall analyses will be used when available to evaluate the quality of the rain gage data and generate an improved spatially and temporally consistent bias corrected rainfall dataset.

Data Analysis

Spatial Distribution of Rainfall

The Storm Water Management Model requires assignment of an input rainfall time series for each stormwater runoff or sanitary sewer rainfall dependent infiltration and inflow basin in the model. Inverse distance-squared weighting is used to estimate rainfall in areas between rain gages in the absence of spatially distributed gage adjusted radar-rainfall data. A 1 km^2 grid is imposed over the Water Department wastewater treatment service area and a rainfall value for every time step is assigned to each grid element either from radar-rainfall estimates if available or by inverse distance-squared weighting of the rainfall values from three nearby surrounding gages. Finally, the gridded precipitation values are area-weighted to provide average rainfall values for each individual sewershed in the model. In this manner, spatially distributed 15-minute accumulated rainfall estimates are provided for all Storm Water Management Model hydrologic basin areas.

Rainfall Event Identification Analysis

Event based analysis of the long-term precipitation record is used to best represent average annual CSO frequency and volume statistics needed for presumptive measurement of collection system performance. Existing rainfall event identification analysis procedures established for the Water Department monitoring programs will be continued under the Comprehensive Monitoring Plan. These event statistics are specific for a given minimum inter-event time used for event definition. CSO occurrence is considered to be 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 order to identify short-term continuous periods likely to generate CSO statistics representative of the long-term record for the LTCPU, continuous 12-month periods selected from a 17-year Water Department 23-raingage record (1990-2006) were evaluated against the long-term record based on the following storm event characteristics:

- Annual number of storm events
- Total annual rainfall volume
- Best fit cumulative distribution function plots of event total rainfall volume, peak hourly rainfall intensity, and inter-event times.

The identification and evaluation of event based rainfall analysis for the purposes of the combined sewer system performance assessment is described in detail in the LTCPU Supplemental Documentation Volume 5 – Precipitation Analysis.

For monitoring related to green stormwater infrastructure under this plan, rainfall events will be identified using the nearest rain gage to control locations. Procedures for adjusting monitored rainfall event data and comparing to historical records and typical year events will be developed as part of the Comprehensive Monitoring Plan.

Rain Gage Bias Adjustment

The identification and adjustment of precipitation time series data for non-climatic changes in recording bias among rain gages can be instrumental in controlling uncertainty in hydrologic models. Existing rainfall gage bias adjustment analyses will be continued under the Comprehensive Monitoring Plan. Hydrologic models depend upon the reliability of precipitation and flow monitoring datasets used for calibration and simulation. Consistent precipitation and flow monitoring measurements are important when attempting to characterize rainfall runoff relationships over time. Hydrologic models require rain gage networks to represent the spatial and temporal distribution of precipitation across a drainage basin and benefit from the normalization of relative rain gage biases across the network.

Calibration of large urban sewer system models, using a moderately dense basin-wide rain gage network and continuous flow monitoring data, is improved by creating continuous homogeneous rainfall records with normalized spatial biases.

Double-mass regression and cumulative residual time series analysis techniques have been used to evaluate and adjust historical rain gage network data to correct for non-homogeneity of individual rainfall records and to normalize spatial bias across the network. Homogeneity of rainfall time series data is evaluated and adjusted by comparison to the rain gage network mean over a 13-year period of record. Spatial bias across the network was then normalized by comparison to continuous calibrated radar-rainfall estimates obtained over a 15-month period.

The rain gage bias adjustment and normalization process used to provide the spatial and temporal consistency necessary for the hydrologic model calibration process for the purposes of LTCPU combined sewer system performance assessment is described in detail in LTCPU Supplemental Documentation Volume 5 – Precipitation Analysis.

7.2.1.2 Philadelphia International Airport Precipitation Data Analysis

Quality Assurance and Control Procedures

The National Weather Service applies quality assurance procedures to the Philadelphia International Airport precipitation data internally prior to its release. Therefore, no quality assurance protocols are conducted or proposed by the Water Department for the Philadelphia International Airport precipitation data for this Comprehensive Monitoring Plan.

Data Analysis

The long-term hydrologic conditions over the Philadelphia combined sewer system area are characterized using the historic hourly precipitation record, 65-year period (1948-2012), for the National Weather Service Cooperative Station located at the Philadelphia International Airport (WBAN#13739). Statistical analyses of the long-term record are performed to determine the average frequency, volume, and peak intensity of rainfall events.

Identification of long-term average hydrologic conditions over the combined sewer system is based primarily upon average annual and monthly precipitation volumes determined from the long-term record at the Philadelphia International Airport. Comparisons are made between the individual annual precipitation volumes and the long-term average to identify relatively “wet” and “dry” years. As described in Section 7.2.1.1, the Philadelphia International Airport rainfall record was used to determine the appropriate 12 month period of rainfall against the long-term record based on the following storm event characteristics:

- Annual number of storm events
- Total annual rainfall volume

- Best fit cumulative distribution function plots of event total rainfall volume, peak hourly rainfall intensity, and inter-event times.

Additional detail about the analysis of the selected average annual rainfall distribution for the purposes of the combined sewer system performance assessment is described in LTCPU Supplemental Documentation Volume 5 – Precipitation Analysis.

Philadelphia International Airport rainfall data will continue to be used to assess rainfall data against the long-term record, especially when utilized to assist in evaluation of green stormwater infrastructure monitoring data and sewer monitoring data.

7.2.1.3 Radar-Rainfall Precipitation Data Analysis

Quality Assurance and Control Procedures

The next-generation radar reflectivity data are evaluated and corrected for anomalies such as beam blockages and ground clutter. Existing radar-rainfall data quality assurance and quality control procedures and documentation established by the Water Department and the professional services vendor providing the radar-rainfall data will be continued under the Comprehensive Monitoring Plan. The Water Department approved, 15-minute unfilled data—which is randomly missing or errant data due to data collection errors that have not been filled in or adjusted using averaging techniques—are provided to the vendor for calibration of the radar-rainfall estimates using mean field or local bias adjustment methods. The radar-rainfall analyst also evaluates the rain gage data to identify suspected mechanical or blockage problems with any of the gages in the Water Department network. Questionable gage data are removed from the radar adjustment process. Comparisons between the gage accumulations and the corresponding adjusted radar accumulations shall be conducted and synchronization timing shall be checked. The results of the quality assurance and quality control analyses will be documented in monthly Radar Rainfall Analysis Summary Reports.

Radar Rainfall Analysis Summary Reports will include a discussion of mechanical, meteorological, and hydrological characteristics pertinent to each significant storm. The reports also include observed gage errors that may indicate mechanical failure, digital file corruption, or improper synchronization of the clock. The reports identify those gaging sites that are not “in-sync” with the other gages. The reports include a discussion on how the gage adjustments and bias adjustments were performed and the magnitude of the required adjustments. The reports also identify winter season storms where the correlation between gage data and the next-generation radar pixels is unacceptable.

Radar-Rainfall Data Analysis

There are several categories of data analyses that are conducted as part of the Comprehensive Monitoring Plan radar-rainfall system:

- Gage fill analyses
- Analyses to identify and flag gages that appear to be malfunctioning
- Analyses to identify and quantify gage bias
- Pixel precipitation analyses

Radar-rainfall data is not available for all precipitation activity so gage-fill analyses need to be conducted. The current radar-rainfall data acquisition plan calls for significant storms to be analyzed. The criterion for a significant storm is designated as a storm where for any given hour at least 20% of all the functioning service area gages had a total accumulation of 0.05 inches or more. During the summer months, for periods rainfall activity that do not meet the criterion requirement for a significant storm, the time-step precipitation values are calculated from adjacent gage data using the inverse distance method. Augmenting the radar-rainfall data with gage data provides a continuous precipitation dataset.

During the winter months, the definition of a significant storm shall be revised to take into account the inherent errors associated with measuring snowfall. Some of the gages in the Water Department network are not heated and many do not have adequate wind protection for accurate snowfall measurement. For storms occurring in winter, the correlation between the next-generation radar pixels and the gaged information is assessed. Where the correlation is acceptable, gage adjustments will be calculated. Where the correlation is not acceptable, gage adjustments will not be calculated and a gage fill analysis will be used to quantify snowfall precipitation.

Rain gage precipitation data will be compared to the next-generation radar data for each storm event to identify gages that appear to perform poorly or exhibit suspect behavior. Gages exhibiting synchronization issues, clogging, mechanical problems, and other suspicious behavior need to be identified and will be excluded from further analysis. The gage performance results can also be used to signal the need for corrective maintenance at individual gage sites.

The current radar-rainfall acquisition plan calls for monthly analysis to generate the time series data for each of the 1-km by 1-km pixels. The radar-estimated rainfall data will be compared with gaged rainfall to identify and quantify any bias. The historic and monthly next-generation radar data will be gage and bias adjusted. The resulting precipitation data will be a combination of measured precipitation gage data and weather radar data accumulated to 15-minute intervals, geo-referenced, gage and bias corrected, and merged into a single and consistent dataset. The monthly radar-rainfall data will be translated from the native polar coordinate system to a one square kilometer Cartesian grid system provided by the Water Department. The dataset will provide an accurate estimate of the quantity, timing, and distribution of rainfall and snowfall over the Water Department service area.

Water Department rain gage data are used to calibrate next-generation radar data in order to create a detailed and accurate rainfall record that preserves the total rainfall volume reported at the gages while incorporating the spatial variability provided by the next-generation radar data. Increased spatial resolution of rainfall data within the City can improve model accuracy as the models are refined with further shed sub-delineation.

7.2.1.4 Precipitation Data Analysis Tools

The use of existing precipitation data analysis tools previously employed by the Water Department will be continued under the Comprehensive Monitoring Plan. NetSTORM is a computer program for rainfall and planning-level rainfall-runoff storage-treatment analysis.

NetSTORM adapts selected algorithms originally included in the HEC-STORM 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 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 intensity-duration-frequency analyses and for screening level evaluation of combined sewer system performance.

7.2.2 Temperature Data Analysis

The National Weather Service applies quality assurance procedures to the Philadelphia International Airport meteorological data internally prior to its release. Therefore, no quality assurance protocols are conducted or proposed for the Philadelphia International Airport temperature data under this Comprehensive Monitoring Plan.

7.2.3 Wind Data Analysis

The National Weather Service applies quality assurance procedures to the Philadelphia International Airport meteorological data internally prior to its release. Therefore, no quality assurance protocols are conducted or proposed for the Philadelphia International Airport wind data.

The process used to analyze and apply wind data requires converting the speed and direction data into Cartesian northing and easting velocities. The wind data can then be input into Environmental Fluid Dynamics Code to validate the model using observed data or plotted using Matlab.

7.2.4 Solar Radiation Data Analysis

As part of the Comprehensive Monitoring Plan the Water Department will develop methods for evaluation of the solar radiation data. The photosynthetically-active radiation data obtained from the USGS gaging stations in the City will be evaluated qualitatively and any suspect or errant data will be removed.

8.0 Groundwater Monitoring

8.1 Background

As described in Section 1, the basis of the Water Department's Combined Sewer Overflow (CSO) Long Term Control Plan Update (LTCPU) wet weather source control strategy is the "capture" and infiltration of stormwater with green stormwater infrastructure. The direct benefits of such an effort are a reduction of stormwater discharged directly to streams, as well as the increased recharge of stormwater to supplement groundwater resources. Increased infiltration, though advantageous in several respects, must be carefully planned and closely monitored to avoid unwanted impacts. Increasing groundwater levels in areas where the depth to water is shallow could result in the saturation of soils close to the surface, potentially causing basement flooding. In addition, building foundations could be impacted by rising groundwater levels.

