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To:
New York City Department of Environmental Protection

From:
Arcadis Team

Date:
November 23, 2015

Subject:
GI-RD Task 2.3 – Current Green Infrastructure Modeling Procedures in New York City

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This technical memorandum summarizes the approaches developed by DEP and its consultants during the long term combined sewer overflow (CSO) control planning for various waterbodies in New York City. The goal is to document the current procedures used for green infrastructure (GI) modeling as an interim deliverable in the GI-RD project, and identify any improvements necessary to enhance the characterization of GI performance based on extensive field data that DEP has been collecting and also on the state-of-the-science approaches being developed by academics and other peer cities in the U.S.

Background

Earlier modeling of GI that supported the 2010 Green Infrastructure Plan (the "GI Plan") development relied on simplified assumptions and modeling tools. Up to one inch of rainfall was deducted from individual event hyetographs and the remainder of the hyetograph was included as net rainfall for the portion of drainage areas managed or controlled by GI practices, while the full rainfall hyetograph was applied on uncontrolled areas. Even though the actual GI practices could include retention and detention, the simplified method used in 2010 GI Plan considered all of the GI to be retention based on this assumption of one-inch rainfall capture.

During the long term control plan (LTCP) process beginning in 2012, this method was modified to explicitly account for the physical processes associated with retention and detention-based GI practices. This is based on the fact that the detention GI practices, implemented in public and private onsite properties in accordance with DEP's July 2012 stormwater performance standard, will reduce peak flows to DEP-allowable levels but will not reduce stormwater volumes entering into the combined sewer system (CSS). In accordance with the 2010 GI Plan, DEP was required to include GI in the evaluation of water quality benefits from the baseline scenario, based on which the engineering alternatives would be evaluated as part of the LTCP process. Since some portion of the GI target in each watershed (for which an LTCP is being developed) is expected to be implemented through detention, this method of explicitly including retention and detention practices was considered more appropriate in the baseline modeling for various LTCPs being developed than the all-retention simplified approach used for 2010 GI Plan.

The LTCP process began in 2012 subsequent to the issuance of an amended consent order (the Order) by New York State Department of Environmental Conservation (DEC). The Order also required DEP to develop neighborhood-scale monitoring pilots with a Post Construction Monitoring Report due August 2014. The purpose of the neighborhood demonstration pilots (Demo Areas) were to quantify the performance of GI implemented at the neighborhood scale (20-30 acres) and the associated reductions in stormwater runoff volumes and peak flows observed in a downstream sewer. Supplemental to this Demo Areas' data were the pilot monitoring performed by DEP since 2010 on individual GI practices such as green roofs, bioswales, and porous pavers. Because the first LTCP for Alley Creek and Little Neck Bay was due in June 2013, the DEP proceeded with modeling of detention and retention practices without explicitly including the lessons learned or outcomes from the Demo Area. Therefore, despite the advancements over the modeling approach used in the 2010 GI Plan development, the improved detention and retention modeling methods used during LTCP were still considered approximations of the unit processes happening within GI.

DEP developed a priority implementation strategy for various combined sewer areas based on the estimated water quality benefits assessed during 2010 GI Plan development. For the confined tributaries, DEP estimated that higher saturation rates of GI would likely produce better water quality benefits, so the 10% citywide GI implementation assumed in the 2010 GI Plan was modified to reflect increased targets in these tributaries. The detention targets were developed by DEP based on extrapolated growth rates for new and redevelopment as described later in this memorandum, and the retention targets were calculated as the difference between total GI target and the detention target.

A typical drainage area serviced by a wastewater treatment plant (WWTP) consists of numerous subcatchments that represent the smaller areas connected to sewer manholes (nodes) included in an InfoWorks model. Generally, pipes larger than 60-inches are modeled, therefore, not every manhole in the CSS is included in New York City's InfoWorks models. As such, lumping of areas contributing up to a modeled manhole is necessary and this lumped area constitutes its subcatchment area.

Description of Technical Approaches

This section describes the retention and detention modeling approaches currently used in LTCP evaluations on a subcatchment level. Figure 1 shows the GI model representation in InfoWorks for one subcatchment that drains into a manhole in the CSS. The retention procedure is described first, followed by the detention-modeling procedure.

Retention

(1) Retention is based only on the controlled or managed impervious area where one inch of runoff is managed by retention-based practices.

(2) Retention targets have been provided by DEP as percentages for the various LTCP waterbodies based on their priority levels. Each waterbody may receive CSO discharges from one or more WWTP service areas. These target percentages on a waterbody basis define the fractions of impervious areas within CSS that are intended to be managed or controlled by retention-based GI practices. As such, the GI targets can be different within subcatchments of a single WWTP service area based on the various waterbodies that the individual CSO outfalls discharge into.

Managed area assumptions are based on the following:

(1) Retention target specified for an LTCP waterbody, multiplied by effective (directly connected) impervious area (DCIA) within the combined sewered area tributary to this LTCP waterbody. Separately sewered areas tributary to this waterbody are modeled without any GI intervention.

(2) Model setup is as follows: DCIA of each subcatchment is divided into controlled and uncontrolled portions, with the controlled (managed) area as defined above. The uncontrolled DCIA portion and pervious area are connected to CSS at the same drain manhole as the pre-GI model. Only the DCIA portion controlled by retention practices is connected to a storage node with a capacity equivalent to managed impervious area multiplied by one-inch of runoff. The runoff in excess of this volume is bypassed to the drain manhole.

(3) Storage node is drained in the model via infiltrating bottom, so captured stormwater is not reintroduced into the system. A uniform vertical infiltration rate of 1.75 in/hr is used for all waterbodies.

Again, it must be recognized that the managed impervious acreage in each subcatchment is calculated based on the GI target specified for that LTCP waterbody, and not based on an actual number of ROW bioswales or other GI assets within that subcatchment. An enhancement to GI modeling work for the 1.5% GI implementation rate is being performed as part of the GI-RD project.

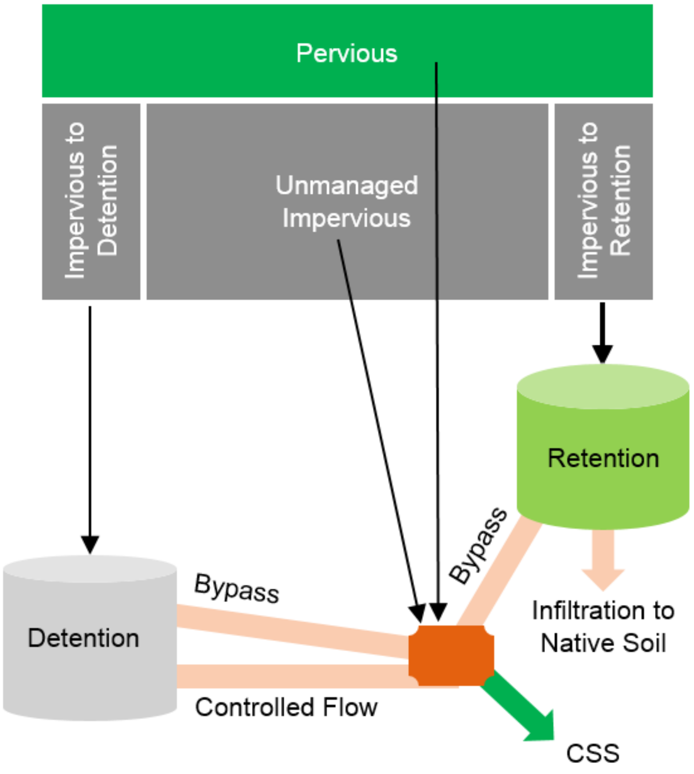

Figure 1: Detention-Retention Representation in an InfoWorks Subcatchment

Onsite Detention

(1) Onsite practices are assumed to be detention only with no infiltration as a conservative assumption, even though there are some detention facilities designed onsite with infiltrating (open) bottom. In essence, all the detention facilities are assumed to be built with impermeable bottom surface. Rooftop and subsurface detentions are assumed to be equal for this processing.

(2) The process for developing onsite detention for each subcatchment is as follows:

   a. A set of categories of lot areas is developed as follows to conduct the detention analysis. DEP provided information from historical building permits on the distribution of building permits into these lot size categories along with the lot sizes so that a total lot area modified within an individual subcatchment can be estimated. This information is separated into two categories: New Buildings (NB) and Major Alterations (MA). Subsequently, the sizes of lots in various categories are rolled up at the spatial scale of a subcatchment for representation in the InfoWorks model.

    i. Size A – 1,000 square feet to 4,999 square feet
    ii. Size B – 5,000 square feet to 9,999 square feet
    iii. Size C – 10,000 square feet to 14,999 square feet
    iv. Size D –15,000 square feet to 29,999 square feet
    v. Size E – 20,000 square feet to 39,999 square feet
    vi. Size F – >40,000 square feet

b. Each of these size categories has a $Q_{allowable}$ and $Q_{restricted}$ associated with them. The $Q_{allowable}$ is developed based on the drainage planning procedure set up in the 2012 July Performance Standard Best Management Practices (BMP) Manual.

    i. For new buildings (NB), the $Q_{allowable}$ is calculated based on allowable weighted runoff coefficient (C_w) and rainfall intensity of individual boroughs (for example for Brooklyn C_w of 0.5 and rainfall intensity of 5 inches per hour). The $Q_{restricted}$ is then estimated. The $Q_{restricted}$ is set based on the new site connection rule (<0.25cfs = $Q_{allowable}$, >0.25cfs = maximum of 0.25cfs or 10% of $Q_{allowable}$).

    ii. For major alterations (MA), the $Q_{allowable}$ is also based on allowable C_w and rainfall intensity of individual boroughs. Lot area is divided into altered and unaltered portions. It is assumed that on an average 50% of the lot is altered. The $Q_{restricted}$ is then developed using $Q_{allowable}$ from altered and unaltered sections of the lots. $Q_{restricted}$ for the altered section of the lot is set based on the new site connection rule (<0.25cfs = $Q_{allowable}$, >0.25cfs = maximum of 0.25cfs and 10% of $Q_{allowable}$). For redeveloped lots the restricted flow is the summation of $Q_{allowable}$ from unaltered section of the lot and $Q_{restricted}$ from altered section of the lot.

c. A $Q_{restricted}$ total is developed as the product of the $Q_{restricted}$ per size class and the numbers of lots in different size classes for both each the NB and MA classes.

d. $Q_{restricted}$ for all categories listed in (b) for both NB and MA lots are added up to get the overall release rate for each subcatchment. This weighted $Q_{restricted}$ is then assigned to the individual combined sewer subcatchments.

e. The $Q_{restricted}$ subcatchment is then divided by a scaling factor which considered both the one-hour rainfall to 5-minute rainfall scaling factor of ($\sqrt{3.3}$) and a factor developed to consider the scale up from multiple storage volumes to a single storage volume for each NB and MA.

f. A subcatchment detention time (t_V) and maximum required detention volume with outflow controlled by an orifice tube or by controlled roof drains (V_V), is calculated using the DEP storage calculation approach for a varying outflow.

Following equations obtained from “Criteria for Detention Facility Design” manual by Bureau of Water & Sewer Operations (June, 2012) are utilized.

Detention Facility with a variable outflow:

$$t_V = 0.27(\frac{0.95A_{Det}}{Q_{DRR}})^{0.5} - 15$$

$$V_V = \left[0.19\frac{0.95A_{Det}}{t_V + 15} - 40Q_{DRR}\right]t_V$$

t_V = Detention time the storm in minutes with a 10-year return frequency requiring the maximum detention volume with a variable outflow; A_{Det} = Area tributary to the detention facility in ft^2 ; Q_{DRR} = $Q_{restricted}$ calculated above in cfs; V_V= Maximum required detention volume in ft^3 with a variable outflow.

g. The total depth of the detention storage node is set to 4 feet.

h. Orifice size is calculated for each subcatchment using orifice equation stated below for re-entrant orifice type (C_D = 0.52) for each of the subcatchments.

$$h = 1930\,(\frac{{Q_{DRR}}^2}{{d_0}^4} + \frac{d_0}{24})$$

h = the maximum storage depth in ft.; Q_{DRR} = detention facility maximum release rate in cfs; d_0 = the nominal diameter of the orifice tube outlet in inches.

The calculation goal is to increase storage until Q_{DRR} is less than $Q_{allowable}$.

(3) Before running with this approach, additional spreadsheet calculations are done to confirm the validity of the approach.

(4) Before implementing this approach, a simulation is performed using a 10-year intensity duration based rainfall hyetograph to make sure the storage volume is filled to the top during the rainfall event. The detention node (tank) is setup with an overflow structure to relieve the excess flows for rain intensities larger than the 10-year intensity duration.

For each subcatchment, the impervious areas to be managed by retention and detention practices are represented as separate runoff producing surfaces in the InfoWorks models. Remainder of the impervious area is represented as uncontrolled surface and the pervious areas are maintained the same as in the calibrated InfoWorks models. Outflows from the retention/detention practices are connected to the same outlet as the uncontrolled and pervious areas for hydraulic routing within the sewers, as shown in Figure 1.

As discussed earlier, the GI targets can vary among subcatchments of a single WWTP service area based on where the outfalls discharge during CSO events. As example, the Tallman Island WWTP service area has CSO outfalls that go into Alley Creek and Little Neck Bay, East River, and Flushing Creek. Separate LTCPs are being developed for each of these waterbodies, and as such, the targets were set based on potential water quality improvement estimated from GI installations in the areas tributary to these waterbodies. Therefore, the subcatchments within Tallman Island InfoWorks model would get the respective GI targets based on the outfalls that discharge into each of these waterbodies.

Summary

This technical memorandum serves as a summary of the current GI modeling procedures being used by DEP in its LTCP efforts. The procedures described here are being reviewed and analyzed in terms of enhancements that can be implemented based on GI performance data that DEP has compiled and also based on a review of modeling procedures documented in academic publications and literature compiled from peer cities.

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From:
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Date:
December 14, 2015

Subject:
GI-RD Task 2.3 – Literature Review

1.0 INTRODUCTION

A literature review was performed to determine common methodologies used for modeling Green Infrastructure (GI) practices, how modeling results compare to monitored performance, and what protocols are used for modeling GI technologies in municipalities with similar urban and climate conditions to New York City. This review examined conference proceedings, peer-reviewed literature, as well as government documents. Due to the large number of references available on this topic, key word searches were used to narrow down the number of papers that were reviewed. The literature focused principally on modeling efforts that could be implemented in InfoWorks, the software used by DEP to model flow through the city's collection system. Additionally, the literature reviewed references to the USEPA Stormwater Management Model (SWMM), primarily because SWMM currently includes the most advanced library of GI modeling tools for distributed GI modeling (called LID controls). Research conducted with other modeling software was also reviewed where it presented general information regarding GI modeling practice.

2.0 METHODOLOGY

Conference papers were pulled from the proceedings of four regularly occurring industry conferences dating back to 2005:

- Low Impact Development (LID) Conference,

- Computational Hydraulics Institute (CHI) Conference,
- Water Environment Federation's Annual Technical Exhibition and Conference (WEFTEC), and
- World Environment & Water Resources Congress (EWRI-WRC).

Peer-reviewed papers were obtained from the Web of Science; government documents consisted primarily of municipal modeling reports prepared by different stormwater utilities and their consultants. The initial search utilized the key word phrases "Green Infrastructure Modeling" and "Low Impact Development Modeling". These key words yielded over 500 papers that were organized in a spreadsheet. To narrow down the number of papers that would be reviewed, a second, more detailed set of key words were applied. These included: "modeling methodology", "Infoworks", "SWMM", "SWMM LID Controls", "Modeling Calibration", "Modeling Validation", "Watershed Scale", and "Site Scale" as well as the names of other common modeling software (e.g. HEC-HMS, FORTRN-HSPF, etc.)[1] After performing this secondary screening process, the abstracts of all remaining papers were reviewed, along with relevant sections of their introductions and conclusions, as appropriate. The most appropriate keyword was then assigned to each of the 434 papers in the spreadsheet. The final list was then re-organized into a matrix (Attachment A), to assist in the review of all relevant papers.

3.0 RESULTS

The review of government reports established that InfoWorks is currently the preferred hydrologic and hydraulic model used by municipal utilities to simulate wet-weather flow through complex urban environments [495]. Many municipalities, including San Francisco, Omaha, Atlanta, Chicago, Baltimore, Seattle and Indianapolis, among others, use calibrated InfoWorks models for strategic sewershed planning [51,98,297,328,332,353,512]. Only utilities in San Francisco, Seattle, and New York have documented how they use this software in GI planning activities, however.

Regardless of which software is used, all GI modeling applications must be preceded by basic decisions regarding scale and resolution. Such decisions are relevant in GI modeling applications, since models constructed at different spatial resolutions offer different possibilities for representing GI, as described below. The key difference is in the size of the hydrologic response units (HRUs) used to represent the watershed surface. So-called "lumped" models usually contain HRUs on the order of 1-100 hectares, whereas "distributed" models, which are able to depict individual land surface types (e.g. roof, sidewalk, lawn, etc.) are typically constructed with HRUs closer to 0.5 hectares in size [519]. HRU resolution also influences the approach taken to simulation of hydraulic features such as pipes and manholes. Lumped models

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[1] An additional set of keywords was created as the papers began the secondary screening process that could potentially inform other subtasks of this project, such as Water Quality and Costing, although these papers were not reviewed further.

require simplifications such as conduit skeletonization (i.e. the deliberate omission of conduits considered to have insignificant hydraulic impact) and subcatchment aggregation (i.e. the aggregation of small subcatchments into larger ones, which are then represented with area-weighted physical characteristics) [495]. Because they contain more HRUs, distributed models allow for, and in some cases require, representation of greater heterogeneity in both urban watershed conditions, and in the hydraulic features of the collection system. As such, they require greater effort to build, to parameterize, and to calibrate. They also offer greater opportunities for physically representing individual GI systems, which in reality are small and distributed throughout the urban watershed.

Though they allow more detailed representation of physical characteristics, distributed models have not been found to always be more advantageous than lumped models and it has been found that subcatchment aggregation did not significantly reduce the accuracy of urban runoff estimation [497]. On the other hand, it has been reported that such claims are not generalizable and are contingent on the choice of modeling software, the catchment characteristics, and the duration and the intensity of the simulated precipitation events [447,495]. It has been suggested that uniform criteria defining the minimum size and number of HRUs to include in urban watershed models be set, though no such standards have been developed nor agreed upon [521]. Overall, it has been reported that lumped models constructed from aggregated datasets are comparable to higher resolution models when used to simulate single events [242]. After comparing the performance of models constructed at different levels of resolution over multiple events, it was found that model resolution yielded negligible difference in the total quantity of predicted outflow although lower resolution models predicted lower peak flows for large storms and higher peak flows for small storms in comparison to the respective results from the higher resolution models [477].

To explore further such tradeoffs, specifically with respect to GI modeling, the remainder of the results are organized into four separate sections. Section 3.1 generally discusses the tradeoffs between continuous and event-based simulations (Section 3.1), while Sections 3.2 and 3.3 discuss techniques that have been used to represent GI in distributed and lumped models, respectively. Section 3.4 discusses where modeling predictions are compared to documented performance and Section 3.5 reviews protocols used in GI modeling.

3.1 CONTINUOUS VERSUS EVENT-BASED SIMULATIONS

Most papers that compared continuous simulations to event-based simulations concluded that the continuous simulations tended to be more accurate for modeling GI practice performance.[59,63,67,155,226,258,374,380,464,505]. This finding is not surprising given that continuous simulations more realistically represent dynamic conditions in between precipitation events, for example by considering changes to soil moisture conditions during dry spells and by more accurately representing the initial conditions for wet spells separated by variable duration dry periods. However, one paper comparing the use of LID controls in SWMM to model GI for both continuous and event-based simulations found that both simulations produced results within the measurement error of field flow measurements [381]. In certain applications, event- based simulations can be more appropriate than continuous simulations, for example if the goal is to forecast flood occurrence in small catchments.

3.2 REPRESENTING GI IN DISTRIBUTED MODELS

Simulation of GI performance in distributed models is currently best enabled through the use of the LID controls built into SWMM, first introduced in 2010 [52]. Though some proprietary models based on SWMM's rainfall runoff relationships have also adopted the LID controls, at the present time, InfoWorks does not support their use. The model domain and calibration parameters from InfoWorks and other models can, however, be exported and used to develop a SWMM model should LID controls use be desired [498,512].

Published reports documenting how well SWMM's LID controls represent GI performance, however, are limited [381]. Most literature that discusses use of the LID Controls began with construction of a baseline model without GI (e.g. the pre-GI model). Different approaches were then used to insert LID controls into the (post-GI) model. A common method discussed repeatedly in the literature involves adding a single LID control to each treated subcatchment [154,381,391], while another method involved representing *each GI measure* as an LID Control in its own separately created subcatchment, to which the treated subcatchment was routed [386,519]. In most papers reviewed, the LID control parameters were typically derived from the tables found in the SWMM Manual and associated documentation. Most papers focused on the simulated difference between baseline (pre-GI) conditions with theoretical (post-GI) performance. No papers were found that attempted to calibrate or to validate post-GI models by adjusting parameters of SWMM's LID controls. When monitoring data was used to calibrate a SWMM model with LID Controls, limited information is provided on how the model was actually calibrated [381]. This is discussed further in Section 3.4.

In distributed models not involving SWMM's LID controls, a very common approach is to model GI systems as 100% pervious subcatchments [185,202,307,314,348]. The depression storage values used for the GI subcatchments are set equivalent to the ponding depth and effective depth of the GI's porous media. Aquifers can then be used to model the infiltrating water from the bioretention practice. This common methodology, which can be implemented using most modeling software, is illustrated in Figure 1.

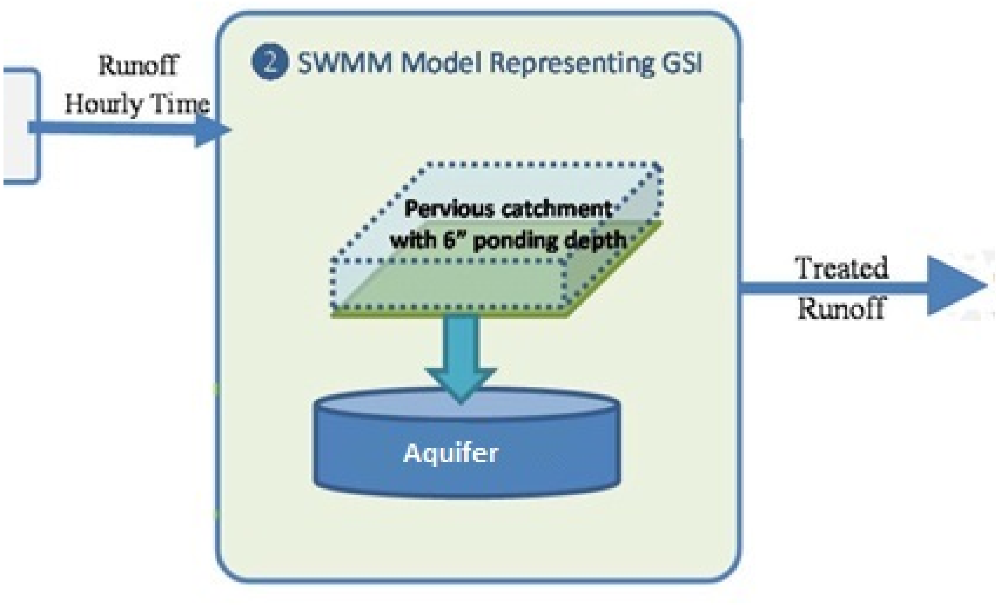

Figure 1: Distributed approach to modeling GI in a Seattle sewershed [307]

3.3 REPRESENTING GI IN LUMPED MODELS

In contrast to distributed models, where many subcatchment properties can be derived from actual physical conditions, in lumped models, weighted averages are typically used to assign initial values to all of the subcatchment parameters [435]. However, since lumped subcatchments are often no longer representative of actual physical conditions, procedures for model calibration of lumped subcatchments are necessary for pre-GI modeling. Calibration typically involves adjusting variables that physically represent the geometry, such as subcatchment length, width, and slope [434].

In lumped Infoworks simulations, GI is typically represented with “storage nodes” inserted into the sewer network [51,226,303,353,510]. Impermeable bottom storage nodes are used for simulating detention GI systems, and permeable bottom storage nodes are used for representing infiltration GI systems, which divert flow away from the collection system [154,349,510,512.] These storage nodes are then connected to the outlet via pipes, overflow weirs and, in the case of no infiltration, with slow release orifices (see Figure 2). This method is common in many cities, including Philadelphia [509], San Francisco [353,510], and Portland [360]. This method does not, however, allow for detailed representation of how GI performance varies based on seasonal changes, maintenance operations, and other complexities of this approach to stormwater management [226].

Other common methods used to model lumped GI include:

- Removing the rainfall depth designed to be managed by all GI from the hyetograph [153],
- Increasing depression storage over impervious areas to match volume managed by GI [349,512], and
- Representing all GI using one LID control in SWMM [381].
- All these methods require splitting the existing model into two subcatchments: one treated and the other untreated.

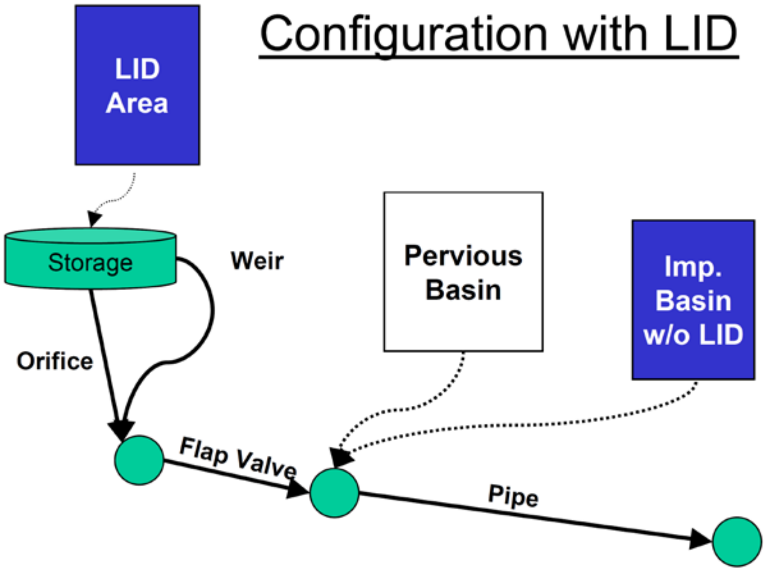

Figure 2: Lumped model representation of GI by the City and County of San Francisco [510]

Other, less common, methodologies include:

- Modeling the infiltration of bioretention practices via an underdrain pipe and adjusting the pipe’s roughness coefficient to provide an equivalent infiltration rate [360] or
- Using a divider to split flow into one storage tank representing porous media storage and another storage tank representing surface ponding (see Figure 3) [392].

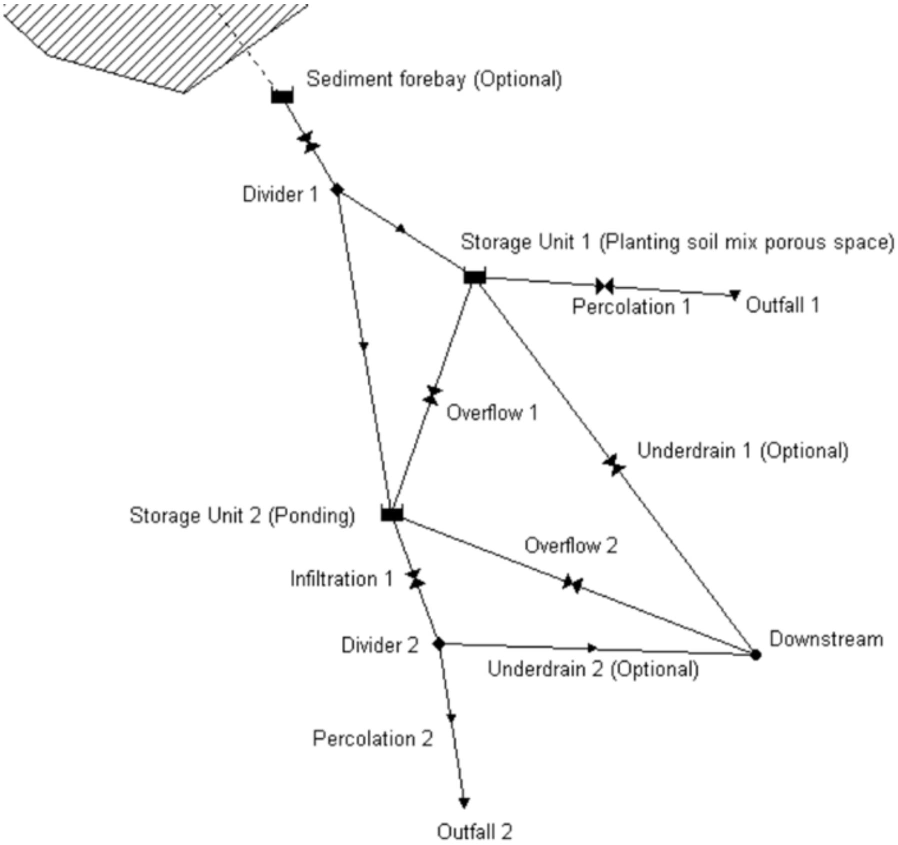

Figure 3: Representation of GI in a lumped model [392]

3.4 MODELING PREDICTIONS VERSUS DOCUMENTED PERFORMANCE

There is limited literature available comparing modeling predictions to documented performance. Multiple papers recognize the limited availability of field measurement comparisons as a gap in determining GI modeling performance [1, 407, 408]. Even where current monitoring programs provide adequate data to calibrate and/or validate a model based on current conditions, long-term performance monitoring is almost always recommended [7,73,80,91,418].

Although GI monitoring data is widely available, there is much variability between the available datasets. Each GI monitoring program is designed for various types of GI control and has different levels of detail. For instance, some studies only consider volume reductions based on inflow and outflow, whereas other datasets include peak runoff, infiltration, evapotranspiration (ET), and water quality parameters [18,34,83]. Field measurements for individual GI sites range from one single event to multiple years of continuous data [3,7,35,58,80,81,96,97,420]. For many GI sites, the hydrologic and hydraulic models are calibrated based on pre-construction data and are not, or still need to be, validated with monitoring data once the GI site is installed [35,49,69,122,412]. Variations in GI data availability and quality is also based on many site-specific factors including monitoring methods, soil properties, and climatic/seasonal patterns [47,58,83,91,116,412]. The limited availability of long-term GI monitoring data is due to the fact that many monitoring programs are only in their pilot stages, and the cost and maintenance requirement for continued monitoring [53,79,83]. Additionally, most of the monitoring data available is for an individual GI site within a sewershed, rather than the cumulative effect of numerous sites [58,73,106].

However, one paper compared measured values and modeling predictions with one storage node and concluded that SWMM performs adequately in terms of modeling runoff volume. This paper observed 10 storm events over a 36-month monitoring period and, using a model efficiency coefficient, determined that SWMM was reliable in simulating runoff. There is a larger discrepancy between observed and modeled performance as precipitation and peak flow increases. However, the paper suggests this is likely due to inaccurate measurements rather than model performance [418]. Alternatively, one paper found a performance issue using the SWMM (Version 5.1.006) LID module. This paper modeled permeable pavement and found simulation time steps significantly affect the runoff reduction rate, although field measurement were not considered in this paper [407]. Overall, the papers in this literature review suggest GI models perform well, however the literature does not provide enough data to comprehensively evaluate GI model performance.

3.5 PROTOCOLS FOR MODELING GI TECHNOLOGIES

Although most municipalities outline protocols for modeling watersheds, such as which subcatchment properties should be estimated from GIS or site visits and which subcatchment properties can be used as calibration parameters, there were limited protocols specifically addressing modeling of GI practices in the literature review. Generally, establishing protocols for modeling GI at a distributed scale can be difficult due to the variable effect of local parameters, such as topography and soil, on the performance of GI [468,500,519].

4.0 DISCUSSION

Overall, the literature review provided a great deal of information on methodologies used for representing GI in both distributed and lumped models. Although distributed models represent a more accurate physical representation of watersheds, it was found that both distributed and lumped models produced similar results in terms of predicting stormwater runoff peak flow and volume.

Looking at common methodologies used to represent GI in distributed models outside of using SWMM's LID controls, creating separate pervious subcatchments to represent the GI was the most common method. Limited new information regarding the use of SWMM's LID Controls was obtained from the literature review. In papers that did discuss LID controls, there were typically no descriptions of how the LID control properties were calibrated, nor of how the model performance compared with field-based observations. Rather, the focus of the distributed post-GI modeling papers was the potential benefits of GI over pre-GI baseline conditions [133,425,509], with the exception of one paper that attempted to calibrate a small scale post-GI model to the results of a laboratory test [407]. No attempts to calibrate or validate the LID control performance to observed post-construction monitoring data at the facility or watershed scale were found in the literature.

On the other hand, the literature review was more helpful in providing information on how GI has been modeled in lumped models. This included information on how lumped models have been constructed, and how GI practices are represented in them. The most common method used to represent GI lumped models, involves using a storage node with infiltration and a bypass weir, similar to the method used by DEP in the existing InfoWorks models as part of the long term combined sewer overflow control planning for various waterbodies in New York City, documented in a separate memorandum.

Finally, there is limited literature available comparing modeling predictions to documented performance with multiple papers recognizing the limited availability of field measurement comparisons as a gap in determining GI modeling performance. Given the limited availability of GI monitoring data and the lack of monitoring multiple GI within entire watersheds, it is not surprising that representing GI in lumped models rather than distributed models is currently a more common practice.