The adaptive management approach being employed for the LTCPU is an iterative process strongly dependent on monitoring. In order to quantify the impact of this long-term effort on groundwater resources, it is necessary to monitor groundwater levels in Philadelphia. The Water Department has partnered with United States Geological Survey (USGS) to increase the geographic scope and frequency of groundwater monitoring in the Philadelphia region. A City-wide groundwater level monitoring network will provide long-term monthly data documenting current water levels and trends in groundwater elevations throughout the City, helping to track the impacts of widespread implementation of stormwater management practices and global climate change.

Data from the groundwater monitoring network will also be used to calibrate a Philadelphia groundwater model and update the USGS groundwater elevation contour map of Philadelphia (Paulachok 1984). In addition to this City-wide long-term groundwater monitoring program, the Water Department is conducting site-scale monitoring to address the effectiveness of individual stormwater management practices (Section 4). The City-wide groundwater monitoring network and site-scale monitoring at green stormwater infrastructure facilities provide complementary information regarding the effects of stormwater management practices at different spatial and temporal scales.

8.2 Methods

The Water Department and USGS identified existing wells that would be suitable for the network and obtained permission for site access. Once wells were identified and accessible, well condition and suitability for inclusion in the monitoring network were investigated by continuous water level monitoring and remote video camera inspection when accessible. Wells that met acceptance criteria were added to the monitoring network. After examining readily available information about existing wells, the Water Department elected to drill additional wells in order to provide better spatial distribution of wells in the monitoring network. USGS staff collect monthly groundwater elevation data and upload the data to the National Water

Information System web server. The Water Department staff periodically downloads water level data from the National Water Information System and summarizes these data annually.

8.2.1 Well Network Establishment

Existing wells in the Philadelphia area were identified by USGS and the Water Department through digital and paper archives as well as through contacting representatives of other City agencies and large institutional landowners (e.g., Philadelphia Fire Department, Philadelphia Department of Parks and Recreation, Philadelphia Gas Works, Southeastern Pennsylvania Transportation Authority, etc.). Priority was given to wells on publicly-owned or large institutional land uses in order to help ensure that wells would remain accessible in the future. The primary goal was to develop a network of wells with a spatial distribution and density sufficient to assess groundwater levels throughout the City of Philadelphia. Other criteria for establishment of the well network were:

- Sufficient density of wells in critical areas with a shallow water table
- No bias given to combined sewer or separate sewer areas
- Denser distribution of monitoring wells in the Northern Piedmont Ecoregion to reflect its more varied groundwater contours.

Wells that met acceptance criteria were assigned USGS location codes and added to the USGS well monitoring network and the National Water Information System database. The well monitoring network contains 19 active sites that are monitored monthly. Additional sites are expected to be added once landowner access agreements are finalized and new wells have been drilled.

8.2.2 Video Camera Inspection

The availability of well attribute information varied from well to well and in most cases the physical characteristics and condition of candidate wells to be added to the network was unknown. USGS staff perform remote video camera inspection, when possible, to determine physical characteristics such as screened intervals, total depth, depth to bottom of casing, and the location of potential water-bearing zones within the bore hole. Wells narrower than 4 inches in diameter and wells with pumps or other plumbing could not accommodate the camera equipment and were not inspected with this method.

8.2.3 Continuous Water Level Monitoring

Monthly measurements are appropriate for monitoring long term trends in groundwater levels. However, it is important to verify that these monthly observations are representative of the unconfined aquifer and not influenced by anthropogenic activity or other conditions. USGS staff used data logging pressure transducers (LevelTroll model 500, In-Situ, Inc.) to conduct continuous water level monitoring in candidate wells. These sensors are vented to the surface of the well to provide atmospheric pressure correction. Continuous monitoring was carried out across all wells in the network to identify any aberrant trends, such as those that might be caused by local pumping operations. Sensors were deployed for three-month periods on a rotating schedule with five wells actively monitored at a time. Wells that appear to be influenced by permanent pumping operations will be removed from the monitoring network (e.g., permanent wells dewatering the stadiums). Wells that are temporarily affected by local, dewatering operations (e.g., a short term construction site), will remain in the system, but data collected during the period when dewatering operations affected the well will not be used in developing estimates of current water levels and water level trends.

8.2.4 Routine Groundwater Observations

USGS staff conducts groundwater observations monthly at each well using a water sensor and graduated tape. Equipment is sterilized in 10% bleach solution prior to and after measurements are taken in order to prevent introducing or transferring contamination between wells. Well level measurements are converted to elevation above the North American Vertical Datum of 1988 (NAVD88) based upon the known elevation correction factor for each well. Water level data are recorded on site in field notebooks along with any pertinent field notes and then uploaded to the National Water Information System web server. The Water Department periodically downloads data from the National Water Information System and summarizes these data annually.

8.3 Monitoring Well Locations

The well monitoring network contains 19 active sites that are monitored monthly (Table 8-1, Figure 8-1). The Water Department is currently in the process of drilling additional wells on City-owned property in order to meet spatial distribution and other well network criteria. Of the 19 active wells, seven are located within the Middle Atlantic Coastal Plain ecoregion, while the remaining 12 wells are located in the Northern Piedmont (Omernik 1987). As stated above, higher well density is required in the latter region to reflect the more complex geology and interactions with groundwater.

Table 8-1: The Water Department-USGS Groundwater Monitoring Well Network Locations

Site ID	Site Name	Lat.	Long.	Established	Observations
USGS-395342075102101	PH 12*	39.895	-75.172	10/22/1978	121
USGS-395353075151501	PH 1052	39.898	-75.254	3/7/2011	2
USGS-395408075104001	PH 63	39.902	-75.177	9/14/1954	20
USGS-395416075150301	PH 1053	39.904	-75.251	4/24/2003	2
USGS-395516075113901	PH 1051	39.921	-75.194	--	2
USGS-395656075100401	PH 136	39.949	-75.167	12/6/1978	21
USGS-395859075085401	PH 1042	39.983	-75.148	2/14/2011	6
USGS-395942075144301	MG 2164	39.995	-75.245	2/14/2011	16
USGS-400211075093701	PH 1050	40.036	-75.16	--	2
USGS-400217075142101	PH 540	40.038	-75.239	3/29/1948	5
USGS-400229075104601	PH 1043**	40.041	-75.179	2/14/2011	14
USGS-400308074592201	PH 397	40.052	-74.989	1/4/1979	19
USGS-400311075101301	PH 1040	40.053	-75.17	2/17/2011	16

Site ID	Site Name	Lat.	Long.	Established	Observations
USGS-400327075152201	PH 1044	40.057	-75.256	3/16/2011	11
USGS-400424075104901	PH 550	40.073	-75.18	--/--/1906	19
USGS-400512075033401	PH 1045	40.087	-75.059	7/18/2011	11
USGS-400516075033201	PH 1046	40.088	-75.059	7/18/2011	11
USGS-400524075042601	MG 2195	40.09	-75.074	--	1
USGS-400527075042801	MG 2193	40.091	-75.074	--	11
USGS-400527075042802	MG 2194	40.091	-75.074	--	11
USGS-400644074590801	PH 1041	40.112	-74.986	2/17/2011	15

* Former Philadelphia County observation well, destroyed by construction activity, will be replaced with new well in same location

** Philadelphia County observation well

Wells were also classified according to predominant underlying geology and type of sewer system, i.e., CSO or separate-sewered (Table 8-2, Figure 8-1). Another consideration for siting new wells was the potential influence of buried utilities and historic creek beds. During the period of rapid expansion of Philadelphia's grid-like network of streets, historic streams were encased in large brick sewers and buried in order to level and prepare land for development. Recent groundwater mapping and modeling work suggests that these brick sewers strongly influence local groundwater elevations (Paulachok 1991, Maimone et al. 2011).

Table 8-2: The Water Department-USGS Groundwater Well Geology and Sewer System Type Classification

Site ID	Site Name	Sewer Type	Geology
USGS-395342075102101	PH 12	Separate	Trenton Gravel
USGS-395353075151501	PH 1052	Separate	Trenton Gravel
USGS-395408075104001	PH 63	Separate	Trenton Gravel
USGS-395416075150301	PH 1053	Separate	Trenton Gravel
USGS-395516075113901	PH 1051	CSO	Magothy Raritan Potomac
USGS-395656075100401	PH 136	CSO	Trenton Gravel
USGS-395859075085401	PH 1042	CSO	Pennsauken and Bridgeton Formation
USGS-395942075144301	MG 2164	Separate	Granitic Gneiss and Granite
USGS-400211075093701	PH 1050	CSO	Wissahickon Formation
USGS-400217075142101	PH 540	Separate	Wissahickon Formation
USGS-400229075104601	PH 1043	CSO	Wissahickon Formation
USGS-400308074592201	PH 397	Separate	Trenton Gravel
USGS-400311075101301	PH 1040	CSO	Wissahickon Formation
USGS-400327075152201	PH 1044	Separate	Wissahickon Formation
USGS-400424075104901	PH 550	CSO	Wissahickon Formation
USGS-400512075033401	PH 1045	Separate	Granitic Gneiss and Granite
USGS-400516075033201	PH 1046	Separate	Granitic Gneiss and Granite
USGS-400524075042601	MG 2195	Separate	Wissahickon Formation
USGS-400527075042801	MG 2193	Separate	Wissahickon Formation
USGS-400527075042802	MG 2194	Separate	Wissahickon Formation
USGS-400644074590801	PH 1041	Separate	Wissahickon Formation

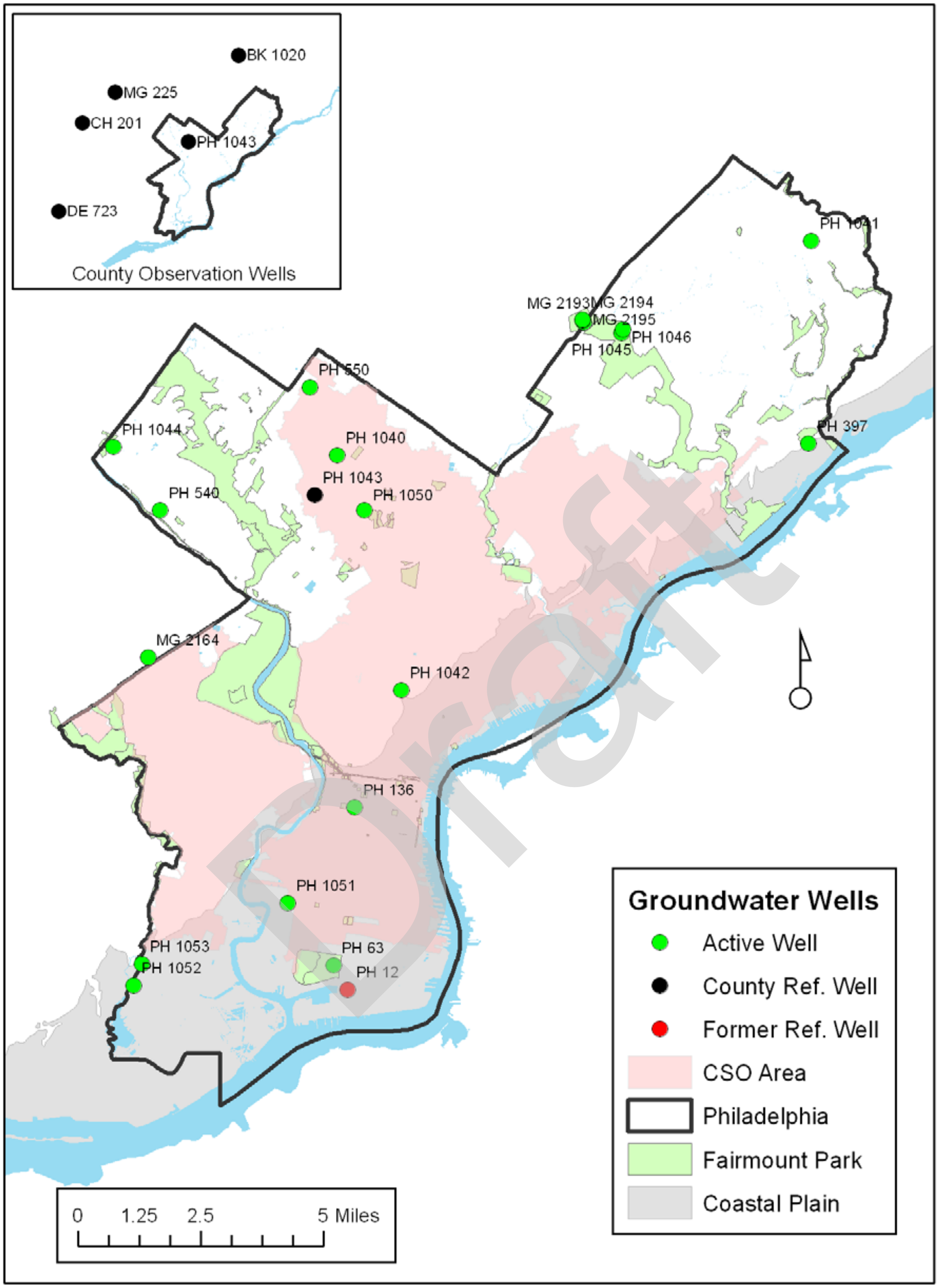

Figure 8-1: The Water Department-USGS Groundwater Monitoring Well Network Locations and County Reference Well Locations

USGS maintains at least one reference well in most Pennsylvania counties. Reference wells located in neighboring counties (Figure 8-1, Table 8-3) may be used as regional reference wells for data analyses. Continuous hourly data are collected at well DE 723 in Delaware County. Reference wells in Chester, Bucks, and Montgomery Counties are not monitored continuously.

Table 8-3: Regional County Observation Wells

Site ID	Site Name	Lat.	Long.	Est.	Observations
USGS-400453075255601	CH 201 Chester County Observation Well	40.136	-75.351	06/19/1978	402
USGS-400808075210401	MG 225 Montgomery County Observation Well	40.199	-75.052	08/15/1956	132
USGS-401157075032001	BK 1020 Bucks County Observation Well	40.081	-75.432	04/13/1968	129
USGS-395512075293701	DE 723 Delaware County Observation Well	39.920	-75.493	1983	157

8.4 Data Analysis

The United States Environmental Protection Agency (US EPA) (2009) published detailed guidance on statistical analysis of groundwater contaminant concentrations. In many of the examples, the same logic and techniques could apply to analysis of groundwater levels. In the case of the Philadelphia groundwater monitoring network, the goal is to understand if groundwater levels are changing over time, at either a single well or group of wells. The main statistical tests to be utilized are a) Seasonal Kendall Test and b) analysis of variance. The tests are briefly described below.

The Seasonal Kendall test performs the Mann-Kendall (MK) trend test for individual seasons of the year, where season is defined by the user. It then combines the individual results into one overall test for whether the dependent variable (i.e., groundwater level) changes in a consistent direction (monotonic trend) over time. The magnitude (i.e., slope) of the trend is also determined. The test is nonparametric, therefore non-normal data can be analyzed (Helsel *et al.* 2006). US EPA (2009) advises that at least 10-12 measurements are needed, whereas Helsel and Hirsch (2002) recommends that the product of number of years and number of seasons be greater than 25. Helsel *et al.* (2006) further caution that with more than 10 years of data, adjusted p-values should be calculated to account for the possibility of serial correlation. The Seasonal Kendall test can be applied to data from a single well, not multiple wells. To examine seasonal trends across multiple wells, the Covariance-Sum test is used (Lettenmaier 1988), which is essentially the execution of multiple Seasonal Kendall tests and calculation of the covariances between them. To analyze regional trends over time from a group of wells, the Regional Kendall test can be applied. The Regional Kendall test essentially functions the same way as the Seasonal Kendall test, except the data is categorized by region rather than season.

An alternate method to analyze temporal trends on either a single well or group of wells is the analysis of variance. For a single well or group of wells with data subdivided by season, a one-way analysis of variance would examine the significance of seasonality as a statistical factor. A two-way analysis of variance would be applied to include location or region as a statistical factor. Either form of analysis of variance assumes that the datasets are normally distributed with constant variance. Group residuals should be tested for normality and for equality of variance. If the data cannot be transformed to a normal distribution, the nonparametric Kruskal-Wallis test can be used instead to detect significance of the specified statistical factor (US EPA, 2009).

9.0 Hydrologic and Hydraulic Modeling

The Water Department currently uses the United States Environmental Protection Agency (US EPA) Storm Water Management Model for hydrologic and hydraulic modeling to characterize the combined sewer system for all permit related requirements. The hydrologic and hydraulic models are continually updated as additional data on the sewer system and its operating characteristics are measured or verified. Much of the monitoring described in the previous sections will be utilized to refine the hydrologic and hydraulic models to establish an accurate baseline condition and assess the projected impact of the *Green City, Clean Waters* program. The methods and application of the hydrologic and hydraulic models are documented in this section. Hydrologic and hydraulic modeling was a strategic part of the Water Department's *Green City, Clean Waters* program, and established modeling practices will continue under the Comprehensive Monitoring Plan.

9.1 Existing Applications of Collection System Model

Development of the baseline model to characterize the combined sewer system for the Long Term Control Plan Update (LTCPU) was important as it is the foundation from which the selected alternative was built and results determined for Consent Order and Agreement (COA) targets. Accurately simulating the hydrologic conditions and hydraulic infrastructure was essential to producing valuable and reliable results. The baseline model was developed using a modified version of the US EPA Storm Water Management Model version 4.4 software, comprising the RUNOFF and Extended Transport modules. Since the approval of the LTCPU and the establishment of the COA the Water Department has converted hydrologic and hydraulic models to US EPA Storm Water Management Model version 5.

9.1.1 Overview of Previous Model Development

Between 1994 and 1997, Tier I hydrologic and hydraulic models of the Water Department's combined sewer system were developed to support permit requirements for development of the System Inventory and Characterization, the System Hydraulic Characterization, the Documentation of the Implementation of the Nine Minimum Controls, and the Long Term Control Plan. The Tier I modeling efforts included applications of a combination of the US EPA Storm Water Management Model's version 3 Extended Transport module for hydraulic models of the combined sewer interceptors and critical hydraulic control points, and the United States Army Corps of Engineer's Storage Treatment Overflow Runoff Model for sewershed hydrology.

Between 1997 and 2000, Tier II, Storm Water Management Model version 4, continuous simulations models were developed to simulate the hydrologic and hydraulic response of the Water Department's collection system to wet weather events. The Tier II models are based on calibrated Tier I Extended Transport models developed for the combined sewer overflow (CSO) compliance program, and included the development of Storm Water Management Model RUNOFF module representations of sewershed hydrology, eliminating reliance on Storage

Treatment Overflow Runoff Model and unifying the modeling system in Storm Water Management Model version 4.

The Tier II models were modified further between 2001 and 2005 to support design-level considerations of the combined sewer system, expanding the system to about 10,000 nodes and pipes. These larger refined and complex models required longer simulation periods, as long as 14-16 hours for each drainage district for a one-year continuous simulation.

For the development of the LTCPU, a planning version of the hydrologic and hydraulic models was produced to support CSO control alternatives analyses. This streamlining of the models was based on a network of about 4,000 nodes and pipes and resulted in a reduction of simulation times to a level suitable to support planning needs, allowing for the many (typical or average) year-long continuous simulations required for the evaluation of the numerous CSO control alternatives required. These streamlined models were used to generate the planning level estimates for the hydrologic and hydraulic portion of the Water Department's LTCPU submitted in September 2009 and the Water Quality Based Effluent Limit portion of the COA finalized in June 2011.

The Water Department decided several years ago that future versions of the City's hydrologic and hydraulic models would be simulated using Storm Water Management Model version 5. The principal reason for the decision to convert the models was because the US EPA no longer was supporting the Storm Water Management Model version 4, because the new version is much more compatible with evolving changes in personal computer operating systems, and because of the improvements to the solution techniques and the hydraulic computations. Since the approval of the LTCPU and the establishment of the COA the conversion to Storm Water Management Model version 5 was completed.

The aim of this conversion process was to convert the existing hydrologic and hydraulic models from Storm Water Management Model version 4 to version 5 with minimal changes to the model structure and results. Initial test results indicate that the new models are fully compatible with previous versions, and simulations produce only modest differences in CSO characteristics, due in part to how the Storm Water Management Model version 5 engine is set up, and in part to the hydraulic enhancements over the Storm Water Management Model version 4 engine that have been implemented. Storm Water Management Model version 5 will continue to be utilized for hydrologic and hydraulic modeling under the Comprehensive Monitoring Plan.

Additional documentation of the hydrologic and hydraulic model development is found in LTCPU Section 5.2.4 and LTCPU Supplemental Documentation Volume 4. Documentation about the conversion of the combined sewer system hydrologic and hydraulic models from US EPA Storm Water Management Model version 4 to version 5 is provided in the COA Appendix E (Supplemental Documentation).

9.1.2 Development of Model Hydrology

Storm Water Management Model 5 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 of interest such as a sewer inlet. The driving force is precipitation, which may be a continuous record, single measured event, or artificial design storm event. The model also simulates rainfall dependent inflow and infiltration in separate sanitary sewer areas using three sets of unit hydrographs defined by the parameters R, T, and K – described in LTCPU Section 5 – values to represent the shape of the rainfall dependent inflow and infiltration hydrograph response to the input precipitation hyetograph.

The hydrologic portion of Storm Water Management Model version 5 requires the input of several physical parameters to determine the rainfall-runoff response from modeled combined sewer and separate sanitary sewer subcatchments, which include:

- Subcatchment area
- Subcatchment width (used to determine overland flow length)
- Percent directly connected impervious area (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
- Rainfall dependent infiltration and inflow parameters or user input hydrographs for sanitary sheds (In the Storm Water Management Model version 5 this has become a node property)
- Baseflow data
- Precipitation data
- Evaporation data
- Temperature data and snowmelt

Documentation of the hydrologic model development for use as part of the LTCPU and its supplements is described in LTCPU Section 5.2.4 and LTCPU Supplemental Documentation Volume 4. Documentation for the rationale for the conversion of the combined sewer system hydrologic and hydraulic models from US EPA Storm Water Management Model version 4 to version 5 is provided in the COA Appendix E (Supplemental Documentation).

9.1.3 Development of Model Hydraulics

The hydraulic portion of Storm Water Management Model version 5 was developed to simulate hydraulic flow routing for open channel and/or closed conduit systems. This portion of the model receives hydrograph inputs at specific nodal locations performed by the hydrologic module and /or by direct user input (e.g., user defined hydrographs for sanitary sheds). Dynamic routing of stormwater and wastewater flows is performed through drainage systems and receiving streams. To calculate the flow in the sewers, Storm Water Management Model version 5 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 and corresponding boundary conditions

The information required to accurately represent these elements within the model were obtained from the return or As-Built plans , contract drawings, and drainage plats available through the document and data management system of the City of Philadelphia.