ITEM #	PAPER	SOURCE	YEAR	MODELING METHODOLOGY	WATERSHED SCALE	SITE SCALE	SWMM LID CONTROLS	SWMM OTHER LID	HEC-HMS	MODELING CALIBRATION	MODELING VALIDATION	FORTRAN / HSPF	COSTING	WATER QUALITY	Mike SHE	HydroCAD	STORM	SUSTAIN	InfoWorks	MIKE URBAN	MOUSE
1	Development of LID Design System for Waterfront Cities	LID	2015					X													
2	Use of Multi-Objective Evolutionary Algorithm Optimization for Low Impact Development Placement	LID	2015	X				X													
3	Application of SWMM in Evaluating the Reduction Performance of Urban Runoff Treatment Systems with Varying Land use	LID	2015					X		X	X			X							
4	Active Hydromodification Control	LID	2015	X				X													
5	Application of the SUSTAIN model to a watershed-scale case for water quality management	LID	2015		X					X	X							X			
6	Continuous Distributed Modeling of LID/GI: Scaling from Site to Watershed	LID	2015		X	X															
7	Comparative Evaluation of Different Types of Permeable Pavement for Stormwater Reduction - St. Louis Green Alley Pilot Study	LID	2015			X															
8	Retrofitting Stormwater Systems with Low-Impact Development Techniques	LID	2015						X												
9	Beyond Green LID Zero Runoff Strategies for Our Cities	LID	2015																		
10	Modeling to Quantify the Benefits of LID for CSO Reduction	LID	2011	X			X														
11	Estimating Annual Runoff Based on the NRCS Runoff Curve Number	LID	2011	X																	
12	A Saturated Seepage Flow Model for Low Impact Development Devices	LID	2011	X																	
13	Hydrogeologic Testing, Engineering, and Start-up of a Gravity Drain System	LID	2011																		
14	A Green Street Retrofit in a Chesapeake Bay Community Using Bioswales	LID	2011										X								
15	Ballard Roadside Raingardens, Phase 1 - Lessons Learned	LID	2011			X		X													
16	The BMP That Keeps on Giving: Quantifying the Impact of Native Plants on Soil Water Properties	LID	2011																		
17	Bioretention Performance Findings from the International Stormwater BMP Database	LID	2011											X							
18	Impacts of Soil Texture, Structure, and Compaction on Bioinfiltration Device Performance: Results of Lab and Field Investigations	LID	2011								X										
19	Nutrient Retention Performance of Advanced Bioretention Systems Results from Three Years of Mesocosm Studies	LID	2011											X							
20	Green Infrastructure for CSO Control in Kansas City, Missouri	LID	2010															X			
21	A Simplified Sizing Tool for LID Practices in Western Washington	LID	2010	X																	
22	An Innovative Decision Support System for Quantifying and Optimizing Benefits of Decentralized BMPs for Los Angeles County	LID	2010									X	X								
23	Brickyard Park and Ride Case Study: Pervious Asphalt and Integrated Site Stormwater Design	LID	2010			X															
24	Pervious Asphalt Roads and Parking Lots: Stormwater Design Considerations	LID	2010			X															
25	A Non-dimensional Modeling Approach for Evaluation of Low Impact Development from Water Quality to Flood Control	LID	2010					X			X										
26	Integrated Stormwater Facility Design to Address Hydromodification on a College Campus, Livermore, California	LID	2010			X															
27	Pervious Concrete Testing Methods	LID	2010																		
28	The Urban Green BioFilter, An Innovative Tree Box Application	LID	2010																		
29	Roadside Stormwater master Plan using Low Impact Development (LID)	LID	2010																		
30	Web-based Low Impact Development Decision Support Tool for Watershed Planning	LID	2010	X																	
31	Normalized Runoff Capture Volumes for Low Impact Designs	LID	2010																		
32	Curve Numbers and Urban Runoff Modeling - Application Limitations	LID	2010	X				X	X												
33	Use of stormwater capture curve for sizing storage-based LID facilities in Korea	LID	2010																		
34	Modeling Bioretention Hydrology with DRAINMOD	LID	2010							X											
35	Effectiveness Site Design and Low-Impact Development on Stormwater Runoff Patters at Partridgeberry Place LID Subdivision	LID	2010	X			X														
36	Comparison of BMP Infiltration Simulation Methods	LID	2010																		
37	Why Single-Event Modeling Doesn't Work for LIDs	LID	2010	X																	
38	Moving Beyond the Percent Removal Paradigm: Using Lower Limit Effluent Concentrations in Design Guidance and Evaluation	LID	2010											X							
39	Green Street Retrofits in the Northeast: Design and Acceptance Challenges for Stormwater Management Retrofits	LID	2010			X															
40	Ultra Urban Green Street Design Criteria	LID	2010																		
41	Development and Application of Modular LID Site Planning Tool	LID	2010										X								
42	Modeling Impervious Area Disconnection with SWMM	LID	2010			X		X													
43	Control Effects Comparison of Three Kinds of Typical LID: Infiltration and Emission Reduction Measures: Beijing Case Study	LID	2010			X															
44	Alternative Site-Assessment Hydrologic Metrics for Urban Development	LID	2010	X				X													
45	Alternative Futures: Economic and Water Resource Analysis of Traditional vs. Low Impact Redevelopment	LID	2010										X	X							
46	On the Physics of Low Impact Development - Pervious Pavement	LID	2010																		
47	Examinations of Pervious Concrete and Porous Asphalt Pavements Performance for Stormwater Management in Northern Climates	LID	2010																		
48	Seattle's Implementation of Green Stormwater Infrastructure to the Maximum Extent Feasible	LID	2010																		
49	Modular Wetland System: A History of Wetland Treatment and Case Study of an Advanced Subsurface Flow Wetland to Treat Stormwater and Continuous Nusiance Flows	LID	2010																		
50	Using the Hydrologic Footprint Residence to Evaluate Low Impact Development in Urban Areas	LID	2010					X	X		X										
51	Lakewood RainCatchers Pilot Project for Reducing Combined Sewer Overflows	LID	2010	X							X			X					X		
52	Green Infrastructure Optimization Analyses for Combined Sewer Overflow (CSO) Control	LID	2010				X														
53	Structural/Hydrologic Design and Maintenance of Permeable Interlocking Concrete Pavement	LID	2010																		
54	Lateral Seepage Flow between Low Impact Development Drainage Devices and the Underground Water Level	LID	2010																		
55	Moving Green Stormwater Infrastructure into Seattle's CSO Control Program	LID	2010										X								
56	Integrated Modeling of Green Infrastructure Components in an Area Served by Combined Sewers	LID	2010	X				X													

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57	From Art to Infrastructure: Designing Flow Control for Efficient LIDs	LID	2010			X										X					
58	An Approach to Analyze the Hydrologic Effect of Rain Gardens	LID	2008	X						X					X						
59	Design and Modeling of Bioretention for Hydromodification Control: An Assessment of Alternative Model Representations	LID	2008	X																	
60	Design of Integrated Bioretention-Infiltration Systems for Urban Retrofits	LID	2008	X												X					
61	Green Streets - An Opportunity to Transform Our Roads	LID	2008	X													X				
62	Subsurface Wetland Systems for On-site Wastewater Treatment and Reuse	LID	2008											X							
63	Case Study: Low Impact Development Retrofit at Pillar Point Air Force Station	LID	2008								X						X				
64	Mimicking Predevelopment Hydrology Using LID: Time for a Reality Check?	LID	2008																		
65	Transforming Gray to Green in the Right-of-Way: Blurring the Lines… Softening the Edges	LID	2008																		
66	Continuous Simulation of Integrated Bioretention-Infiltration Systems for Urban Retrofits	LID	2008					X								X					
67	Continuous Hydrology with Subbasin Specificity and LID: The Flow Duration Design Model	LID	2008	X								X									
68	Determining Cost Effective Pollution Reduction BMP Scenarios for Low Impact Redevelopment and a Watershed Plan using WinSLAMM	LID	2008										X								
69	Development and Calibration of a High Resolution SWMM Model for Simulating the Effects of LID Retrofits on the outflow hydrograph of a dense urban watershed	LID	2008	X				X													
70	LID Analysis Considerations in Western Washington	LID	2008			X						X									
71	Stochastic Analysis of the Effectiveness of BMP Implementation in a Watershed	LID	2008	X																	
72	LID Design for a Residential Lot in the Truckee River Watershed, CA	LID	2008																		
73	Innovative Stormwater Management in Canada	LID	2008																		
74	Design and Hydologic Estimation Method of Multi-purpose Rain Garden: Beijing Case Study	LID	2008	X		X															
75	The Road to LID Plan Approval in Coastal North Carolina: Development of a Spreadsheed Modeling Tool for LID Based Designs	LID	2008																		
76	A Simplified Approach for Sizing Green Stormwater Infrastructure in the City of Seattle	LID	2008	X								X									
77	Enhancement of the Green Build-out Model to Quantify Stormwater Reduction Benefites in Washington, DC	LID	2008	X																X	
78	A Practical Methodology to Evaluate Hydromodification Performance of Conventional and Low Impact Stormwater Controls	LID	2008						X												
79	Stormwater Concepts - No Adverse Impact	LID	2008																		
80	Integrated Water Management Demonstration Project for Low Impact Development Urban Retrofit and Decentralized Wastewater Treatment Systems in the Upper Patuxent River Watershed, Prince George's County Maryland	LID	2008										X								
81	Estimation of Evapotranspiration and Groundwater Recharge from Bioretention Areas Using Weighing Lysimeters	LID	2008								X										
82	Design, Engineering, Installation, and O&M Considerations for Incorporating Stormwater Low Impact Development (LID) Practices in Urban, Suburban, Rural, and Brownfield Sites	LID	2008			X							X								
83	Advance Drainage Concepts Using Green Solutions for CSO Control - The KC Approach	LID	2008	X				X		X											
84	Greening Stormwater Infrastructure: Integrating Low-Impact Development with Traditional Methods in Washington State	LID	2008									X									
85	Risk Analysis Application for Assessing the Cost-effectivement of Low Impact Development for CSO Control using LIDRA	LID	2008	X									X								
86	Green Infrastructure Approaches to Control of Combined Sewer Overflows	LID	2008	X				X													
87	Portland's Green Streets: Lessons Learned Retrofitting our Urban Watersheds	LID	2008																		
88	Modeling Bioretention Basins to Meet Water Quality Drawdown Requirements	LID	2007	X										X							
89	Rethinking Bioretention Design Concepts	LID	2007																		
90	Effectiveness of Time of Concentration Elongation on Peak Flow Reduction	LID	2007																		
91	Modeling a BioInfiltration Best Management Practice	LID	2007			X			X												
92	Evaluation and Verification of a Vadose Zone Model Applied to Stormwater Infiltration	LID	2007																		
93	LATIS: A Spatial Decision Support System to Assess Low Impact Site Development Strategies	LID	2007										X								
94	The Integration of Low Impact Development and Conservation Design: The New Castle County, Delaware, Experience	LID	2007	X																	
95	LID on the SC Coastal Plain: Benefits, Costs, and Constraints	LID	2007										X	X							
96	Practical Considerations of Pervious Pavement Design and Construction in Piedmont Soils Friday Center Park and Ride Lot	LID	2007																		
97	Evaluation of Various Types of Permeable Pavements with Respect to Water Quality Improvement and Flood Control	LID	2007							X				X							
98	Automated Geospatial Watershed Assessment Tool (AGWA)	WRC	2015		X																
99	TMDL Modeling Approaches, Model Surveys, and Advances	WRC	2015	X										X							
100	Clogging Progression Prediction of Permeable Pavement Laboratory Model Using Artificial Neural Networks	WRC	2015																		
101	Evaluation of Green Infrastructure Designs Using the Automated Geospatial Watershed Assessment Tool	WRC	2015			X															
102	Using a Two-dimensional Watershed Model to Estimate Flood Magnitude and Frequency under Changing Climate	WRC	2015		X																
103	Quantifying Benefits of Green Stormwater Infrastructure in Philadelphia	WRC	2015				X						X								
104	Physical-Economic Approach for Urban Stormwater Management: Applications in the City of Los Angeles, California	WRC	2015		X								X								
105	Neural Networks Models for Captured Runoff Prediction of Permeable Interlocking Concrete Pavements	WRC	2015																		
106	Low Impact Development Placement Investigation using a Multi-Objective Evolutionary Optimization Algorithm	WRC	2015				X														
107	Hydrologic Response of Sustainable Urban Drainage to Different Climate Scenarios	WRC	2015					X													
108	Green Infrastructure Prioritization for Blacksnake Creek Stormwater Separation	WRC	2015					X					X								
109	Estimating swale performance in volume reduction	WRC	2015			X															
110	Combined 1D and 2D Hydraulic Modeling within HEC-RAS	WRC	2015																		

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111	Comparative Effectiveness and Reliability of NEXRAD Data to Predict Outlet Hydrographs Using the GSSHA and HEC-HMS Hydrologic Models	WRC	2015						X												
112	Gridded Surface Subsurface Hydrologic Analysis Modeling for Analysis of Flood Design Features at the Picayune Strand Restoration Project	WRC	2015		X					X											
113	Sanitary Sewer Overflow Reduction Optimization Using Genetic Algorithm	WRC	2015					X		X											
114	Towards Sustainable Urban Stormwater Infrastructure: Improving the Estimation of Effective Impervious Area	WRC	2015																		
115	1D/2D Modeling of Decentralized Stormwater Control Measures for Flood Mitigation in Austin, Texas	WRC	2015				X														
116	Alternative Treatment of Flow Monitoring Data to Evaluate the Impact of Green Infrastructure on Stormwater Volume Reduction in Combined Sewers	WRC	2015								X										
117	TMDL Model Applications and Recommendations for Model Selection	WRC	2015											X							
118	Relating DEM spatial resolution and hyetograph temporal resolution to flood modeling accuracy	WRC	2015																		
119	Extended Detention Stormwater Basins Outlet Structure Flows - Physical Model Study	WRC	2015																		
120	Changing the Paradigm: Stormwater Management for the Greater New Orleans Area	WRC	2014					X													
121	Estimating Time of Concentration of Overland Flow on Impervious Surface using Particle Tracking Model	WRC	2014																		
122	Evaluation of Retrofitted Green Infrastructure Stormwater Controls in Urban Areas Served by Combined and Separate Sewer Systems in Cincinnati, OH	WRC	2014			X								X							
123	Determining Infiltration Loss of a Grassed Swale	WRC	2014			X															
124	Modeling Hydrologic Performance of Permeable Pavement with DRAINMOD in North Carolina and Ohio	WRC	2014																		
125	Performance of Pervious Concrete on Runoff Reduction in Grand Forks, ND	WRC	2014				X				X										
126	Integrating Hydrologic and Water Quality Variability into Land Use Based Stormwater Load Modeling	WRC	2014					X						X							
127	Estimating Effective Permeable Areas in Consolidated Urban Watersheds Based on Satellite Image Analysis and Field Survey	WRC	2014																		
128	Incorporating climate variability in a nonparametric modeling framework for improving hydrologic predictions	WRC	2014																		
129	Coastal Floodplain Mapping and Evaluation Using GIS and HEC-GeoRAS Models	WRC	2014																		
130	Integration of Coastal Storm Inundation Model (GSSHA) with Grid Surface and Subsurface Hydrological Model	WRC	2014																		
131	Climate Change Impacts on Urban Runoff in a New York City watershed	WRC	2014				X														
132	LID Implementation to Mitigate Climate Change Impacts on Urban Runoff	WRC	2014				X														
133	Real-time analysis of moisture and flow data to describe wet weather response in a permeable pavement parking lot	WRC	2014								X										
134	Benchmark exercise for comparing computational performance of two-dimensional flood models in CPU, Multi-CPU and GPU frameworks	WRC	2014	X																	
135	Implications of SRTM- and ASTER-based DEMs on Hydrologic Responses at Various Catchment Scales	WRC	2014		X				X												
136	Columbia River Treaty 2014/2024 Integrating Numerical Models, HEC-WAT Plug-in Technology	WRC	2014	X					X												
137	Columbia River Treaty 2014/2024 HEC-WAT Innovations for CRT Computes	WRC	2014	X																	
138	Columbia River Treaty 2014/2024 Distributed Computing for HEC-WAT/FRA	WRC	2014	X																	
139	Columbia River Treaty 2014/2024 Monte Carlo Simulation in HEC-WAT	WRC	2014	X																	
140	Columbia River Treaty 2014/2024 HEC-WAT and the FRA Compute Option	WRC	2014	X					X												
141	Estimating Time of Concentration on Low-Slope Planes using Diffusion Hydrodynamic Model	WRC	2012								X										
142	A Review of Impact of ET on Green Infrastructure and Urban Runoff	WRC	2012					X													
143	Analysis of the Contribution of Linear Parks in Urban Flood Control	WRC	2012		X			X													
144	Application of the Integrated Urban Water Model to Evaluate Most Appropriate Water Conservation Practices under Varying Hydrologic Conditions	WRC	2012										X								
145	Calibration of Runoff Curve Numbers for a Small Urban Watershed	WRC	2012						X	X											
146	Decentralization of LID (i.e. Municipal Rainwater Harvesting Program) for Reducing Stormwater Runoff	WRC	2012					X													
147	Effects of Initial Abstraction Ratio in SCS-CN Method on Modeling the Impacts of Urbanization on Peak Flows	WRC	2012		X				X		X										
148	High Resolution Urban Hydrologic Modeling	WRC	2012	X				X													
149	Linking Stormwater BMP Systems Water Quality and Quantity Performance to Whole Life Cycle Cost to Improve BMP Selection and Design	WRC	2012					X					X	X							
150	A Tool and Dataset for Place-based Impervious Surface Estimation: Applications for Land Use and Water Resources Planning	WRC	2012	X																	
151	Application of USEPA SSOAP Software to Sewer System Modeling	WRC	2012					X		X											
152	2-D Fine Grid Hydrodynamic Modeling For More Accurate Floodplain Mapping in Southern California	WRC	2012	X																	
153	Prioritization of Green Infrastructure for CSO Communities - Identifying Effective Implementation Opportunities	WRC	2012	X									X								
154	Seeing Green by Going Green: Maximizing Ecosystem/Community Services Benefits through Strategic Green Storm-Water Infrastructure Design	WRC	2012				X						X								
155	Uncertainty Analysis and Calibration of SWMM Using a Formal, Bayesian Methodology	WRC	2012					X		X											
156	BMP Performance Algorithms for the BMP Selection/Receiving Water Protection Toolbox	WRC	2012											X							
157	Evaluation of the Infiltration Capacity of a Permeable Paving Block for Urban Flood Disaster Reduction	WRC	2012								X										
158	How Buoyant Flow Control Devices Can Reduce Pond Size Requirements	WRC	2012								X										
159	Regional Stormwater Quality Model Calibration using the National Stormwater Quality Database	WRC	2012							X				X							
160	A Formal, Bayesian Approach for Uncertainty Analysis of a Watershed Model	WRC	2012							X											
161	Mastering Stormwater Management: A Decade of Growth	WRC	2010	X				X													
162	Modeling the Effectiveness of Maryland's Environmental Site Design Criteria	WRC	2010			X								X							

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163	Applications of Artificial Neural Networks in Urban Water System	WRC	2010								X			X							
164	Automation Innovations in Stormwater Modeling Case Study: City of Ramsey, Minnesota Surface Water Management Plan	WRC	2010					X													
165	Effect of Detention Basin Release Rates on Flood Flows: Application of a Hydrological Simulation Program-FORTRAN model to an Urbanizing Watershed	WRC	2010	X								X									
166	Integrated Modeling of Green Infrastructure Components in an Area Served by Combined Sewers	WRC	2010											X							
167	A hydraulic modeling framework for producing urban flooding maps in Zanesville, Ohio	WRC	2010	X																	
168	Municipal Stormwater Permit Compliance in Wisconsin: Calculating Pollutant Loads and Selecting Best Management Practices Across Multiple Watersheds Simultaneously	WRC	2010											X							
169	The challenges of mitigating hydrologic impacts of development: lessons learned in Dane County, Wisconsin	WRC	2010																		
170	Water-Sensitive Urban Design: An Integral Piece of Ecological Sustainable Development	WRC	2010																		
171	Modeling Best Management Practices (BMPs) with HSPF	WRC	2010	X								X									
172	The AGWA - KINEROS2 Suite of Modeling Tools	WRC	2010	X	X																
173	Modeling the Impacts of Hydromodification	WRC	2010									X									
174	Sampling Schemes for Uncertainty Assessment of a Hydrologic Simulation Model	WRC	2010						X	X											
175	Design Flood Estimation Using Monte Carlo Simulation and RORB Model: Stochastic Nature of RORB Model Parameters	WRC	2010	X																	
176	Unit Process Simulation of a BioInfiltration Stormwater Control Measure	WRC	2010			X															
177	A Randomized Process for Modeling Constructed Wetlands with an Optimization Example	WRC	2010						X												
178	Finding Flooding Solutions Using Interfacing Tools to Aid in Model Calibration and Public Collaboration	WRC	2010						X	X											
179	Flooding Impacts and Modeling Challenges of Tropical Storms in Eastern Yemen	WRC	2010						X												
180	Comparison of Model Evaluation Methods to Develop a Comprehensive Watershed Simulation Model	WRC	2010																		
181	Developments in LIDRA 2.0: a planning level assessment of the cost-effectiveness of Low Impact Development	WRC	2010			X							X								
182	Current Capabilities and Planned Enhancements of SUSTAIN	WRC	2010	X														X			
183	Development of a Rainfall Statistical Analysis Tool for Analytical Probabilistic Models for Urban Stormwater management Analysis	WRC	2010																		
184	Regenerative Stormwater Conveyance: An Innovative Approach to Meet a Range of Stormwater Management and Ecological Goals	WRC	2010			X										X					
185	The Potential for Green Infrastructure Practices to Reduce Combined Sewer Overflows as Examined in Nashville, Tennessee	WRC	2010				X				X										
186	Urban runoff and stormwater quality management using the Los Angeles County Flood Control District's Watershed Management Modeling System: A pilot application	WRC	2010			X								X							
187	Incorporating Storm Sewer Exfiltration into SWMM: Proof of Concept	WRC	2010					X													
188	Regional Flood Modelling: Use of Monte Carlo Cross-Validation for the Best Model Selection	WRC	2010								X										
189	Real Time Savings: Using High Density Real Time Monitoring and Control to Optimize South Bend, IN's CSO System	WRC	2010																		
190	Large Interceptor Capacity Analysis Using a Dynamic Hydraulic Model	WRC	2010							X									X		
191	Integrating Green Infrastructure into a Combined Sewer Service Area Model	WRC	2010					X													
192	Optimizing the Placement of Low Impact Development in an Urban Watershed	WRC	2010					X	X												
193	Watershed-based Optimal Stormwater Management: Part 1 - Application of StormWISE to Little Crum Creek in Suburban Philadelphia	WRC	2010															X			
194	Watershed-based Optimal Stormwater Management: Part 2 - Hydrologic Modeling of LID/BMP Sites on Little Crum Creek in Suburban Philadelphia	WRC	2010		X			X		X											
195	An Innovative Approach for Modeling Large Urban Hydrologic Systems	WRC	2009	X																	
196	Design of Integrated Bioinfiltration-Detention Urban Retrofits with Continuous Simulation Methods	WRC	2009					X			X										
197	Developing A Water Budget For A Constructed Stormwater Wetland	WRC	2009			X									X						
198	Evaluation and Optimization of Distributed Stormwater Controls in Spreadsheet	WRC	2009			X															
199	Watershed Models for Storm Water Management: Comparing Hydrologic and Hydraulic Procedures	WRC	2009	X																	
200	Design and Implementation of Optimized Hydrologic Unit Watersheds for Rainfall-Runoff Modeling	WRC	2009		X			X		X											
201	Assessment of the Capability of Hydrologic and Artificial Neural Network Models for Flood Warning System in Land use Change Condition	WRC	2009		X				X												
202	From Grey to Green: Strategies and Concepts for Implementing Green CSO and Wet Weather Solutions	WRC	2009	X			X														
203	HCFCD M3 System Maximizing and Maintaining Local Investments in Floodplain Modeling	WRC	2009						X												
204	Hydrologic Footprint Residence: A New Metric to Assess Hydrological Alterations Due to Urbanization	WRC	2009					X	X												
205	Improving Hydrologic Sustainability of Texas A&M University Campus	WRC	2009					X	X												
206	Kansas City Balancing Green Infrastructure with Traditional Approaches for CSO Control	WRC	2009					X													
207	Urban Stormwater Management in 2050	WRC	2009	X				X													
208	New Floodplain Delineation Capabilities in HEC-RAS	WRC	2009	X																	
209	Modeling Techniques to Incorporate Low Impact Development Features into Detention Analyses	WRC	2009	X				X	X			X				X					
210	Sensitivity Analysis of HEC-HMS Hydrologic Model to the Number of Sub-basins: Case Study	WRC	2009	X	X				X												
211	Developing Green Streets Prototypes to Reduced Combined Sewer Overflows for Cincinnati, Ohio	WRC	2009										X								
212	A Robust and Fast Model for Simulating Street Flooding	WRC	2009	X																	
213	Unit Process Modeling of Stormwater Flow and Pollutant Sorption in a Bioretention Cell	WRC	2009											X							
214	Use of the Basin Development Factor to Evaluate Urban Watershed Response	WRC	2009		X																
215	Development of watershed management modeling system: the Los Angeles County Flood Control District's watershed based approach for urban runoff and storm quality	WRC	2009	X	X																

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216	Redesigning Constructed Stormwater Wetlands: an integrated modeling approach to optimize form and function	WRC	2009			X															
217	State of the Practice of Wet Weather Flow Analysis	WRC	2009					X		X											
218	Integrated Water Resources Analysis Using the Watershed Analysis Tool (HEC-WAT)	WRC	2007	X					X												
219	A North Caronlina Piedmont Application of Protocols for Studying Wet Weather Impacts and Urbanization Patterns	WRC	2007				X			X											
220	Effect of Raingage Density on Runoff Simulation Modeling	WRC	2007					X			X										
221	Evaluation of the Impact of Stormwater Best Management Practices on a Sub-watershed and Watershed Using XPSWMM	WRC	2007		X		X														
222	Gravel Wetland Design and Performance for Stormwater Management	WRC	2007			X								X							
223	Re-conceiving the Villanova University Constructed Stormwater Wetland	WRC	2007			X			X		X										
224	An Infiltration Model of an Underground Rock Storage Bed Infiltration BMP	WRC	2007								X										
225	Vadose Zone Modeling Applied to Stormwater Infiltration	WRC	2007								X			X							
226	Critical Issues in the Representation of BMPs in Urban Drainage Models	WRC	2007	X			X									X			X		
227	The Use of a Decentralized Wireless Sensor Network for CSO Abatement and Control	WRC	2007																		
228	Morphologic Approach in Studying Urbanized and Suburbanizing Watersheds	WRC	2007																		
229	Stormwater Runoff Control Using Full Spectrum Detention	WRC	2007					X													
230	Two-Dimensional Hydrodynamic and Sediment Transport Modeling of the Lower Willamette River, Oregon	WRC	2007																		
231	Effect of Radar-Rainfall Errors on Rainfall-Runoff Modeling	WRC	2007																		
232	The Use of HydroWAMIT and WASP for Modeling Large Scale Watersheds in New Jersey	WRC	2007							X		X		X							
233	Performannce Study of Parallel Algorithms in pWASH123D	WRC	2007		X																
234	GIS-Based 1-d Diffusive Wave Overland Flow Model	WRC	2007																		
235	NEXRAD Flood Warning System and Floodplain Library For Houston, TX	WRC	2007																		
236	Frequency Analysis by Bootstrap, SIR Algorithm, and Parametric Method	WRC	2007						X												
237	Developing Tools and a Graphical User Interface For the Regional Simulation Model	WRC	2007	X																	
238	Rainfall Input for Master Urban Drainage Planning: the Integrated Catchment Study of Auckland City (New Zealand)	WRC	2007												X				X		X
239	A Filter Approach to Turning a City Greener One BMP at a Time	WRC	2007			X							X								
240	Low Impact Development: A Better Approach for Water Resources in the Tampa Area	WRC	2007										X								
241	Spatial Discretization of Large Urban Watersheds	WRC	2007		X			X		X											
242	Disaggregated Modeling for Urban Hydrologic Controls	WRC	2007			X	X														
243	Comparison of Flow and Sediment Modeling Using SWAT and HSPF for Watersheds in the Illinois River Basin	WRC	2007		X							X									
244	Comparison of linear and non-linear optimization models for storm water and non-point source pollution best management practice decision support	WRC	2007	X																	
245	Water Resources Management: Optimizing within a Watershed Context	WRC	2007																		
246	Calibrating a Watershed Simulation Model Involving Human Interference-An Application of Multi-objective Genetic Algorithms	WRC	2007							X											
247	Plug-and-Play Integration of Watersheds in the Regional Simulation Model Part I: Interoperability of Lumped Basin and Discretized Mesh Components	WRC	2007																		
248	Multipurpose Detention Pond Design for Improved Watershed Management	WRC	2007					X					X								
249	Water Balance and Flood Control by the Expansion of the Upo Wetland in Korea	WRC	2007																		
250	City of Seattle - Stormwater Low Impact Development Practices	WRC	2006			X															
251	Advancing Sustainable Stormwater Management at Villanova University	WRC	2006			X															
252	The SPAW Model: Application to Infiltrating BMP Facilities	WRC	2006																		
253	BMP Decision Support System for Evaluating Watershed-based Stormwater Management Alternatives	WRC	2006					X													X
254	Using Long-Term Simulation for Improving a Sewer System Overflow Control Strategy	WRC	2006																		
255	Effects of Catchment Modification on the Flow Frequency Curve Modeled Using the EPA-SWMM Model	WRC	2006					X													
256	Quantifying Urban-induced Flow Regime Alternation and Evaluating Mitigation Alternatives Using Mathematical Models and Hydrologic Metrics	WRC	2006				X														
257	Improvement of the EXTRAN block in Storm Water Management Model (SWMM4.4h)	WRC	2006					X				X									
258	Simulation of Infiltration and Surface Runoff - A Windows-Based Hydrologic Modeling System HYDROL-INF	WRC	2006	X																	
259	An Integrated Approach to Water Quality Assessment in Support of a Long-Term Control Plan	WRC	2006					X						X							
260	Optimized Vegetation Buffer Strips Design for Integrated Management of Goodwin Creek Watershed in Mississippi	WRC	2006																		
261	Developing a Comparative Tool for both Conventional and Green Stormwater Management Techniques	WRC	2006			X															
262	Application of multi-criteria tool in MIKE SHE model development and testing	WRC	2006								X				X						
263	Development of Fuzzy Rules Based System for Rainfall-Runoff Modeling	WRC	2006		X			X													
264	Use of EPA SWMM5 for Generation of BMP Effluent EMC Distribution	WRC	2006			X	X							X							
265	Key Technologies for Urban Flood Mitigation	WRC	2006	X																	
266	Investigating Urban Land Use Effects on Runoff by Using the Distributed Large Basin Runoff Model	WRC	2006		X					X											
267	Stochastic GIS-Based Water Resources/Quality Modeling of the Land Water Interface	WRC	2006																		
268	Flood Hazard Analysis and Protection Plan for a Residential Development	WRC	2006																		
269	A Storm Runoff Simulator to Evaluate Grass Filter Strips and Other Storm Water Management System	WRC	2006						X												
270	Using Genetic Algorithms and Particle Swarm Optimization for Optimal Design and Calibration of Large and Complex Urban Stormwater Management Models	WRC	2006					X		X											
271	Numerical Modeling of Culvert Hydraulics: Modernization of Existing HY8 Software	WRC	2006																		
272	An Innovative Geocentric Decision Support Soluntion to Comprehensive Planning, Design, Operation, and Management of Urban Drainage Systems	WRC	2006					X		X											
273	NRCS Geo-Hydro - ArcView GIS Interface to WinTR-20	WRC	2005																		

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274	Methodology for Calculating Water Quantity and Quality Changes in CITYgreen Software	WRC	2005											X							
275	Calculating the Value of Nature with CITYgreen Software	WRC	2005											X							
276	Using CITYgreen and High Resolution Multi-Spectral Imagery to Analyze the Urban Ecosystem	WRC	2005											X							
277	HSPF-Based WWHM: A Tool for Stormwater Design Using Flow Duration Criteria	WRC	2005	X								X									
278	Practical issues in hydrologic modeling for flood management of watercourses running through urban environments in Greece	WRC	2005						X												
279	Innovative Modeling Techniques for Watershed Planning	WRC	2005					X	X												
280	Cost-Effective TMDL Implementation Planning and Hydrology as a Critical Decision-Aiding Tool	WRC	2005					X													
281	A Model Framework to Support Integrated Watershed Planning	WRC	2005				X														
282	Rainfall-Runoff in the Albuquerque, New Mexico Area: Measurements, Analyses and Comparisons	WRC	2005																		
283	Impact of Urbanization in Watersheds on Stream Stability and Flooding	WRC	2005																		
284	Tookany/Tacony-Frankford Watershed Plan: Restoring and Urban Stream	WRC	2005				X														
285	Multistage Hierarchical Optimization for Land Use Allocation to Control Nonpoint Source Water Pollution	WRC	2005	X										X							
286	A Milwaukee Model for LID Hydrologic Analysis	WRC	2005	X																	
287	Measurement and Modeling of Hydrologic Response in a Southern New Jersey Watershed	WRC	2005		X																
288	Regional Stormwater Management Planning in Southern New Jersey	WRC	2005																		
289	Normalized technology verification of structural BMPs, Low Impact Development (LID) designs, and manufactured BMPs	WRC	2005																		
290	GIS Interface for GWLF Watershed Model	WRC	2005		X									X							
291	Design and Implementation of a Water Quality Field Monitoring Program in Support of CSO Long Term Control Planning	WRC	2005											X							
292	Integrated Stormwater Management Planning: Diverse Interests Unite Behind LID Approaches at Celebrate Virginia North	WRC	2005																		
293	Using GIS for Stormwater Management and Responsible Land Use Planning	WRC	2005																		
294	GIS-Based Watershed Modeling	WRC	2005		X				X												
295	Optimal Number and Location of BMPs for Stormwater Management	WRC	2005	X																	
296	Urban Catchment Management	WRC	2005		X							X									
297	Implementing Cost Effective Green Infrastructure for CSO Control in Omaha	WEFTEC	2014																		
298	The State of the Science and Practice of Using Urban Trees as a Stormwater Control Measure	WEFTEC	2014																		
299	Conversion of the Hydrological Simulation Program, FORTRAN, to Hydrological Simulation Program, PYTHON	WEFTEC	2014		X							X									
300	A Change in Combined Sewer Overflow Strategy is Precipitated by Stormwater Policies and Watershed-Based Modeling	WEFTEC	2014										X	X							
301	I Love That Dirty Water - Modeling Water Quality in the Boston Drainage System	WEFTEC	2013	X				X						X							
302	Integrated Catchment Modeling	WEFTEC	2013																		
303	Taking NYC's LTCP Modeling to the Next Level: A Unique Approach to Recalibrating 13 InfoWorks Sewer System Models	WEFTEC	2013			X													X		
304	An Optimization Planning Framework for Cost-effective Wet-Weather Planning A Case Study From Evansville, Indiana	WEFTEC	2013					X													
305	Green Infrastructure for the Central Corridor Light Rail Transit Project	WEFTEC	2013																		
306	A Toolbox for Integrated Watershed Planning at Sanitation District No. 1 of Northern Kentucky: Management and Decision-Making Tools	WEFTEC	2013								X	X		X							
307	Evaluating and Implementing Seattle's Green Stormwater Infrastructure Approaches at a Creek Watershed Scale	WEFTEC	2013	X	X		X														
308	Green Infrastructure Opportunities in Gray Wet Weather Plans	WEFTEC	2013				X														
309	A Tale of Three Cities in 2D	WEFTEC	2012					X													
310	Advanced 2-D Modeling for Flood Reduction Studies and Storm Drain Master Planning	WEFTEC	2012	X											X					X	
311	Application of the Integrated Urban Water Model to Evaluate Impacts of Hydrology on Efficacy of Water Conservation Practices	WEFTEC	2012																		
312	Water Quality Assessment and Quantification Model for Sustainable Watershed Management of Flood Channels	WEFTEC	2012											X							
313	Urban Stormwater BMP Performance and Cost-Effectiveness	WEFTEC	2012								X		X								
314	Integrating Stormwater Runoff Quantity and Quality Requirements in a Coastal County	WEFTEC	2012			X	X														
315	Stormwater Reuse Opportunities and Effects on Urban Infrastrucutre Manangement; Review of Practices and Proposal of WinSLAMM Modeling	WEFTEC	2012																		
316	Reducing Pollutant Loads from Philadelphia's Combined Sewer System with Green Stormwater Infrastructure	WEFTEC	2012					X						X							
317	Optimizing Green Infrastructure Techniques to Reduce CSO Volume in Seattle	WEFTEC	2012			X	X														
318	Planning & Prioritizing Green Infrastructure to Achieve Detroit's Goals for Volume Reduction while Reshaping the City	WEFTEC	2012																		
319	Going for Green: Quantifying the Benefits of Green Infrastructure for CSO Reduction in Milwaukee	WEFTEC	2011								X	X						X			
320	Ecological and Best Management Practices Planning to Address Combined Sewer Overflows in New York City	WEFTEC	2011			X															
321	Utilizing GIS, HEC-GeoHMS, HEC-GeoRAS, and ArcHydro Interfacing Tools	WEFTEC	2011						X												
322	How to Grow Large Trees in Urban Areas to Reduce CSO Problems: Rethinking Street Trees as Urban Infrastructure	WEFTEC	2011										X								
323	Use of Green Infrastructure Integrated with Conventional Gray Infrastructure for Combined Sewer Overflow Control: Kansas City, MO	WEFTEC	2011					X										X			
324	Measuring the Benefits of Total Water Management Using a Systems Modeling Approach	WEFTEC	2011																		
325	Evaluating Implementation of LID/BMP in Storm Water System using EPA SUSTAIN	WEFTEC	2011					X					X					X			