Documentation of the hydraulic model development for use as part of the LTCPU and its supplements is described in LTCPU Section 5.2.4 and LTCPU Supplemental Documentation Volume 4. Documentation for the rationale for the conversion of the combined sewer system hydrologic and hydraulic models from US EPA Storm Water Management Model version 4 to version 5 is provided in the COA Appendix E (Supplemental Documentation).

9.2 Hydrologic and Hydraulic Model Validation

Development of the Storm Water Management Model for the LTCPU was followed by validation and optimization of the parameters for both the hydrologic and hydraulic simulation components. For the Comprehensive Monitoring Plan, the term "validation" will be used to describe the comprehensive process of model calibration and model verification. In several cases the limited quantity of available data did not facilitate the segregation of independent data sets for separate model calibration and verification processes. During the validation 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 equipment and/or site condition error and uncertainty, while the model is an approximation of the system hydrology and hydraulics and also subjected to a range of uncertainty. Therefore, the measured data must be thoroughly reviewed, the uncertainty ranges clearly defined, and any limitations must be identified before adjusting calibration parameters. Note that the model validation is accomplished by finding the best comparison between simulated and measured characteristics over a range of storm events.

Model calibration is accomplished by adjusting initial estimates of the selected variables (calibration parameters), within acceptable limits, to obtain a satisfactory correlation between simulated and measured values. Sometimes, an independent monitoring data set (not used for model calibration) is established and used after the calibration process to verify the calibrated model. The criteria for a satisfactory correlation need to take into account the uncertainty ranges of both the monitored data and the model results. The variables selected to adjust or calibrate are parameters that typically cannot be measured directly/accurately. Common model calibration parameters are percentage directly connected impervious area, width of subcatchment, soil infiltration parameters, and pervious and impervious area depression storage. The ongoing hydrologic and hydraulic model validation processes and the resulting refinement of the existing hydrologic and hydraulic models will continue under the Comprehensive Monitoring Plan.

For the hydrologic validation, the following data were assessed and are further described in subsection 9.2.1 below:

- Precipitation data
- Combined Sewer System Trunk Sewer Monitor data
- Directly Connected Impervious Area Validation
- RTK distribution

For the hydraulic validation, the following elements were considered and described in subsection 9.2.2 below:

- Water Pollution Control Plant inflow and pumping data
- Measures of "goodness-of-fit"
- Validation results

The hydrologic and hydraulic models are continually updated as additional data of the sewer system and its operating characteristics are measured and verified. The refinement processes for hydrologic and hydraulic model validation will continue as new monitoring data are collected and analyzed. Much of the monitoring described in this report will also be utilized to further refine the hydrologic and hydraulic models and also to assess the projected impact of the *Green City, Clean Waters* program.

9.2.1 Hydrologic Validation

Validation of the hydrologic model is an iterative process by which hydrologic parameters are 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.

9.2.1.1 Precipitation Data

Precipitation data are evaluated in conjunction with sewer system monitoring data to adjust and validate models to best simulate observed rainfall and runoff responses. Further detail on the precipitation evaluation process is discussed in Comprehensive Monitoring Plan Section 5 and LTCPU Supplemental Documentation Volume 3: Hydrologic and Hydraulic Modeling and Volume 5: Precipitation Analysis. Similar analyses will be completed as part of the ongoing Comprehensive Monitoring Plan data collection and model validation processes.

9.2.1.2 Combined Sewer System Trunk Sewer Monitoring Data

For the LTCPU, flow data taken from flow monitors located in trunk sewers throughout the combined sewer system area were analyzed and then used to adjust calibration parameters for the hydrologic models. From 2002 through 2006 there were six combined trunk sewer monitors having sufficiently usable data to perform validation analyses. Since the development of the LTCPU, the temporary flow monitoring program (Section 5) has increased sewer system monitoring coverage and additional data are available for model validation purposes. Combined sewer system coverage will continue to expand, additional combined sewer system monitoring will be conducted, and the model refinement process will continue under the Comprehensive Monitoring Plan.

For model validation during dry weather periods, the wastewater flow monitoring data are used directly. For model validation during wet weather periods, the process includes hydrograph deconstruction of the monitoring data to extract the wet weather portion from the total monitored flow. This extracted wet weather flow is used to compare monitored data to the simulated model flow. To assess the goodness-of-fit of the model output to observed data, a series of plots will be created including scatter plots of event volumes, time to peak and peak flows, cumulative frequency distributions, cumulative mass regression plots, and time-series plots for each event. A selection of result plots for monitor 83 of the previous validation process is presented collectively as Figure 9-1 and Figure 9-2. 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 are organized into a performance spreadsheet and the best fit validation scenario is chosen. The criteria from the best fit validation scenario are applied to the remaining combined sewer district for similar sewersheds without monitoring data. For sheds draining to the additional trunk monitors, the site specific calibrated data is used. The preparation and use of time series plots, scatter plots, cumulative frequency distribution plots, and performance spreadsheets will continue under the Comprehensive Monitoring Plan.

9.2.1.3 Directly Connected Impervious Area Validation

For all sewersheds with monitored trunk sewers evaluated for the LTCPU, directly connected impervious area in the best-fit model was lower than gross impervious cover derived from aerial photography. The ratio of directly connected impervious area to total gross impervious area ranged from 50% to 100%. Because the majority of sewersheds were unmonitored and the measurements themselves have uncertainty ranges associated with them, it is reasonable to present this value as a range. Based on the LTCPU modeling validation, the mean and most common adjustment is 70% of directly connected impervious area. This value was used in the best-fit model, with the exception of monitored sheds.

Proposed Comprehensive Monitoring Plan activities for directly connected impervious area adjustment based on updated remotely sensed datasets of impervious cover are discussed further in Section 9.4.1. Additional directly connected impervious area adjustments may be made to sewersheds based on evaluation of additional sewer system monitoring data.

Storm Water Management Model version 5 has the ability to simulate flow routing from impervious areas to pervious area. This method of running on a portion of flow from impervious area to pervious area (RUNON method) to achieve flow and volume from simulated sewershed to match observed data is a better way of representing and simulating than reducing the gross impervious (directly connected impervious area method). For sewersheds with a high percentage of impervious area, the RUNON method may not be the best method. For those cases directly connected impervious area method may be used. Under proposed future

Comprehensive Monitoring Plan activities, when the model sewershed parameters are calibrated, the RUNON method will be used as default and if this method does not yield good results then the directly connected impervious area method will be used.

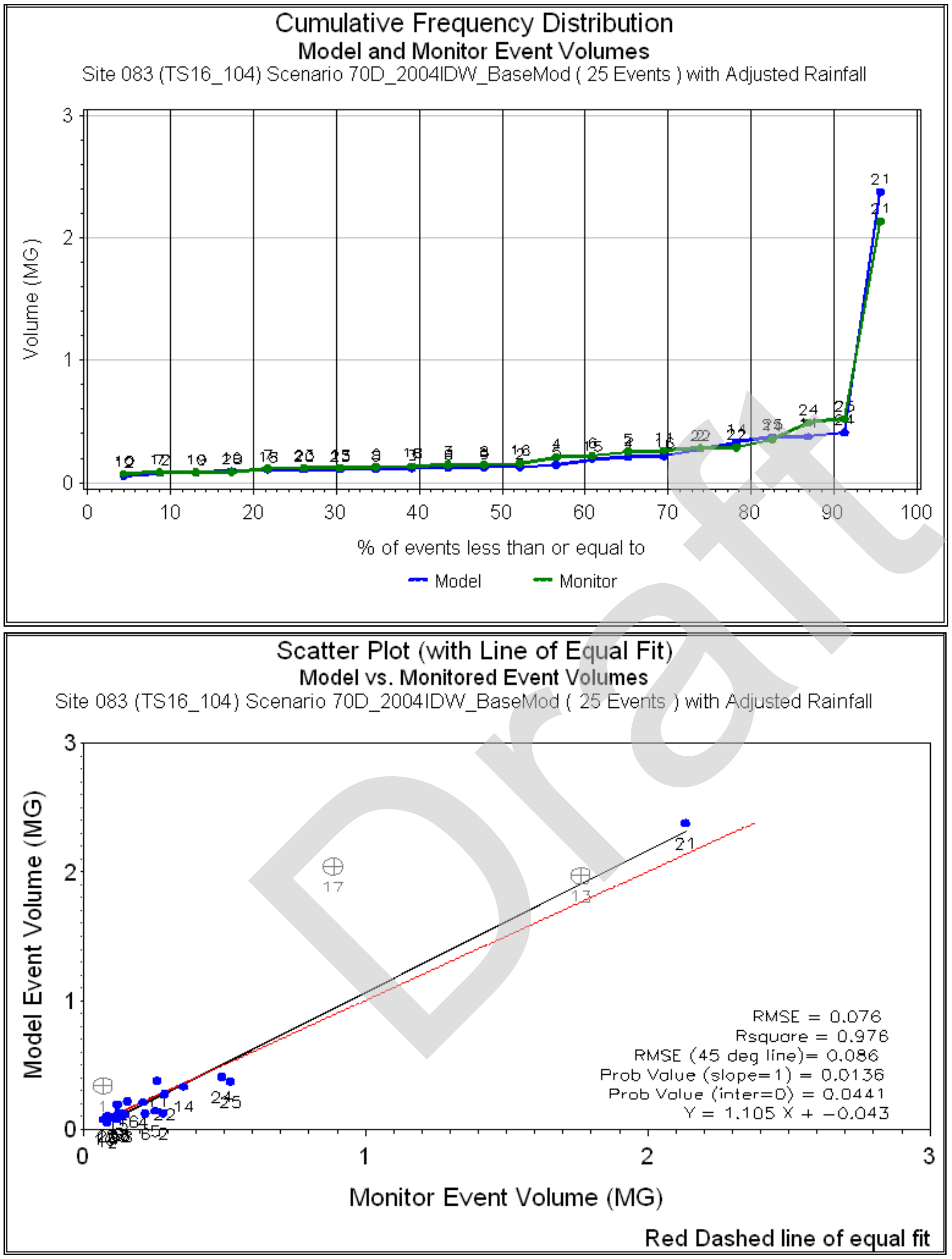

Figure 9-1: Result Plots for Site 83 Including the Cumulative Frequency Distribution, Event Volume Scatter Plot

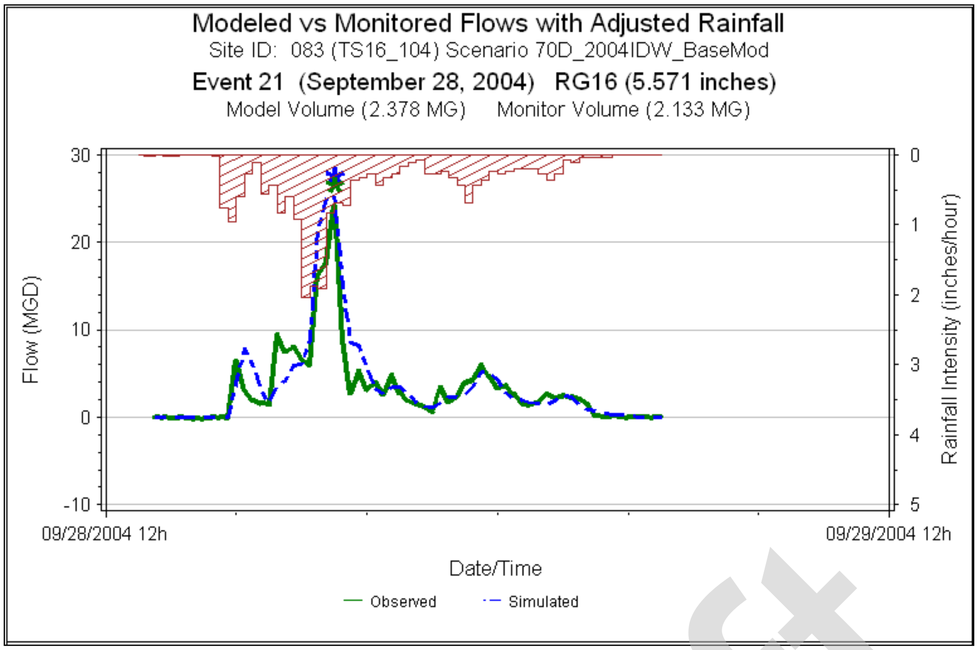

Figure 9-2: Result Plots for Site 83 - 2004 Event Time-series Plot

9.2.1.4 RTK Distribution

The LTCPU model validation processes determined an acceptable average R-value range within the simplified Storm Water Management Model version 5 to represent rainfall dependent infiltration and inflow volumes across all un-monitored separate sanitary sewer areas. The existing rainfall dependent infiltration and inflow values from the 39 flow monitoring sites discussed in LTCPU Section 5 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 the following:

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

Continuing RTK refinement will be an ongoing process under the Comprehensive Monitoring Plan as more observed data is obtained.