ITEM #	**PAPER**	**SOURCE**	**YEAR**	MODELING METHODOLOGY	WATERSHED SCALE	SITE SCALE	SWMM LID CONTROLS	SWMM OTHER LID	HEC-HMS	MODELING CALIBRATION	MODELING VALIDATION	FORTRAN / HSPF	COSTING	WATER QUALITY	Mike SHE	HydroCAD	STORM	SUSTAIN	InfoWorks	MIKE URBAN	MOUSE
326	Analytical and Modeling Tools for Integrated Water Resources Management in Urban Environments	WEFTEC	2010				X					X			X			X			
327	Mobile LiDAR: Supporting Multiple Data Needs for Mapping and Modeling Urban Environments	WEFTEC	2010	X																	
328	A Multi-Scale Modeling Approach for Green Stormwater Management Planning	WEFTEC	2010	X																	
329	Updating the Ann Arbor, Michigan WWTP Site to Manage Stormwater Using Low Impact Solutions	WEFTEC	2010					X													
330	A Tale of Two Models: How Agent Based Modeling Filled in the Human Variables of Hydraulic Modeling for Low Impact Development in Somerville, MA	WEFTEC	2010					X		X	X										
331	Identifying and Correcting Rain Gauge Measurement Errors Using a Highly Accurate Hydrologic Model and Radar Reflectivity Data	WEFTEC	2010	X																	
332	Innovative Approach for Integrated Combined Sewer Modeling and Floodplain Mapping	WEFTEC	2010	X							X								X		
333	Don't Let Your Model Sit on a Shelf: Are You Getting the Most Out of Your Model	WEFTEC	2010																		
334	Rapid Assessment and Integration of Green Stormwater Infrastructure in CSO Reduction Plans	WEFTEC	2009										X								
335	Modeling the Performance of Advanced Stormwater Management Options and the use of Decision Analysis in Selecting the most Appropriate Set of Controls	WEFTEC	2009										X	X							
336	Evaluation and Performance Assessment of Watershed Models	WEFTEC	2009							X	X	X		X							
337	Leveraging an Open Framework for Expanded Modeling Capabilities in BASINS 4.0	WEFTEC	2009		X			X				X									
338	Effective Integration of Green Infrastructure into CSO Control Planning	WEFTEC	2009										X								
339	Development and Application of Hydrologic and Hydraulic Modeling for Green Stormwater Practices	WEFTEC	2008	X					X												
340	Large-Scale Stormwater Management in an Urban Area Served by Combined Sewers: A Green Approach to Overflow Control	WEFTEC	2008		X			X		X											
341	Integrated Geospatial Data Management for Hydrologic Model Development: A Case Study from Chicago's Combined Sewer System	WEFTEC	2008					X													
342	Evaluation of Best Management Practices for Urban Stormwater Management	WEFTEC	2008											X							
343	Green Infrastructure Planning in Highly Urbanized Watersheds: A New York City Example	WEFTEC	2008													X			X		
344	HSPF Toolkit: A Tool for Stormwater Management at the Watershed Scale	WEFTEC	2008									X									
345	Water Quality and Flow Performance-Based Assessments of Stormwater Control Strategies During Cold Weather Months	WEFTEC	2008																		
346	Expanding the Green Build-out Model to Quantify Stormwater Reduction Benefits in Washington, DC	WEFTEC	2008	X			X													X	
347	Investigating Urban Growth Planning Impacts on Stormwater Control Measure Performance	WEFTEC	2008	X																	
348	A Green Approach to Combined Sewer Overflow Control: Source Control Implementation on a Watershed Scale	WEFTEC	2008	X	X			X													
349	Assessment of Low Impact Development on CSO	WEFTEC	2008				X			X											
350	Philadelphia's Storm Water and CSO Programs: Putting Green First	WEFTEC	2008					X													
351	Quality Control and Assessment of the Calibration of a Model of the City of Pittsburgh Sewer System	WEFTEC	2008							X											
352	Integrated Watershed Management Planning Approaches to Setting and Achieving Water Quality Goals in CSO Receiving Waters	WEFTEC	2008				X														
353	Low Impact Development: San Fransico's Green Approach to Stormwater Management	WEFTEC	2007	X															X		
354	Utilization of Historic Wet-weather Monitoring Data to Calibrate and Urban Application of Hydrologic Simulation Program - FORTRAN	WEFTEC	2007							X		X		X							
355	Development of a Green Build-out Model for Washington, DC: Quantifying the Stormwater Benefits of Trees and Green Roofs	WEFTEC	2007				X							X						X	
356	A North Carolina Piedmont Application of Protocols for Studying Wet Weather Impacts and Urbanization Patterns	WEFTEC	2007					X													
357	SUSTAIN - an EPA BMP Process and Placement Tool for Urban Watersheds	WEFTEC	2007	X														X			
358	Developing a Typical Rainfall Period for Long Term CSO Analysis in San Fransico, California	WEFTEC	2007																X		
359	Developing a Detailed Collection System Model for the San Fransico Sewer Master Plan	WEFTEC	2007																X		
360	Modeling of Stormwater Removal and Peak/Volume Reduction Effects of Green Solutions (Inflow Controls) Using an Explicit Combined/Sanitary Sewer Model	WEFTEC	2007	X		X		X													X
361	Planning for Water Quality Improvement and a Sustainable Landscape in Urbanizing Southern California Aided by Innovative GIS Solutions	WEFTEC	2006																		
362	Protocols for Evaluating the Effects of Land-use Patterns and Runoff Management on Urban Streams	WEFTEC	2006					X													
363	10 Years Experience of CSO Management in the United Kingdom	WEFTEC	2006																		
364	Modeled Flow Duration Variations, Pollutant Discharges, and Costs for Different Stormwater Controls	WEFTEC	2006											X							
365	Slicer.com - Innovative On-line Software for Wet Weather Analysis	WEFTEC	2006	X																	
366	Creative Solutions for Urban Watersheds: Watershed Management Planning in Densely Populated Fairfax County, VA	WEFTEC	2005	X																	
367	Impervious Surfaces in Urban Watersheds	WEFTEC	2005																		
368	Post-Project Monitoring of BMPS/SUDS to Determine Performance and Whole Life Costs	WEFTEC	2005								X		X								
369	WERF: Strategies for Managing Stormwater: Infiltration vs. Surface Water Discharge	WEFTEC	2005											X							
370	Identification of Sites for BMP Implementation and Retrofitting: Challenges and Strategies	WEFTEC	2005																		
371	Low Cost Hydraulic Modeling… Is it possible?	WEFTEC	2005					X					X								
372	Calibration Techniques for Modeling Complex Systems - A Madison, Wisconsin Case Study	WEFTEC	2005							X											X
373	Integrative GIS and Modeling Tools for Large City Master Plan Evaluation	WEFTEC	2005							X			X						X		
374	A Critical Review of BMP Models and Guidance for Selection	WEFTEC	2005	X																	
375	Evaluation of Long-Term Performance of Best Management Practices in Two Small Watersheds	WEFTEC	2005							X											
376	Flow Duration Hydrograph Analyses for Assessing LID Performance	CHI	2015	X				X													
377	Spatial Translation and Scaling Up of Low Impact Development Designs in an Urban Watershed	CHI	2015	X	X					X											

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378	Application of PCSWMM to Assess Wastewater Treatment and Urban Flooding Scenarios in Phnom Penh, Cambodia: A Tool to Support Eco-City Planning	CHI	2015	X																	
379	A Right-of-Way Stormwater Low Impact Development Practice	CHI	2015																		
380	Monitoring Performance of Low Impact Development Measures Implemented at the Conestoga College South Campus	CHI	2014	X						X											
381	Shades of Green: Using SWMM LID Controls to Simulate Green Infrastructure	CHI	2013	X			X			X											
382	Low Impact Development Modeling to Assess Localized Flood Reduction in Thailand	CHI	2013	X																	
383	BMP Economics and Sizing	CHI	2013										X								
384	Modeling Rain Garden LID Impacts on Sewer Overflows	CHI	2012	X			X														
385	Calibration of Distributed Rainfall-Runoff Model in Hamilton County, Ohio	CHI	2012	X				X		X											
386	An Evaluation of Modeling Green Infrastructure Using LID Controls	CHI	2012	X			X														
387	Modeling Green Infrastructure Components in a Combined Sewer Area	CHI	2011	X																	
388	Model Predictive Control with SWMM	CHI	2011																		
389	Characterization of Green Roof Stormwater Runoff Quality	CHI	2011											X							
390	Small Storm Hydrology and BMP Modeling with SWMM5	CHI	2010																		
391	Modeling Low Impact Development Alternatives with SWMM	CHI	2010	X			X														
392	Representation of Low Impact Development Scenarios in SWMM	CHI	2010	X			X														
393	Low Impact Development for Stormwater Quantity and Quality	CHI	2010	X				X						X							
394	An Evaluation of Stormwater Management Practices to Provide Flood Protection for Watershed-Based Targets	CHI	2009	X						X											
395	Structural BMPs for Stormwater Treatment Control – a Performance Based Design Method for Urban Drainage System	CHI	2009																		
396	Characterization of Urban Green Roofs' Stormwater Runoff	CHI	2009																		
397	Assessing the Effectiveness of Proprietary Stormwater Treatment Devices	CHI	2008																		
398	Modeling the Stormwater Benefits of Green Roofs in the City of Toronto	CHI	2008	X	X																
399	Representation of Non-Directly Connected Impervious Area in SWMM Runoff Modeling	CHI	2008							X											
400	Evapotranspiration and Related Calculations for Bioretention Devices	CHI	2008																		
401	Techniques to Assess Rain Gardens as Stormwater Best Management Practices	CHI	2008																		
402	CSO Discharge Reporting using a Continuous Modeling Approach	CHI	2007	X																	
403	Evolution of an Integrated 1D/2D Modeling Package for Urban Drainage	CHI	2007	X																	
404	A Modeling Framework and Preliminary Results in Assessing Phnom Penh's Sewage Discharges	CHI	2007																		
405	Evaluating the simulation times and mass balance errors of component-based models: An application of OpenMI 2.0 to an urban stormwater system	WOS	2015	X				X													
406	The impact of considering uncertainty in measured calibration/validation data during auto-calibration of hydrologic and water quality models	WOS	2015																		
407	Hydrologic modeling of Low Impact Development systems at the urban catchment scale	WOS	2015		X		X														
408	SWMM Simulation of the Storm Water Volume Control Performance of Permeable Pavement Systems	WOS	2015	X			X														
409	Stochastic Multiobjective Optimization Model for Urban Drainage Network Rehabilitation	WOS	2015					X													
410	Multi-objective model auto-calibration and reduced parameterization: Exploiting gradient-based optimization tool for a hydrologic model	WOS	2015																		
411	Analysis of the Effects of Climate Change on Urban Storm Water Runoff Using Statistically Downscaled Precipitation Data and a Change Factor Approach	WOS	2015	X	X			X													
412	Modelling and assessment of hydrological changes in a developing urban catchment	WOS	2015	X				X													
413	Uncertainty assessment of water quality modeling for a small-scale urban catchment using the GLUE methodology: a case study in Shanghai, China	WOS	2015	X				X													
414	Calibration and Verification of SWMM for Low Impact Development	WOS	2015				X														
415	Build-Up/Wash-Off Monitoring and Assessment for Sustainable Management of First Flush in an Urban Area	WOS	2015					X													
416	The influence of depression storage on runoff from impervious surface of urban catchment	WOS	2015		X			X													
417	The Influence of Objective Function and Acceptability Threshold on Uncertainty Assessment of an Urban Drainage Hydraulic Model with Generalized Likelihood Uncertainty Estimation Methodology	WOS	2015					X													
418	Optimization of the design of an urban runoff treatment system using stormwater management model (SWMM)	WOS	2015			X	X														
419	Assessment of porous pavement effectiveness on runoff reduction under climate change scenarios	WOS	2015			X		X													
420	Statistical evaluation of bioretention system for hydrologic performance	WOS	2015				X														
421	Assessment of LID practices for restoring pre-development runoff regime in an urbanized catchment in southern Finland	WOS	2015				X														
422	Combined sewer overflow control with LID based on SWMM: an example in Shanghai, China	WOS	2015	X			X														
423	Analysis of effects of climate change on runoff in an urban drainage system: a case study from Seoul, Korea	WOS	2015	X				X													
424	Influence of Applying Infiltration and Retention Objects to the Rainwater Runoff on a Plot and Catchment Scale - Case Study of Sluzewiecki Stream Subcatchment in Warsaw	WOS	2015		X	X		X													
425	Low-Impact Development Practices to Mitigate Climate Change Effects on Urban Stormwater Runoff: Case Study of New York City	WOS	2015	X	X		X														
426	Coupling Land Use Change Modeling with Climate Projections to Estimate Seasonal Variability in Runoff from an Urbanizing Catchment Near Cincinnati, Ohio	WOS	2015					X				X									
427	Application of the SUSTAIN Model to a Watershed-Scale Case for Water Quality Management	WOS	2014		X													X			
428	Sensitivity Analysis for Urban Drainage Modeling Using Mutual Information	WOS	2014			X		X													
429	A closed urban scenic river system using stormwater treated with LID-BMP technology in a revitalized historical district in China	WOS	2014				X														
430	Development of probability distributions for urban hydrologic model parameters and a Monte Carlo analysis of model sensitivity	WOS	2014	X				X													

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431	Modeling of a lot scale rainwater tank system in XP-SWMM: A case study in Western Sydney, Australia	WOS	2014			X		X													
432	Investigating effects of low impact development on surface runoff and TSS with a calibrated hydrodynamic model	WOS	2014	X			X							X							
433	Evaluation of accuracy of linear regression models in predicting urban stormwater discharge characteristics	WOS	2014					X						X							
434	Calibration of Rainfall-Runoff Model in Urban Watersheds for Stormwater Management Assessment	WOS	2014		X			X													
435	Spatial resolution considerations for urban hydrological modelling	WOS	2014	X			X														
436	THE COMPARATIVE ACCURACY OF TWO HYDROLOGIC MODELS IN SIMULATING WARM-SEASON RUNOFF FOR TWO SMALL, HILLSLOPE CATCHMENTS	WOS	2014					X						X							
437	Assessment of the SWMM model uncertainties within the generalized likelihood uncertainty estimation (GLUE) framework for a high- resolution urban sewershed	WOS	2014	X				X													
438	Parallel flow routing in SWMM 5	WOS	2014	X				X													
439	A modelling approach to assessing variations of total suspended solids (tss) mass fluxes during storm events	WOS	2014					X						X							
440	Evaluation of multi-use stormwater detention basins for improved urban watershed management	WOS	2014				X														
441	Areal rainfall intensity distribution over an urban area and its effect on a combined sewerage system	WOS	2014					X													
442	Performance improvement with parallel numerical model simulations in the field of urban water management	WOS	2014	X	X			X													
443	Impact of SWMM Catchment Discretization: Case Study in Syracuse, New York	WOS	2014					X													
444	Calibration of stormwater management model using flood extent data	WOS	2014	X				X													
445	Effects of Land Use Change on Hydrologic Response at a Watershed Scale, Arkansas	WOS	2013	X	X			X													
446	MODELING HYDROLOGIC BENEFITS OF LOW IMPACT DEVELOPMENT: A DISTRIBUTED HYDROLOGIC MODEL OF THE WOODLANDS, TEXAS	WOS	2013	X																	
447	A high resolution application of a stormwater management model (SWMM) using genetic parameter optimization	WOS	2013			X		X													
448	Bayesian Approach for Uncertainty Analysis of an Urban Storm Water Model and Its Application to a Heavily Urbanized Watershed	WOS	2013				X														
449	Reliability-Based Flood Management in Urban Watersheds Considering Climate Change Impacts	WOS	2013	X	X																
450	OpenMI-based integrated sediment transport modelling of the river Zenne, Belgium	WOS	2013					X						X							
451	Analysis of the characteristics of non-point pollutant runoff applied LID techniques in industrial area	WOS	2013					X						X							
452	Comparative Case Study of Rainfall-Runoff Modeling between SWMM and Fuzzy Logic Approach	WOS	2013					X													
453	Simulation-Optimization Approach to Design Low Impact Development for Managing Peak Flow Alterations in Urbanizing Watersheds	WOS	2013	X									X								
454	Effectiveness of low impact development practices in two urbanized watersheds: Retrofitting with rain barrel/cistern and porous pavement	WOS	2013	X	X																
455	Using the Storm Water Management Model to predict urban headwater stream hydrological response to climate and land cover change	WOS	2013		X			X													
456	Simulating future trends in urban stormwater quality for changing climate, urban land use and environmental controls	WOS	2013	X				X													
457	Modeling low impact development potential with hydrological response units	WOS	2013	X	X		X														
458	Analysis of the impact of low impact development on runoff from a new district in Korea	WOS	2013			X	X														
459	SIZING AND MODELING OF THE SEWAGE SYSTEM IN THE CITY OF WROCLAW	WOS	2013					X													
460	Urbanization and climate change impacts on future urban flooding in Can Tho city, Vietnam	WOS	2013	X				X													
461	Calibrated Hydrodynamic Model for Sazlidere Watershed in Istanbul and Investigation of Urbanization Effects	WOS	2013					X													
462	Application of a Sampling Based on the Combined Objectives of Parameter Identification and Uncertainty Analysis of an Urban Rainfall-Runoff Model	WOS	2013	X				X													
463	Modeling urban storm rainfall runoff from diverse underlying surfaces and application for control design in Beijing	WOS	2013					X													
464	A watershed-scale design optimization model for stormwater best management practices	WOS	2012		X													X			
465	Tradeoffs among watershed model calibration targets for parameter estimation	WOS	2012																		
466	Integration of urban runoff and storm sewer models using the OpenMI framework	WOS	2012	X				X													
467	Modelling runoff quantity and quality in tropical urban catchments using Storm Water Management Model	WOS	2012					X													
468	Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research	WOS	2012	X										X							
469	Influence of lag time on event-based rainfall-runoff modeling using the data driven approach	WOS	2012	X				X													
470	Storm-Water Investment Strategy Evaluation Model for Impaired Urban Watersheds	WOS	2012	X	X																
471	Sewer model development under minimum data requirements	WOS	2012					X													
472	Comparative Case Study of Rainfall-Runoff Modeling between SWMM and Fuzzy Logic Approach	WOS	2012	X		X		X													
473	Planning of LID-BMPs for urban runoff control: The case of Beijing Olympic Village	WOS	2012			X	X														
474	HYDRODYNAMIC MODELLING OF THE COMBINED SEWAGE SYSTEM FOR THE CITY OF PRZEMYSL	WOS	2012					X													
475	Multi-objective optimization for combined quality-quantity urban runoff control	WOS	2012				X							X							
476	Rainwater harvesting to control stormwater runoff in suburban areas. An experimental case-study	WOS	2012				X														
477	Effects of Spatial Resolution in Urban Hydrologic Simulations	WOS	2012	X	X			X													
478	HYDROLOGICAL IMPACTS OF URBAN IMPERVIOUSNESS IN WHITE ROCK CREEK WATERSHED	WOS	2012	X				X													
479	Laboratory Simulation of Urban Runoff and Estimation of Runoff Hydrographs with Experimental Curve Numbers Implemented in USEPA SWMM	WOS	2011					X													

ITEM #	PAPER	SOURCE	YEAR	MODELING METHODOLOGY	WATERSHED SCALE	SITE SCALE	SWMM LID CONTROLS	SWMM OTHER LID	HEC-HMS	MODELING CALIBRATION	MODELING VALIDATION	FORTRAN / HSPF	COSTING	WATER QUALITY	Mike SHE	HydroCAD	STORM	SUSTAIN	InfoWorks	MIKE URBAN	MOUSE
480	Integrated Use of a Continuous Simulation Model and Multi-Attribute Decision-Making for Ranking Urban Watershed Management Alternatives	WOS	2011	X				X													
481	A novel application of a neuro-fuzzy computational technique in event-based rainfall-runoff modeling	WOS	2011					X													
482	A pattern-oriented approach to development of a real-time storm sewer simulation system with an SWMM model	WOS	2010					X													
483	SIMULATION OF COMBINED BEST MANAGEMENT PRACTICES AND LOW IMPACT DEVELOPMENT FOR SUSTAINABLE STORMWATER MANAGEMENT	WOS	2010	X																	
484	ANALYSES OF URBAN DRAINAGE NETWORK STRUCTURE AND ITS IMPACT ON HYDROLOGIC RESPONSE	WOS	2010		X		X														
485	Application of SWMM for evaluating NPS reduction performance of BMPs	WOS	2010	X				X						X							
486	A new applications manual for the Storm Water Management Model (SWMM)	WOS	2010				X														
487	Modeling Techniques of Best Management Practices: Rain Barrels and Rain Gardens Using EPA SWMM-5	WOS	2010	X			X														
488	Design of Integrated Bioinfiltration-Detention Urban Retrofits with Design Storm and Continuous Simulation Methods	WOS	2010				X									X					
489	Water Harvesting of Urban Runoff in Kuwait	WOS	2010					X						X							
490	Hydrological model for urban catchments - analytical development using copulas and numerical solution	WOS	2010	X				X													
491	Dynamic neural networks for real-time water level predictions of sewerage systems-covering gauged and ungauged sites	WOS	2010	X	X			X													
492	Comparative evaluation of runoff and water quality using HSPF and SWMM	WOS	2010		X			X				X									
493	Management of combined sewer overflows based on observations from the urbanized Liguori catchment of Cosenza, Italy	WOS	2010					X													
494	GIS-based urban rainfall-runoff modeling using an automatic catchment-discretization approach: a case study in Macau	WOS	2009		X			X													
495	Potential Dangers of Simplifying Combined Sewer Hydrologic/Hydraulic Models	WOS	2009	X	X			X	X												
496	Effect of Infiltration and Inflow in Dry Weather on Reducing the Pollution Loading of Combined Sewer Overflows	WOS	2009					X						X							
497	Effect of the aggregation level of surface runoff fields and sewer network for a SWMM simulation	WOS	2009	X	X	X		X													
498	Sewerage network modelling in Latvia, use of InfoWorks CS and Storm Water Management Model 5 in Liepaja city	WOS	2008	X			X												X		
499	Automatic calibration of the US EPA SWMM model for a large urban catchment	WOS	2008		X			X													
500	A hydrologic/water quality model application protocol	WOS	2008	X										X							
501	Using SWMM as a tool for hydrologic impact assessment	WOS	2007	X				X													
502	A review of models for low impact urban stormwater drainage	WOS	2007	X			X														X
503	Assessing the importance of conduit geometry and physical parameters in karst systems using the storm water management model (SWMM)	WOS	2006	X				X													
504	Integrating legacy components into a software system for storm sewer simulation	WOS	2006	X				X													
505	Comparative assessment of two distributed watershed models with application to a small watershed	WOS	2006	X	X																
506	Assessment of possible impacts of climate change in an urban catchment	WOS	2006					X													
507	A PCSWMM/GIS-based water balance model for the Reesor Creek watershed	WOS	2006	X				X													
508	Comparison of kinematic-wave and nonlinear reservoir routing of urban watershed runoff	WOS	2005	X				X													
509	Philadelphia Combined Sewer Overflow Long Term Control Plan Update	City of Phila	2009	X				X				X									
510	City and County of San Fransico 2030 Sewer System Master Plan	City of SF	2009	X	X														X		
511	GI Master Plan	ARCADIS/Buffalo Sewer Authority																			
512	From Desktop to Design: Citizens Energy Group's First Green-Dominated CSO Solution	SWM		X		X		X											X		
513	A Case Summary of Green Infrastructure: Pilot Projects and Opportunities	WEFTEC	2012				X						X								
514	MSDGC Modeling Guidelines and Standards Volume I System Wide Model	City of Cincinnati	2013	X				X													
515	Save Millions with Alternative Green Infrastructure	WEFTEC	2012										X								
516	Application of Groundwater Modeling Tools to Evaluate Potential Impacts from Stormwater Infiltration in Philadelphia	WEFTEC	2012	X	X																
517	Upper Allegheny H & H Model Validation and Characterization Report	ALCOSAN	2010																		
518	Modeling of Stormwater Removal and Peak/Volume Reduction Effects of Green Solutions (Inflow Controls) Using an Explicit Combined/Sanitary Sewer Model	WEFTEC	2007	X		X		X													X
519	BMP Modeling Concepts and Simulation	USEPA	2006	X	X	X	X														
520	Observed and Modeled Performances of Prototype Green Roof Test Plots Subjected to Simulated Low- and High-Intensity Precipitations in a Laboratory Experiment	WOS	2010	X				X													
521	Effect of Aggregation of On-Site Storm-Water Control Devices in an Urban Catchment Model	WOS	2009	X	X	X															

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MEMO

To:
New York City Department of Environmental Protection

From:
Arcadis Team

Date:
May 13, 2016

Subject:
GI-RD Task 2.3 – Utility Survey

Executive Summary

New York City Department of Environmental Protection (DEP) has been implementing and evaluating green infrastructure (GI) performance since 2010. DEP sought to understand how other peer utilities with combined sewer systems are evaluating GI performance. A questionnaire was developed to support the documentation of other selected utilities' GI modeling programs/procedures, and 15 utilities of various sizes across the country agreed to respond to the questionnaire. This technical memorandum summaries the data and information acquired from the questionnaire's application as well as information resulting from interviews of DEP staff and review of existing documentation on current DEP-specific modeling practices. This technical memorandum will be shared with utilities responding to this survey for reference. DEP will use this information along with its current practices to develop updated GI modeling guidelines for future performance evaluations at different spatial scales.

The responses gathered from 15 utilities represent the current state of the industry in terms of modeling approaches for GI and consistency was found across nearly all sizes of utilities and geographic locations. The findings also indicate that the industry is likely to migrate towards a more process-oriented GI modeling approach. Naturally, there were differences in the approach utilized to represent specific GI facilities within a model based on individual utilities preferences and level of effort investment.

The GI modeling approach and procedures being used by DEP are comparable to those being used by most utilities surveyed, and can be carried forward for macro-scale evaluations. Additional GI data to be collected in the GI-RD project can lead to further assessment and refinement of the lumped and distributed GI facilities representation approaches in the future.

1.0 INTRODUCTION

Since 2010, New York City DEP has been constructing GI assets throughout the City's combined sewer tributary areas. The types of GI assets include but are not limited to bioinfiltration, permeable paving, subsurface retention systems, stormwater harvesting and reuse systems and green roofs. DEP is using existing InfoWorks combined sewer system models, developed as part of the CSO Long Term Control Plans (LTCP), to quantify the annual stormwater runoff and CSO reduction resulting from the implemented GI and to project the benefits of future GI installations. The current GI modeling approach used in the LTCP models includes lumped retention and detention representation as further described in section 2.3 of this memorandum. To assist with validating the current lumped GI modeling approach and/or developing a detailed (also referred to as distributed) approach for modeling GI performance, DEP conducted a survey of peer utilities across the United States.

DEP sought to understand how other peer utilities with combined sewer systems were evaluating GI performance. A questionnaire was developed to support the documentation of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

This technical memorandum summarizes the data and information acquired from the questionnaire's application as well as information resulting from interviews of DEP staff and review of existing documentation on current DEP-specific modeling practices.

2.0 DATA COLLECTION

To assess the current state-of-the-science for GI modeling practices, gathering data from other large and regional utilities was identified as the starting point. A questionnaire was developed, and the team contacted 17 utilities across the country and in the UK.

2.1 Questionnaire Development

To ensure consistency in the data collection phase, a straightforward, 10-part questionnaire was developed. The goal was to gather standard background data on each utility's operational and system characteristics. The other driver was to gather as much detail on each utility's approach to GI modeling without overwhelming the respondents with requests for specific details. After working with DEP, the final questionnaire was developed for distribution. The questionnaire is included in Appendix A.

2.2 Interview with Utilities

Once the questionnaire was prepared, DEP and Arcadis Team identified key utilities to target for responses. The utilities selected included other large utilities, regional utilities and utilities with known contacts. The following utilities were ultimately identified:

- Allegheny County Sanitary Authority (ALCOSAN), Pittsburgh, Pennsylvania
- Boston Water and Sewer Commission (BWSC), Boston, Massachusetts
- Bureau of Environmental Services (BES), Portland, Oregon
- Citizens Energy Group (CEG), Indianapolis, Indiana
- Columbus Division of Sewerage and Drainage (DOSD), Columbus, Ohio
- Detroit Water and Sewerage Department (DWSD), Detroit, Michigan
- District of Columbia Water and Sewer Authority (DC Water)
- Metropolitan Water Reclamation District of Greater Chicago (MWRD), Chicago, Illinois
- Metropolitan Sewer District (MSD), Louisville, Kentucky
- Metropolitan Sewer District of Greater Cincinnati (MSD GC), Cincinnati, Ohio
- Northeast Ohio Regional Sewer District (NEORSD), Cleveland, Ohio
- Onondaga County, Syracuse, New York
- Philadelphia Water Department (PWD), Philadelphia, Pennsylvania
- Pittsburgh Water and Sewer Authority (PWSA), Pittsburgh, Pennsylvania
- San Francisco Public Utilities Commission (SFPUC), San Francisco, California
- Seattle Public Utilities (SPU), Seattle, Washington
- Thames Water, London, United Kingdom

From October 2015 through January 2016 all 17 utilities were initially contacted to discuss the questionnaire. Through discussions and phone calls, 15 utilities ultimately responded to the questionnaire and expressed interest in the findings of the study.

2.3 Review of Existing DEP Documentation

Concurrent with the interviews of other utilities, Arcadis Team reviewed DEP's current approach to GI modeling. The Citywide InfoWorks Modeling Report (available from DEP's website http://www.nyc.gov/html/dep/pdf/cso_long_term_control_plan/infoworks-citywide-recalibration-report.pdf) was reviewed. In reviewing the document, the evolution of InfoWorks watershed models in various drainage areas and calibration at multiple spatial scales using data collected at upland locations, regulator/outfall, treatment plant inflows, CSO retention tanks, and SCADA locations at select regulators was examined. Arcadis Team prepared a technical memorandum on DEP's existing GI modeling approaches that was previously submitted to DEP in November, 2015. GI modeling approaches used to-date by the DEP LTCP team are primarily based on lumped representations of retention and detention GI practices. Additionally, Arcadis Team concurrently completed microscale evaluations of lumped and distributed GI modeling approaches for already implemented GI practices. The evaluation recommendation is to use a distributed modeling approach for already planned/constructed GI (1.5% of the impervious area) where more design and site specific data are available while continue using the existing lumped approach for future GI (between 1.5% and 10% of the impervious area). The evaluation results and recommendations are documented in the GI-RD Task 2.3 – Microscale Modeling Approach Technical Memorandum (DEP, April, 2016).

3.0 FINDINGS

Once all the completed questionnaires were collected, the results were compiled and summarized to provide a current state-of-the-science view of GI modeling approaches and trends. In general, the common approach is relatively similar across most utilities. The following sections and tables present the findings. Appendix B contains the detailed responses from each utility. Table 3-1 summarizes the contact information for the utilities that responded to the questionnaire.

Table 3-1. Utility Name and Location

Utility Name	Address
Allegheny County Sewer Authority (ALCOSAN)	3300 Preble Avenue, Pittsburgh, PA 15233
Boston Water and Sewer Commission (BWSC)	980 Harrison Avenue, Boston, MA 02119
Citizens Energy Group (CEG)	Indianapolis, IN
Columbus Division of Sewerage and Drainage (DOSD)	Columbus, OH
District of Columbia Water and Sewer Authority (DC Water)	Washington, D.C.
Louisville Metropolitan Sewer District (MSD)	Louisville, KY
Metropolitan Sewer District of Greater Cincinnati (MSD GC)	Cincinnati, OH
Metropolitan Water Reclamation District of Greater Chicago (MWRD)	Chicago, IL
Northeast Ohio Regional Sewer District (NEORSD)	3900 Euclid Avenue, Cleveland, OH 44115
Onondaga County	Syracuse, NY
Philadelphia Water Department (PWD)	Philadelphia, PA
Pittsburgh Water and Sewer Authority (PWSA)	1200 Penn Avenue, Pittsburgh, PA 15222
Bureau of Environmental Services (BES)	Portland, OR

Utility Name	Address
San Francisco Public Utilities Commission (SFPUC)	San Francisco, CA
Seattle Public Utilities (SPU)	Seattle, WA

The responding utilities provided a broad range of utility size and customer accounts, ranging from service areas of 11 sq. miles to 884 sq. miles and populations ranging from 325,000 to 5.25 million. Physical sewer system statistics also varied greatly in terms of miles of sewers and number of Combined Sewer Overflow outfalls (CSOs). Table 3-2 summaries the utilities' characteristics; if the utility did not provide a response, the field is left blank.

Table 3-2. Utility Characteristics

Utility Name	Number of Customers Accounts/Taps	Service Area Size (Sq. Miles)	Population Served	Total Miles of Public Sanitary Sewer (Mains Only)	Total Miles of Public Combined Sewers (Mains Only)	Number of Combined Sewer Overflow Locations
New York City Department of Environmental Protection (NYC DEP)	835,000[1]	312	8,000,000	2,220[1]	3,330[1]	430
Allegheny County Sewer Authority (ALCOSAN)	320,000	309	890,000	2,800	1,200	360
Boston Water and Sewer Commission (BWSC)	87,864	48	655,884	679	185	37
Bureau of Environmental Services (BES), Portland, OR		145		1,001	910	5
Citizens Energy Group (CEG)	270,000	337	800,000	2,260	915	1
Columbus Division of Sewerage and Drainage (DOSD)	271,341	642	809,798	2,782	167	29
District of Columbia Water and Sewer Authority (DC Water)		735	2,000,000	1,900[2]		47

Utility Name	Number of Customers Accounts/Taps	Service Area Size (Sq. Miles)	Population Served	Total Miles of Public Sanitary Sewer (Mains Only)	Total Miles of Public Combined Sewers (Mains Only)	Number of Combined Sewer Overflow Locations
Louisville Metropolitan Sewer District (MSD)	220,000	385	700,000	2,660	540	101
Metropolitan Sewer District of Greater Cincinnati (MSD GC)	230,000	290+	850,000		3,000[3]	270
Metropolitan Water Reclamation District of Greater Chicago (MWRD)	10,000	884	5,250,000		554	39
Northeast Ohio Regional Sewer District (NEORSD)	327,000	365[4]	1,000,000		315[5]	122
Onondaga County		11		17	69	26[6]
Philadelphia Water Department (PWD)	640,000	143	1,500,000	760	1,800	164
Pittsburgh Water and Sewer Authority (PWSA)	83,000	58	325,000	1,200	925	194
San Francisco Public Utilities Commission (SFPUC)		47	800,000 (residents) - 1,500,000 (daytime total)		1,000	
Seattle Public Utilities (SPU)		84	630,000	448	520	87

1. Number of DEP bill-paying customers
2. State of the Sewers, 2012 http://www.nyc.gov/html/dep/pdf/reports/state-of-the-sewers.pdf
3. 1,900 miles includes both sanitary and combined sewers
4. 3,000 miles of sanitary and combined sewers
5. Includes 81 sq. miles is combined area
6. 315 miles (NEORSD owned); 3600+ miles (locally owned)
7. 26 CSOs currently operational; "operational" is defined as discharging during a 1-year, 2-hour design storm; system originally had 72 CSOs

In discussing the purposes behind GI modeling, most respondents reported that the consistent driver for the use of GI modeling is to evaluate CSO volume, frequency, and pollutant load reductions. Half of the respondents indicated that they also used GI modeling to evaluate drainage or water quality improvements, and six respondents identified flood mitigation evaluations as another use of GI modeling.