9.2.2 Hydraulic Validation

Water Pollution Control Plant Inflow and Pumping Data

For the LTCPU validation process, 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 water pollution control plant influent flow and level data for the calendar year 2005. The Water Department monitors level and inflow at its three water pollution control plants. These flows were compared to simulated flows for a range of storm events during the calendar year 2005. Water pollution control plant influent flow and pump wet-well level data are stored in average hourly time intervals. A quality assurance 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 deconstruction and the wet-weather portion of the flow coming to the plant was extracted.

The model parameters adjusted to best match the monitored water pollution control plant influent flow and level data included plant head boundaries, pump curves, system head losses, and regulator gate settings.

Collection System Monitoring Data

Ongoing validation of the hydraulic system will be completed as additional combined trunk and interceptor sewer monitoring data is collected and analyzed under the Comprehensive Monitoring Plan, following a similar process completed for the LTCPU hydrologic modeling. These tasks include:

- Measures of “Goodness-of-Fit” for event characteristics:
    - Event volume
    - Event peak flow
    - Time to peak
- Validation Results, such as:
    - Linear regression analyses comparing model estimated wet weather flow volumes (y-axis) to monitored event volume (x-axis) using rainfall data, see Figure 9-3 for an example
    - Model and monitored event volumes displayed as cumulative frequency distributions, see Figure 9-4 for an example
    - Individual model and monitored hydrograph time-series plots for visual evaluation, see Figure 9-5 for an example

9.2.3 Evaluation and Adaptation Plan Validation Summary

As part of the COA, the City must submit an Evaluation and Adaptation Plan every five years. The Evaluation and Adaptation Plan will be a comprehensive assessment of the City’s progress with implementing the approved LTCPU up until that time, and will include a description of program elements anticipated to be implemented in the next five-year period. Included in the Evaluation and Adaptation Plan will be performance tracking of the CSO Program in the form of hydrologic and hydraulic modeling with verification using metered data. The Evaluation and Adaptation Plan will serve as a format to summarize hydrologic and hydraulic model improvements made through ongoing Comprehensive Monitoring Plan data collection and model validation activities.

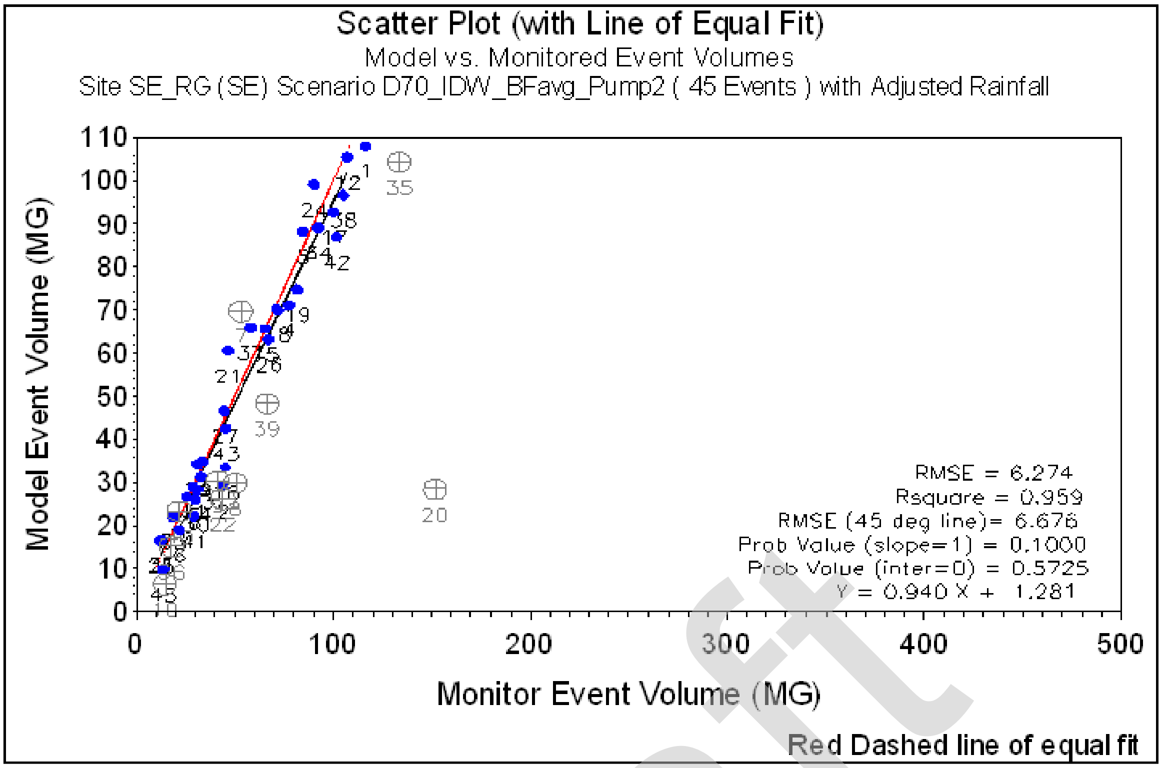

Figure 9-3: Example Linear Regression of Modeled versus Monitored Event Volumes

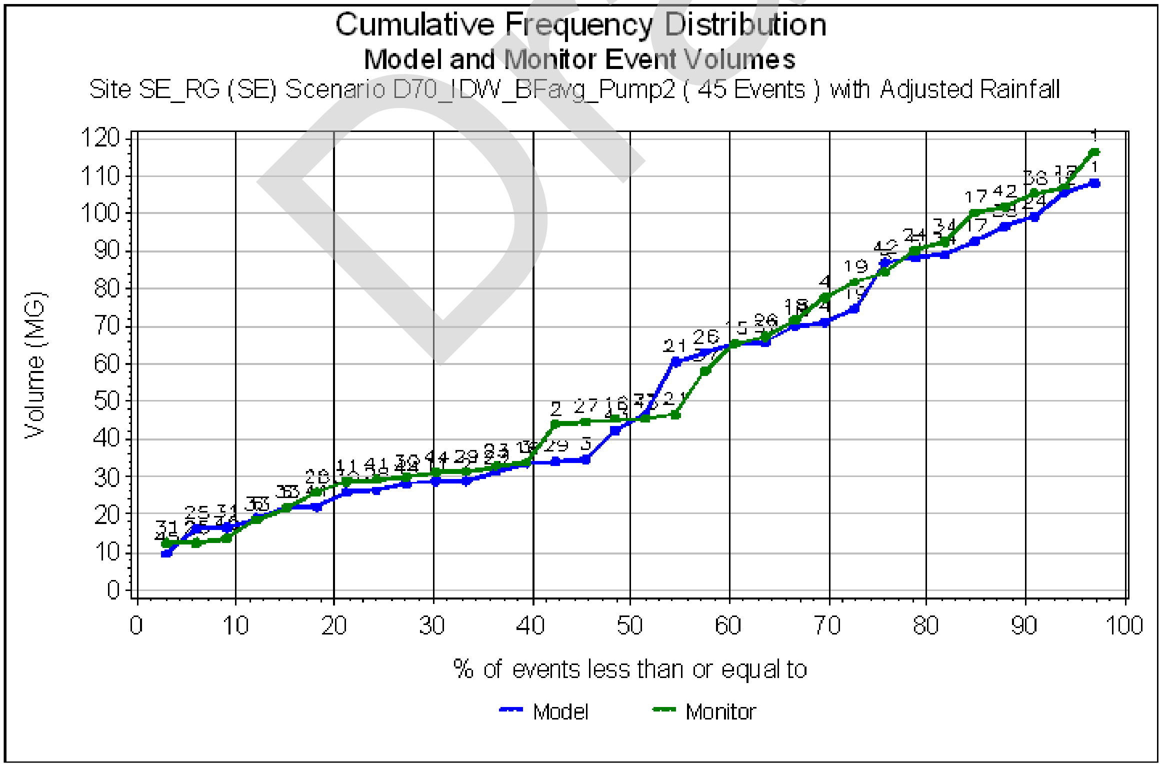

Figure 9-4: Example Cumulative Frequency Distribution Plots of Monitored and Modeled Event Volumes

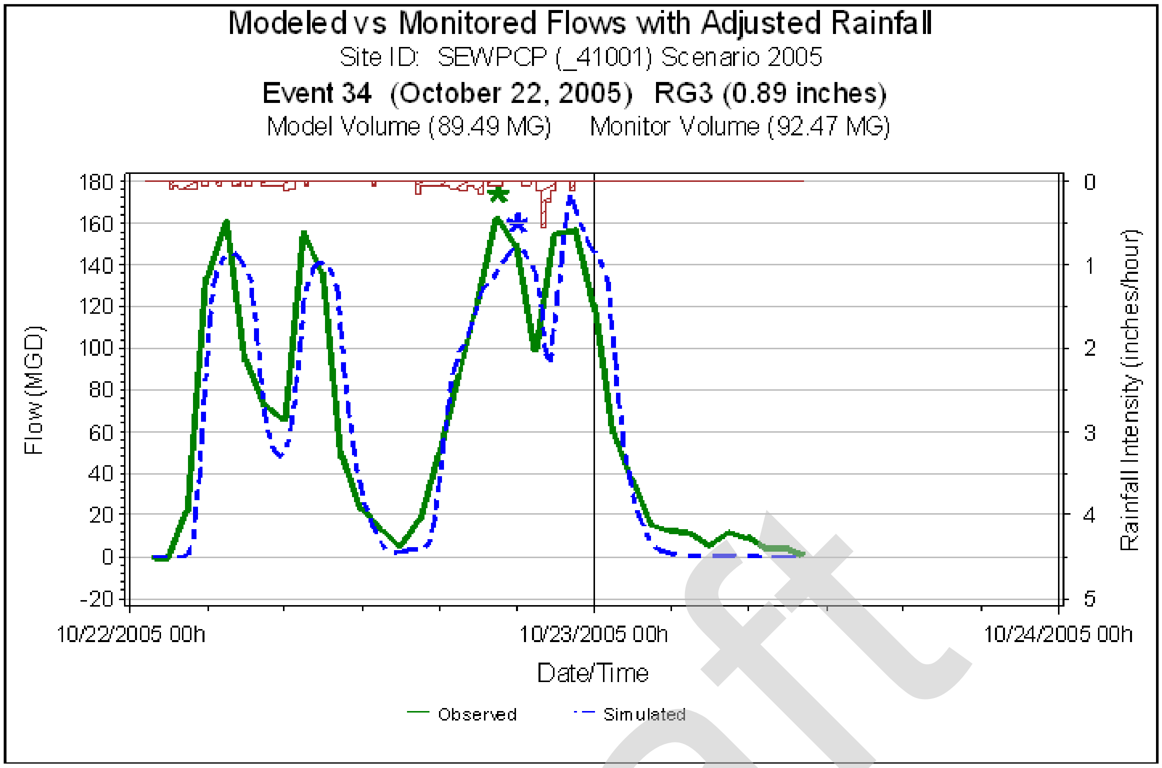

Figure 9-5: Example Model and Monitored Single Event Wet-weather Flow Time-series Plot

9.3 Existing Applications of Collection System Model

The collection system model developed for the LTCPU is utilized for many applications, each of which can contribute to model enhancements that could adjust the model for compliance reporting requirements. The collection system model is considered a planning level model, optimized for assessments at drainage district and city-wide scales. The applications of the hydrologic and hydraulic model discussed in this section are supported by monitoring efforts discussed throughout the Comprehensive Monitoring Plan.