All respondents except MWRD noted that they performed GI modeling during the planning stage, as shown in Figure 3-1. Several utilities had used GI modeling during the design phase and during post-construction monitoring, but only four (DC Water, Onondaga County, PWD and PWSA) actively apply GI modeling during annual reporting efforts. DEP is currently using GI modeling for planning, post-construction monitoring, and CSO reporting as identified in Figure 3-1.

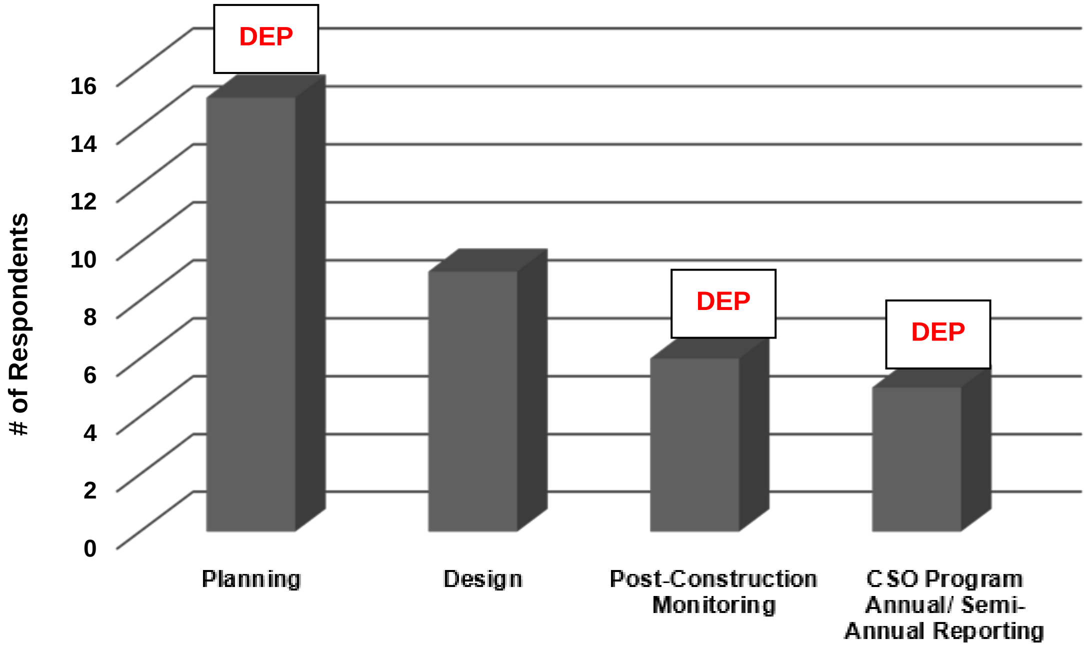

Figure 3-1. GI Modeling Performed During Various Stages for DEP and Surveyed Utilities

Most of the respondents reported that GI evaluations were performed within the framework of their collection system model. A few utilities such as Boston BWSC, Columbus DOSD and Portland BES noted that they have begun also evaluating GI within the framework of their full-system stormwater models, including both combined and separate systems. Some additional utilities such as DC Water, Onondaga, Philadelphia PWD and San Francisco SFPUC reported that they have developed stand-alone, detailed models for GI characterization and then externally link the model outputs to their existing collection system model.

Interestingly, the range of GI technologies modelled varied greatly from utility to utility, but the driver behind this may be due to each individual utility's preferred GI technology. Table 3-3 presents the GI technologies modelled across all the utilities. DEP's technologies modelled are presented for comparison purposes. It should be noted that ALCOSAN has not yet begun modeling specific technologies as their GI program is in its infancy.

Table 3-3. GI Technologies Modeled

Utility Name	Bioretention/ Stormwater Planters	Tree Boxes	Infiltration Trenches	Permeable Pavement	Green Roofs	Blue Roofs	Swales	Ponds & Wetlands
New York City Department of Environmental Protection (NYC DEP)	✓			✓	✓	✓	✓	
Allegheny County Sewer Authority (ALCOSAN)								
Boston Water and Sewer Commission (BWSC)	✓		✓	✓			✓	
Bureau of Environmental Services (BES), Portland, OR	✓		✓	✓	✓		✓	✓
Citizens Energy Group (CEG), Indianapolis, IN	✓	✓					✓	
Columbus Division of Sewerage and Drainage (DOSD)	✓			✓				
District of Columbia Water and Sewer Authority (DC Water)	✓	✓		✓	✓			
Louisville Metropolitan Sewer District (MSD)	✓	✓	✓	✓				
Metropolitan Sewer District of Greater Cincinnati (MSD GC)	✓		✓	✓				✓
Metropolitan Water Reclamation District of Greater Chicago (MWRD)								
Northeast Ohio Regional Sewer District (NEORSD)	✓		✓	✓				✓
Onondaga County	✓	✓	✓	✓	✓		✓	✓
Philadelphia Water Department (PWD)	✓	✓	✓	✓	✓	✓	✓	✓
Pittsburgh Water and Sewer Authority (PWSA)	✓		✓					
San Francisco Public Utilities Commission (SFPUC)	✓		✓	✓	✓	✓		✓
Seattle Public Utilities (SPU)	✓			✓			✓	

The majority of the utilities use US EPA's SWMM5 modeling package for their evaluations, as well as some of the commercially based software packages that utilize the SWMM5 engine. Figure 3-2 summarizes the modeling packages used. It must be noted that multiple models may be used by some utilities, so the total number of models shown in Figure 3-2 is larger than the number of interviewed utilities. Only DC Water, Louisville MSD, Onondaga County and San Francisco SFPUC reported using a 2-dimensional overland flow model, in addition to a traditional 1-dimensional model, to represent the surface-subsurface interaction during wet weather. DEP is using InfoWorks and is included in Figure 3-2.

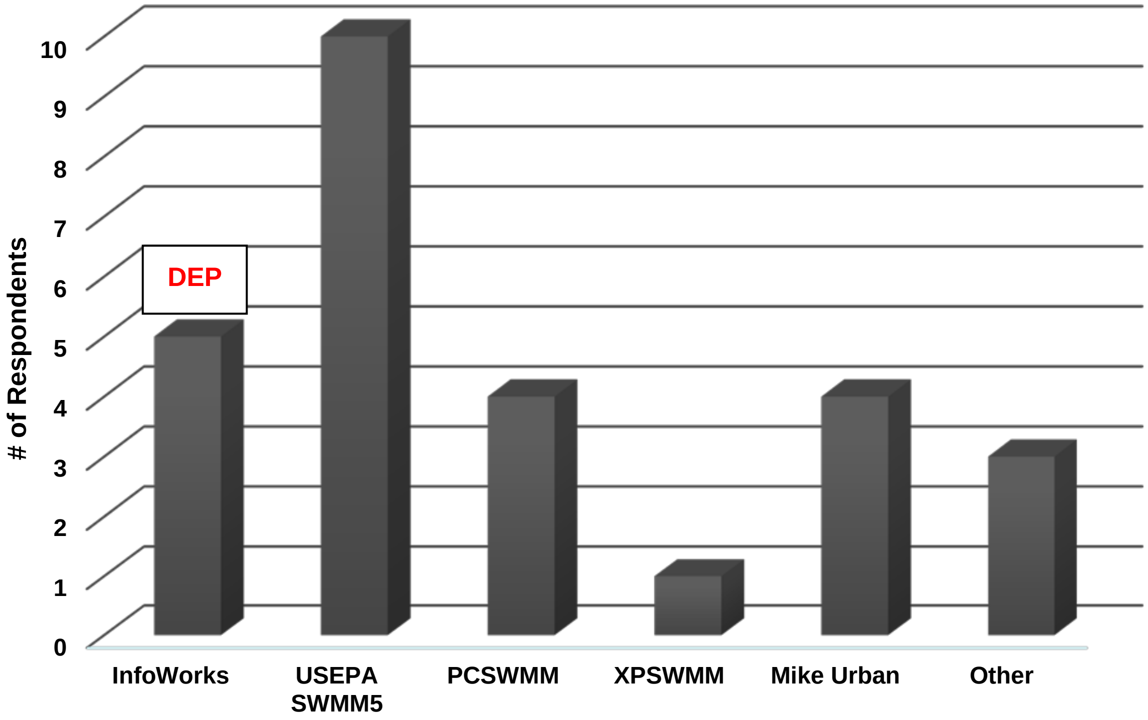

Figure 3-2. Modeling Software Package Usage

The methods used to model GI response varied from utility to utility; no single approach was identified as the leading approach to modeling GI. Most utilities simply reduce the hydrologic losses and/or impervious area percentage contributing to sewers. Yet, some utilities have begun creating customized hydraulic representations including Philadelphia PWD, which only uses customized hydraulic representations to model GI. Table 3-4 summarizes the variations across the utilities, with DEP's LTCP approach of lumped retention and detention presented for comparison purposes. More specifically, the utilities were asked to identify the level of detail in which they model GI, such as modeling each individual GI facility or lumping GI based on technology or location. Table 3-5 presents the results, with DEP's LTCP lumped and GI-RD distributed approaches also presented.

Table 3-4. GI Modeling Methods

Utility Name	Reducing Impervious Area Percentage	Increasing Initial Abstract/ Depression Storage	Increasing Evapotranspiration	Physically Representing the Planned GI Using Built-In Model Features	Physically Representing the Planned GI Using a Customized Hydraulic Representation
New York City Department of Environmental Protection (NYC DEP)				✓	✓
Allegheny County Sewer Authority (ALCOSAN)	✓	✓	✓		
Boston Water and Sewer Commission (BWSC)				✓	
Bureau of Environmental Services (BES), Portland, OR	✓	✓			✓
Citizens Energy Group (CEG)	✓	✓			✓
Columbus Division of Sewerage and Drainage (DOSD)				✓	
District of Columbia Water and Sewer Authority (DC Water)	✓	✓	✓	✓	✓
Louisville Metropolitan Sewer District (MSD)[1]	✓			✓	✓
Metropolitan Sewer District of Greater Cincinnati (MSD GC)	✓	✓		✓	✓
Metropolitan Water Reclamation District of Greater Chicago (MWRD)					
Northeast Ohio Regional Sewer District (NEORSD)[2]	✓				
Onondaga County				✓	✓
Philadelphia Water Department (PWD)					✓
Pittsburgh Water and Sewer Authority (PWSA)				✓	
San Francisco Public Utilities Commission (SFPUC)[3]	✓	✓		✓	✓
Seattle Public Utilities (SPU)				✓	

1. Reducing impervious area percentage is used for initial evaluations of GI impacts and benefits. Physically representing the planned GI is used for a more detailed analysis of GI alternatives.

<table>
<tr><th>Utility Name</th><th>Reducing Impervious Area Percentage</th><th>Increasing Initial Abstract/ Depression Storage</th><th>Increasing Evapotranspiration</th><th>Physically Representing the Planned GI Using Built-In Model Features</th><th>Physically Representing the Planned GI Using a Customized Hydraulic Representation</th></tr>
<tr><td colspan="6">2. Development of example hydraulic representations of various GI projects is being considered but is not available at this time.
3. The most typical employed methodology is to create runoff surfaces in InfoWorks Integrated Catchment Modeling (ICM) that simulate the performance of various GI types. We have created approximately 12 or so GI runoff surfaces, typically large and small sizes of the most common BMP types. The entire drainage area feeding a BMP is converted to the runoff surface type. All GI types were modeled directly in EPA SWMM first and results were translated back into ICM runoff surfaces.</td></tr>
</table>

Table 3-5. GI Modeling Approach

Utility Name	Detailed GI Representation in Model	Lumped Approach	Inlet Control / Bypass Representation
New York City Department of Environmental Protection (NYC DEP)	✓ (GI-RD Project)	✓ By GI Technology and Location (LTCP and GI-RD Project)	✓
Allegheny County Sewer Authority (ALCOSAN)	To be determined		
Boston Water and Sewer Commission (BWSC)	✓		
Citizens Energy Group (CEG)		✓By Location	
Columbus Division of Sewerage and Drainage (DOSD)	✓		
District of Columbia Water and Sewer Authority (DC Water)	✓	✓ By GI Technology	✓
Louisville Metropolitan Sewer District (MSD)[1]	✓	✓By Location	✓
Metropolitan Sewer District of Greater Cincinnati (MSD GC)	✓	✓ By GI Technology and Location	✓
Metropolitan Water Reclamation District of Greater Chicago (MWRD)			
Northeast Ohio Regional Sewer District (NEORSD)[2]		✓ By Location	

Utility Name	Detailed GI Representation in Model	Lumped Approach	Inlet Control / Bypass Representation
Onondaga County	✓		
Philadelphia Water Department (PWD)		✓ By GI Technology	
Pittsburgh Water and Sewer Authority (PWSA)	✓	✓By Location	✓
Bureau of Environmental Services (BES), Portland, OR	✓	✓ By GI Technology	
San Francisco Public Utilities Commission (SFPUC)	✓	✓ By GI Technology	✓
Seattle Public Utilities (SPU)	✓	✓ By GI Technology and Location	

1. Louisville MSD models individual GI facilities/technologies during more detailed GI analyses and during capital cost evaluations. The lumped modeling approach is used first to determine the benefits of GI before migrating to individual GI modeling. For the lumped approach other forms are used when GI opportunities exist.
2. The NEORSD's modeling standards/protocols do not specifically identify the approach beyond lumping.

Boston Water and Sewer Commission (BWSC), Metropolitan Sewer District of Greater Cincinnati (MSD GC), and Philadelphia Water Department (PWD) are modeling the water quality performance of the GI facilities. BWSC models the GI water quality using SWMM, and MSD GC utilizes WinSLAMM. PWD models the percent removal or reductions based on literature values. All three utilities are open to additional discussions with DEP on their approaches. The remaining utilities report that they do not model the water quality of the GI facilities, partly due to their consent orders/decrees focusing on volumetric targets for CSO reductions and also due to lack of monitoring data to support quantification of pollutant load reductions.

Most of the utilities that are actively evaluating GI within their models do have documented procedures for GI modeling, and many are willing to share.

4.0 CONCLUSIONS AND RECOMMENDATIONS

This overview of the current state of the industry in terms of modeling approaches for GI finds consistency across nearly all sizes of utilities and geographic locations. The findings also indicate the direction the industry approach is likely to migrate towards more detailed GI process representation (i.e., incorporation of all processes such as ET, infiltration, bypass, and inlet/outlet designs) as well as distributed GI modeling (i.e., representation of each GI practice at the small spatial scale). While the focus of most GI modeling has been for CSO reductions, some of the surveyed utilities are starting to model GI for flood mitigation and water quality benefit evaluations. Flood mitigation benefits, especially the relief for nuisance flooding for small storms, have been quantified by utilities such as SFPUC and Portland BES using distributed modeling approaches. All utilities questioned are using GI modeling during the planning phases of projects, and some have moved forward with using GI modeling all the way through design, post-construction monitoring and for annual reporting. Levels of detail in the GI modeling approaches have often been tied directly to this end goal of planning, design, or regulatory compliance.

Differences between the approach to representing specific GI facilities within a model is to be expected based on individual utilities preferences and level of effort investment. The surveyed utilities are using a mix of modeling distributed and lumped GI representations to evaluate the overall impact of GI at the subcatchments level. The distributed approach does require additional effort, both in the original model development (to ensure the hydrology within the model is amenable modifying to represent site specific GI technologies) and in the utility's commitment to identifying specific locations and GI types to a high degree. It is apparent that monitoring at different spatial scales will guide the refinement of models to represent GIs robustly in collection system models and use for performance evaluations. While modeling at finer scales is achievable with modest increases in computational effort, the key appears to be the monitoring data availability at different spatial scales and for various GI technologies.

To-date, DEP has primarily focused on implementing standardized Right-of-Way Bioswales (ROWB) that represent about 90% of approximately 4,470 assets that have already been constructed or are expected to be constructed by end of 2016. DEP has performed GI monitoring since 2010 at individual pilot locations with various GI technologies and has also completed pre- and post-GI monitoring in Demonstration (Demo) Areas saturated with ROWBs. GI practice and neighborhood-scale Demo Area monitoring data have provided DEP with an opportunity to develop and validate a detailed modeling representation for its most common GI asset to-date (ROWB), which in turn allows using a distributed modeling approach by applying this representation Citywide (for more details refer to the GI-RD Task 2.3 – Microscale Modeling Approach Technical Memorandum (DEP, April, 2016)).

Overall, DEP's current approach of using both lumped and distributed modeling of GI facilities is comparable to those being used by other utilities surveyed. Most utilities appear to use lumped approaches to evaluate GI benefits on watershed and system-wide scales and use distributed modeling to evaluate individual GI facilities or technologies. Under the GI-RD modeling efforts, DEP is overlaying both approaches to determine GI benefits Citywide with the distributed approach used for already planned/constructed GI and the lumped approach used for future GI modeling.

Finally, as utilities progress in utilizing the models through GI planning, design and post construction monitoring, detailed representations of GI locations and types become more common leading to a distributed modeling approach. As the GI analysis and implementation continues to develop, data collected in the GI-RD Project can lead to further assessment and refinement of the approaches in the future.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: ________________________________

Date: ________________________________

1. General Information

Utility Name and Location: ____

Utility Contact Name and Contact Information: ____

____

Utility Characteristics:

- Number of customer accounts/taps: _____________
- Service area size (sq. miles): _____________
- Population served: _________________
- Total miles of public sanitary sewer (mains only): _____________________________________

- Total miles of public combined sewer (mains only): ____________________
- Total miles of lateral sewers (services) in rights-of-way and/or easements: _________________
- Combined Sewer Overflows:
    - Number of CSOs: ____________________

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
    - CSO reductions
    - Drainage or water quality improvements
    - Flood mitigation
2. We perform GI model evaluations during:
    - Planning
    - Design
    - Post-Construction Monitoring
    - CSO Program annual/semi-annual reporting
3. Evaluations of GI are performed:
    - Within the framework of our collection system model
    - Within the framework of our stormwater system model
    - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model
4. We have modeled the following types of GI:
    - Bioretention /Stormwater planters
    - Tree Boxes
    - Infiltration Trenches
    - Permeable pavement
    - Green Roofs
    - Blue Roofs
    - Swales
    - Ponds & Wetlands
    - Retention

3. General Modeling Approach

5. Our utility models GI by doing the following:
    - Reducing impervious area percentage
    - Increasing initial abstraction/depression storage
    - Increasing evapotranspiration
    - Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption)
    - Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.)

6. Our utility uses the following model(s) to for GI planning/design (check all that apply):

    ____ InfoWorks

___ USEPA SWMM5

___ PCSWMM

___ XPSWMM

___ Mike Urban

___ Other: ____

7. Our utility models GI in the:
   - 1D pipe network
   - 2D overland flow

8. Our general modeling approach includes (check all that apply):

___ Modeling individual GI facilities/technologies

___ Lumped modeling approach

Subgrouping for lumped approach (check all that apply):

___ Based on GI type

___ Location within subcatchment(s)

___ Other: ____

___ Inlet control/bypass representation

9. We have modeled water quality performance of GI? Yes / No

- If Yes, we model water quality performance using (check all that apply):

___ Event mean concentrations (EMCs)

___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

___ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

___ Other: ____

10. Our utility has documented procedures for GI modeling approaches: Yes / No

- If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

___ Literature reviews on modeling of GI performance

___ Triple Bottom Line / Co-benefits documentation

___ Other: ____

11. Please provide any additional details beyond what has been requested above.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: _Laura McGinnis_______________________________

Date: _11/6/2015_______________________________

1. General Information

Utility Name and Location: _ALCOSAN 3300 Preble Ave, Pittsburgh, PA 15233 ____

Utility Contact Name and Contact Information: Timothy Prevost, Manager of Wet Weather Programs 412-734-8731 timothy.prevost@alcosan.org ____

____

Utility Characteristics:

- Number of customer accounts/taps: 320,000_____________
- Service area size (sq. miles): 309_____________
- Population served: 890,000_________________

- Total miles of public sanitary sewer (mains only):2,800 ____
- Total miles of public combined sewer (mains only): 1,200 ______________________
- Total miles of lateral sewers (services) in rights-of-way and/or easements: Unknown ___________________
- Combined Sewer Overflows:
  - Number of CSOs: 360__________________

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
   - [✓ CSO reductions]
   - Drainage or water quality improvements
   - Flood mitigation
2. We perform GI model evaluations during:
   - [✓ Planning]
   - Design
   - Post-Construction Monitoring
   - CSO Program annual/semi-annual reporting
3. Evaluations of GI are performed:
   - [✓ Within the framework of our collection system model]
   - Within the framework of our stormwater system model
   - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model
4. We have modeled the following types of GI:
   - Bioretention /Stormwater planters
   - Tree Boxes
   - Infiltration Trenches
   - Permeable pavement
   - Green Roofs
   - Blue Roofs
   - Swales
   - Ponds & Wetlands
   - Retention

3. General Modeling Approach

5. Our utility models GI by doing the following:
   - [✓ Reducing impervious area percentage]
   - [✓ Increasing initial abstraction/depression storage]
   - [✓ Increasing evapotranspiration - Maybe]
   - Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption)
   - Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.)

6. Our utility uses the following model(s) to for GI planning/design (check all that apply):

   ___ InfoWorks

   X__ USEPA SWMM5

   ___ PCSWMM

   ___ XPSWMM

   ___ Mike Urban

   ___ Other: ______________________________

7. Our utility models GI in the:
   - [✓ 1D pipe network]
   - 2D overland flow

8. Our general modeling approach includes (check all that apply): Undetermined at this point

   ___ Modeling individual GI facilities/technologies

   ___ Lumped modeling approach

   Subgrouping for lumped approach (check all that apply):

   ___ Based on GI type

   ___ Location within subcatchment(s)

   ___ Other: ______________________________

   ___ Inlet control/bypass representation

9. We have modeled water quality performance of GI? Yes / [✓ No]

   - If Yes, we model water quality performance using (check all that apply):

   ___ Event mean concentrations (EMCs)

   ___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

   ___ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

   ___ Other: ______________________________

10. Our utility has documented procedures for GI modeling approaches: Yes / [✓ No] - It is anticipated that GI modeling approaches will be developed

    - If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

___ Literature reviews on modeling of GI performance

___ Triple Bottom Line / Co-benefits documentation

___ Other: ____

11. Please provide any additional details beyond what has been requested above.

ALCOSAN's GI modeling is still in its infancy. They are committed to evaluating GI, but the specifics have not yet been formalized. They are committed to spending $4 million a year in GI projects with a goal of $40-$45over 10 years.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: _Laura McGinnis, Arcadis_______________________________

Date: __February 24, 2016______________________________

1. General Information

Utility Name and Location: _____Boston Water and Sewer Commission, Boston, MA______________

Utility Contact Name and Contact Information: ____Paul W. Keohan, Boston Water and Sewer Commission, 980 Harrison Ave., Boston, MA, 02119________________________________

Utility Characteristics:

- Number of customer accounts/taps: _______87,864______
- Service area size (sq. miles): __48 sq mi___________
- Population served: ________655,884_________
- Total miles of public sanitary sewer (mains only): ____679 miles______________________

- Total miles of public combined sewer (mains only): __185 miles__________________
- Total miles of lateral sewers (services) in rights-of-way and/or easements: _________________
- Combined Sewer Overflows:
    - Number of CSOs: _______37___________

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
    - CSO reductions
    - Drainage or water quality improvements
    - Flood mitigation
2. We perform GI model evaluations during:
    - Planning
    - Design
    - Post-Construction Monitoring
    - CSO Program annual/semi-annual reporting
3. Evaluations of GI are performed:
    - Within the framework of our collection system model
    - Within the framework of our stormwater system model
    - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model
4. We have modeled the following types of GI:
    - Bioretention /Stormwater planters
    - Tree Boxes
    - Infiltration Trenches
    - Permeable pavement
    - Green Roofs
    - Blue Roofs
    - Swales
    - Ponds & Wetlands
    - Retention

3. General Modeling Approach

5. Our utility models GI by doing the following:
    - Reducing impervious area percentage
    - Increasing initial abstraction/depression storage
    - Increasing evapotranspiration
    - Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption)
    - Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.)

6. Our utility uses the following model(s) to for GI planning/design (check all that apply):

    ____ InfoWorks

___ USEPA SWMM5

x___ PCSWMM

___ XPSWMM

x___ Mike Urban

___ Other: ______________________________

7. Our utility models GI in the:
   - [✓ 1D pipe network]
   - 2D overland flow

8. Our general modeling approach includes (check all that apply):

_x_ Modeling individual GI facilities/technologies

___ Lumped modeling approach

Subgrouping for lumped approach (check all that apply):

___ Based on GI type

___ Location within subcatchment(s)

___ Other: ______________________________

___ Inlet control/bypass representation

9. We have modeled water quality performance of GI? [✓ Yes] / No

   - If Yes, we model water quality performance using (check all that apply):

_x_ Event mean concentrations (EMCs)

___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

_x_ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

___ Other: ______________________________

10. Our utility has documented procedures for GI modeling approaches: [✓ Yes] / No

   - If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

_x_ Literature reviews on modeling of GI performance

___ Triple Bottom Line / Co-benefits documentation

___ Other: ______________________________

11. Please provide any additional details beyond what has been requested above.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: ______________________

Date: ______________________

1. General Information

Utility Name and Location: Citizens Energy Group; Indianapolis, Indiana

Utility Contact Name and Contact Information: DEREK SUTTON, dsutton@citizensenergygroup.com

Utility Characteristics: (SEWER ONLY)

- Number of customer accounts/taps: 270,000
- Service area size (sq. miles): 337
- Population served: approx. 800,000
- Total miles of public sanitary sewer (mains only): 2,260

- Total miles of public combined sewer (mains only): 915
- Total miles of lateral sewers (services) in rights-of-way and/or easements: unknown
- Combined Sewer Overflows:
    - Number of CSOs: 1

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
    - CSO reductions ✓
    - Drainage or water quality improvements
    - Flood mitigation
2. We perform GI model evaluations during:
    - Planning ✓
    - Design ✓
    - Post-Construction Monitoring
    - CSO Program annual/semi-annual reporting
3. Evaluations of GI are performed:
    - Within the framework of our collection system model ✓
    - Within the framework of our stormwater system model
    - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model
4. We have modeled the following types of GI:
    - Bioretention /Stormwater planters ✓
    - Tree Boxes ✓
    - Infiltration Trenches
    - Permeable pavement
    - Green Roofs
    - Blue Roofs
    - Swales ✓
    - Ponds & Wetlands
    - Retention ✓

3. General Modeling Approach

5. Our utility models GI by doing the following:
    - Reducing impervious area percentage ✓
    - Increasing initial abstraction/depression storage ✓
    - Increasing evapotranspiration
    - Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption)
    - Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.) ✓

6. Our utility uses the following model(s) to for GI planning/design (check all that apply):

    ✓ InfoWorks

___ USEPA SWMM5

___ PCSWMM

___ XPSWMM

___ Mike Urban

___ Other: ______________________________

7. Our utility models GI in the:
   - 1D pipe network ✓
   - 2D overland flow

8. Our general modeling approach includes (check all that apply):

___ Modeling individual GI facilities/technologies

✓ Lumped modeling approach

Subgrouping for lumped approach (check all that apply):

___ Based on GI type

___ Location within subcatchment(s)

✓ Other: By subcatchment

___ Inlet control/bypass representation

9. We have modeled water quality performance of GI? Yes [✓ No]

   - If Yes, we model water quality performance using (check all that apply):

___ Event mean concentrations (EMCs)

___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

___ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

___ Other: ______________________________

10. Our utility has documented procedures for GI modeling approaches [✓ Yes] No

   - If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

___ Literature reviews on modeling of GI performance

___ Triple Bottom Line / Co-benefits documentation

✓ Other: memorandums for specific projects (will need approval to share)

11. Please provide any additional details beyond what has been requested above.

Currently consider GI to be 50% effective in model representations, i.e. storm sewer separation by reducing impervious area contribution.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

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The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: _Chris Ranck______________________________

Date: _January 19, 2016_____________________________

1. General Information

Utility Name and Location: ___Philadelphia Water ____

Utility Contact Name and Contact Information: __Jessica Brooks, GSI Implementation Program_______________________________________

_(215) 397-7070, Jessica.K.Brooks@phila.gov____

Utility Characteristics:

- Number of customer accounts/taps: _640,000____________
- Service area size (sq. miles): _143__________

- Population served: _1.5 million_______
- Total miles of public sanitary sewer (mains only): _760 (this is total not just mains)__
- Total miles of public combined sewer (mains only): _1800 (this is total not just mains)
- Total miles of lateral sewers (services) in rights-of-way and/or easements: _________________
- Combined Sewer Overflows:
    - Number of CSOs: _______164__________

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
    - CSO reductions (Yes)
    - Drainage or water quality improvements (Yes)
    - Flood mitigation (have done some preliminary evaluations)
2. We perform GI model evaluations during:
    - Planning (Yes)
    - Design
    - Post-Construction Monitoring (may be)
    - CSO Program annual/semi-annual reporting (Yes/ 5 year reports)
3. Evaluations of GI are performed:
    - Within the framework of our collection system model (yes)
    - Within the framework of our stormwater system model (no)
    - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model (yes)
4. We have modeled the following types of GI:
    - Bioretention /Stormwater planters (yes)
    - Tree Boxes (yes)
    - Infiltration Trenches (yes)
    - Permeable pavement (yes)
    - Green Roofs (yes)
    - Blue Roofs (yes)
    - Swales (yes)
    - Ponds & Wetlands (yes)
    - Retention (yes)

3. General Modeling Approach

5. Our utility models GI by doing the following:
    - Reducing impervious area percentage (no)
    - Increasing initial abstraction/depression storage (no)
    - Increasing evapotranspiration (study is underway)
    - Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption) (no)
    - Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.) (yes)

6. Our utility uses the following model(s) to for GI planning/design (check all that apply):

___ InfoWorks

X USEPA SWMM5

___ PCSWMM

___ XPSWMM

___ Mike Urban

___ Other: ______________________________

7. Our utility models GI in the:

- 1D pipe network (yes)
- 2D overland flow (no)

8. Our general modeling approach includes (check all that apply):

___ Modeling individual GI facilities/technologies

X Lumped modeling approach

Subgrouping for lumped approach (check all that apply):

X___ Based on GI type

___ Location within subcatchment(s) (plan on doing this)

___ Other: ______________________________

___ Inlet control/bypass representation

9. We have modeled water quality performance of GI? Yes

- If Yes, we model water quality performance using (check all that apply):

___ Event mean concentrations (EMCs)

___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

X___ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

___ Other: ______________________________

10. Our utility has documented procedures for GI modeling approaches: Yes

- If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

___ Literature reviews on modeling of GI performance

___ Triple Bottom Line / Co-benefits documentation

X__ Other: The process is described in the LTCPU 2009.

11. Please provide any additional details beyond what has been requested above.

New York City DEP Green Infrastructure – Research & Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: Eric Harold, Arcadis

Date: DC Water completed form; reviewed by E Harold 11/16/2015

1. General Information

Utility Name and Location: DC Water, Washington, D.C.

Utility Contact Name and Contact Information: Bethany Bezak (Bethany.bezak@dcwater.com; 202-787-4466)

Utility Characteristics:

- Number of customer accounts/taps: Confirm at dcwater.com
- Service area size (sq. miles): approximately 735 sq. miles (61 within the District of Columbia)
- Population served: > 2 million people (District of Columbia, Montgomery County and Prince George's County MD, Fairfax County and Loudoun County VA)
- Total miles of public sanitary sewer (mains only): 1900 miles total of sanitary and combined

- Total miles of public combined sewer (mains only): Reference previous question

- Total miles of lateral sewers (services) in rights-of-way and/or easements: Confirm at dcwater.com

- Combined Sewer Overflows:
    - Number of CSOs: 47 (active)

- Municipal Separate Storm Sewer System (MS4)? ~~Yes~~ / No
    - If yes, who is responsible for managing the MS4? District of Columbia Department of Environment and Energy – Jeff Seltzer / jeffrey.seltzer@dc.gov

2. Purpose of GI Modeling

➔ Underline is Yes, ~~Strikeout is no~~

1. Our utility has evaluated GI for:
    - CSO reductions
    - Drainage or water quality improvements
    - Flood mitigation
2. We perform GI model evaluations during:
    - Planning
    - Design
    - Post-Construction Monitoring
    - CSO Program annual/semi-annual reporting
3. Evaluations of GI are performed:
    - Within the framework of our collection system model
    - ~~Within the framework of our stormwater system model~~
    - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model
4. We have modeled the following types of GI:
    - Bioretention /Stormwater planters
    - Tree Boxes
    - ~~Infiltration Trenches~~
    - Permeable pavement
    - Green Roofs
    - ~~Blue Roofs~~
    - ~~Swales~~
    - ~~Ponds & Wetlands~~
    - Retention

3. General Modeling Approach

1. Our utility models GI by doing the following:

    →Note: Differs depending on specific modeling exercise

    a. Reducing impervious area percentage
    b. Increasing initial abstraction/depression storage
    c. Increasing evapotranspiration

d. Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption)
e. Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.)

2. Our utility uses the following model(s) to for GI planning/design (check all that apply):

___ InfoWorks

X__ USEPA SWMM5

___ PCSWMM

___ XPSWMM

X__ Mike Urban

X__ Other: Custom calculators/spreadsheets/scripts

3. Our utility models GI in the:
   a. 1D pipe network
   b. 2D overland flow

4. Our general modeling approach includes (check all that apply):

X__ Modeling individual GI facilities/technologies

X__ Lumped modeling approach

Subgrouping for lumped approach (check all that apply):

__X Based on GI type

___ Location within subcatchment(s)

___ Other: ______________________________

X__ Inlet control/bypass representation

5. We have modeled water quality performance of GI? ~~Yes~~ / No

We take water quality into account at the receiving water/CSO level, not the GI practice level.

a. If Yes, we model water quality performance using (check all that apply):

___ Event mean concentrations (EMCs)

___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

___ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

___ Other: ______________________________

6. Our utility has documented procedures for GI modeling approaches: Yes / ~~No~~

   a. If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

___ Literature reviews on modeling of GI performance

___ Triple Bottom Line / Co-benefits documentation

X Other: Technical memos regarding modeling approach (available at dcwater.com, 'resources' section)

7. Please provide any additional details beyond what has been requested above.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: __Sue Pressman, Arcadis_______________________________

Date: __February 2016_______________________________

1. General Information

Utility Name and Location: _Metropolitan Sewer District of Greater Cincinnati ______________

Utility Contact Name and Contact Information: Joe Koran, 513-557-7172, joseph.koran@concinnati-oh.gov ____

Utility Characteristics:

- Number of customer accounts/taps: 230,000______________
- Service area size (sq. miles): 290+______________
- Population served: 850,000__________________
- Total miles of public sanitary sewer (mains only): 3,000 miles sanitary & combined__________

- Total miles of public combined sewer (mains only): ____________________
- Total miles of lateral sewers (services) in rights-of-way and/or easements: _NA________________
- Combined Sewer Overflows:
  - Number of CSOs: 270__________

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
   - CSO reductions
   - Drainage or water quality improvements
   - Flood mitigation
2. We perform GI model evaluations during:
   - Planning
   - Design
   - Post-Construction Monitoring
   - CSO Program annual/semi-annual reporting
3. Evaluations of GI are performed:
   - Within the framework of our collection system model
   - Within the framework of our stormwater system model
   - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model
4. We have modeled the following types of GI:
   - Bioretention /Stormwater planters
   - Tree Boxes
   - Infiltration Trenches
   - Permeable pavement
   - Green Roofs
   - Blue Roofs
   - Swales
   - Ponds & Wetlands
   - Retention

3. General Modeling Approach

5. Our utility models GI by doing the following:
   - Reducing impervious area percentage
   - Increasing initial abstraction/depression storage
   - Increasing evapotranspiration
   - Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption)
   - Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.)