9.3.1 Planning Level Models

For the LTCPU alternatives analysis, the baseline models were modified and/or hydrologic features and hydraulic infrastructure were added to represent various alternatives intended to mitigate CSOs within each watershed for evaluation (LTCPU Section 5.1).

The models also currently provide for an indispensable tool for several Water Department programs, including:

- Storm flood relief planning and alternatives analysis
- Green stormwater infrastructure evaluation and support
- Pollutant Mass Loading
- Capital projects design support

- Stream restoration design and evaluation support
- Inflow and Infiltration Reduction Assessment
- Water Quality Modeling Linkage

9.3.2 Storm Flood Relief Alternatives Analysis Modeling

Alternatives are being developed to address basement and surface flooding in certain areas of the city as part of the storm flood relief program. The planning model is edited and refined to address areas where more hydraulic detail is necessary to characterize these flooding conditions. This refined model is used to analyze alternatives to reduce both surface and basement flooding conditions. Improvements to the planning level model for storm flood relief purposes may be carried over for use in combined sewer system modeling. The updated models are assisting to refine the detail of the CSO planning model by incorporating smaller pipes and drainage area delineations. Temporary flow monitoring prioritized to areas for storm flood relief alternative analysis will provide additional data for refinement of combined sewer system characterization.

Detailed Models

Highly detailed models are in development for selected areas of the City that experience basement flooding to locate and address problems at a finer scale than the simplified storm flood relief and planning models. These models are being developed with the goal of representing nearly all sewer pipes and junctions in the affected areas. The precision of these models facilitates simulating infrastructure improvement alternative effects on individual parcels and properties. These simulations can identify smaller scale infrastructure improvements to alleviate sewer system flooding. Modeling and monitoring activities to support the ongoing storm flood relief program will continue through the period of the Comprehensive Monitoring Plan. Improvements to the hydrologic and hydraulic models for storm flood relief purposes may be carried over for use in combined sewer system modeling. The updated models are assisting to refine the detail of the CSO planning model by incorporating smaller pipes and drainage area delineations.

9.3.3 Evaluation of Green Stormwater Infrastructure for CSO Control

Philadelphia's stormwater regulations require post-construction stormwater management facilities to achieve or exceed a minimum level of performance. To efficiently analyze this level of performance within each watershed a generalized approach was adopted in representing green stormwater infrastructure within the models. A generic stormwater management facility was modeled to meet management goals through some combination of storage, infiltration, and slow release.

To improve modeling efficiency, stormwater management was modeled separately from combined sewer hydraulics. Outflow hydrographs from stormwater management facilities were used as inflow hydrographs for the sewer system. The hydrologic surface flow routing is shown in Figure 9-6.

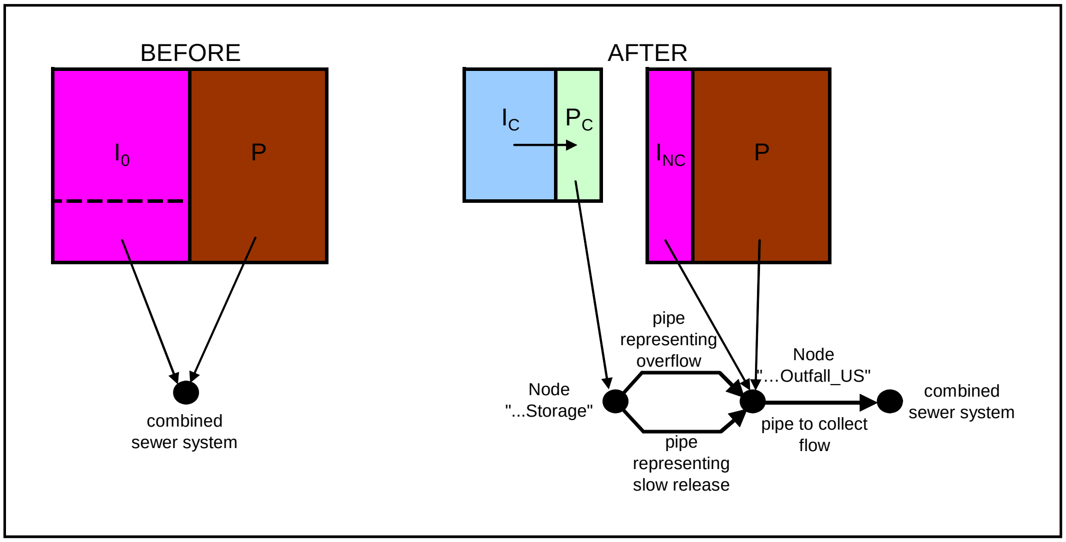

Figure 9-6: Visual Representation of How a Portion of a Subcatchment is Controlled and Routed through Green Infrastructure within the Model

Further detail of the simplified green stormwater infrastructure modeling technique is provided in LTCPU Section 5.4.1.1 and LTCPU Supplemental Document 3 Hydrologic and Hydraulic Modeling. This modeling approach will be continued under the Comprehensive Monitoring Plan for reporting purposes until model improvements through validation with green stormwater infrastructure are included.

For the LTCPU, model simulations were generated for a range of areal coverage using green infrastructure with high and low estimates of total directly connected impervious area. This range of model simulations was replicated during the Storm Water Management Model version 5 upgrade process. Output from each model simulation included values for annual total CSO volume and capture volume, as well as volumes for green infrastructure overflow, green infrastructure treatment, infiltration, evaporation, and others. The outputs from the green infrastructure models were compared to the baseline model to determine each alternative’s effectiveness for managing CSOs. This modeling approach will be enhanced with green stormwater infrastructure monitoring data through validation under the Comprehensive Monitoring Plan.

The proposed baseline model and green stormwater infrastructure modeling enhancement approach, discussed in Section 4, involves a step-wise process. The Comprehensive Monitoring Plan will build upon the base scale simulation, developed for the LTCPU and its supplements, and use the monitoring data in validated hydrologic & hydraulic and water quality models of larger scales. The proposed process is to construct and validate hydrologic & hydraulic models of increasing scales to prove the efficacy of green stormwater infrastructure from single controls to sub-sewersheds of several controls to CSO sewersheds and eventually entire collection systems. The approach allows additional time to assess the sewer system for existing conditions to validate models at the sub-sewershed and sewershed scale. This will create a baseline to assess improvements at reducing combined sewer flows when green stormwater infrastructure implementation levels have reached adequate levels distributed throughout the City.

9.3.4 Design/Construction Support of Capital Projects

Achieving the quantitative performance standards of the Water Quality Based Effluent Limit in the COA may require implementation of controls and combined sewer system improvements beyond green stormwater infrastructure. Projects that are implemented as part of other Water Department priorities, such as basement and surface flooding relief, may also provide CSO reductions. The mutual benefits of these projects necessitate a capital planning, design, and construction process that incorporates project changes to ensure project goals are achieved and intended benefits are maintained. The Water Department updates the hydrologic and hydraulic models as projects move from planning to design and from design to construction, adjusting model parameters with design changes and final construction status. Projects that achieve construction complete status are incorporated into the planning level model and their effects on the combined sewer system are represented in reported performance.

9.3.5 Pollutant Mass Loading

Pollutant mass performance targets for the Water Quality Based Effluent Limit of the COA were developed by following guidelines to meet option iii in Section II.C.4.a of the National CSO Policy. This option required a comparison of the pollutant removal by mass of the LTCPU selected alternative with an alternative that achieves 85% capture by volume using a traditional treatment approach. In following Section II.C.4.a of the National CSO Policy, the Water Department defined the 85% by volume traditional alternative as satellite primary clarification and disinfection of the CSOs prior to discharge. To decide on the appropriate pollutant removal efficiencies, the results of sampling of the primary settling tanks from the Water Department wastewater treatment plants were used. The removal rates for the pollutants of concern are discussed in COA Appendix E (Supplemental Documentation), as well as the expected concentrations in the untreated stormwater and sanitary sewage, and the expected concentrations of the effluent from green stormwater infrastructure assuming it passes through soil as part of the treatment.

These removal rates and concentrations will be used for reporting purposes under the Comprehensive Monitoring Plan. As discussed in the Implementation and Adaptive Management Plan and Section 1 of this plan, the hydrologic and hydraulic model results combined with these removal rates and concentrations will prepare estimates to report progress towards 25 year targets at each 5 year reporting period.

9.3.6 Stream Restoration Design and Evaluation Support

The Water Department is designing and implementing stream restoration projects along the mainstem sections of the Cobbs and Tookany/Tacony-Frankford streams. The hydrologic and hydraulic models are utilized to assist designing these projects and evaluating the constructed morphologies' effects on stream flow conditions. In addition, the enhancement of the stream system will be utilized in coordinating the linkage between the hydrologic and hydraulic models and the receiving water quality models. This modeling will be continued under the Comprehensive Monitoring Plan.

9.3.7 Inflow and Infiltration Reduction Assessment

The Water Department collection system's sanitary sewers often experience increased flows during wet weather. As part of the requirements of the COA and as a portion of the Comprehensive Monitoring Plan, the Water Department will undertake an evaluation of these sanitary sewer flows utilizing the hydrologic and hydraulic models and determine if wet weather inflow and infiltration reduction could benefit CSO control. As discussed in the Implementation and Adaptive Management Plan Section 6.9.1, the Water Department will complete the process in three phases. The first two phases are part of a sewer system evaluation survey and include data collection and a detailed study. The third phase is a summary report of documenting, if appropriate, potential improvements to sanitary sewer systems that may benefit CSO control.

As part of the sewer system evaluation survey process, described in Section 6.9.1, the Water Department will determine the dry weather and wet weather flow components of the outlying community connection points. The Water Department will utilize the hydrologic and hydraulic models to assist in the evaluation and will use the results to complete a report identifying any outlying communities that contribute excessive wet weather flows that increase CSOs. In addition, the report will summarize the Water Department's efforts to reduce outlying community wet weather flows, primarily through contract terms and requirements. The Water Department will submit this report to the Pennsylvania Department of Environmental Protection for its use to assist these municipalities in completing the remaining portions of the sewer system evaluation survey. The Outlying Communities Report will be completed by June 1, 2015.

9.3.8 Water Quality Modeling Linkage

A software tool will be developed to translate output from the hydraulic and hydrologic models into appropriate format for the water quality model. This will allow the water quality model to simulate the effect of CSOs on fecal coliform concentrations and dissolved oxygen in the Tacony-Frankford and Cobbs Creeks. Additional information and discussion regarding the water quality model is found within Comprehensive Monitoring Plan Section 10.