6. Our utility uses the following model(s) to for GI planning/design (check all that apply):

   ____ InfoWorks

X__ USEPA SWMM5

X__ PCSWMM

___ XPSWMM

___ Mike Urban

___ Other: ____

7. Our utility models GI in the:
    - [✓ 1D pipe network]
    - 2D overland flow

8. Our general modeling approach includes (check all that apply):

X__ Modeling individual GI facilities/technologies

X__ Lumped modeling approach

Subgrouping for lumped approach (check all that apply):

X__ Based on GI type

X__ Location within subcatchment(s)

___ Other: ____

X__ Inlet control/bypass representation

9. We have modeled water quality performance of GI? [✓ Yes, but not in SWMM] / No

- If Yes, we model water quality performance using (check all that apply):

X__ Event mean concentrations (EMCs)

X__ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

X__ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

X__ Other: GI water quality performance has not been performed through SWMM. WinSLAMM has been used for the Lick Ryun watershed project, and for other partnership projects such as Cincinnati State and the Cincinnati Zoo._________

10. Our utility has documented procedures for GI modeling approaches: [✓ Yes] / No

- If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

___ Literature reviews on modeling of GI performance

___ Triple Bottom Line / Co-benefits documentation

X__ Other: MSDGC Modeling guidelines and Standards, Version 3, 2013, Section 6.13. Guidelines is located on website at msdgc.org__________________________

11. Please provide any additional details beyond what has been requested above.

MSD has been primarily focused on larger public source control and stormwater detention projects using green infrastructure rather than private property implementation.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: Jerry Kleyman & Laura McGinnis, Arcadis

Date: March 2, 2016

1. General Information

Utility Name and Location: Metropolitan Sewer District – Louisville, KY

Utility Contact Name and Contact Information:

Stephanie Laughlin, MSD, (502)540-6000 stephanie.laughlin@louisvillemsd.org_

Bill Sanders, Heritage Engineering, (502) 562-1412

Utility Characteristics:

- Number of customer accounts/taps: 220,000
- Service area size (sq. miles): 385
- Population served: 700,000

- Total miles of public sanitary sewer (mains only): 2,660
- Total miles of public combined sewer (mains only): 540_

- Total miles of lateral sewers (services) in rights-of-way and/or easements: _________________

- Combined Sewer Overflows:
  - Number of CSOs: ____________________

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
   - CSO reductions - Yes
   - Drainage or water quality improvements - Yes
   - Flood mitigation Yes, partially.
2. We perform GI model evaluations during:
   - Planning- Yes
   - Design - Yes
   - Post-Construction Monitoring No, but will be utilized in the future
   - CSO Program annual/semi-annual reporting No, but will be used to support reporting
3. Evaluations of GI are performed:
   - Within the framework of our collection system model - Yes
   - Within the framework of our stormwater system model No
   - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model Any stormwater modeling in the separate sanitary system is in a separate framework and not integrated with the InfoWorks model.
4. We have modeled the following types of GI:
   - Bioretention /Stormwater planters - Yes
   - Tree Boxes- Yes
   - Infiltration Trenches - Yes
   - Permeable pavement - Yes
   - Green Roofs No
   - Blue Roofs No
   - Swales No
   - Ponds & Wetlands No
   - Retention - Yes

3. General Modeling Approach

5. Our utility models GI by doing the following:
   - Reducing impervious area percentage- Yes, used for initial evaluations of GI impacts and benefits
   - Increasing initial abstraction/depression storage No
   - Increasing evapotranspiration No
   - Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption) – Yes, used for a more detailed analysis of GI alternatives

- Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.) – Yes, used for a more detailed analysis of GI alternatives

6. Our utility uses the following model(s) to for GI planning/design (check all that apply):

_X_ InfoWorks

___ USEPA SWMM5

___ PCSWMM

___ XPSWMM

___ Mike Urban

___ Other: ____

7. Our utility models GI in the:
   - 1D pipe network – Yes
   - 2D overland flow – Yes

8. Our general modeling approach includes (check all that apply):

_X_ Modeling individual GI facilities/technologies – Yes, during more detailed GI analyses and during capital costs evaluations

_X_ Lumped modeling approach – Yes, first used to determine the benefits of GI before migrating to individual GI modeling (see above)

Subgrouping for lumped approach (check all that apply):

___ Based on GI type

_X Location within subcatchment(s)

_X_ Other: Where GI opportunities exist________________________

____X Inlet control/bypass representation

9. We have modeled water quality performance of GI? Yes / [✓ No]

- If Yes, we model water quality performance using (check all that apply):

___ Event mean concentrations (EMCs)

___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

___ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

___ Other: ____

10. Our utility has documented procedures for GI modeling approaches: Yes / No, no formal SOPs have been developed. They are currently being developed.

- If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

____ Literature reviews on modeling of GI performance

____ Triple Bottom Line / Co-benefits documentation

____ Other: ____

11. Please provide any additional details beyond what has been requested above.

Louisville MSD is half way through the implementation of the Consent Decree. They have completed demonstrative GI projects as well as full scale GI implementation. MSD uses GI modeling to first evaluate the potential benefit of GI on a large scale, then, if found feasible, to evaluate GI at a more detailed scale. The use of GI eliminated the need for Gray Infrastructure in two CSO basins (CSO 130 and CSO 190). In other CSO basins (CSO019), GI was evaluated as an alternative but ultimately not selected. Per their Consent Decree they are to spend $47M on GI projects. At this point in the implementation they are also using GI to supplement deficiencies realized after the completion of Gray Instructure and to reduce AAOV.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: __Chris Ranck______________________________

Date: __11/20/2015______________________________

1. General Information

Utility Name and Location: __Metropolitan Water Reclamation District of Greater Chicago_(MWRDGC), Chicago, IL____

Utility Contact Name and Contact Information: _Richard Fisher, FisherR@mwrd.org>;

____

Utility Characteristics:

- Number of customer accounts/taps: __10,000 from individual communities and cities___________
- Service area size (sq. miles): __883.5___________
- Population served: ___5.25 million______________

- Total miles of public sanitary sewer (mains only): ____
- Total miles of public combined sewer (mains only): ____554_________________
- Total miles of lateral sewers (services) in rights-of-way and/or easements: __________________
- Combined Sewer Overflows:
  - Number of CSOs: _______39___________

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
   - CSO reductions
   - Drainage or water quality improvements
   - Flood mitigation
2. We perform GI model evaluations during: **(MWRDGC has not been directly involved in GI modeling efforts)**
   - Planning
   - Design
   - Post-Construction Monitoring
   - CSO Program annual/semi-annual reporting
3. Evaluations of GI are performed:
   - Within the framework of our collection system model
   - Within the framework of our stormwater system model
   - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model
4. We have modeled the following types of GI:
   - Bioretention /Stormwater planters
   - Tree Boxes
   - Infiltration Trenches
   - Permeable pavement
   - Green Roofs
   - Blue Roofs
   - Swales
   - Ponds & Wetlands
   - Retention

3. General Modeling Approach

1. Our utility models GI by doing the following: **(MWRDGC has not been directly involved in GI modeling efforts)**
   - Reducing impervious area percentage
   - Increasing initial abstraction/depression storage
   - Increasing evapotranspiration
   - Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption)
   - Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.)

2. Our utility uses the following model(s) to for GI planning/design (check all that apply):

    ___ InfoWorks

    ___ USEPA SWMM5

    ___ PCSWMM

    ___ XPSWMM

    ___ Mike Urban

    ___ Other: ____

3. Our utility models GI in the:
    - 1D pipe network
    - 2D overland flow

4. Our general modeling approach includes (check all that apply):

    ___ Modeling individual GI facilities/technologies

    ___ Lumped modeling approach

    Subgrouping for lumped approach (check all that apply):

    ___ Based on GI type

    ___ Location within subcatchment(s)

    ___ Other: ____

    ___ Inlet control/bypass representation

5. We have modeled water quality performance of GI? Yes / **No**

    - If Yes, we model water quality performance using (check all that apply):

    ___ Event mean concentrations (EMCs)

    ___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

    ___ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

    ___ Other: ____

6. Our utility has documented procedures for GI modeling approaches: Yes / **No**

    - If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

    ___ Literature reviews on modeling of GI performance

___ Triple Bottom Line / Co-benefits documentation

___ Other: ____

7. Please provide any additional details beyond what has been requested above.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: ________________________________

Date: February 3, 2016

1. General Information

Utility Name and Location:

Northeast Ohio Regional Sewer District (NEORSD); Cleveland, Ohio

Utility Contact Name and Contact Information:

Devona A. Marshall, P.E.
Deputy Director of Engineering & Construction
Engineering & Construction Department
Northeast Ohio Regional Sewer District
216-881-6600 ext. 6452
marshalld@neorsd.org

Utility Characteristics:

- Number of customer accounts/taps: approx. 327,000 customer accounts
- Service area size (sq. miles): 365 sq. miles including 81 sq. miles of combined area
- Population served: Approx. approx.1 million

- Total miles of public sanitary sewer (mains only):
- Total miles of public combined sewer (mains only):
  Approx. 315 miles of NEORSD-owned sanitary or combined sewers/interceptors/tunnels; 3600+ miles of locally-owned sanitary or combined sewers

- Total miles of lateral sewers (services) in rights-of-way and/or easements: not available

- Combined Sewer Overflows:
  - Number of CSOs: 122 permitted CSOs plus 2 permitted plant bypasses. Over 400 tributary regulators to CSOs.

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
   - CSO reductions
   - Drainage or water quality improvements
   - Flood mitigation
2. We perform GI model evaluations during:
   - Planning
   - Design
   - Post-Construction Monitoring (required as part of CSO CD performance compliance)
   - CSO Program annual/semi-annual reporting
3. Evaluations of GI are performed:
   - Within the framework of our collection system model
   - Within the framework of our stormwater system model (anticipate this will be the case as the stormwater projects move forward under recently reinstated Regional Stormwater Program)
   - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model
4. We have modeled the following types of GI:
   - Bioretention /Stormwater planters
   - Tree Boxes
   - Infiltration Trenches
   - Permeable pavement
   - Green Roofs
   - Blue Roofs
   - Swales
   - Ponds & Wetlands
   - Retention

3. General Modeling Approach

5. Our utility models GI by doing the following: NEORSD modeling standards/protocols for combined sewer systems have been provided in response to this question. The NEORSD is also in the process of developing stormwater modeling standards that can be provided upon completion.
    - Reducing impervious area percentage
    - Increasing initial abstraction/depression storage
    - Increasing evapotranspiration
    - Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption)
    - Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.)

6. Our utility uses the following model(s) to for GI planning/design (check all that apply):

    ___ [✓ InfoWorks] (This is NEORSD's standard model platform for combined system modeling and planned standard platform for separate sanitary system modeling.

    ___ USEPA SWMM5

    ___ PCSWMM

    ___ XPSWMM

    ___ Mike Urban

    ___ [✓ Other:] Other various modeling programs are used by designers to size facilities.

7. Our utility models GI in the:
    - [✓ 1D pipe network]
    - 2D overland flow

8. Our general modeling approach includes (check all that apply):

    NEORSD modeling standards/protocols for combined sewer systems have been provided in response to this question. The NEORSD is also in the process of developing stormwater modeling standards that can be provided upon completion.

    ___ Modeling individual GI facilities/technologies

    ___ Lumped modeling approach

    Subgrouping for lumped approach (check all that apply):

    ___ Based on GI type

    ___ Location within subcatchment(s)

    ___ Other: ____

    ___ Inlet control/bypass representation

9. We have modeled water quality performance of GI? Yes / [✓ No]

- If Yes, we model water quality performance using (check all that apply):

___ Event mean concentrations (EMCs)

___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

___ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

___ Other: ____

10. Our utility has documented procedures for GI modeling approaches: [✓ Yes] / No

- If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

___ Literature reviews on modeling of GI performance

___ Triple Bottom Line / Co-benefits documentation

NEORSD performed an anticipated co-benefit analysis for GI being implemented as part of CSO Consent Decree. This report is available on the NEOSD's web page:

http://www.neorsd.org/I_Library.php?SOURCE=library/Co-Benefits_Report_FINAL_032715.pdf&a=download_file&LIBRARY_RECORD_ID=6519

___ Other: NEORSD modeling standards/protocols for combined sewer systems have been provided in response to this survey. The NEORSD is also in the process of developing stormwater modeling standards that can be provided upon completion.

11. Please provide any additional details beyond what has been requested above.

NEORSD has also established flow monitoring standards which have been provided in response to this survey.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Form completed by:

Name: Matthew Marko

Date: October 27, 2015

1. General Information

Utility Name and Location: Onondaga County (Syracuse) NY

Utility Contact Name and Contact Information: Matt Marko (CH2M), GI Program Manager

Utility Characteristics:

- Number of customer accounts/taps: NA
- Service area size (sq. miles): 11
    - Source: 2014 ACI report
- Population served: ________________
- Total miles of public sanitary sewer (mains only): 17

- Total miles of public combined sewer (mains only): 69 (Combined and trunk sewers)
- Total miles of lateral sewers (services) in rights-of-way and/or easements: ___________________
- Combined Sewer Overflows:
  - Number of CSOs: 26 current operational CSOs (originally 72; "operational" defined as discharging during a 1-year 2-hour design storm)
- Municipal Separate Storm Sewer System (MS4)? ~~Yes~~ / No
  - If yes, who is responsible for managing the MS4? Name / Contact information
  - Note: City of Syracuse has some MS4 obligations within the City limits, although most of the system is combined

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
   - CSO reductions
   - ~~Drainage or water quality improvements~~
   - ~~Flood mitigation~~
2. We perform GI model evaluations during:
   - Planning
   - Design
   - Post-Construction Monitoring
   - CSO Program annual/semi-annual reporting
3. Evaluations of GI are performed:
   - Within the framework of our collection system model
   - ~~Within the framework of our stormwater system model~~
   - In a separate model *(post-processing spreadsheet calculations)* prepared for focused GI evaluations, and external linkage to collection system ~~or stormwater system~~ model
4. We have modeled the following types of GI:
   - Bioretention /Stormwater planters
   - Tree Boxes
   - Infiltration Trenches
   - Permeable pavement
   - Green Roofs
   - ~~Blue Roofs~~
   - Swales
   - Ponds & Wetlands
   - Retention

3. General Modeling Approach

1. Our utility models GI by doing the following:
   a. Reducing impervious area percentage
   ~~b. Increasing initial abstraction/depression storage~~
   ~~c. Increasing evapotranspiration~~
   d. Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption)

e. Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.)

2. Our utility uses the following model(s) to for GI planning/design (check all that apply):

___ InfoWorks

_X_ USEPA SWMM5

_X_ PCSWMM

___ XPSWMM

_X_ Mike Urban

___ Other: ____________________

3. Our utility models GI in the:
   a. 1D pipe network
   b. 2D overland flow
   c. Other: Hydrology and hydraulics of 1D SWMM model

4. Our general modeling approach includes (check all that apply):

_X_ Modeling individual GI facilities/technologies

___ Lumped modeling approach

Subgrouping for lumped approach (check all that apply):

___ Based on GI type

___ Location within subcatchment(s)

___ Other: ____________________

___ Inlet control/bypass representation

5. We have modeled water quality performance of GI? ~~Yes~~ / No

   a. If Yes, we model water quality performance using (check all that apply):

___ Event mean concentrations (EMCs)

___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

___ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

___ Other: ____________________

6. Our utility has documented procedures for GI modeling approaches: Yes / ~~No~~

a. If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

___ Literature reviews on modeling of GI performance

___ Triple Bottom Line / Co-benefits documentation

_X_ Other: ACJ Reports (methodology based on SWMM LID module documentation)

7. Please provide any additional details beyond what has been requested above.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: _Chris Ranck______________________________

Date: _January 19, 2016_____________________________

1. General Information

Utility Name and Location: ___Philadelphia Water
____

Utility Contact Name and Contact Information: __Jessica Brooks, GSI Implementation Program_____________________________________

_(215) 397-7070, Jessica.K.Brooks@phila.gov____

Utility Characteristics:

- Number of customer accounts/taps: _640,000____________
- Service area size (sq. miles): _143__________

- Population served: _1.5 million_______
- Total miles of public sanitary sewer (mains only): _760 (this is total not just mains)__
- Total miles of public combined sewer (mains only): _1800 (this is total not just mains)
- Total miles of lateral sewers (services) in rights-of-way and/or easements: _________________
- Combined Sewer Overflows:
  - Number of CSOs: _______164__________

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
   - CSO reductions (Yes)
   - Drainage or water quality improvements (Yes)
   - Flood mitigation (have done some preliminary evaluations)
2. We perform GI model evaluations during:
   - Planning (Yes)
   - Design
   - Post-Construction Monitoring (may be)
   - CSO Program annual/semi-annual reporting (Yes/ 5 year reports)
3. Evaluations of GI are performed:
   - Within the framework of our collection system model (yes)
   - Within the framework of our stormwater system model (no)
   - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model (yes)
4. We have modeled the following types of GI:
   - Bioretention /Stormwater planters (yes)
   - Tree Boxes (yes)
   - Infiltration Trenches (yes)
   - Permeable pavement (yes)
   - Green Roofs (yes)
   - Blue Roofs (yes)
   - Swales (yes)
   - Ponds & Wetlands (yes)
   - Retention (yes)

3. General Modeling Approach

5. Our utility models GI by doing the following:
   - Reducing impervious area percentage (no)
   - Increasing initial abstraction/depression storage (no)
   - Increasing evapotranspiration (study is underway)
   - Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption) (no)
   - Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.) (yes)

6. Our utility uses the following model(s) to for GI planning/design (check all that apply):

___ InfoWorks

X USEPA SWMM5

___ PCSWMM

___ XPSWMM

___ Mike Urban

___ Other: ________________________________

7. Our utility models GI in the:
- 1D pipe network (yes)
- 2D overland flow (no)

8. Our general modeling approach includes (check all that apply):

___ Modeling individual GI facilities/technologies

X Lumped modeling approach

Subgrouping for lumped approach (check all that apply):

X Based on GI type

___ Location within subcatchment(s) (plan on doing this)

___ Other: ________________________________

___ Inlet control/bypass representation

9. We have modeled water quality performance of GI? Yes

- If Yes, we model water quality performance using (check all that apply):

___ Event mean concentrations (EMCs)

___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

X Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

___ Other: ________________________________

10. Our utility has documented procedures for GI modeling approaches: Yes

- If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

___ Literature reviews on modeling of GI performance

___ Triple Bottom Line / Co-benefits documentation

X__ Other: The process is described in the LTCPU 2009.

11. Please provide any additional details beyond what has been requested above.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: ________________________________

Date: ________________________________

1. General Information

Utility Name and Location: Bureau of Environmental Services, City of Portland, OR

Utility Contact Name and Contact Information: Arnel Mandilag, arnel.mandilag@portlandoregon.gov, 503-823-7267

Utility Characteristics:

- Number of customer accounts/taps: _____________
- Service area size (sq. miles): 145 sq mi
- Population served: _________________

- Total miles of public sanitary sewer (mains only): 1001 mi

- Total miles of public combined sewer (mains only): 910 mi

- Total miles of lateral sewers (services) in rights-of-way and/or easements: ________________

- Combined Sewer Overflows:
    - Number of CSOs: limited, on average, to 4-5 per year (4 per winter, 0.3 per summer)

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
    - CSO reductions - yes
    - Drainage or water quality improvements - yes
    - Flood mitigation – yes (Basement backup risk)
2. We perform GI model evaluations during:
    - Planning - yes
    - Design - yes
    - Post-Construction Monitoring - rarely
    - CSO Program annual/semi-annual reporting - no
3. Evaluations of GI are performed:
    - Within the framework of our collection system model - yes
    - Within the framework of our stormwater system model – usually (this is not yet well developed; we're in the middle of a stormwater system planning effort)
    - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model - no
4. We have modeled the following types of GI:
    - Bioretention /Stormwater planters - yes
    - Tree Boxes - no
    - Infiltration Trenches - yes
    - Permeable pavement - yes
    - Green Roofs - yes
    - Blue Roofs - no
    - Swales - yes
    - Ponds & Wetlands - yes
    - Retention - yes

3. General Modeling Approach

5. Our utility models GI by doing the following:
    - Reducing impervious area percentage - Yes
    - Increasing initial abstraction/depression storage – Yes (trees)
    - Increasing evapotranspiration - No
    - Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption) - No
    - Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.) - Yes

6. Our utility uses the following model(s) to for GI planning/design (check all that apply):

___ InfoWorks

Y USEPA SWMM5 (Currently, SWMM 4 for Hydrology; Planned for cutover to SWMM 5 next year)

___ PCSWMM

Y XPSWMM (Currently, for hydraulics only)

Y Mike Urban (Currently, for hydraulics only)

___ Other: ____

7. Our utility models GI in the:
   - 1D pipe network - yes
   - 2D overland flow - no

8. Our general modeling approach includes (check all that apply):

Y Modeling individual GI facilities/technologies

Y Lumped modeling approach

Subgrouping for lumped approach (check all that apply):

Y Based on GI type – generally divide our GIs between parking, roof, and right-of-way controls and lump parking and roof into a subcatchment; ROW controls are each modeled on their own

___ Location within subcatchment(s)

___ Other: ____

___ Inlet control/bypass representation

9. We have modeled water quality performance of GI? Yes / No - No

   - If Yes, we model water quality performance using (check all that apply):

___ Event mean concentrations (EMCs)

___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

___ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

___ Other: ____

10. Our utility has documented procedures for GI modeling approaches: Yes / No - Yes

    - If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

Y Literature reviews on modeling of GI performance – I don't believe I've seen this, but I know of it being done

Y Triple Bottom Line / Co-benefits documentation – I haven't seen this either, but I think we have a document for it

Y Other: Modeling procedures____

11. Please provide any additional details beyond what has been requested above.

We are currently redeveloping our methods for modeling green infrastructure to a more standardized way, and to account for the more varied versions of inflow controls that are being developed.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: **John Ross, Arcadis**

Date: **1/14/16**

1. General Information

Utility Name and Location: **Pittsburgh Water & Sewer Authority – City of Pittsburgh, PA**

Utility Contact Name and Contact Information:

James Stitt – Manager of Sustainability
412.255.8800 x8544
jstitt@pgh2o.com
Pittsburgh Water and Sewer Authority
1200 Penn Ave, Pittsburgh PA 15222

Utility Characteristics:

- Number of customer accounts/taps: **83,000**
- Service area size (sq. miles): **58 sq. miles**
- Population served: **325,000**

- Total miles of public sanitary sewer (mains only): **1,200 mi**
- Total miles of public combined sewer (mains only): **925 mi**
- Total miles of lateral sewers (services) in rights-of-way and/or easements: __________________
- Combined Sewer Overflows:
  - Number of CSOs: **194**

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
   - CSO reductions
   - Drainage or water quality improvements
   - Flood mitigation
2. We perform GI model evaluations during:
   - Planning
   - Design
   - Post-Construction Monitoring
   - CSO Program annual/semi-annual reporting
3. Evaluations of GI are performed:
   - Within the framework of our collection system model
   - ~~Within the framework of our stormwater system model~~
   - ~~In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model~~
4. We have modeled the following types of GI:
   - Bioretention /Stormwater planters
   - ~~Tree Boxes~~
   - Infiltration Trenches
   - ~~Permeable pavement~~
   - ~~Green Roofs~~
   - ~~Blue Roofs~~
   - ~~Swales~~
   - ~~Ponds & Wetlands~~
   - ~~Retention~~

3. General Modeling Approach

5. Our utility models GI by doing the following:
   - ~~Reducing impervious area percentage~~
   - ~~Increasing initial abstraction/depression storage~~
   - ~~Increasing evapotranspiration~~
   - Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption)
   - ~~Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.)~~

6. Our utility uses the following model(s) to for GI planning/design (check all that apply):

___ ~~InfoWorks~~

X___ USEPA SWMM5

X___ PCSWMM

___ ~~XPSWMM~~

___ ~~Mike Urban~~

___ ~~Other:~~ ____________________

7. Our utility models GI in the:
   - 1D pipe network
   - ~~2D overland flow~~

8. Our general modeling approach includes (check all that apply):

X___ Modeling individual GI facilities/technologies

X___ Lumped modeling approach

Subgrouping for lumped approach (check all that apply):

___ ~~Based on GI type~~

X___ Location within subcatchment(s)

___ ~~Other:~~ ____________________

X___ Inlet control/bypass representation

9. We have modeled water quality performance of GI? Yes / [✓ No]

- ~~If Yes, we model water quality performance using (check all that apply):~~

___ ~~Event mean concentrations (EMCs)~~

___ ~~Unit processes that account for settling, adsorption etc. based on detailed representation in the model~~

___ ~~Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)~~

___ ~~Other~~: ____________________

10. Our utility has documented procedures for GI modeling approaches: [✓ Yes] / No

- If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

___ ~~Literature reviews on modeling of GI performance~~

In Process Triple Bottom Line / Co-benefits documentation

X__ Other: Step-by-Step procedures for SWMM LID

11. Please provide any additional details beyond what has been requested above.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: _Chris Ranck, Arcadis_______________________________

Date: ___11/4/2015____________________________

1. General Information

Utility Name and Location: _Seattle Public Utilities_________________________________

Utility Contact Name and Contact Information: _Tracy Tackett (206) 386-0052 Tracy.Tackett@seattle.gov____

Utility Characteristics:

- Number of customer accounts/taps: _____________
- Service area size (sq. miles): ___84___- KTCWD serves 420 sq. miles separately
- Population served: __630,000 by SPU, 1.5 million by KTCWD_______________
- Total miles of public sanitary sewer (mains only): ____448________________________________
- Total miles of public combined sewer (mains only): ___520_________________

- Total miles of lateral sewers (services) in rights-of-way and/or easements: _________________

- Combined Sewer Overflows:
  - Number of CSOs: 87 – a separate 38 are managed by King County Wastewater Treatment Division (KCWTD)

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
   - **CSO reductions**
   - Drainage or water quality improvements
   - Flood mitigation
2. We perform GI model evaluations during:
   - **Planning**
   - **Design**
   - Post-Construction Monitoring
   - CSO Program annual/semi-annual reporting
3. Evaluations of GI are performed:
   - Within the framework of our collection system model
   - Within the framework of our stormwater system model
   - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model
4. We have modeled the following types of GI:
   - **Bioretention /Stormwater planters – also consider deep infiltration techniques**
   - Tree Boxes
   - Infiltration Trenches
   - **Permeable pavement**
   - Green Roofs
   - Blue Roofs
   - **Swales – as "Cascade Bioretention"**
   - Ponds & Wetlands
   - **Retention – As cisterns (modeled as bioretention)**

3. General Modeling Approach

5. Our utility models GI by doing the following:
   - Reducing impervious area percentage
   - Increasing initial abstraction/depression storage
   - Increasing evapotranspiration
   - **Physically representing the planned GI using built-in model features (i.e. SWMM LID**, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption)
   - Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.)

6. Our utility uses the following model(s) to for GI planning/design (check all that apply):

   ____ InfoWorks

X__ USEPA SWMM5

___ PCSWMM

___ XPSWMM

___ Mike Urban

X__ Other: Washington DOT MGSFlood Model – HSPF derived program

7. Our utility models GI in the:
   - **1D pipe network**
   - 2D overland flow

8. Our general modeling approach includes (check all that apply):

X__ Modeling individual GI facilities/technologies

X__ Lumped modeling approach

Subgrouping for lumped approach (check all that apply):

__X Based on GI type

__X Location within subcatchment(s)

___ Other: ___

___ Inlet control/bypass representation

9. We have modeled water quality performance of GI? Yes / **No**

- If Yes, we model water quality performance using (check all that apply):

___ Event mean concentrations (EMCs)

___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

___ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

___ Other: ___

10. Our utility has documented procedures for GI modeling approaches: **Yes** / No

- If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

___ Literature reviews on modeling of GI performance

___ Triple Bottom Line / Co-benefits documentation

X Other: Green Storwmater Infrastructure Modeling Methods (SPU, February 2014)

11. Please provide any additional details beyond what has been requested above.

New York City DEP – Green Infrastructure (GI) Research and Development

GI Performance Modeling Procedures Questionnaire

New York City Department of Environmental Protection (DEP) has been undertaking system-wide evaluation of green infrastructure (GI) performance since 2010, starting with pilot (site-scale), demonstration (neighborhood-scale) and in the future subwatershed/watershed-scale evaluations. As part of this, DEP desires to develop a set of state-of-the-science water quantity and quality modeling and scale-up practices that can be applied to data gathered at pilot/demonstration scale applications as well as procedures for predicting future performance of GI in attaining targeted stormwater control (e.g., capture of 1-inch of runoff) and targeted CSO reductions at end-of-pipe, along with estimation of associated pollutant load reductions.

The purpose of this Questionnaire is to support the documenting of other selected utilities' GI modeling programs/procedures in the areas of:

- Purpose (Drivers/priorities)
- General GI modeling approaches
- Tools for GI evaluations
- Calibration/validation of tools and associated field investigations
- Emerging Ideas (e.g., climate change, sustainability, etc.)

DEP will use this information along with its current practices to develop updated GI modeling guidelines.

Data and information acquired from the Questionnaire's application, and information resulting from interviews of NYC DEP staff and review of existing NYC DEP documentation on current DEP-specific modeling practices will be memorialized in a "benchmarking" technical memorandum (TM). When finalized, this TM will be shared with utilities responding to this survey for reference. DEP sincerely appreciates your timely response to this survey.

Interview conducted by:

Name: ________________________________

Date: ________________________________

1. General Information

Utility Name and Location:

San Francisco Public Utilities Commission (SFPUC)

San Francisco, CA____

Utility Contact Name and Contact Information: _

Sarah Minick (sminick@sfwater.org) – SFPUC

Scott Durbin (sdurbin@lotuswater.com) - Lotus Water (Consultant)

Utility Characteristics:

- Number of customer accounts/taps: _____________

- Service area size (sq. miles): _47 sq. mi, 90% is combined sewer____________
- Population served: _800,000 residents and daytime population of 1.5 million________________
- Total miles of public sanitary sewer (mains only): ____________________________________
- Total miles of public combined sewer (mains only): __1000__________________
- Total miles of lateral sewers (services) in rights-of-way and/or easements: _________________
- Combined Sewer Overflows:
  - Number of CSOs: Varies by receiving water – design criteria in Permit is less than or equal to 8 per year at Ocean outfalls, 4 in northern bayfront, 10 in central bayfront, 1 in southern bayfront. All overflows receive "equivalent primary" treatment in the form of baffling and settling prior to discharge.

2. Purpose of GI Modeling

1. Our utility has evaluated GI for:
    - CSO reductions - Yes
    - Drainage or water quality improvements - Yes
    - Flood mitigation - Yes
2. We perform GI model evaluations during:
    - Planning - Yes
    - Design - Yes
    - Post-Construction Monitoring – We use results from post-construction monitoring to help validate model assumptions, but most modeling approaches were developed using industry standards based on research and available non-local data. Local post-construction monitoring of GI by the SFPUC is in its relative infancy, having begun about 3 years ago.
    - CSO Program annual/semi-annual reporting – Results of GI modeling have been used in CSO reports requested by the permitting authority, but the City is not under a consent decree and is not required to show performance results tied to GI as part of annual reporting.
3. Evaluations of GI are performed:
    - Within the framework of our collection system model - Yes
    - Within the framework of our stormwater system model – 90% of the system is combined, there is not a separate stormwater system model.
    - In a separate model prepared for focused GI evaluations, and external linkage to collection system or stormwater system model – This has occurred to evaluate specific planned projects or proposed GI programs. Typically, external evaluations are done in SWMM (EPA, XP, or PC-SWMM), with EPA SWMM being the most common. Results are typically translated back to the collection system model via a time series input, change in impervious area, or more commonly, via a special runoff surface created to mimic the performance of the GI project or program.
4. We have modeled the following types of GI:
    - Bioretention /Stormwater planters - Yes
    - Tree Boxes – No
    - Infiltration Trenches - Yes
    - Permeable pavement - Yes
    - Green Roofs - Yes

- Blue Roofs - Yes
- Swales – Minimally, typically not a great fit for the density of SF and the performance needs of the combined sewer.
- Ponds & Wetlands – Large-scale stormwater management BMPs are typically modeled directly in InfoWorks using storage nodes and links.
- Retention – We've modeled rainwater harvesting, and rainwater harvesting with detention. If this is referencing retention ponds, we have not really modeled those other than to evaluate expected losses from existing ponds in park areas. Largely those losses were estimated based on flow monitoring and calibration rather than direct representation.

3. General Modeling Approach

5. Our utility models GI by doing the following:

The most typical employed methodology is to create runoff surfaces in InfoWorks ICM that simulate the performance of various GI types. We have created approximately 12 or so GI runoff surfaces, typically large and small sizes of the most common BMP types (bioretention, permeable pavement, green streets, infiltration gallery/trench, rainwater harvesting). The entire drainage area feeding a BMP is converted to the runoff surface type. All GI types were modeled directly in EPA SWMM first and results were translated back into ICM runoff surfaces. For larger-scale BMPs, such as creek daylighting and detention basins, we recommend coding them into the ICM model directly. We rarely code small-scale BMPs into the model directly because of the existing complexity of the model and the added computation time it would cause and because it's easier to isolate the storm flows from the sanitary flows if the representation happens at the subcatchment level rather than in the network.

- Reducing impervious area percentage – for planning level analyses, on occasion
- Increasing initial abstraction/depression storage – yes, as part of building a runoff surface that represents a GI type.
- Increasing evapotranspiration – typically only in spreadsheet models running hydrograph calcs that were built to help developers comply with the redevelopment stormwater management requirements.
- Physically representing the planned GI using built-in model features (i.e. SWMM LID, InfoWorks SUDS, etc.) available as unit processes (e.g., bottom/side infiltration, evaporation, transpiration, nutrient uptake, and adsorption) – See above answer. Yes in SWMM, but typically those results are translated back to InfoWorks in the form of a runoff surface, not via SUDS.
- Physically representing the planned GI using a customized hydraulic representations (e.g., storage, seepage, storm inlet configuration/capacity, etc.) – Yes for larger-scale BMPs.

6. Our utility uses the following model(s) to for GI planning/design (check all that apply):

x___ InfoWorks

x___ USEPA SWMM5

____ PCSWMM

____ XPSWMM

____ Mike Urban

___ Other: ______________________________

7. Our utility models GI in the:
    - 1D pipe network
    - 2D overland flow

    See response under #6. Most commonly modeled within the subcatchment. Creek daylighting has been modeled within the 2D mesh. Detention Basins have been modeled via 1D pipe network.

8. Our general modeling approach includes (check all that apply):

    x___ Modeling individual GI facilities/technologies

    x___ Lumped modeling approach

    Subgrouping for lumped approach (check all that apply):

    __x_ Based on GI type

    ___ Location within subcatchment(s)

    ___ Other: ______________________________

    x___ Inlet control/bypass representation (has been done, typically only for large scale BMPs, e.g., creek daylighting and detention basins)

9. We have modeled water quality performance of GI? Yes / No - No, modeling has focused on combined portion of system and WQ has not been as much of a driver.

    - If Yes, we model water quality performance using (check all that apply):

    ___ Event mean concentrations (EMCs)

    ___ Unit processes that account for settling, adsorption etc. based on detailed representation in the model

    ___ Percent removal or reductions (annual/seasonal) based on literature values (e.g., International BMP database, National Stormwater Quality Database)

    ___ Other: ______________________________

10. Our utility has documented procedures for GI modeling approaches: Yes / No Yes, we have written up our procedures in a modeling approach TM. This document is not currently public and likely could not be shared at this time. Other reports produced for the SFPUC touch on a number of the GI modeling approaches, literature review results, and TBL output. Some of these likely could be shared.

    - If yes, please indicate below what types of documentation has been completed, and whether you would be willing to share these with NYC DEP (check all that apply):

___ Literature reviews on modeling of GI performance

___ Triple Bottom Line / Co-benefits documentation

___ Other: ____

11. Please provide any additional details beyond what has been requested above.

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MEMO

To:
New York City Department of Environmental Protection

From:
Arcadis Team

Date:
April 13, 2016

Subject:
GI-RD Task 2.3 – Microscale Modeling Approach

1.0 INTRODUCTION

The 2012 Order on Consent (the Order) between the New York City Department of Environmental Protection (DEP) and the New York State Department of Environmental Conservation (DEC) requires the City to develop and submit to DEC combined sewer overflow (CSO) performance metrics, including the cumulative Citywide CSO volume reduction associated with the implementation of green infrastructure (GI) to manage stormwater runoff from 1.5% of the impervious cover within combined sewer tributary areas. Additionally, DEP is required to report an equivalency rate based on the 1.5% GI implementation. InfoWorks CS (InfoWorks) models initially developed as part of the Long Term Control Plan (LTCP) efforts were utilized to assess performance of these GI assets. This memorandum summarizes the development and validation of the distributed modeling approach used to predict performance of constructed or to be constructed GI assets presented in the Green Infrastructure Performance Metrics Report.

As part of the ongoing LTCP efforts, DEP has developed a lumped representation of GI that uses a set of high-level Citywide assumptions to estimate CSO reduction benefits. This lumped approach is valid for planning-level evaluations of future GI under the 10% GI implementation for each waterbody plan (for more details, refer to the GI-RD Task 2.3 – Current GI Modeling Procedures in NYC (DEP, November, 2015)). This lumped modeling approach has been confirmed as a common methodology used by other utilities via literature review and utility survey activities (refer to GI-RD Task 2.3 – Literature Review (DEP, December, 2015), and GI-RD Task 2.3 – Utility Survey (DEP, May, 2016), respectively). However, for the purposes of the Performance Metrics Report, a more detailed modeling representation of the GI assets, already constructed or to be constructed as part of the 1.5% GI implementation scenario, is needed to take into account the specific attributes of these known GI assets to characterize their benefits and to fulfill the requirements of the Order.

To-date, DEP has primarily focused on implementing standardized Right-of-Way Bioswales (ROWBs) which represent about 90% of approximately 4,470 assets that have already been constructed or are expected to be constructed by the end of 2016. As part of the Order requirements, DEP implemented, monitored, and reported on GI performance in three Neighborhood Demonstration Areas (“Demo Areas”) saturated with ROWBs and some limited on-site GI assets within public housing sites. Neighborhood and site scale data collected by DEP as part of this Demo Area monitoring provided invaluable information on the performance of its most common GI asset constructed in New York City (NYC) to-date (ROWB). The findings of the Demo Area study are presented in the Post Construction Monitoring (PCM) Report (DEP, 2014).

DEP determined it was important to conduct the microscale modeling analysis because the only available GI performance monitoring data to-date was on a neighborhood scale (20-30 acres) while the existing LTCP InfoWorks models represent the collection system on a Citywide scale with much larger subcatchments. Using this monitoring data for establishing and validating the most appropriate modeling approaches for accurate representation of ROWB performance required modeling evaluations on a similar scale. The information gained as a part of the PCM study, especially the pre- and post-GI neighborhood scale monitoring data, was used extensively in the development and validation of a detailed modeling representation of the ROWB performance, as discussed in this memo. The ROWB modeling approach validated by microscale modeling at the Demo Area scale was then applied on the macroscale (at the level of the wastewater treatment plant service area models) to assess performance of GI for the 1.5% implementation rate Citywide using the LTCP InfoWorks models.

2.0 DESCRIPTION OF DEMO AREAS

2.1 Demonstration Area 1 – Hutchinson River

According to DEP’s Post-Construction Monitoring Report for Green Infrastructure Neighborhood Demonstration Areas (PCM Report, 2014), Demo Area 1 (Figure 1) consists of multi-family high-rise, elevator buildings. This area is 24.1 acres in size, consisting of predominantly impervious surfaces, constituting 81% of the land coverage. The flow contributing to the CSO from the right-of-way (ROW) and from most lots within Demo Area 1 drains in the northeasterly direction via a single 36-inch combined sewer where flow was monitored.

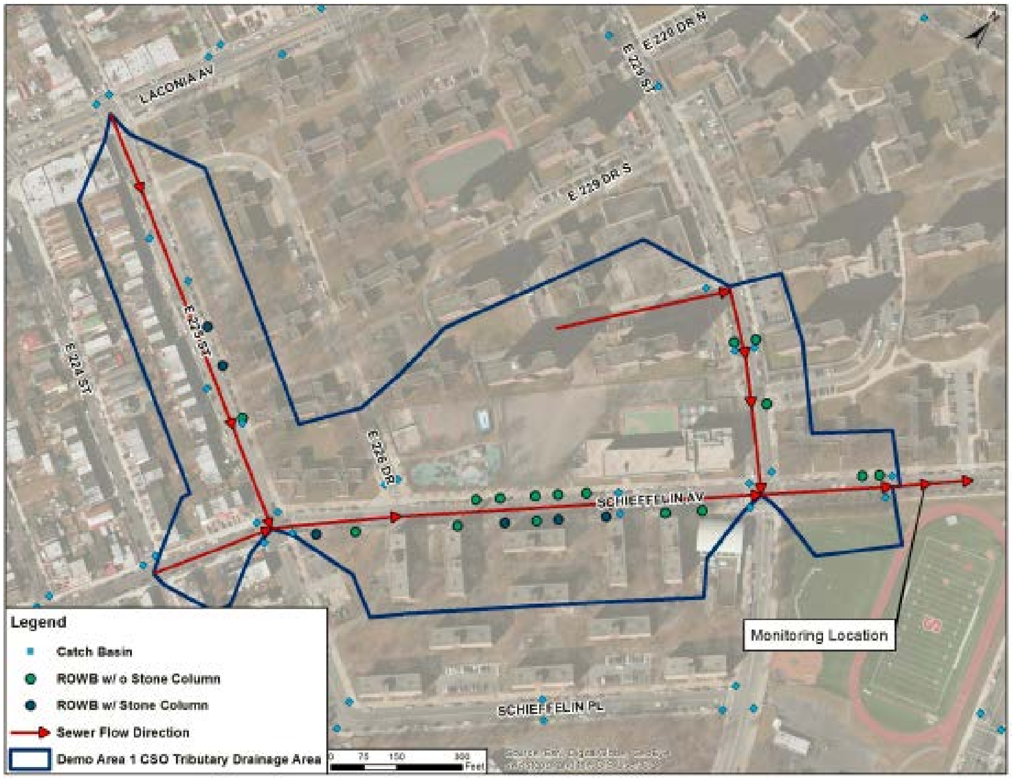

Figure 1. Demo Area 1 Boundary with Location of Installed GI

DEP monitored flow in one downstream manhole both before and after construction of 22 GI assets. The pre- and post-GI monitoring was performed over several months and included storms of different total depths, intensities, and durations. A tipping bucket rain gauge installed within Demo Area 1 recorded rainfall depths every 5 minutes. Evapotranspiration data were not collected onsite, but historical monthly averages were obtained from the Northeast Regional Climate Center at Cornell University for New York City region. Soil permeability tests were performed for most GI practices installed in the Demo Area, and total volumetric storage capacities for each GI practice were computed (PCM Report, 2014). The same methodology was used for Demo Areas 2 and 3.

DEP had previously documented several potential issues in Demo Area 1 including moving of the flow meter location, construction of ROWBs at different times that made the post-GI period to be shorter, high groundwater table in a few ROWBs due to high bedrock conditions, etc. For this reason, it was not included as part of the analysis presented in this memo.

2.2 Demonstration Area 2 – 26th Ward

Demo Area 2 (Figure 2) consists of predominantly industrial, manufacturing, transportation, and utility land uses. This area is 22.7 acres in size, with an approximate 92% impervious cover. All of the flow from the right-of-way (ROW) and from most lots within Demo Area 2 drains to one monitored manhole, located at the southern end of Demo Area 2. Flow from a small fraction (less than 1%) of the lots flows to an unmonitored manhole that drains out of the Demo Area 2.

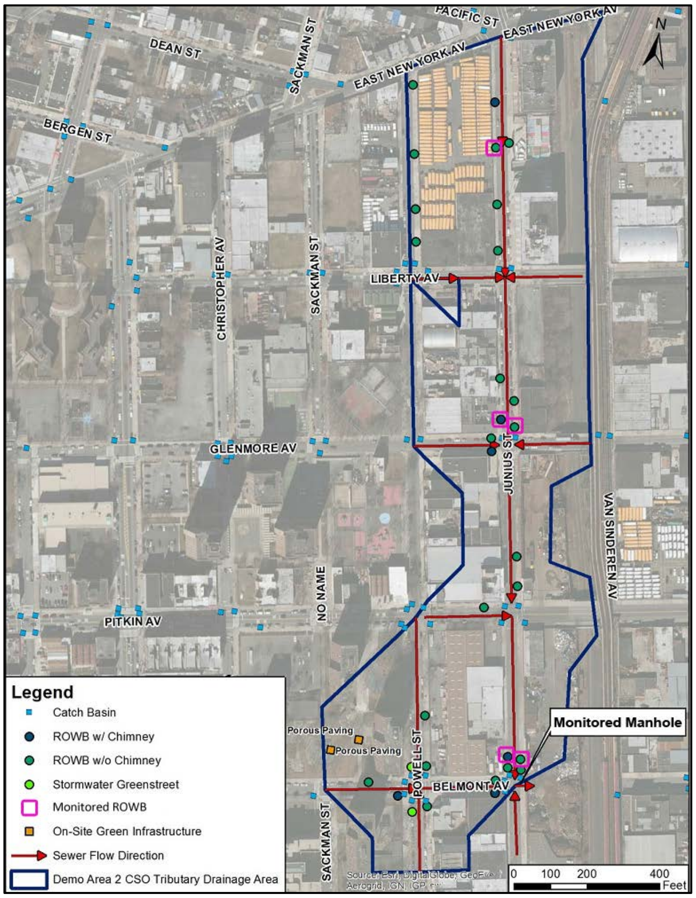

Figure 2. Demo Area 2 Boundary with Location of Installed GI

DEP monitored flow in one downstream manhole both before and after construction of 31 GI assets. The pre- and post-GI monitoring was performed over several months and included storms of different total depths, intensities, and durations. Site scale monitoring was also performed for five GI practices in Demo Area 2, in which water level and soil moisture data were collected continuously, which provides information on how quickly the water captured in a ROWB during a rain event gets depleted due to vertical and horizontal infiltration.

The pre-GI monitoring period for Demo Area 2 took place from November 23, 2011 through October 1, 2012. The post-GI monitoring period lasted from December 15, 2012 through April

30, 2014. In total, there are 27 months of data for Demo Area 2. Post-GI monitoring data used to validate ROWB performance in Demo Area 2 was selected for the precipitation events starting December 17, 2012 through September 22, 2013, which predated the on-site GI construction completion date (September 30, 2013).

2.3 Demonstration Area 3 – Newtown Creek

Demo Area 3 (Figure 3) consists of predominantly multi-family walk-up buildings and multi-family, high-rise elevator buildings. This area is 19.3 acres in size, with an approximate 92% impervious cover. However only 70% of the total area considered is hydraulically connected to the combined sewer system and considered to be ROW area. The flow from the ROW within Demo Area 3 drains in the northerly direction through a single 18-inch sewer where flow was monitored. Additionally, flow from NYCHA's Hope Gardens Houses leaves the demo area through a 12-inch sewer which was monitored separately.

Figure 3. Demo Area 3 Boundary with Location of Installed GI

DEP monitored flow in three downstream manholes before and four downstream manholes after construction of 19 GI assets. Site-scale monitoring was also performed for six GI practices in Demo Area 3, in which water level and soil moisture data were collected. Soil permeability tests were performed for most GI practices installed in the Demo Area, and total volumetric storage capacities for each GI practice were computed (PCM Report, 2014).

The pre-GI monitoring period for Demo Area 3 took place from November 23, 2011 through March 15, 2013, and was defined using the same criteria as for Demo Area 2 due to the similar method of construction. The post-GI monitoring period began when the ROWB stone layer and engineered soil had been installed, and lasted from April 1, 2013 through April 30, 2014. In total, there are 29 months of data for Demo Area 3. Post-GI monitoring data used to validate ROWB performance in Demo Area 3 was selected for the precipitation events starting April 10, 2013 through September 21, 2013, which predated the on-site GI construction completion date (September 30, 2013).

3.0 CONSTRUCTION OF DEMO AREA MODELS

3.1 Pre-GI Model Development

Microscale models for Demo Areas were developed from the existing DEP InfoWorks models. DEP's current macroscale InfoWorks models (at the scale of wastewater treatment plant service area) have been constructed to support the development of LTCPs that propose engineering alternatives to mitigate the impacts of combined sewer overflows (CSOs) on the City's waterbodies. Because the InfoWorks models were built to simulate sewer system performance throughout the city, by necessity those were constructed at a relatively coarse resolution with subcatchment areas in the range of 50-300 acres or larger.

By contrast, the microscale modeling effort presented in this memorandum focuses on three small Demo Areas in the range of 20-30 acres, each being incorporated as part of a larger subcatchment within the corresponding LTCP model. The first step in developing microscale models for each Demo Area was to "carve out" the Demo Area catchment from a larger subcatchment of the corresponding LTCP model and prepare the microscale model to represent pre-GI conditions. Due to these scale differences of subcatchment representations, some of the original InfoWorks model input parameters had to be refined in pre-GI microscale models as part of this process to match the details and specifics of each Demo Area. This refinement was performed in accordance with the procedures established in the InfoWorks Recalibration Report (DEP, 2012).

The following hydrologic and sanitary sewer flow parameters were refined from the macroscale InfoWorks model to a microscale (Demo Area) model in order to accurately reflect the specific characteristics of each Demo Area such as fixed runoff coefficients (DCIA factors) for both the impervious and pervious surfaces based on land use; flow length; impervious surface initial loss; population; and per capita wastewater flows.

Additionally, the DCIA, which is very similar in definition to the runoff coefficients commonly used in hydrologic systems design, represents the fraction of total impervious area directly connected to the sewers. The DCIA parameter specified in the existing LTCP InfoWorks models was defined at the large subcatchment scales, and had to be refined to reflect the local characteristics for the subcatchments in the microscale evaluations. Similar changes were warranted for the sanitary flow, subcatchment slope, roughness, etc. For example, the dry weather flow (DWF) currently in the LTCP models for large subcatchments needs to be scaled down for smaller geographical areas such as Demo Areas. Since the flow monitoring data provides more accurate estimates of flow at this Demo Area scale, the DWF was adjusted appropriately and subtracted from the larger subcatchment that originally encompassed the Demo Area. Further details are provided below in sections describing each Demo Area. Refined pre-GI models were then used as a starting point for post-GI modeling evaluations. No additional refinements were made to post-GI models that were used to validate GI performance in each Demo Area.

The subcatchment representations in pre-GI models for Demo Areas 2 and 3 as represented in InfoWorks are presented in the Figures 3 a and b.

Figure 3. Subcatchment representation in pre-GI InfoWorks models for a) Demo Area 2 and b) Demo Area 3

3.2 Detailed ROWB Representation

In order to track constructed GI assets, DEP has developed a Geographical Information Systems (GIS)-based project tracking system called *GreenHUB* for DEP's thousands of assets. *GreenHUB* tracks all construction details for the GI assets represented in the database, including type of GI, construction status, dimensions, local permeability data, and calculated volume capacity of the asset. As of February 2016, the *GreenHUB* database contained information for 4,469 assets that have already been constructed or are expected to be constructed by end of December 2016. Of these assets, approximately 90% are ROWBs.

To complete the distributed model for the 1.5% GI scenario, a detailed representation of each ROWB was developed to accurately reflect the site-specific data available at those ROWB locations. A schematic of the various unit processes modeled in each ROWB is shown in Figure 4.

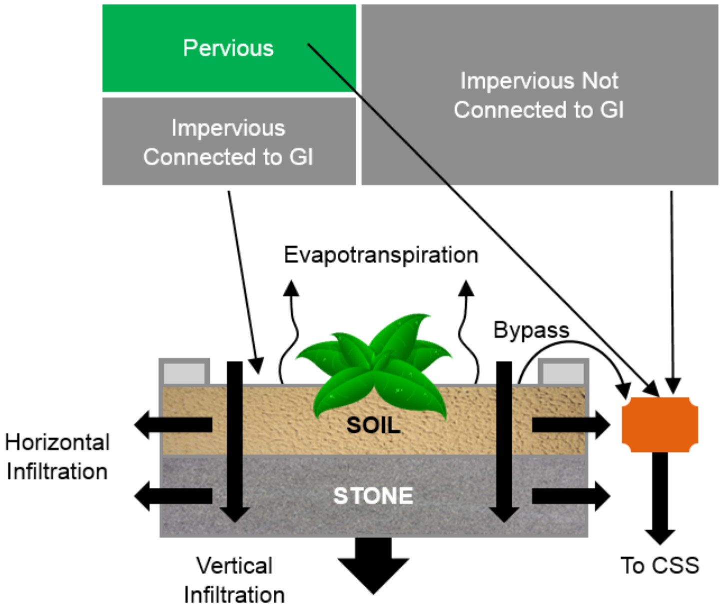

Figure 4. A schematic of the unit processes modeled in each ROWB in InfoWorks

Each unit was modeled as a pond storage node with evapotranspiration and horizontal and vertical infiltration with a bypass weir length as per DEP standard design. ROWB storage volume and infiltration values were obtained from *GreenHUB*. Horizontal infiltration rates were assumed equal to the vertical infiltration rates.

The impervious area connected to each practice was obtained using the GIS analysis based on the exact location of each ROWB while maintaining the larger catchment hydrologic characteristics.

3.2 EVALUATIONS OF DEMO AREA INFOWORKS MODELS

Once the pre-GI models of each Demo area were constructed, the following activities were performed as part of the Demo Area model evaluations:

- As part of the pre-GI refinement activities, each Demo area model was run for a series precipitation events captured during pre-GI period and a model refinement was concluded by achieving a “best fit” between monitored and modeled flows and volumes in the downstream sewer.

- For post-GI validation activities, specific design and site data from GreenHUB for all the GI assets within each subcatchment were brought into the pre-GI InfoWorks model to assess the overall stormwater reduction achieved by these assets. Bypasses from these units, as applicable, were then routed through the sewer system along with the runoff from unmanaged impervious areas and pervious areas. No refinements to post-GI models were done under this step.

- The post-GI model was run for a series of precipitation events captured in each Demo Area during post-GI monitoring. The available Demo Area monitoring data in individual ROWBs and in the downstream sewer were reviewed against the model outputs to validate the ROWB performance in the model.

Further discussions are provided in sections below describing each Demo Area.

3.2.1 Pre-GI Refinement and Post-GI Validation of Demo Area 2

As described in Section 3.1, hydrologic model parameters were refined from the macroscale InfoWorks model to a microscale (Demo Area) model in order to accurately reflect the specific characteristics of Demo Area 2.

Once the refinements were completed, this pre-GI model served as a starting point for post-GI evaluations. The Post-GI model was generated by incorporating model representations of the ROWBs. No additional refinements were made in the post-GI model. The post-GI model was then run for the post-GI monitoring period to validate the ROWB performance. The results of these two sets of simulations are shown in Figure 5 and Figure 6. Figure 5 presents a comparison of the simulated peak flows for the monitored events in Demo Area 2, for both Pre-GI and Post-GI conditions. As shown in the figures, there is an excellent correlation for both conditions, with the model being slightly aggressive. Figure 6 presents a comparison of the simulated volume for the monitored events in Demo Area 2.

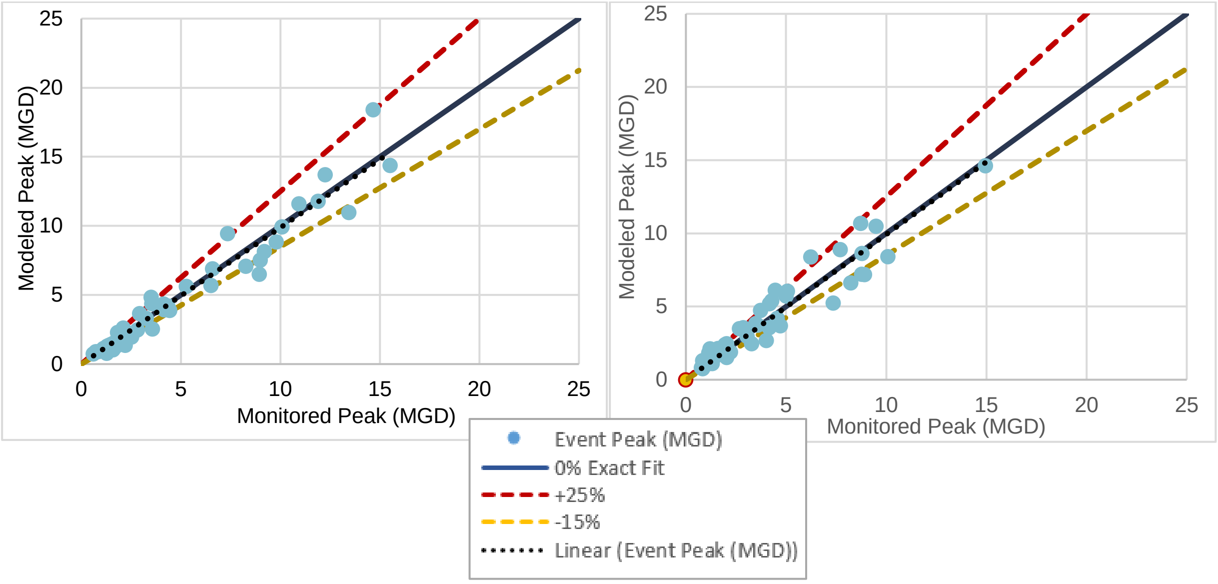

Figure 5. a) Peak flow result comparisons of Demo Area 2 – Pre-GI conditions b) Peak flow result comparisons of Demo Area 2 – Post-GI conditions

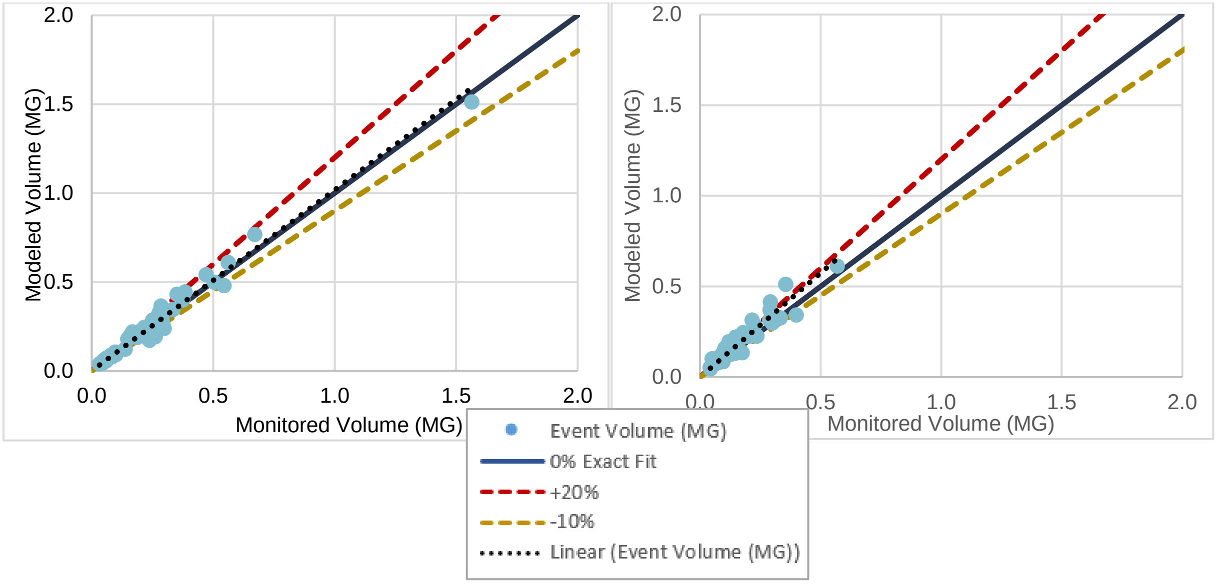

Figure 6. a) Volume result comparisons of Demo Area 2 – Pre-GI conditions b) Volume result comparisons of Demo Area 2 - Post-GI conditions

As shown in the figures, the correlation is excellent for Pre-GI condition and acceptable and conservative for the Post-GI condition, which suggests the ROWB performance is under represented.

In order to evaluate the performance of individual ROWBs, piezometric data was used to monitor the depth of water within select GI assets over time. The primary processes for draining water from the ROWB during and after the precipitation event include vertical and horizontal infiltration and after the event includes evapotranspiration. The speed with which the water is capable of infiltrating into the surrounding subsurface soil is extremely important when considering the performance of a ROWB during back-to-back rain events. Actual vertical infiltration rates were measured for each ROWB location during design and used in the model for these evaluations. The evapotranspiration rates used for the evaluations were obtained from the calibrated InfoWorks LTCP models and in general are much lower than the infiltration rates to impact the ROWB performance.

Figure 7 presents the Demo Area 2 ROWB location B-8 piezometric data for a storm event on April 10, 2013, with the modeled depth in the ROWB for the same event using the modeling assumptions discussed above. The piezometer data was converted to an equivalent water column depth by multiplying the actual values by the average ROWB media porosity. As shown in the figure, for the evaluated event, modeled ROWB water depth is approximately 55% higher than the monitored depth and it takes approximately 18 more hours for the ROWB to drain after the event in the model as compared to the monitored data. The longer dewatering time observation clearly supports the previous conclusion that the ROWB performance in the model is conservatively underrepresented.

While measured vertical infiltration rates are provided in *GreenHUB*, the horizontal infiltration rate values are much more uncertain. For the purpose of this analysis, a conservative ratio of 1:1 ratio between the vertical and horizontal rates was assumed.

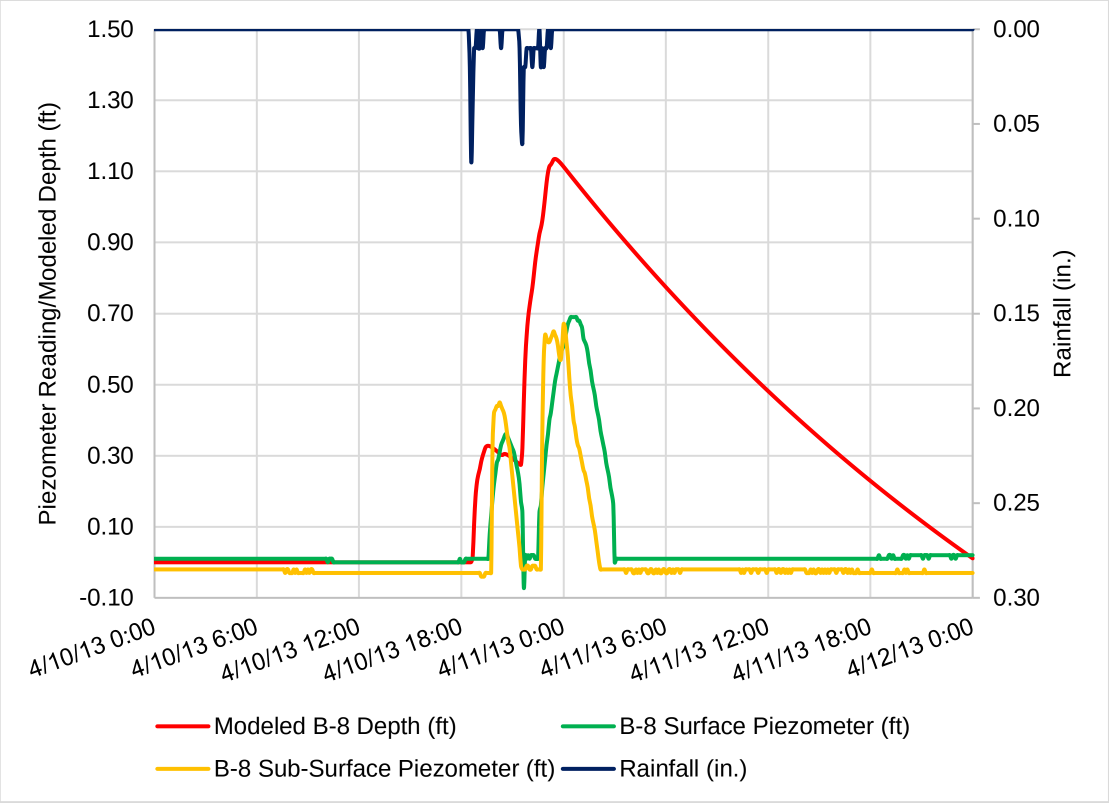

Figure 7. April 10, 2013 Storm – ROWB B8 – Initial horizontal infiltration

3.2.2 Pre-GI Refinement and Post-GI Validation of Demo Area 3

Similar to Demo Area 2 and as described in Section 3.1, hydrologic model parameters were refined from the macroscale InfoWorks model to a microscale (Demo Area) model in order to accurately reflect the specific characteristics of Demo Area 3.

Once the pre-GI refinements were completed, the post-GI model was generated by incorporating model representations of the ROWBs. Again, no refinements were made in the post-GI model. The post-GI model was then run for the post-GI monitoring period to validate the post-GI performance. The results of these two sets of simulations are shown in Figure 8 and Figure 9. Figure 8 presents a comparison of the simulated peak flows for the monitored events in Demo Area 3, for both pre-GI and post-GI conditions. As shown in the figures, the model representation is conservative for both conditions, though more so for the post-GI conditions. Figure 9 presents a comparison of the simulated volume for the monitored events in Demo Area 3. As shown in the figures, the correlation is very good but the post-GI condition is showing a more conservative volume, which suggests the ROWB performance is under represented as was the case in Demo Area 2.

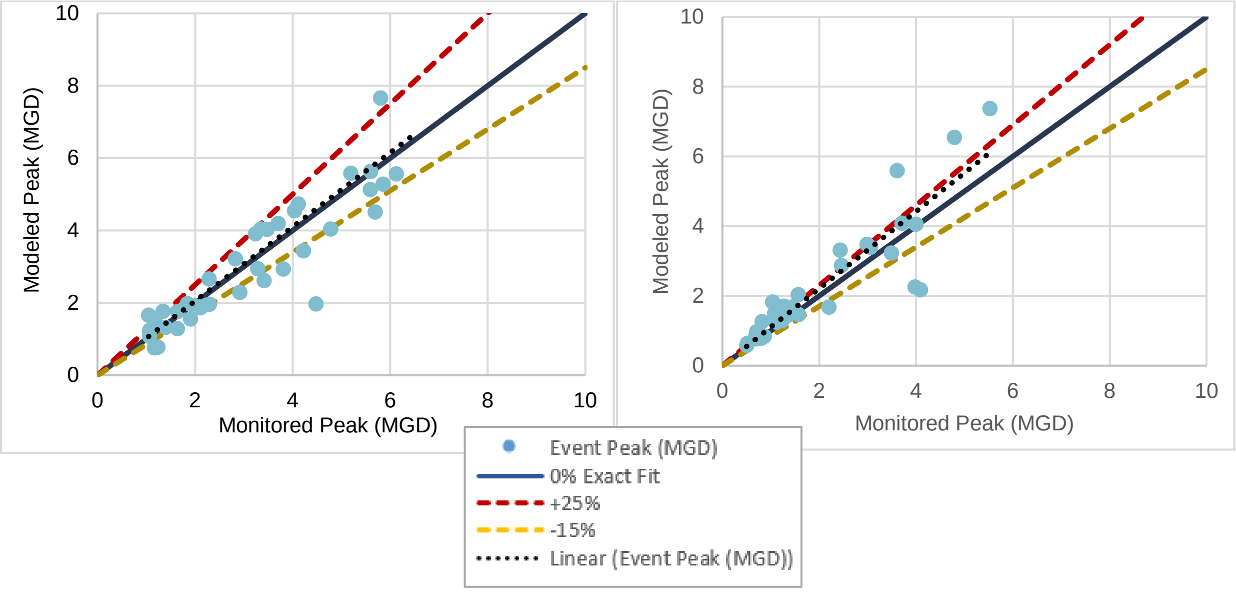

Figure 8. a) Peak flow result comparisons of Demo Area 3 – Pre-GI conditions b) Peak flow result comparisons of Demo Area 3 – Post-GI conditions

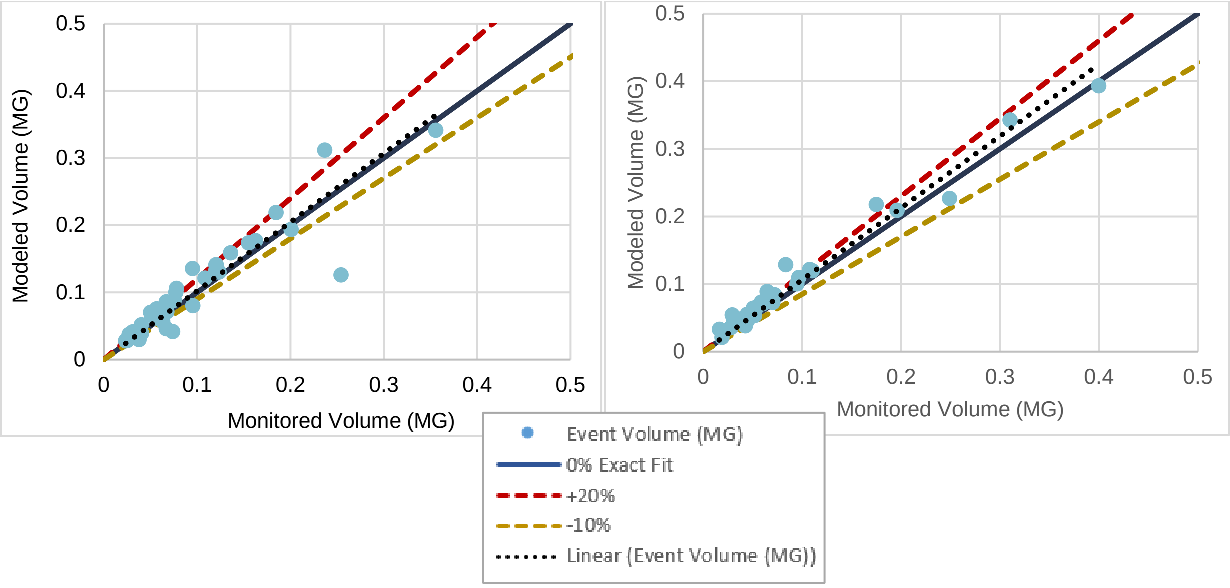

Figure 9. a) Volume result comparisons of Demo Area 3 – Pre-GI conditions b) Volume result comparisons of Demo Area 3 – Post-GI conditions

4.0 DISCUSSIONS

For Demo Areas 2 and 3, the distributed ROWB representation in the microscale InfoWorks models provided a very good correlation between the modeling results and monitored data. The model-predicted ROWB performance of stormwater runoff volume reduction is conservative for both Demo Areas, which is likely attributed to the conservative assumption made for the horizontal infiltration rates used in the model.

Additional monitoring activities are required to better define horizontal infiltration values and their relationship to vertical infiltration rates. Horizontal infiltration experiments have been included into the recently developed GI monitoring protocol. For the purpose of the analysis conducted as part of the performance metrics report, horizontal infiltration rates equivalent to the vertical infiltration rates have been used as a conservative assumption.