9.4 Hydrologic and Hydraulic Model Refinement

Proposed future development activities under the Comprehensive Monitoring Plan for the hydrologic and hydraulic models include the following elements:

- Refinements of the sewershed delineations and characteristics (i.e., area, slope, impervious cover, etc.) in response to improvements in the quality of the remotely sensed data sources used in the City geographic information system (GIS)
- Using gage calibrated radar rainfall estimates for model calibration, system performance evaluation and regulatory reporting.
- Model technology improvements to better represent evapotranspiration and potential application of snow melt-runoff capabilities

- Converting to the new Storm Water Management Model 5 hydrodynamic representations of hydraulic structures such as weirs and orifices
- Employing the new low impact development/green stormwater infrastructure features of the most recent model code releases.

As these refinements and improvements are implemented, the model-based estimates of overflow frequency, volume, and duration, and the associated estimation uncertainty, will be refined and redefined.

9.4.1 Refinement of Characteristics from Improved Remotely Sensed Data Sources

9.4.1.1 Subcatchment Area

For the hydrologic and hydraulic models to be an accurate representation of the sewer system, the sewershed, catchment, and subcatchment areas need to be as realistic as possible. Ongoing activities under this Comprehensive Monitoring Plan will continue to refine area delineations within the City and outlying communities. 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 for the LTCPU was determined based on detailed sewer plans within the City and the topographic maps needed to determine surface drainage to sewer inlet locations. The delineation of sanitary sewer subcatchment area inside the City was based on detailed sewer plans. Subcatchment areas outside of the City were delineated with a tool in GIS using United States Geological Survey 30-meter DEMs to identify drainage divides. Subcatchment areas within the City were defined based on detailed sewer plats. The hydrologic component of Storm Water Management Model 5 represents most stormwater runoff subcatchments as rectangular areas defined by the subcatchment width parameter. Storm Water Management Model 5 simulates surface runoff from drainage areas using three “planes” of overland flow. One plane represents all impervious surfaces directly connected to the hydraulic system and include initial abstraction or surface detention storage (puddles, cracks, etc.) which do not permit immediate runoff. A second plane represents all pervious areas and impervious areas not directly connected to the hydraulic system. The third plane is defined as the fraction of the directly connected area that provides no detention storage and thus produces runoff immediately. The runoff from the drainage area is the sum of the flow off the three planes. The complete hydrologic model consists of approximately 2100 subcatchments, as of the completion of the LTCPU, representing the entire Water Department service area.

Updates and improvements in the quality of the remotely sensed data that affects subcatchment area estimation (i.e., topography, parcel information and land use types) may lead to adjustment of the original subcatchments. Furthermore, refinements in the combined sewer system models driven by Storm Flood Relief Program alternatives analyses (extension of represented trunk sewer systems to smaller pipes) may lead to additional adjustment of subcatchments. Each of these adjustments could have cascading effects on additional model characteristics discussed in this section.

9.4.1.2 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 LTCPU Combined sewer system models, width was initially taken to be double the square root of the subcatchment's area and later treated as a calibration parameter. Adjustments to subcatchment area driven by source data improvements, model refinements or validation may affect subcatchment widths.

9.4.1.3 Subcatchment Impervious Area

The percent imperviousness of a subcatchment is a parameter that can be reasonably estimated from aerial photos and/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 a pervious area, this should not be included as directly connected. The total percent impervious area is used as the initial effective impervious area and then may be reduced or flow generated from the impervious area routed on to the pervious area during the model validation process to best simulate the observed hydrologic response over a range of precipitation events.

In generating estimates of gross impervious cover for the LTCPU model development, the following method was employed. For all areas within the City of Philadelphia, GIS coverage of impervious areas derived from 2004 orthodigital photographs was used. This coverage delineates all land use in the City into pervious or "natural surfaces," comprising 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 drainage area 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.

Updates and improvements in the quality of the GIS data that affects impervious land use types will lead to adjustment of the original impervious area estimations and may drive the adjustment of subcatchment areas and widths. The Comprehensive Monitoring Plan will include the continuing refinement of impervious area representation in the hydrologic and hydraulic models as new information becomes available.

9.4.1.4 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 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.

GIS was utilized in order to calculate the slopes for these subcatchments. 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.

Updates and improvements in the quality of the remotely sensed data that affects subcatchment slope estimation (topography and parcel information) may lead to adjustment of the original subcatchment slope. Similar to other characteristics discussed in this section, refinements to other characteristics and updates to combined sewer system models driven by Storm Flood Relief Program alternatives analyses may lead to additional adjustment of subcatchment slope. The Comprehensive Monitoring Plan will include the continuing refinement of surface slope representation in the hydrologic and hydraulic models as new information becomes available.

9.4.2 Hydrologic Model Technology Improvements

9.4.2.1 Evaporation Input Data

Evaporation data is required by the model in the form of average monthly evaporation rates, although finer time increments may be entered as negative flows by creating an evaporation time series. Evaporation data is obtained from the National Weather Service or from other published pan evaporation measurements.

Limited long-term daily evaporation data exists for the Philadelphia area. Neither the Philadelphia Airport nor the Wilmington Airport records evaporation data. For the development of the LTCPU models, average monthly evaporation (inches per day) were used for all Storm Water Management Model 4 models and were determined from New Castle County, Delaware recorded daily evaporation data from 1956 through 1994 and are summarized in Section 7.1.6.

Evaporation data may be modified if more current observed data (evaporation and evapotranspiration) is available. Additionally, evapotranspiration may be investigated as part of the assessment of green stormwater infrastructure practices and could be included as a model refinement under the Comprehensive Monitoring Plan.

9.4.2.2 Temperature Input Data and Snowmelt

Temperature time series input data can be used to run a snowmelt routine in Storm Water Management Model 5. 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 in LTCPU development modeling. 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 Water Department non-heated rain gage observations, Philadelphia International Airport observed hourly snowfall, daily snow cover, and daily maximum temperatures.

Potential utilization of this portion of Storm Water Management Model 5 will be investigated and evaluated for the Comprehensive Monitoring Plan based on availability of reliable snowfall and snowmelt data in conjunction with Philadelphia International Airport meteorological data.

9.4.3 Hydraulic Structure Improvements

The upgrade to Storm Water Management Model 5 compared to Storm Water Management Model 4 has improved the solution techniques, such as the one used to solve the dynamic wave equation for flow. This improvement allows the Saint Venant equations to be solved by a successive approximation technique that helps the solutions converge faster. Additionally, Storm Water Management Model 5 uses the orifice and weir equations, whereas Storm Water Management Model 4 used equivalent pipe approximations, improving the way these hydraulic structures are simulated.

The initial phase of updating the combined sewer system model to Storm Water Management Model 5 did not include converting all weirs and orifices from equivalent pipes. This model improvement will be made as part of the ongoing model refinement process under the Comprehensive Monitoring Plan.

9.4.4 Green Stormwater Infrastructure Module

The green stormwater infrastructure component of Storm Water Management Model 5, or LID Controls as they are referenced in Storm Water Management Model 5 application, incorporates adjustments to subcatchments to simulate processes of this type of stormwater management technique. Storm Water Management Model 5 has included five specific green stormwater infrastructure controls and has described them as follows (US EPA Storm Water Management Model 5 Help):

- "*Bioretention Cells - are depressions that contain vegetation grown in an engineered soil mixture placed above a gravel drainage bed. They provide storage, infiltration and evaporation of both direct rainfall and runoff captured from surrounding areas. Rain gardens, street planters, and green roofs are all variations of bio-retention cells.*
- *Infiltration Trenches - are narrow ditches filled with gravel that intercept runoff from upslope impervious areas. They provide storage volume and additional time for captured runoff to infiltrate the native soil below.*

- *Continuous Porous pavement - systems are excavated areas filled with gravel and paved over with a porous concrete or asphalt mix. Normally all rainfall will immediately pass through the pavement into the gravel storage layer below it where it can infiltrate at natural rates into the site's native soil. Block Paver systems consist of impervious paver blocks placed on a sand or pea gravel bed with a gravel storage layer below. Rainfall is captured in the open spaces between the blocks and conveyed to the storage zone and native soil below.*
- *Rain Barrels (or Cisterns) - are containers that collect roof runoff during storm events and can either release or re-use the rainwater during dry periods.*
- *Vegetative Swales - are channels or depressed areas with sloping sides covered with grass and other vegetation. They slow down the conveyance of collected runoff and allow it more time to infiltrate the native soil beneath it."*

The first three controls, bioretention cells, infiltration trenches, and porous pavement can be simulated with underdrains, similar to the representation of green stormwater infrastructure for the LTCPU alternatives analysis.

The Water Department will remain active in communicating with the Storm Water Management Model 5 development team and the Storm Water Management Model user community about the LID control module. This process will allow the Water Department to understand, evaluate, and improve these green stormwater infrastructure representations. The Storm Water Management Model 5 LID module may be incorporated once a thorough understanding of the simulation processes involved for these green stormwater infrastructure representations are completed and it has been determined that the simulations represent the physical processes closely and provide results that represent the observed results in varied scenarios.

10.0 Water Quality Modeling

The Consent Order and Agreement requires the development of receiving water quality models for the tidal Delaware and Schuylkill Rivers and the Tacony-Frankford and Cobbs Creeks. Development of these models requires the collection of field data for model development and validation, as described in Section 6. Additional tasks include reviews of previous similar studies, alternative evaluations and report preparation. The models will be used to simulate improvements in receiving water quality conditions resulting from the implementation of the *Green City, Clean Waters* program.

10.1 Bacteria Models for the Tacony-Frankford and Cobbs Creeks

The United States Environmental Protection Agency Water Quality Analysis Simulation Program will be used to create a bacteria water quality models for the Tacony-Frankford and Cobbs Creeks. The development of the models involves several tasks focused around data acquisition leading to model formulation. The models will be used to assess the projected impact of the *Green City, Clean Waters* program on fecal coliform concentrations, fate, and transport in future years, and to evaluate alternative implementation options. The process and results will be summarized in the Tributary Water Quality Modeling Report for Bacteria due June 1, 2013.

10.1.1 Data Acquisition and Preparation

Receiving water monitoring data required for the bacteria models for the Tacony-Frankford and Cobbs Creeks needs to be identified, acquired, and prepared to set up boundary and initial conditions for the models. The Water Department will compile a database of fecal coliform measurements that were obtained by the Water Department and other sources listed in Section 6. In addition, dry and wet weather validation periods and sites will be identified. A concurrent time series of creek flow rate, water temperature, and outfall flow rates will be assembled. As the models are developed, any further data acquisition needs will be determined.

10.1.2 Literature Reviews of Similar Analyses

A summary of previous studies and key processes to simulate will be compiled to assist in the construction of the models. This will help to learn from successes and failures of similar models to more efficiently build the Tacony-Frankford and Cobbs Creeks bacteria models.

10.1.3 Hydraulic and Water Quality Model Linkage

A software tool will be developed to translate output from the Storm Water Management Model version 5 hydraulic and hydrologic models into appropriate format for the Water Quality Analysis Simulation Program water quality models. This will allow the Water Quality Analysis Simulation Program models to simulate the effect of Combined Sewer Overflows (CSOs) on fecal coliform concentrations in the Tacony-Frankford and Cobbs Creeks.

10.1.4 Development of Boundary and Initial Conditions

Boundary and initial conditions for both wet and dry weather will be developed for the bacteria water quality models. The boundary conditions include the fecal coliform concentrations and stream temperature entering into the most upstream segment of the models, fecal coliform concentrations, stream temperature entering from the CSO outfalls, and overland runoff. Initial conditions in wet and dry weather will be determined for each segment of the models for fecal coliform and stream temperature.