5.0 CONCLUSIONS

The analyses described in this memorandum were used to develop and validate the modeling approach to model constructed and predicted GI performance as part of the performance metrics analysis.

A detailed GI modeling representation of each ROWB using the available design and site data was developed and validated for distributed GI modeling in InfoWorks for Demo Areas 1, 2 and 3. Availability of sufficient data for pre and post-GI conditions in Demo Area 1, due to reasons explained in the 2015 Post Construction Monitoring, limited this analysis to Demo Areas 2 and 3. Based on the evaluation results for Demo Areas 2 and 3 the selected modeling approach provided an accurate yet conservative representation of the ROWB performance when compared to monitored data. Additional ROWB model representation refinements may be available in the future but as a conservative approach and due to the need for additional monitoring data, these refinements are not considered necessary at this time.

Based on the microscale modeling results, a distributed representation approach is recommended for macroscale InfoWorks modeling of all GI planned, designed and constructed for the 1.5% GI implementation scenarios. Note that similar to the post-GI microscale modeling evaluations presented in this report, no hydrologic (DCIA or other) refinements will be made to the LTCP InfoWorks models as part of GI performance modeling. This was only necessary to refine pre-GI models from a macro to microscale to accurately evaluate performance in the Demo Areas. The additional 8.5% GI for the 10% GI implementation scenario will continue using the existing LTCP lumped approach and all original assumptions as documented in the GI-RD Task 2.3 – Current Green Infrastructure Modeling Procedures in New York City Memorandum (DEP, November 2015) and in the 2012 InfoWorks Recalibration Report.

6.0 REFERENCES

New York City Department of Environmental Protection. 2012. Guidelines for the Design and Construction of Stormwater Management Systems.

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The City of New York
Department of Environmental Protection

GREEN INFRASTRUCTURE MONITORING STRATEGY AND PROTOCOLS REPORT

June 2016

Prepared By:

ARCADIS Design & Consultancy for natural and built assets *in association with* eDESIGN DYNAMICS AKRF

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ACRONYMS AND ABBREVIATIONS

API	Application Program Interface
CWA	Clean Water Act
COC	Chain of Custody
CSO	Combined Sewer Overflow(s)
CSV	Comma-Separated Value
DEP	New York City Department of Environmental Protection
FTP	File Transfer Protocol
GI	Green Infrastructure
GI-RD	Green Infrastructure – Research and Development
HASP	Health and Safety Plan
HLR	Hydraulic Loading Ratio
LTCPs	Long-Term Control Plans
OGI	Office of Green Infrastructure
O&M	Operations and Maintenance
QA	Quality Assurance
QAM	Quality Assurance Manager
QAPP	Quality Assurance Project Plan
QC	Quality Control
ROW	Right-of-way
ROWB	Right-of-way Bioswale
SGS	Stormwater Greenstreet
SL	Scientific Lead
TDA	Tributary Drainage Area
THA	Task Hazards Analysis

EXECUTIVE SUMMARY

The *Green Infrastructure Monitoring Strategy and Protocols Report* was prepared for the New York City Department of Environmental Protection (DEP) as part of their Green Infrastructure Program (the Program) established to implement stormwater management source controls, or green infrastructure (GI), to reduce Combined Sewer Overflows (CSO) and improve water quality in New York Harbor. The Program's goals are to manage one inch of precipitation on ten percent of the City's impervious area within combined sewer tributary areas. To meet the Program's goals, DEP identified Priority Areas for GI implementation based on several criteria including CSO volume and frequency, current water quality standards, planned system improvements, and, in some cases, proximity to planned or existing public access locations.

The Green Infrastructure – Research and Development (GI-RD) Project was undertaken to support the Program through monitoring of existing, as well as new, GI installations. The strategies and protocols described in this *Monitoring Strategy and Protocols Report* and its Appendices are intended to support DEP in the data collection and analysis necessary for documenting GI performance for various types of GI practices and in various types of conditions. The GI-RD Project is also intended to ensure that the Program is technically feasible, reliable over the long-term, and cost-effective. Findings from the GI-RD Project will assist decision-makers in their efforts to assess GI performance over time, draw relevant conclusions, and adaptively refine the long-term GI implementation process.

To assemble the GI-RD Project information, DEP has developed a comprehensive list of experiments with associated purposes and hypotheses, along with additional experimental details, for work beginning in 2016. The list was developed and refined through coordination with and review by the Project Team, and submitted for peer review by five interdisciplinary experts. Experiments are broken into four site categories: C1: Instrumented Field Sites, C2: Non-Instrumented Field Sites, C3: Laboratory/Greenhouse Sites, and C4: New Technology/Ideas. A few experiments, especially those with multiple hypotheses, utilize multiple site categories.

Experiments have been configured primarily to assess reductions in stormwater runoff volumes and, in some experiments, peak wet weather flows, and for consideration of the key performance metrics of interest to DEP. Additional co-benefits are also addressed, specifically urban heat island mitigation and effects on biodiversity. The detailed monitoring protocols specific to each experiment will be developed by the Scientific Leads of the GI-RD Project as the next phase of the Project advances.

The *Monitoring Strategy and Protocols Report* also summarizes previous GI monitoring efforts conducted in New York City and outlines the range of equipment and instrumentation that might be utilized, data management practices, training, equipment testing, and scheduling. As the Project proceeds, it is expected that the Quality Assurance Project Plan, Health and Safety Plan, and Task Hazard Analyses will be modified to meet the requirements of each protocol. Pertinent comments from the peer reviewers will be incorporated as necessary to the experiments as their implementation progresses.

The *Monitoring Strategy and Protocols Report* is a living document that will be updated as necessary on an annual basis throughout the Project in order to assure that the monitoring efforts support DEP’s goal of improving water quality in New York City’s waterways.

1 INTRODUCTION

1.1 Background

DEP plans to employ a combination of grey infrastructure and green infrastructure (GI) to attain water quality standards in New York City's waterways and to comply with Clean Water Act (CWA) requirements. It is paramount, therefore, that DEP's GI Program be technically feasible, reliable over the long-term, and cost-effective. The Green Infrastructure – Research and Development (GI-RD) Project was established as an innovative and effective Project to support the Green Infrastructure Program through the monitoring of existing, as well as new GI installations. These installations will be monitored for a series of parameters through laboratory and field experiments, and the data collected will be analyzed to draw conclusions and provide guidance to support the long-term implementation process. This Project employs a multiyear, iterative approach to optimize the benefits of the research and development effort.

The types or combinations of installations considered "green infrastructure" for the GI-RD Project include, but are not limited to:

- Bioinfiltration systems (e.g., Right-of-way Bioswales, Right-of-way Stormwater Greenstreets, Right-of-way Rain Gardens, bioretention in large open spaces or areas);
- Green roofs;
- Retention/detention systems (e.g., blue roofs, sub-surface retention and detention systems with infiltration capability, rainwater harvesting or cistern systems);
- Porous pavements including porous concrete/asphalt and permeable pavers; and
- Constructed wetlands.

DEP's Office of Green Infrastructure (OGI) developed design standards for various types of green infrastructure such as those listed above, that is built in the City. These design standards can be found at the following web address: http://www.nyc.gov/html/dep/html/stormwater/green_infrastructure_standards.shtml.

Since 2010, several monitoring efforts have been implemented throughout New York City to support DEP's GI Program. To date, DEP has run three main monitoring programs: the initial GI pilots, neighborhood demonstration areas, and co-benefits monitoring. A brief summary of these monitoring programs and their impact on this Project is described in Section 2 of this report.

1.2 Project Goals, Objectives, and Research Targets

The Green Infrastructure – Research and Development Project is guided by the following goals, objectives, and research targets:

Goals. Early in the conception of the GI-RD Project, DEP determined that the *Monitoring Strategy and Protocols Report* should be organized around two main goals:

1. To build upon monitoring protocols established for DEP's pilot monitoring program (the subject of the 2011 Preliminary Pilot Monitoring Results report and its annual updates), and add redundancy where necessary; and
2. To monitor for new parameters and types of sites to complement DEP's current effort to quantify performance data for stormwater management and additional GI benefits (e.g., water quality improvements and co-benefits).

The *Monitoring Strategy and Protocols Report* lays the groundwork for the monitoring activities under the GI-RD Project by describing the rationale for monitoring and the plan for implementation. Additionally, this document advances the first goal of the Project which involves the expansion of DEP's monitoring program.

Objectives. In order to specify further, DEP also developed a detailed list of research targets for the GI-RD Project that outline specific questions that the monitoring efforts shall attempt to answer. Five objectives for the monitoring program, listed below, were derived from these research targets during protocol development. They address the goals described above.

1. Quantify performance of GI already constructed for reporting purposes;
2. Improve GI designs based on performance knowledge;
3. Refine development of cost-effective GI construction maintenance standards;
4. Develop GI strategies to address priority watershed sites inadequately treated with existing GI designs; and
5. Inform potential future private property incentive programs and/or stormwater rules.

Appendix A contains a table with the specific DEP research targets under each of the GI-RD Project objectives. These objectives were used not only to address the Project goals and research targets but to also make key decisions about the GI typologies, types of sites to be monitored, parameters to be monitored, and performance metrics to be considered. The targets were also ranked so priorities could be considered as the monitoring plan was conceived. The process to identify sites and setups to conduct the experiments was initiated once typologies, parameters, and metrics were derived from the DEP research targets. Section 3 describes in detail the site selection process.

1.3 Report Organization

The remainder of this document is organized as follows.

- Section 2 summarizes the previous GI monitoring efforts in New York City undertaken by DEP and briefly discusses metrics and co-benefits;
- Section 3 presents the development of experiments and an overview of the site selection process;
- Section 4 describes the monitoring procedures to be employed during the monitoring efforts;
- Section 5 presents the prioritization and scheduling of monitoring experiments;
- Section 6 summarizes the data management plan for this Project;
- Section 7 describes the quality assurance/quality control measures which will be followed during the monitoring effort; and
- Section 8 discusses the next steps and the monitoring implementation schedule.

1.4 Report Review

A peer review committee was convened by DEP to review and provide feedback on the draft *Monitoring Strategy and Protocols* document. The committee was composed of five interdisciplinary experts representing a wide range of research areas relevant to the field of stormwater management/green infrastructure monitoring and assessment. The peer reviewers were asked to review the draft document against DEP’s research targets and monitoring objectives, and provide comments on accuracy, completeness, and quality. DEP expresses its appreciation for their efforts and insights in shaping this Project. The following individuals comprised the peer review committee:

- Dr. Robert Traver, P.E. (Chair) – Villanova University
- Dr. David Chandler – Syracuse University
- Dr. Elizabeth Fassman-Beck – Stevens Institute of Technology
- Dr. Richard Shaw – United States Department of Agriculture
- Dr. Brian Vant-Hull – City College of New York

Following the peer review process, Dr. Traver, the review committee chair, summarized the committee’s suggestions and observations into ten general comments. These general comments and the specific comments provided by the other peer reviewers are attached to this document as Appendix B. The comments have been reviewed by the Project Team and incorporated into the experimental means and methods in order to improve the monitoring efforts. Below, the general comments are listed along with responses from the GI-RD Project Team.

Comment 1. Metrics for success need to be extended past site performance and targeted to CSO reduction. For example percent removal for smaller storms may not be significant, as well as the performance during extreme events were [sic] combined sewer overflows cannot be prevented. The metrics need to be targeted to the frequent CSO producing events.

Response: Under a separate task of the GI-RD Project, DEP utilized existing NYC InfoWorks models developed as part of the LTCPs to estimate stormwater and CSO reduction benefits from implemented and planned GI installations. Demonstration area data collected by DEP for neighborhood and GI site scales have provided invaluable information to validate the current GI modeling approach and further refine and validate detailed ROWB representation in the LTCP InfoWorks models. The modeling and evaluation results were not included in the peer review package, but will become available as part of the *Performance Metrics Report* issued June 2016. Additional neighborhood-and sewershed-scale monitoring may be useful for further validation and refinement of the GI performance modeling and will be considered under this Project.

Comment 2. If not already completed, the accuracy, precision and reliability of past monitoring efforts should be reviewed to ensure that the hydrologic data collected will support answering the research questions asked. This should be extended to a review of sensor accuracy and reliability.

Response: Some of the initial reviews have been performed under the *Performance Metrics Report* discussed above. Additional evaluations will be heeded during the monitoring implementation.

Comment 3. QA/QC protocols should include hydrologic monitoring, as well as environmental to ensure the data it collects and analyzes supports the project requirements. The document should include data review procedures, and actions to be taken when systems malfunction.

Response: Section 3.2.4 of the Quality Assurance Project Plan (Appendix G) has been updated to include hydrologic and environmental monitoring. Section 7 of this report addresses the review procedures and actions to be taken when systems malfunction.

Comment 4. In several areas, reviewers identified the need for periodic analysis of soil properties, to further understanding of soil moisture dynamics, and relate to hydrologic performance over time. Multiple comments were made regarding soils on the experiment E-20 from several reviewers. These comments should be reviewed, and incorporated as appropriate.

Response: Several of the comments on Experiments 20 and 13 were incorporated into their Experimental Protocol Summary Sheets in Appendix C. Additional considerations were also added to several experiments to be kept in mind during the further development of the experimental means and methods.

Comment 5. On the environmental side, please check the detection limits of test kits, as often the stormwater quality parameter will record lower than the detection limit.

Response: In response to this comment, the Project Team will instead deploy in-situ continuous water quality sondes in order to get higher quality data with lower detection limits.

Comment 6. There are several comments that track across different experiments that relate to “controls” or duplicate experiments. For example (E-20), it was suggested that a street planter be built without a stone column, and another with side impermeable fabrics as controls. This of course also connects to the side infiltration experiment (E-22). Linkages in developing sites with variations intended to demonstrate differences would be a benefit to this project.

Response: Experiment 20 investigates the effect of stone columns on the stormwater retention of bioswales. The control for this experiment will come from E4 which will perform similar retention tests on bioswales without stone columns. Experiment 22 will be performed on sites with HDPE barriers and sites without, and therefore the sites without the HDPE barriers will be the control sites.

Comment 7. It was commented that the plant health sections should be reviewed by qualified plant professionals, (if not done so) and it sounded too much like and engineer wrote it.

Response: Qualified plant professionals have been retained to participate in all experiments regarding plant health.

Comment 8. The use of modeling is suggested to compliment the monitoring to address spatial and temporal questions. May also be of use when implementing E-37 (Slow Release).

Response: DEP is engaged in extensive modelling activities as described in the response to the first comment. The data collected in many of these experiments will be used in future modeling efforts.

Comment 9. The statement was made that the Data Management Plan “is wonderful,” but the data backup frequency should be made clear.

Response: Project data will be available through the web interface at all times. In addition, project data can be downloaded for external viewing and analysis as needed. The Data Management Plan has been revised to also indicate that quarterly or annual downloads of all project data will be performed, as directed by DEP.

Comment 10. The role of peer review in the monitoring and experimental processes need to be developed.

Response: It is DEP’s intent to conduct independent (from the Project Team) reviews of monitoring methods, results, data interpretations and conclusions on a regular basis. The role of peer review in the monitoring and experimental processes will be further defined under the monitoring implementation.

The *Monitoring Strategy and Protocols Report* is a living document that will be updated yearly throughout the Project. Comments from the peer reviewers will continue to be reviewed and incorporated as necessary to the experiments as their implementation progresses.

2 SUMMARY OF PREVIOUS GI MONITORING EFFORTS, METRICS, AND CO-BENEFITS CONSIDERATIONS

2.1 NYC DEP Monitoring Efforts

Since 2010, several monitoring programs have been implemented throughout New York City to support DEP's GI initiative.[1] DEP has run three main monitoring programs: the initial GI pilots, neighborhood demonstration areas, and co-benefits monitoring.

The initial GI pilots focused on evaluating the impact of different GI controls on the volume and rate of stormwater runoff. The more than 30 constructed pilots included enhanced tree pits, street-side infiltration swales, right-of-way (ROW) bioretention, blue and green roofs, and other onsite treatment practices such as porous pavement and subsurface detention systems. The pilot studies concluded that the GI assets are providing effective stormwater runoff management for a one inch storm, but that further monitoring efforts were necessary to inform future GI implementation efforts.

The Neighborhood Demonstration Areas project consisted of neighborhood-scale GI monitoring in three areas: the Jamaica Bay-26th Ward, Newtown Creek, and the Bronx River (later modified to Hutchinson River) watersheds. These areas were selected so that the outflow from a defined combined sewer tributary drainage area (TDA) discharges into a single pipe at a manhole, in order to isolate the variable of interest – the impact of green infrastructure on the volume of runoff flowing into the combined sewer system. The GI installed within the Demo Areas consisted mostly of Right-of-way Bioswales (ROWBs) and Right-of-way Stormwater Greenstreets (SGSs), supplemented by larger onsite practices. Monitoring was conducted pre- and post-construction at the manhole to assess the difference in flows, and at individual assets, to assess their performance. The study concluded that it was possible to find locations within the Demonstration Areas to install combinations of ROW and onsite GI that can be designed to manage the runoff from a one inch rain event from 10% of the CSO impervious areas.

In addition to its role in managing urban runoff, GI can provide other community co-benefits. DEP commissioned a co-benefits study to quantify the possible environmental, social, and economic benefits that GI could provide for the City. Three different types of analysis were undertaken – a literature review,

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[1] Reports on previous GI monitoring efforts conducted by DEP can be found at the following web address: http://www.nyc.gov/html/dep/html/stormwater/nyc_green_infrastructure_pilot_monitoring_results.shtml.

pilot site monitoring, and a life cycle analysis. DEP studies to date have recognized the following co-benefits:

- carbon sequestration,
- urban heat island mitigation,
- building energy demand reduction,
- urban habitat provision,
- air quality improvement,
- quality of life improvement,
- stormwater treatment need reduction, and
- related (green) jobs generation.

Co-benefits will be studied as part of the GI-RD Project as well, as described Section 2.2.2.

Existing protocols from the previously mentioned monitoring projects were reviewed in order to extract the lessons learned from their efforts. The reviews brought to light the need for a thorough monitoring plan to be established at the outset of the GI-RD Project in order to ensure consistency throughout the duration of the Project from all parties involved in the monitoring efforts. Additionally, when established protocols are followed, it ensures the quality of the collected data and increases confidence in the conclusions drawn.

Additionally, the GI-RD team met with researchers at several academic institutions to discuss their prior and ongoing monitoring activities in the City and to create an up-to-date list of existing monitored sites. The existing monitoring data collected by these institutions and others in New York City may be useful as reference information for the GI-RD Project.

2.2 Metrics and Co-Benefits Considerations

2.2.1 Metrics Considerations

Measurement and quantification of the benefits resulting from GI implementation require the use of GI monitoring performed at various spatial scales and the definition of appropriate metrics to assess performance. The key performance metric of interest to DEP is City-wide CSO volume reductions corresponding to the amount of impervious cover managed by GI in different watersheds.

CSO volume reduction is not a linear function of managed impervious cover in the contributing watershed. Hydraulic conditions within combined and interceptor sewers moderate the benefits in terms of the reductions in peak flows/volumes achieved by individual GI assets. This results in varied benefits for a gallon of stormwater reduced by GI to the equivalent CSO volume reduction into a waterbody. In order to accurately measure it, DEP establishes an equivalency rate for a given GI application rate to the corresponding CSO volume reduction.

Several experiments in this Project including E4, E20, E22, E10, E8, E9, E37, E36, and E11 listed in Appendix C, Pages C-1 through C-3, were designed to quantify stormwater retention and detention provided by different types of GI installations. Once an accurate water budget of the installations occurs, GI equivalent volume can be estimated for specific performance metrics tracked by DEP. Knowing the amount of retention/detention is also needed to determine the managed impervious area and the volume of stormwater reduced through GI.

2.2.2 Co-Benefits Considerations

Realizing co-benefits. In the quest to reduce CSOs and achieve the benefits associated with meeting water quality standards, DEP is also realizing the co-benefits of the investment in green infrastructure. While often more challenging to quantify than traditional stormwater-related benefits, co-benefits are other tangible changes that NYC residents may observe in day-to-day life. It is expected that as the research proceeds, the knowledge and understanding of co-benefits will likewise advance and provide new and expanded information for use in decision-making.

Co-Benefits Monitoring Requirements. The DEP Research Targets, described in Appendix A, specifically identify two areas of monitoring directly related to co-benefits as a starting point for research of co-benefits under the GI-RD Project. The monitoring of each of the areas will inform the success of current approaches and need for adjustments to improve performance.

1. Observe and record bird, insect/pollinator species at GI sites both near existing natural areas and isolated from them (Item 4.a)

Native pollinators are the reproductive strategy of 80% of the planet’s plant life, making them foundational to ecosystems. These pollinators are most frequently bees, but also include beetles, ants, birds, moths, butterflies, flies, gnats, and small mammals, such as bats. The absence of pollinators across ecosystems is paired with the collective simplification and potential unraveling of those systems. Without pollinators, plants have a much-reduced seed set. GI practices may possibly provide an important opportunity to maintain and create important biodiversity in an urban setting to build plant community resilience and to help sustain urban and adjacent regional food sources (e.g., fruit, vegetables, and grain).[2]

2. Monitor temperature changes within and surrounding the GI Practice (Item 4.b)

A common phenomenon in urban areas during summer months is heat absorption and retention by impervious surfaces such as pavement and rooftops that cause elevated air temperatures, as compared to rural or undeveloped baselines. This urban heat island effect can generate higher temperatures, public health risks, and higher energy demand (associated with cooling) during warm weather. Any mitigation of this effect should, in theory, be accompanied by a reduction in energy use. Strategies to mitigate the heat island effect include increasing the average albedo (solar reflectivity) of rooftops and pavement and enhancing vegetation density. The latter is nicely aligned with many GI practices such as right-of-way bioswales, green roofs, greenstreets, and other native plantings.[3]

Groundwater Mounding

Another research task identified by DEP for the GI-RD Project includes the evaluation of potential groundwater mounding. Groundwater mounding is typically thought of as a negative impact on adjacent structures. However, it may have positive impacts on area landscaping given the significant changes on water table levels because of urbanization. Groundwater mounding is a potential side-effect associated with widespread implementation of GI in highly urban areas. Peer cities such as Philadelphia have been both monitoring and modeling this condition for the last five years. Results from some of Philadelphia's modeling studies suggest that groundwater mounding directly beneath infiltration practices (e.g., bioswales) can be as much as 1 meter; however, this mounding has been observed to be temporary, dissipating over several days. Regional-scale impacts under widespread implementation scenarios show more long-term water table responses. Specifically, modeling suggests that water tables could establish higher equilibrium elevations, particularly in areas where groundwater elevations are relatively deep (greater than 3 meters). Lessons from these types of studies and data collection efforts associated with this Project will be used to develop and support design guidance and criteria that reflects these potential side-effects. For example, establishing setbacks (e.g., 10 feet) from structures to minimize risks of

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[2] Pollinator Pathway. http://www.pollinatorpathway.com/why/. Accessed Jan 18, 2016.

[3] City of Portland Bureau of Environmental Services. 2010. Portland's Green Infrastructure: Quantifying the Health, Energy, and Community Livability Benefits. Prepared by Entrix.

unwanted water intrusion and disallowing infiltration practices where groundwater tables are already high.[4]

The monitoring effort in this Project will enable DEP to determine the site scale and long-term regional scale water table response caused by infiltrating GI practices such as bioswales and permeable paving. The data can be used to calibrate and verify appropriate groundwater models whose outputs can then be used to establish or revise design criteria and guidelines for siting and constructing these types of GI practices.

Future Monitoring for Co-benefits. In future years, additional consideration will be given to expanding and/or modifying data collection to more fully describe co-benefits and meet the DEP research targets for this Project. The information yielded from the additional data will further quantify the benefits gained from the investment in the infrastructure and lead to increased sustainability and resilience in the design.

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[4] Maimone, M. D. E. O'Rourke, J. O. Knighton, and C. P. Thomas. 2011. Potential Impacts of Extensive Stormwater Infiltration in Philadelphia. *Environmental Engineer*. Vol 14, Fall 2011.

3 MONITORING PROTOCOLS

This section describes the process of developing a comprehensive experiment list to address DEP research targets. It provides a complete list of proposed experiments with associated purposes and hypotheses, along with additional experimental details for work beginning in 2016, the first monitoring season (Year 1). The monitoring protocols specific to each experiment will be developed by the Scientific Leads of the GI-RD Project. The experiments conducted at the start of the monitoring implementation are all site-scale experiments, however, neighborhood and sewershed-scale (outfall) level experiments will be incorporated into the Project in the future. The overall progression from DEP's research targets to monitoring protocols is shown in Figure 3-1 below, with individual components described in subsequent subsections.

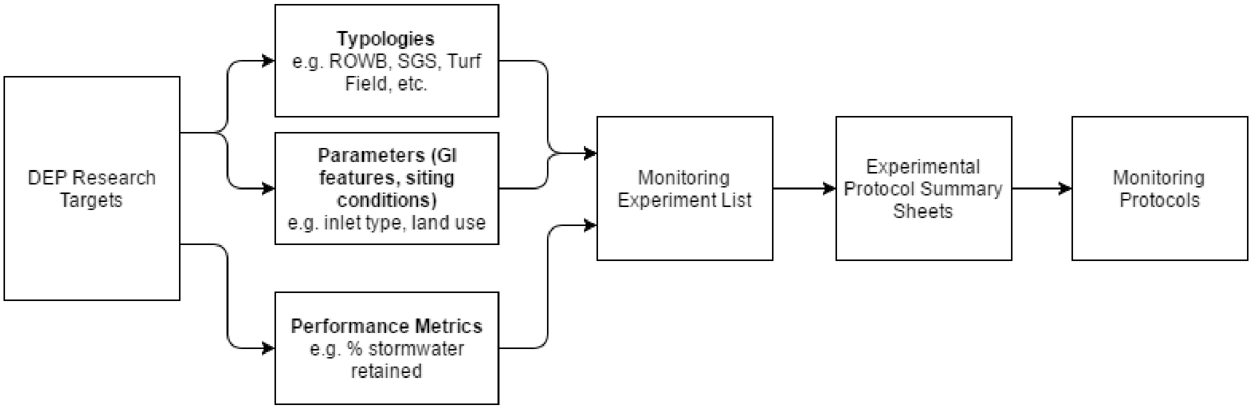


Figure 3-1. DEP Research Targets and Key Monitoring Decisions

3.1 Experiment List Development

Given the wide range of existing and emerging GI technologies in New York City, as well as the numerous benefits to be quantified, DEP's research targets are multifaceted and cover a wide range of considerations. To facilitate the development of experiments that cumulatively address all of DEP's needs, each of DEP's research targets was filtered through three lenses: 1) typologies: on which type of GI should the target be assessed?; 2) parameters: what are the relevant characteristics of the GI systems that should be varied systematically in the monitoring effort?; and 3) performance metrics: what will be quantified?

Typologies include ROWBs and SGSs, but also include less common strategies such as turf fields or treatment wetlands. Parameters include specific GI features, such as inlet type, but also include siting conditions such as street slope or land use. Performance metrics could include the percent of tributary stormwater retained in the facility, as well as co-benefit metrics. Together, these three lenses were used to translate the DEP research targets into experiments with clear purposes, hypotheses, and activities.

Appendix C documents the full list of experiments with their associated purposes and hypotheses. These experiments were first prioritized with DEP as Priority 1 (high priority) and 2 (medium priority). Priority 1 experiments, which will begin in Year 1, have been further categorized based on their emphasis in the first year and the number of potential experiments, as presented in Table 3-1. For example, some experiments will begin with data collection, while others may first require review of previously collected data to inform future new data collection efforts. Priority 2 experiments will likely begin in Year 2.

Table 3-1. Experiment Prioritization

	# of experiments
Priority 1	**24**
Data Collection – plan and deploy experiment, collect and analyze data	8
Review of Existing Data – review existing data from previous monitoring efforts to address research targets. Some experiments may require additional data collection.	9
Conceptual Design Development – confirm hypothesis and identify ways of constructing models or modifying green infrastructure facilities to address research targets. Design conceptual set-ups to enable experiments.	6
High priority but likely to postpone data collection to Year 2 after more sites are constructed	1
Priority 2	**9**

3.1.1 Experimental Protocol Summary Sheets – Year 1

Experimental purposes and hypotheses were critical to developing and prioritizing experiments, however, further details are required to advance to subsequent planning phases such as scheduling and budget allocation. For experiments beginning in Year 1, Experimental Protocol Summary Sheets were developed (see Appendix C) to provide additional details. These include potential equipment and instrument needs, along with proposed experimental methods. An estimated monitoring duration and overall cost level (high, medium, low) are presented as well. By providing key experimental details, these summary sheets will facilitate review and collaboration with DEP, project partners, and the peer review panel. Each experiment will be assigned a Scientific Lead, an individual with expertise on the specific scientific areas being investigated in the experiment. The Scientific Lead will review, and if necessary, refine, the Experimental Protocol Summary Sheets to finalize a scientific methodology that will be implemented by a team of field technicians. Implementation of each experiment may include a desktop review of existing data and/or collection of new data for the experiment. After the Scientific Lead for each experiment is selected, the specific monitoring protocol development and site selection process will proceed in subsequent phases of the GI-RD Project.

3.2 Equipment and Instrumentation

A wide array of equipment and instruments will be required to perform the monitoring experiments. Table 3-2 below describes several of these items. This list should be used as a reference only, as the Scientific Leads will ultimately determine the final equipment and instruments required based on the experimental needs.

Table 3-2. Monitoring Equipment

Equipment/Instrumentation	Purpose
Data Logger (and associated terminal blocks or modules)	Records and stores data from sensors
Field-embedded web gateway	Sends data directly to the project-specific data management platform through a secure connection
Cell modem	Transmits the remotely sensed data from the logger to the database
Weather resistant box enclosure	Protects on-site equipment from weather damage and vandalism
Mounting device and bracket/boom	Protects equipment from vandalism and ensures climate and solar equipment are not blocked by vegetation or nearby poles
Solar panel	Provides power for equipment
Charge controller/charging regulator	Controls battery charging from solar power
Large marine batteries	Provide remote power supply
Rain gage	Measures rainfall at remote sensing locations
Radiometer	Measures incoming and outgoing long-wave and/or short-wave solar radiation
Soil core Sampler	Collects soil core samples
Wind anemometer	Measures wind speed/direction
Temperature and humidity sensor	Measures temperature and humidity
Pressure transducer	Continuously and remotely monitors water level
Well tape	Utilized to measure depth to water manually

Equipment/Instrumentation	Purpose
Soil sensor	Measures volumetric moisture content (models available to also test soil temperature and electrical conductivity)
Weighing lysimeter	Measures change in weight of a soil column due to evapotranspiration
Flume (Trapezoidal and/or H-flumes); Weirs (thelmar and/or broadcrested)	Measures inflow/outflow (must be used in combination with a water level sensor or flow meter)
Flow meter	Measures volumetric flow rate
Piezometer	Measures pressure head at a particular depth in the subsurface
Shallow well	Measures depth of water above the surface
Permeameter/Infiltrometer	Measures soil permeability
Cover/conduit	Protects wires and other equipment
Water Quality Sonde	Continuously measures water quality parameters
Optical oxygen sensor	Measures oxygen levels
Turbidity probe	Measures turbidity and TSS
IR thermometer gun	Measures thermal radiation to infer surface temperature
Drill, screwdriver, hammer, saw, wrenches (adjustable, socket, and hex), wire cutters, measuring tape, level, utility knife, pliers, shovels, crow bar, ladder	Various work tools utilized for installation

3.3 Site Selection

Many of the experiments outlined in the previous Monitoring Protocols section will be performed at, or rely upon, existing GI sites. Thus, in order to perform the experiments successfully, it is critical for the selected portfolio of monitoring sites to consist of the necessary site characteristics as defined by the experimental design. This section first provides a description of the four site categories that make up the monitoring site portfolio. It then provides an overview of the site selection components and associated considerations, as well as a flow chart that describes the progression of these components. Finally, an example map with a cluster of selected sites is presented to display the various GI and site characteristics to be considered throughout the site selection process.

3.3.1 Site Categorization

Given that the monitoring experiments address a range of desired information, such as stormwater retention capacity or biodiversity richness, the criteria used to select monitoring sites vary. For example, one experiment may require a site to be instrumented to gather data continuously, while another may only require the site be accessible for field observation. These variations in experimental needs have resulted in the development of four site categories (C1, C2, C3, and C4) as defined in Table 3-3 below.

Table 3-3. Monitoring Site Categories

Site Category	Description
C1: Instrumented Field Sites	C1 sites are field sites that are instrumented for continuous data monitoring. Once the associated instrumentation is installed, C1 sites generate environmental data sets during a range of climatic conditions. C1 sites will require regular maintenance to ensure instrumentation functionality, but they would not require staff members to be present during data collection. Example: ROWB instrumented to continuously measure inflow, outflow, and soil moisture content.
C2: Non-Instrumented Field Sites	C2 sites are non-instrumented field sites that are evaluated periodically using portable monitoring equipment. Given that these sites do not require an extensive installation process, they allow for flexibility in site selection and for a larger portfolio of sites. C2 sites would require staff members to be onsite during data collection. Example: Portfolio of ROWBs assessed for biodiversity by count of observed pollinators.
C3: Laboratory/Greenhouse Setup	C3 sites are laboratory or greenhouse experimental setups located at the GI-RD field station, laboratory, or greenhouse. These sites allow for environmental controls and equipment that may be difficult to implement in the field. Results from C3 sites may inform subsequent investigations at C1, C2, or C4 sites. Example: Soil laboratory for assessing the effect of saturation on soil bearing capacity.
C4: New Technology/Ideas	C4 sites are innovative pilot sites built specifically to test GI features not currently found in the field. These sites will fill in gaps of C1, C2, and C3 experiments and provide the opportunity to study additional typologies or variations in GI designs. Example: Design and construction of an end-of-pipe constructed treatment wetland prototype

The table in Appendix A links DEP's research targets to the four site type categories. While many of the experiments will consist of a site portfolio within a single site category, a few experiments, especially those with multiple hypotheses, may utilize multiple site categories. For example, the Evaluation of Inlet Performance and Development of New Inlet Types Experiment (E16) includes the evaluation of existing inlets at C1 and C2 sites as well as the potential development of a new inlet type at a C4 site that is first tested in a laboratory setup (C3). Additionally, the Effect of Engineered Soil Specifications on Stormwater Retention and Plant Health Experiment (E13) includes sampling from a range of C2 sites and performing the experiments in a laboratory, or C3 site. Despite these multiple designations, the overall site categories per experiment allow for strategic planning of overall instrumentation needs, laboratory or greenhouse needs, as well as the number of innovative pilot sites.

These categories, specifically the distinction between C1 and C2, also allow for the site selection process to consider the current or previous monitoring activities of constructed sites. Sites with functioning monitoring equipment or existing conduits will be strong candidates for future C1 sites for a few reasons. The first is that the retrofitting process may be faster and more cost effective than a new equipment installation. Secondly, previously monitored sites may also have an elevated level of site characterization, which would assist in reducing the overall site preparation time. Finally, the existing monitoring data may serve as reference for future data collection.

3.3.2 Site Selection Considerations

There are several key steps required to develop a final sampling of experimental sites, all of which are experiment specific. These steps are detailed below and the overall process is visually depicted in (Figure 3-2) as a flow chart.