10.1.5 Model Parameterization, Sensitivity Analysis, and Validation

Model parameterization will include the assignment of value ranges to key model parameters such as decay rate, dispersion coefficient, and others. After the framework of the models is developed, a sensitivity analysis will be conducted to analyze the effect of various parameters, baseflow loads, and CSO loads on model output. After parameterization and the sensitivity analysis, the models will be validated using receiving water monitoring data. Validation statistics and plots will be created to compare with the monitoring data. After the models are validated, a table will be produced to confirm all parameter values and boundary conditions.

10.1.6 Simulation of Alternate Scenarios

Flow model and water quality boundary conditions will be developed for each scenario of the *Green City, Clean Waters* program. This will determine the impact of each alternative on fecal coliform concentrations. A summary of alternative scenario results will be compiled for comparison.

10.2 Dissolved Oxygen Models for the Tacony-Frankford and Cobbs Creeks

Water Quality Analysis Simulation Program has the ability to simulate dissolved oxygen processes, and will be used to create the dissolved oxygen models for the Tacony-Frankford and Cobbs Creeks. The development of the models involves several tasks focused around data acquisition leading to model formulation. The models will be used to assess the projected impact of the *Green City, Clean Waters* program on the concentrations, fate, and transport of organic pollutants and nutrients in future years, and to evaluate alternative implementation options. The process and results will be summarized in the Tributary Water Quality Modeling Report for Dissolved Oxygen due June 1, 2014.

10.2.1 Data Acquisition and Preparation

Receiving water monitoring data required for the dissolved oxygen models for the Tacony-Frankford and Cobbs Creeks needs to be identified, acquired, and prepared to set up boundary and initial conditions for the models. A database of parameters related to dissolved oxygen – including biochemical oxygen demand, ammonia, and nutrients – will be compiled using receiving water monitoring measurements from the Water Department and other sources listed in Section 6. In addition, dry and wet weather validation periods and sites will be identified. A concurrent time series of creek flow rate, water temperature, and outfall flow rates will be assembled. Sediment oxygen demand data will be collected to be included in the database of parameters. As the models are developed, any further data acquisition needs will be determined.

10.2.2 Literature Reviews of Similar Analyses

A summary of previous studies and key processes to simulate will be compiled to assist in the construction of the models. This will help to learn from successes and failures of similar models to more efficiently build the Tacony-Frankford and Cobbs Creeks dissolved oxygen models.

10.2.3 Hydraulic and Water Quality Model Linkage

A software tool will be developed to translate output from the Storm Water Management Model 5 hydraulic and hydrologic models into appropriate format for the Water Quality Analysis Simulation Program water quality models. This will allow the Water Quality Analysis Simulation Program models to simulate the effect of CSOs on dissolved oxygen in the Tacony-Frankford and Cobbs Creeks.

10.2.4 Development of Boundary and Initial Conditions

Boundary and initial conditions for both wet and dry weather will be developed for the dissolved oxygen water quality models. The boundary conditions include biochemical oxygen demand, dissolved oxygen, nitrogen and phosphorus series concentrations, and stream temperature entering into the most upstream segment of the models, from the CSO outfalls, and from overland runoff. A solar radiation time series with adjustments for riparian shading will also be included in the boundary conditions. Initial conditions in wet and dry weather will be determined for each segment of the models for biochemical oxygen demand, dissolved oxygen, periphyton, nitrogen and phosphorus series concentrations, and stream temperature.

10.2.5 Model Parameterization, Sensitivity Analysis, and Validation

Model parameterization will include the assignment of value ranges to key model parameters such as decay rates, periphyton kinetics, sediment oxygen demand, and others. After the framework of the models is developed, a sensitivity analysis will be conducted to analyze the effect of various parameters, baseflow loads, and CSO loads on model output. After parameterization and the sensitivity analysis, the models will be validated using receiving water monitoring data. Validation statistics and plots will be created to compare with the monitoring data. After the models are validated, a table will be produced to confirm all parameter values and boundary conditions.

10.2.6 Simulation of Alternate Scenarios

Flow model and water quality boundary conditions will be developed for each scenario of the *Green City, Clean Waters* program. This will determine the impact of each alternative on organic pollutants and nutrient concentrations. A summary of alternative scenario results will be compiled for comparison.

10.3 Hydrodynamic and Water Quality Model for the Tidal Delaware and Schuylkill Rivers

The 3-dimensional hydrodynamic model is being developed from existing data used previously for the Water Department's 2-dimensional model of the system, and will incorporate additional data yet to be collected. The building and validation of the hydrodynamic model is intended to facilitate the development of the water quality modules for bacteria and dissolved oxygen. The process and results will be summarized in the Tidal Water Quality Modeling Report due June 1, 2014.

10.3.1 Hydrodynamic Model

The hydrodynamic model will be used to simulate 3-dimensional flow in the Delaware and Schuylkill Rivers to assist in determining the fate and transport of pollutants.

10.3.1.1 Data Acquisition and Preparation

In order to develop a hydrodynamic model, a database of inputs must be created. The necessary inputs include bathymetry data, point sources, tidal inputs, salinity data, water temperature, and meteorological inputs.

10.3.1.2 Grid Development

The hydrodynamic numerical model solves three-dimensional equations of motion for turbulent flow in a coordinate system. A grid for the tidal Delaware and Schuylkill Rivers will be generated with bathymetry integration to set up the model.

10.3.1.3 Model Validation to Water Level, Currents, and Salinity Concentrations

After the framework of the model is developed, it will be validated with receiving water monitoring data for water level, current, and salinity.

10.3.2 Bacteria Water Quality Model

Water Quality Analysis Simulation Program will be used to create a bacteria water quality model for the tidal Delaware and Schuylkill Rivers. The development of the model involves several tasks focused around data acquisition leading to model formulation. The model will be used to assess the projected impact of the *Green City, Clean Waters* program on fecal coliform concentrations, fate, and transport in future years, and to evaluate alternative implementation options.

10.3.2.1 Data Acquisition and Preparation

Receiving water monitoring data required for the bacteria model for the tidal Delaware and Schuylkill Rivers needs to be identified, acquired, and prepared to set up boundary and initial conditions for the model. The Water Department will compile a database of fecal coliform measurements and loadings that were obtained by the Water Department and other sources such as the Delaware River Basin Commission, the New Jersey Department of Environmental

Protection, the Pennsylvania Department of Environmental Protection, the Delaware Department of Natural Resources and Environmental Control, the United States Geological Survey (USGS), and the University of Delaware. In addition, dry and wet weather validation periods and sites will be identified. A concurrent time series of river and boundary input flow conditions and concentrations will be assembled. As the model is developed, any further data acquisition needs will be determined.

10.3.2.2 Literature Review

A summary of previous studies and key processes to simulate will be compiled to assist in the construction of the model. This will help to learn from successes and failures of similar models to more efficiently build the tidal Delaware and Schuylkill Rivers bacteria model.

10.3.2.3 Hydrodynamic Model Linkage

The bacteria water quality model will be linked with the hydrodynamic model to simulate the fate and transport of bacteria.

10.3.2.4 Development of Boundary and Initial Conditions

Boundary and initial conditions for both wet and dry weather will be developed for the bacteria water quality model. The boundary conditions include the fecal coliform concentrations and water temperature entering from above and below the model domain, tributaries, and CSO outfalls as well as overland runoff. Initial conditions in wet and dry weather will be determined for each segment of the model for fecal coliform and water temperature.

10.3.2.5 Model Parameterization, Sensitivity Analysis, and Validation

Model parameterization will include the assignment of value ranges to key model parameters such as decay rate, dispersion coefficient, and others. After the framework of the model is developed, a sensitivity analysis will be conducted to analyze the effect of various parameters, baseflow loads, and CSO loads on model output. After parameterization and the sensitivity analysis, the model will be validated using receiving water monitoring data. Validation statistics and plots will be created to compare with the monitoring data. After the model is validated, a table will be produced to confirm all parameter values and boundary conditions.

10.3.2.6 Simulation of Alternate Scenarios

Flow model and water quality boundary conditions will be developed for each scenario of the *Green City, Clean Waters* program. This will determine the impact of each alternative on fecal coliform concentrations. A summary of alternative scenario results will be compiled for comparison.

10.3.3 Dissolved Oxygen Water Quality Model

Water Quality Analysis Simulation Program has the ability to simulate dissolved oxygen processes, and will be used to create the dissolved oxygen model for the tidal Delaware and Schuylkill Rivers. The development of the model involves several tasks focused around data acquisition leading to model formulation. The model will be used to assess the projected impact of the *Green City, Clean Waters* program on the concentrations, fate, and transport of organic pollutants and nutrients in future years, and to evaluate alternative implementation options.

10.3.3.1 Data Acquisition and Preparation

Receiving water monitoring data required for the dissolved oxygen model for the tidal Delaware and Schuylkill Rivers needs to be identified, acquired, and prepared to set up boundary and initial conditions for the model. A database of parameters related to dissolved oxygen – including biochemical oxygen demand, ammonia, and nutrients – will be compiled using receiving water monitoring measurements from the Water Department and other sources such as the Delaware River Basin Commission, the New Jersey Department of Environmental Protection, the Pennsylvania Department of Environmental Protection, the Department of Natural Resources and Environmental Control, USGS, the University of Delaware, the US Army Corps of Engineers, and the Academy of Natural Sciences. In addition, dry and wet weather validation periods and sites will be identified. A concurrent time series of creek flow rate, water temperature, and outfall flow rates will be assembled. Sediment oxygen demand data will be collected to be included in the database of parameters. As the model is developed, any further data acquisition needs will be determined.

10.3.3.2 Literature Reviews

A summary of previous studies and key processes to simulate will be compiled to assist in the construction of the model. This will help to learn from successes and failures of similar models to more efficiently build the tidal Delaware and Schuylkill Rivers dissolved oxygen model.

10.3.3.3 Hydrodynamic Model Linkage

The bacteria water quality model will be linked with the hydrodynamic model to simulate the fate and transport of bacteria.

10.3.3.4 Development of Boundary and Initial Conditions

Boundary and initial conditions for both wet and dry weather will be developed for the dissolved oxygen water quality model. The boundary conditions include nitrogenous biochemical oxygen demand, carbonaceous biochemical oxygen demand, dissolved oxygen, nitrogen and phosphorus series concentrations, phytoplankton, and water temperature entering from above and below the model domain, from the CSO outfalls, and from overland runoff. A solar radiation time series with adjustments for riparian shading will also be included in the boundary conditions. Initial conditions in wet and dry weather will be determined for each segment of the model for nitrogenous biochemical oxygen demand, carbonaceous biochemical oxygen demand, dissolved oxygen, nitrogen and phosphorus series concentrations, phytoplankton, and water temperature.

10.3.3.5 Model Parameterization, Sensitivity Analysis, and Validation

Model parameterization will include the assignment of value ranges to key model parameters such as decay rates, phytoplankton kinetics, light extinction, sediment oxygen demand, and others. After the framework of the model is developed, a sensitivity analysis will be conducted to analyze the effect of various parameters, baseflow loads, and CSO loads on model output. After parameterization and the sensitivity analysis, the model will be validated using receiving water monitoring data. Validation statistics and plots will be created to compare with the monitoring data. After the model is validated, a table will be produced to confirm all parameter values and boundary conditions.

10.3.3.6 Simulation of Alternate Scenarios

Hydrodynamic model and water quality boundary conditions will be developed for each scenario of the *Green City, Clean Waters* program. This will determine the impact of each alternative on organic pollutants and nutrient concentrations. A summary of alternative scenario results will be compiled for comparison.

References

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