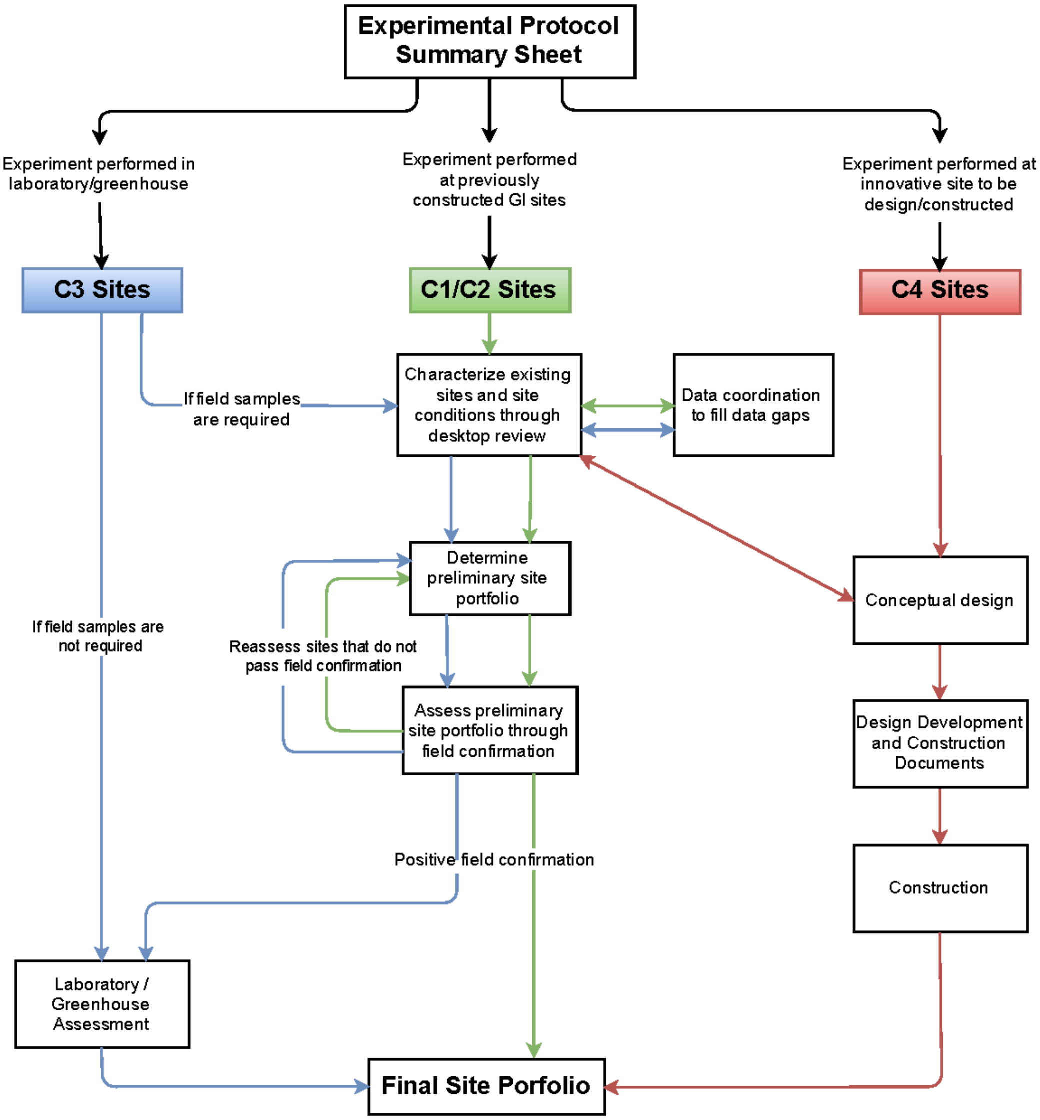


Figure 3-2. Site Selection Process Flow Chart

Desktop Review

A robust and comprehensive desktop review is necessary for the site selection process, and as a precursor to finalization of the experimental design. Specifically, selection of an appropriate sampling of sites for monitoring needs can only be performed if the distribution of key parameters across the population of all GI sites across the City is known. For example, an experiment that assesses hydraulic loading ratio (HLR) should be designed based on the range of existing and planned HLRs expected from all GI sites, so that the experimental sample is representative of the true population. Once the population has been queried, acceptable ranges for key control variables in the sample can be defined. The selection of individual sites will be determined within the context of these ranges, both for assessment and control.

The first step in desktop review is to query the various databases of existing GI sites. These include DEP's GreenHUB, which represents the most comprehensive database of existing GI sites, as well as compiled listings of other GI sites that may not already be included in GreenHUB. Once these databases have been compiled, the various distributions can be determined, resulting in a subset of potential site locations, from which the final sample can be selected. While many GI and site conditions are already captured through GreenHUB, an experiment may require additional information that is not readily compiled, such as the engineering soil specifications. Thus, the second step in desktop review is to perform a document review or GIS analysis to fill any data gaps.

Data Coordination

Given the multitude of GI features and site conditions, it is possible that the experiments may require details beyond the site database and readily available reports. For example, the as-built drawings may be required to assess the location of utilities. Thus, ongoing data coordination is critical throughout the desktop review process.

Preliminary Site Portfolio

Through desktop review and data coordination, a subset of sites can be determined that meet all required GI features and site conditions. Depending on the prevalence of the investigated site typology and variation, this subset may consist of many more sites than required. Thus, prior to the subsequent field confirmation phase, the sites are ranked using a random number generator in order to randomize the sites selected for field validation. The randomization is necessary to ensure that biases are not introduced into the experiments as a result of the sites chosen (or not chosen) for experimentation. The current preliminary site portfolio can be found in Appendix D.

Field Validation

After the preliminary site portfolio is determined, the sites need to be field verified to confirm that the GI features and site conditions are consistent with the desktop review characterization. Verification methods can include surveying of ground elevations, visual inspection/photography, cursory soil sampling and classification, etc. Any discrepancies between the field verification and the desktop review should be noted in the central site database. Site access and other monitoring procedural components can be noted as well.

If too many sites are disqualified due to field confirmation, an iterative process of updating the preliminary site portfolio based on field results may be required to determine additional sites while maintaining experimental design criteria. To manage variability, the number of sites per experiment could be increased as well. The final site portfolio per experiment will consist of sites that pass field verification and final approval from the Research Team.

Conceptual Design to Construction

Given that C4 sites are sites which feature new technologies or embody new design ideas that most likely do not yet exist in New York City, they need to be designed and built prior to any monitoring efforts. Thus, while design development, construction documents, and construction are not inherently parts of site selection, they are still mentioned in this section as necessary to final site portfolio determination. The conceptual design phase of these sites may consider existing GI typologies or site conditions through desktop review, but this is dependent on the specific requirements of the experiment.

Laboratory/Greenhouse Assessment

To determine the location of C3 experiments (laboratory or greenhouse setups), available facilities will be evaluated based on both experimental and logistical needs. Experimental needs include: analytical equipment, temperature controls, bench space, storage, drainage capability, etc. Logistical needs pertain to site accessibility. Each of these requirements will be assessed per individual experiment.

3.3.3 Site Selection Example

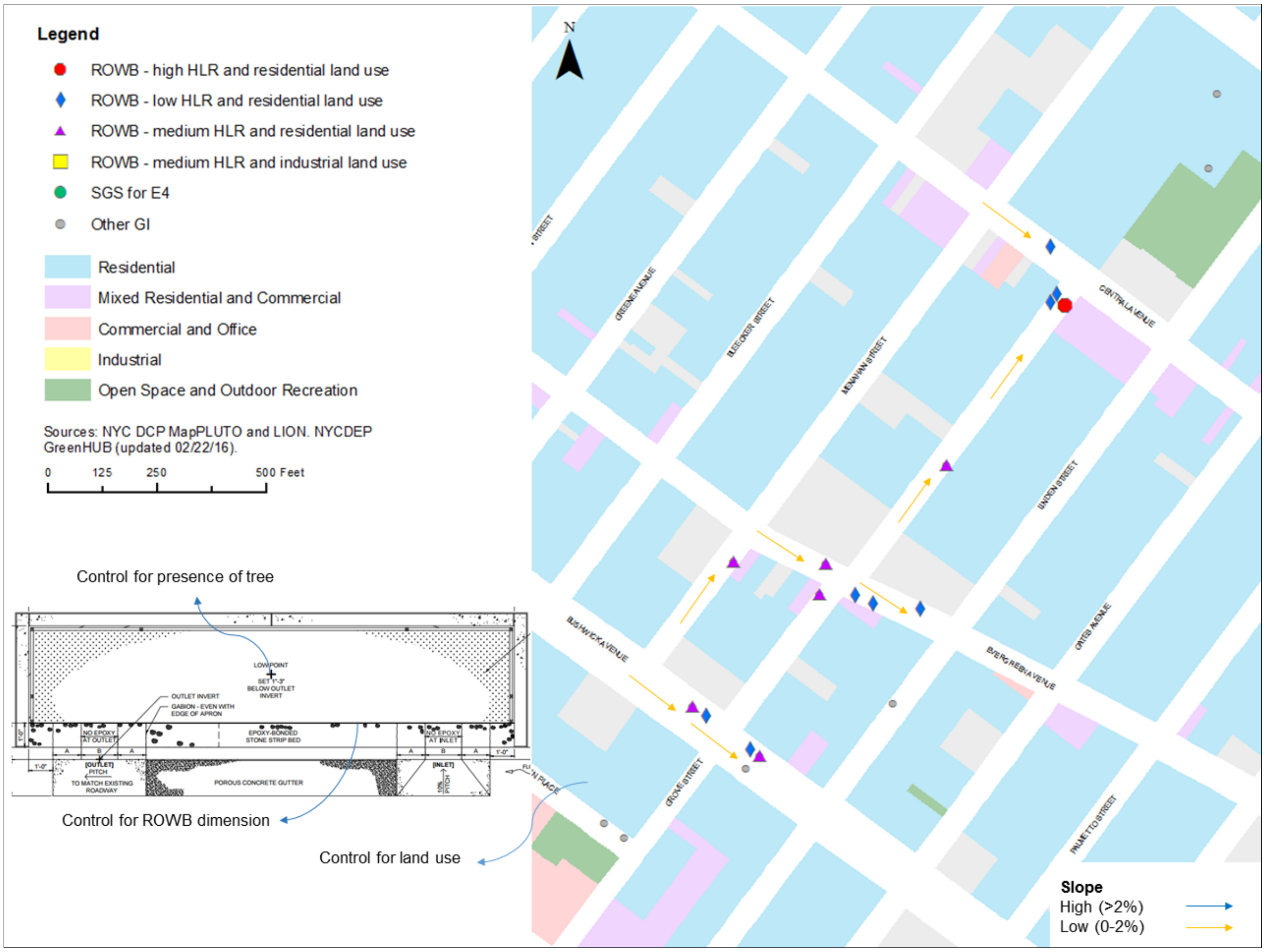
This section demonstrates the preliminary site selection process for a set of ROWBs of varying HLRs in residential areas. Considerations of the site selection process are shown in callouts within Figure 3-3. While this process will vary for other experiments, this example demonstrates the overall process. In order to assess the HLR for each constructed or in-construction right-of-way asset in GreenHUB, a GIS analysis was performed to determine the connected impervious area per asset. This analysis utilized parcel footprints, street centerlines, catch basin locations, and a 1-foot digital elevation model to delineate the connected impervious areas to their associated assets. These areas were then manually confirmed in GIS through review of each individual asset. Finally, asset areas were obtained through GreenHUB to calculate HLR.

For this specific experiment, the HLR distribution for ROWBs was determined through a calculation using estimated tributary drainage area data from roughly 3,000 constructed or in-construction ROWBs and dividing it by the area of the ROWB. HLR ranges were determined by calculating the 33rd and 67th percentiles. The ranges are listed below.

- High: >105
- Medium: 55-105
- Low: <55

Sites were selected within those determined ranges. All other variables, including GI features and land use conditions, were controlled. See Appendix D for an explanation of how the preliminary site portfolios for Year 1 experiments are determined. Appendix D also contains a series of tables with the preliminary site portfolio for the experiments that will be implemented during Year 1.

Figure 3-3. Site Selection Process Example – Hydraulic Loading Ratio Assessment for ROWBs in Residential Areas



4 MONITORING PROCEDURES

Monitoring procedures, including staffing hour requirements, vary depending on the typology and monitoring parameters. This section provides an overview of monitoring procedures that will be necessary at most or all sites to ensure data quality and continuity. These procedures apply to the GI monitoring activities, installation, and maintenance, and will assure the expected level of quality.

This section should be viewed as a list of considerations. Specific monitoring activities for specific sites will be determined based on experimental goals and site specific conditions. It must also be noted that unforeseen equipment and site-specific issues may require an adaptation to these monitoring procedures and expected staffing requirements.

4.1 Procedure Components

Installation

Installation procedures vary depending on the monitoring plan associated with each site. Installation refers to the initial installation of monitoring equipment to C1 sites with no prior monitoring, a retrofit or reuse of monitoring equipment at C1 sites with prior monitoring, as well as seasonal installation and subsequent winterization of C1 sites with temperature-sensitive equipment. It also refers to the temporary equipment setup for monitoring C2 sites. Given that C2 sites are non-instrumented sites, they may require a limited installation process to facilitate certain monitoring protocols.

For both C1 and C2 sites, installation requires access to and transportation of equipment, materials, and tools. There must also be a plan for data collection and transmission: either manually or automatically using a cell modem or Wi-Fi connection. Additionally, if a site is continually monitored, there must be a power connection for stationary equipment and data loggers. Typical power sources for GI sites include:

- Solar panel with battery,
- Battery, and/or
- Nearby electrical connection.

Each of these sources comes with additional safety and labor considerations. Solar panels must be exposed to enough sunlight to power the site and battery back-up should occasionally be monitored to ensure the exposure has not been modified. If batteries alone are used at a site, they must be routinely charged and/or replaced. An electrical connection requires authorization and the connection must be completed in a manner that does not present a safety concern.

Installation procedures must also ensure that instrumentation and equipment does not present any pedestrian hazards (tripping, falling, etc.) or allow any exposure to vandalism. Measures shall be taken to avoid people intentionally or inadvertently tampering with equipment, which could harm the data's integrity. In order to conceal the wiring, appropriate conduits must be installed in new sites, utilized as-is in existing sites, or re-installed in existing sites.

Prior to and/or upon completion of installation, all instrumentation must undergo an initial calibration. Subsequent calibrations will continue routinely and on an as-needed basis.

Equipment Storage

Storage for instrumentation, tools, and equipment is an important consideration for monitoring activity procedures at all site types. Equipment is required at various times during monitoring procedures for installation, maintenance, and mobile experimentation. When equipment and other supplies are not in use, they must be kept in a secure, safe location to reduce damaging and misplacing monitoring materials. Additionally, some of the equipment must be stored in a location that provides accessibility for use at multiple sites. An ideal equipment storage facility would serve the following functions:

- Storage location for sensors and supplies obtained from previous DEP consultants;
- Shipping destination for new monitoring equipment, soil, aggregate, plants, and other supplies and equipment;
- Location for equipment testing, calibration, storage, and repairs by Research Team;
- Staging and preparation area for mobile experimentation on C2 sites by Research Team;
- Temporary storage of water and soil samples, and other items, to prepare for C3 experiments and analysis; and
- Winter storage of temperature-sensitive remote sensing equipment.

Health and Safety

A Health and Safety Plan (HASP) will be prepared for the monitoring activities, in accordance with DEP's Health and Safety Program, as part of the experiment protocol development. Task Hazard Analyses (THA) will be developed for all experiments in order to ensure safe working conditions at monitoring sites. A Health and Safety Officer will be responsible for ensuring that the HASP is followed. For more information on this topic, consult the Quality Assurance Project Plan.

Site Access

Some site typologies, especially green roofs, require access coordination. While conducting monitoring activities procedures, staff members must have the proper keys or authorities to not only enter the site, but also to access the secured equipment within the site. While sites in the right-of-way may not require access coordination, staff members should be prepared to discuss the activities with interested community members, as well as provide informational material to assist with community engagement and education.

Monitoring Related Maintenance

Maintenance at each site is critical for the collection of quality monitoring data. However, it must be performed in accordance with the specific monitoring needs. For example, an assessment of inlet bypass should ensure that the inlet is clear of debris prior to experimentation. However, to assess sedimentation in the GI, inlets should only be maintained at their standard frequency so as to not bias the results. Maintenance may also include weeding non-native species from the sites, but only if the experiment is not specifically assessing plant health or biodiversity. All maintenance activities that pertain to the GI function must be reviewed by the Scientific Lead of the pertinent experiment(s).

The equipment in the field and used in the laboratory or greenhouse must also be maintained. This should occur on both a regular and on an as-needed basis. Regular maintenance procedures include cleaning the equipment, especially rain gauges that may become clogged, and calibrating the equipment. Cleaning the equipment may require additional assistance and a ladder to reach the climate station. Additional maintenance includes fixing broken equipment at each site on an as-needed basis. This presents a challenge when predicting labor demands, because these issues may occur at unforeseen times.

Depending on each site, the maintenance may be completed by multiple parties. It is important to establish a procedure to document all maintenance activity and observations in a database. Overall, it is likely that each site will require at least one visit a month plus visits on an as-need basis.

Data (Quality Assurance)

During routine maintenance and experimental site visits, procedures must be followed to ensure that quality data is collected and that all relevant information about the site is properly recorded. This may include documenting the current site conditions, natural and anthropogenic conditions and debris, and the observed biodiversity at each site. Pictures and field notes must be available to anyone maintaining the database to account for possible data variability. Each site visit should follow a regular schedule to maintain data continuity; site visits should also occur when issues in the transmitted data are detected. See Section 6: Data Management and Section 7: Monitoring Quality Assurance/Quality Control for further details.

4.2 Procedure Methodology

Figure 4-1 provides an overview of the monitoring activities procedures required to advance a confirmed site (from the site selection process) to data collection. This begins by determining whether the site requires instrumentation for continuous monitoring (C1 site) or whether the site will be periodically monitored with portable equipment (C2 site). Upon this determination, the monitoring activities procedures can be established so that all labor, equipment, and utility needs for site installation and monitoring can be met and sustained. After the site is fully functional, maintenance procedures are finalized, and the site is ready for data collection.

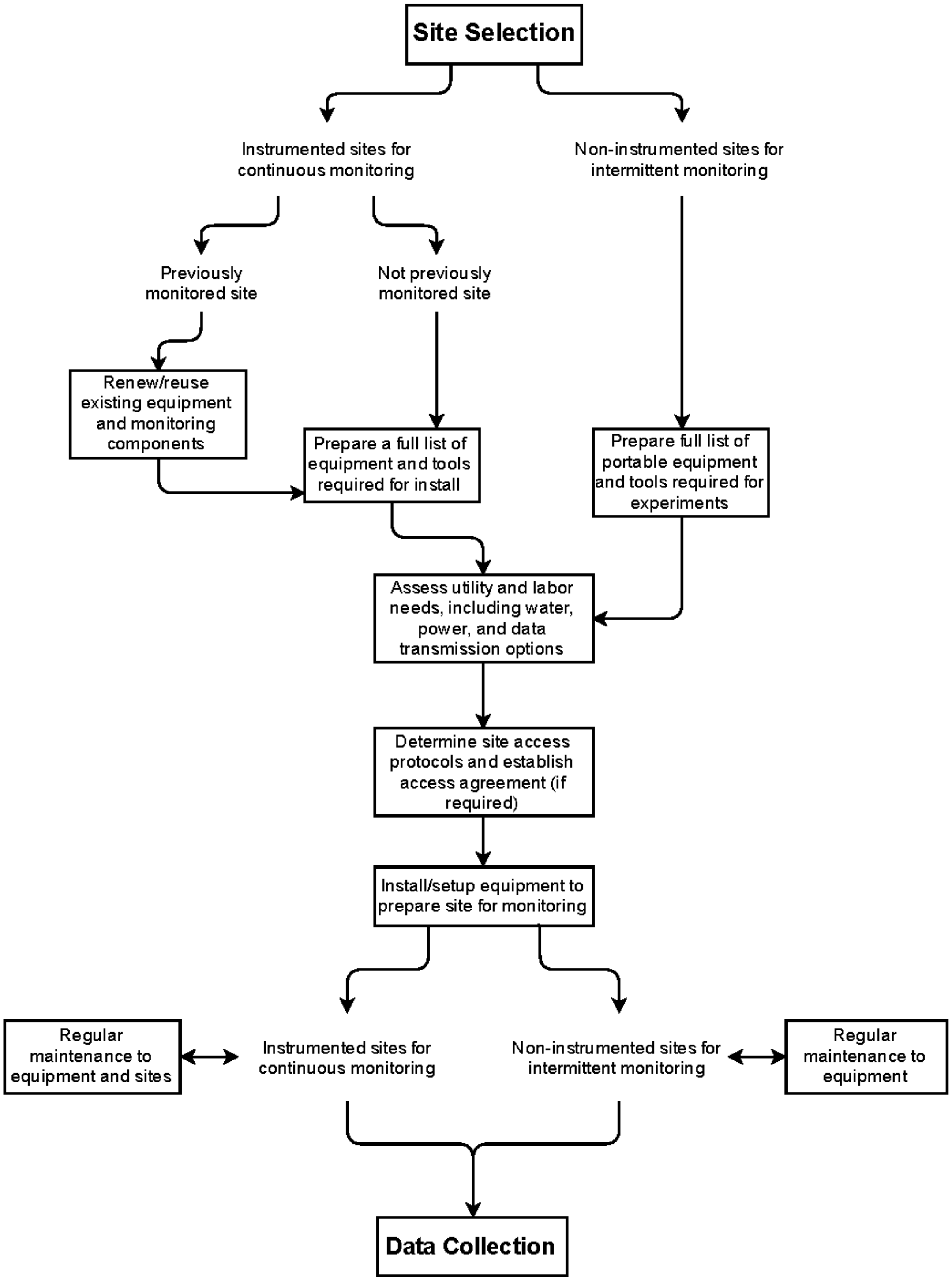


Figure 4-1. Monitoring Procedures Flow Chart

4.3 Runoff Simulation

Some experiments may require a strategy for runoff simulation. This is especially critical regarding initial calibration of instruments and equipment at C1 sites, and all hydrologic and hydraulic experiments at C2 sites. The two runoff simulation options are a hydrant test or a truck mounted water tank.

Both strategies must consider the available flow rate and volume/duration of testing. The hydrant can provide flow for an extended duration, but is only available at limited flow rates (<80 gallons per minute, or GPM) for safety concerns. Depending on the experimental needs, these flow rates may not be high enough to provide the necessary ranges of flow. Hydrants are certainly capable of higher flow rates, but this may require supervision or assistance from the New York City Fire Department and DEP's Bureau of Water and Sewer Operations. Additionally, hydrant flow may be inconsistent, especially if the hydrant is located across the street from the GI practice and requires an extended hose set-up. The truck mounted water tank has a limited volume and duration, but at 500 gallons, can provide 80 GPM for 6 minutes or 250 GPM for 2 minutes, which may better represent the range of rainfall intensities and contributing areas. Both of these options require permitting to utilize the hydrant, either directly or to fill the water tank. Ultimately, the runoff simulation method chosen will depend on the experimental requirements as well as the site conditions.

5 SCHEDULE

Three aspects were considered in developing a comprehensive monitoring schedule: duration of experiment phases, coordination between experiments, and DEP's prioritization of experiments. This section describes these considerations and provides the resulting schedule of experiments.

5.1 Experiment Phases

There are three phases to each experiment:

- Preparation,
- Data collection, and
- Data analysis and recommendations.

The duration of each phase varies depending on the type of experiment.

Preparation for all experiments requires review of existing sites to determine the most appropriate locations to perform the experiments (see Site Selection section.) Other preparation work includes retrofitting C1 sites that require continuous monitoring, reviewing existing information prior to collecting data at C2 sites, and finalizing the design and construction of C4 sites.

Duration of data collection is based on the individual experiment needs and varies from a few months to several years. Specifically, data collection for experiments that aim to evaluate specific GI components (such as inlets or stone columns) can be completed in a few months. These experiments are typically part of C2 sites for which data can be collected immediately upon site selection. Experiments that need to characterize response to varying rainfall intensities and durations will require data collection for at least one monitoring season. These are typically C1 sites which will be continuously monitored. Data collection can also last over the course of several years for some experiments, such as those that evaluate long-term plant health and establishment.

Finally, data analysis and recommendations for each experiment will occur both throughout data collection and after data collection has been completed, thus requiring that data collection for all experiments to be completed before the final year of the Project.

5.2 Experiment Coordination

Coordination between experiments involves determining which experiments can occur simultaneously based on experiment priorities and other scheduling factors. This is done by assessing the nature of each experiment and the duration of each phase. For example, experiments that require multiple sites to be retrofitted will require preparation to take place concurrently, since data analysis cannot be completed unless data is collected from all sites for the same duration. Similarly, experiments that have a short preparation phase can also take place concurrently.

Prioritization. Prioritization of experiments was based on DEP’s considerations, including the need to develop a maintenance protocol, determine performance evaluation of GI, and inform future designs. Experiments were categorized into Priority 1, which are to begin immediately, and Priority 2, which are to begin after the first year.

Scheduling. After assessing the scheduling considerations discussed previously, the schedule in Appendix E was created, which documents a cursory timetable for each experiment. Each experiment contains an ID, a description, a purpose, an assigned priority, anticipated emphasis in Year 1 (Priority 1 sites only), and the expected duration of each phase.

6 DATA MANAGEMENT

Environmental monitoring data collected and used during this project will be managed and stored using a web-based platform during project execution. The data will also be exported to DEP servers or Cloud storage, as directed by DEP. The platform is hosted on Microsoft Azure's cloud storage service, with a web-based user interface that allows direct upload, download, visualization, validation, and analysis of the data. The objective of the project data management protocol is to store all project data while ensuring:

- Availability: Data is fully and easily accessible by DEP and the Project Team;
- Interpretability: Data is well-organized for validation, analysis, and reporting;
- Security: Access to data is limited to approved users and systems;
- Quality: Appropriate quality assurance measures are taken during all phases of the Project (acquisition, handling, summary and analysis, reporting, and archival); and
- Longevity: Data is easily transferred or migrated to future platforms
    - Auditable by DEP
    - Properly documented.

6.1 Data Management Process

The Project Team will incorporate data into the database through one of several pathways, always accompanied by metadata describing its source and attributes. For the purposes of this Project, data ingestion has been segregated into four categories according to the mechanism for incorporation.

Direct sensor connection - the least labor-intensive, most automated method for incorporating new data. Sensors in the field send data directly to the web-based platform through a secure field-embedded web gateway device. The platform is prepared for the encrypted data stream after the Project Team configures its metadata. The raw sensor signal is preserved, then calibrated according to sensor-specific settings, and available instantly for viewing, export, and validation.

Web services - the web-based platform communicates directly with other online data sources. After initial metadata configuration and parameter settings, the web-based platform submits regularly scheduled Application Program Interface (API) calls to other online data sources, such as the United States Geological Survey and National Weather Service. These calls return near real-time updates of third party data, which are then available for viewing, export, and validation on the platform. This is the most streamlined approach for third party data to become part of the project data set. The web-based platform will be configured to support a collection of web services as part of this scope of work, after which users with necessary permissions will be able to connect specific streams of data from those web services to the platform.

Automated upload - similar to web services, the web-based platform communicates directly with other online data sources. However, this category represents sources that do not have public APIs available, such as file transfer protocol (FTP) storage databases. After configuration tailored to the specific site, the web-based platform will be enabled to automatically and repeatedly upload data from these online data sources with minimal Project Team interference. An example of this category of upload is retrieving data sent to FTP servers by Campbell Scientific services. These data sources will be available for viewing, export, and validation after conducting the automated upload.

User upload - project data that does not fall into the previous three categories; the most labor-intensive method. These data sources cannot be directly connected, are not available through web services, and are not stored in readily accessible upload formats. After metadata configuration, the project team will compile the data into pre-defined templates for manual upload. The platform will be configured to accept a defined collection of manual uploads, to be determined by the combination of historical data availability, site investigation objectives, and monitoring procedures. These data sources will be available for viewing, export, and validation on the project platform after each user upload and verification.

Once properly configured and ingested, all project data will be stored in a cloud-based table database that is geographically redundant and uses a common sequential time key. The table storage is specifically designed to adapt to the evolving needs of the Project without requiring significant configuration changes. User-friendly views of data are stored in a cache database so that they can be accessed quickly through the web user interface.

The database user interface is available through restricted log-in access on an internet browser. All Project Team members will be assigned access levels according to their role in the Project. From the user interface, users can view, interact with, and download the data in a format that facilitates quality control and validation. Manual uploads will also be processed through the user interface and will be available based on user access restrictions.

While some analysis functions will be built into the data storage platform as the project progresses to facilitate repeatable research activities unique to this project (defined elsewhere), the project team members will most typically download data in consistent formats to execute study experiments. The final list of supported formats will be determined as part of experiment designs. However, it is expected that comma-separated value (CSV) will provide the primary means of universal download and upload functionality. CSV files are widely accepted as a standard import/export format for data analysis and data management tools.

Figure 6-1 presents a conceptual representation of the flow of data into, through, and out of the project storage system. For the duration of the GI-RD Project, the data will be maintained and stored within the cloud platform. Periodic exports will be available to local DEP servers in an acceptable format, or to Cloud storage, as directed by DEP. At the conclusion of the study, DEP will determine whether to continue using the web-based platform to store and manage data or to complete a full export to local or other cloud storage.

Figure 6-1. Project Data Flow

6.2 Key Functions

The following functions will be developed and supported as part of the GI-RD Project. Additional details on the data management structure, plan, and supported functionality are included in Appendix F.

Data Audit Log/Chain of Custody - An audit log will be associated with each time series data stream stored on the platform. Recording all changes to data, intentional or unintentional, will provide confidence in the project data set.

Data Validation - A core function of any environmental data management structure must be to support quality assurance and quality control activities such that only valid data is used in study experiments. The data validation process will use the roles and permissions described in Appendix F to tag data as users perform necessary reviews.

Data Visualization - The storage platform will not be the only tool that the Project Team uses to visualize data. However, rapid data viewing will facilitate management of active experiments, data review, and communication among the Project Team.

Facilitated Reporting - As the Project and experiments progress, the storage platform will facilitate efficient work processes by automating the creation of standard, repeatable reports.

Derivative Data Streams - Derivative data streams are the result of raw data combined with mathematical transformations. A simple example is minute-by-minute rainfall totals transformed to hourly rainfall intensities. As the Project progresses the Project Team will identify repeatable transformations that can be integrated into the data storage platform.

7 MONITORING QUALITY ASSURANCE/QUALITY CONTROL

This section describes the quality assurance/quality control procedures that will be used as the experiments are implemented in the field or in laboratories. The preliminary Quality Assurance Project Plan (QAPP) for this project is attached to this document as Appendix G.

7.1 Quality Assurance Responsibilities

The Project Quality Assurance Manager (QAM) will be responsible for Quality Assurance (QA). The QAM will coordinate with the Scientific Lead (SL) for a specific experiment prior to initiation of field activities to ensure that the Project Team is familiar with the procedures in the QAPP. It is the responsibility of the QAM to ensure that any variance in the QAPP is properly documented and approved by the Project Manager and Monitoring Task Manager before it is implemented. Additionally, the QAM will review analytical data and coordinate third-party data validation.

7.2 Measurement Performance Criteria

Measurement performance criteria for the Project include the following:

- Precision – the agreement between numeric values for two or more assessments that have been obtained in an identical manner (i.e., duplicate samples);
- Accuracy – the degree of agreement of a measurement with its accepted or true value (obtained through field calibration, laboratory control samples, etc.);
- Completeness – the quantity of valid data obtained via measurement compared to the quantity that was expected based on the monitoring plan;
- Comparability – the consistency between sampling and analytical procedures that ensures that one data set can be compared to another; and
- Sensitivity – the ability of a method or instrument to detect a constituent of concern at the expected concentration/level of interest.

7.3 Documentation and Records

Project-related records will be stored in a project file, which will include project correspondences, meeting minutes/notes, project schedules, calibration records, field sample results, calculations, analytical/monitoring data, and any other Project-related documents. The project file will be maintained by the Project Manager/Monitoring Task Manager and QAM.

Field documentation will be maintained in weatherproof field log books or electronic recording equipment (e.g., field laptops, PDAs, etc.). Field documentation will include sample collection data, visual observations, description of equipment used, calculations, and calibration data. Some field activities may correspond to specific field data sheets, which will be noted in the log book when used.

7.4 Special Training and Equipment Requirements

Field staff working on the Project will be required to review the Project Health and Safety Plan (HASP) prior to performing any field work. Additionally, a Task Hazard Analysis (THA) will be prepared for each sampling task, listing the various hazards that may be encountered during the task. SLs and the QAM will be responsible for ensuring that the safety procedures outlined in the HASP and THA are followed by field staff. The HASP will be updated on a yearly basis.

The subcontracted laboratories are required to maintain the required state/agency certifications and accreditation for the provided analytical services.

7.5 Equipment Testing, Inspection and Maintenance

Maintenance of field equipment will be performed by field staff and overseen by the SLs. Field work will not proceed until the properly-working condition of all equipment has been verified. Maintenance will consist of decontamination (via water rinse, non-phosphate detergent, and deionized water rinse) and calibration (to be carried out at the time of equipment installation or per the manufacturer's recommendations).

7.6 Assessment, Oversight, and Reporting

The Project Manager/Monitoring Task Manager, QAM, and SLs will periodically evaluate the implementation of the QAPP by auditing field activities including sampling, chain of custody (COC) preparation, and equipment calibration. Any deviations from the QAPP will be noted in daily field log books and corrective action will be applied as necessary to bring deviations back into compliance with the QAPP. Deviations from the QAPP will be reported to the QAM and Project Manager/Monitoring Task Manager.

Quality Assurance/Quality Control (QA/QC) issues related to laboratory analytical procedures will be identified and corrected by laboratory staff according to the laboratory's quality control standards.

7.7 Data Management and Validation

Project data will be provided to the Project Manager/Monitoring Task Manager by the SLs. The PM/Monitoring Task Manager will maintain the data within the project file. Laboratory data will undergo verification and review to ensure that the laboratory's QA/QC procedures were followed. Review of laboratory data will include: checking whether holding time requirements were satisfied, COCs were properly recorded, appropriate analytical procedures were used, equipment was properly calibrated, QC samples were properly analyzed, and control limits were attained. Once validated, the laboratory data will be reduced to tabular format or other format as needed for each experiment for reporting.

7.8 Data Usability

Usability of the water quality and other monitoring data for the Project will be determined by reviewing the precision, accuracy, representativeness, completeness, and comparability (PARCC parameters) of the data:

- Precision will be evaluated by calculating the Relative Percent Difference between duplicate samples.
- Accuracy will be evaluated by calculating the percent recovery of matrix spike/matrix spike duplicate samples and laboratory control samples.
- Representativeness will be ensured by properly selecting sampling locations and ensuring that sample handling procedures are conducted in accordance with the protocols outlined in the QAPP.
- Completeness will be attained by having at least 90% of samples validated.
- Comparability will be achieved by using standard techniques to collect and analyze samples and by reporting results in appropriate units so that results can be readily compared to other data sets.

8 NEXT STEPS AND IMPLEMENTATION SCHEDULE

Upon approval of this monitoring strategy, the Project Team will begin implementation. In order to plan for the upcoming monitoring season, an implementation schedule will be developed. The implementation schedule will detail the timeline for final site selection, field validation of sites, procurement of monitoring equipment and instrumentation, equipment installation and calibration, and the commencement of field activities.

This document will be updated annually since, as described in Section 5, experiments will be in varying phases throughout the duration of the Project and will therefore require different protocols. As a result, the schedule, Experimental Protocol Summary Sheets, monitoring site list, equipment list, data management plan, QAPP, and HASP, among other documents, may need to be revised in order to reflect the current status of the Project. In accordance with DEP’s adaptive management approach, this Project is a multiyear, iterative effort in which the Project Team will incorporate lessons learned and update its approach as needed.