Chapter 7 Drainage & Wastewater System Modeling

Appendices

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Chapter 7 DRAINAGE & WASTEWATER SYSTEM MODELING

This chapter of the Design Standards and Guidelines (DSG) presents Seattle Public Utilities (SPU) standards and guidelines for the construction and use of hydrologic and hydraulic (H/H) models of drainage and wastewater (DWW) collection facilities in the City of Seattle (the City). Specific DSG standards are highlighted as underlined text for easier reference.

Typical City projects that require H/H modeling are combined sewer overflow (CSO) abatement design, pump station upgrades, storm drain facility planning and design, claims investigation, and mainline capacity analysis.

7.1 KEY TERMS

Abbreviations and definitions given here follow either common American usage or regulatory guidance.

7.1.1 Abbreviations

Abbreviation	Term
BMP	best management practices
BSF	base sanitary flow
CCF	100 cubic feet (i.e. centum cubic feet)
CIP	Capital Improvement Program
CSO	combined sewer overflow
DHI	Danish Hydraulic Institute
DSG	Design Standards and Guidelines
DWF	dry weather flow
DWW	drainage and wastewater
EPA	U.S. Environmental Protection Agency
EPA SWMM	U S. Environmental Protection Agency’s Stormwater Management Model
ESRI	Environmental Systems Research Institute
FOP	Facility Operation Plan
ft	feet

Abbreviation	Term
GIS	geographic information systems
GSI	green stormwater infrastructure
H/H	hydrologic and hydraulic
HSPF	Hydrologic Simulation Program Fortran
I/I	infiltration and inflow
KCDOA	King County Department of Assessment
LiDAR	light detection and ranging
LOB	line of business
LRFP	left and right floodplain
MH	maintenance hole (a.k.a. manhole)
NPDES	National Pollutant Discharge Elimination System
O&M	Operation and Maintenance
PLC	programmable logic controller
PSRC	Puget Sound Regional Council
QA	quality assurance
QC	quality control
ROW	right-of-way
RTC	real time control
SCADA	Supervisory Control And Data Acquisition
SOPA	System Operation, Planning, and Analysis
SDCI	Seattle Department of Construction and Inspections
SDOT	Seattle Department of Transportation
SPU	Seattle Public Utilities
STAZ	Statewide Traffic Analysis Zone
WWF	wet weather flow

7.1.2 Definitions

Term	Definition
base flow	Flow in a conveyance system during dry weather is the base flow (also called dry-weather flow [DWF]) of the conveyance system. This base flow is consisted of seasonal non-rainfall related groundwater infiltration and direct inflows during dry weather. Direct inflows can include flow from underground springs through pipe defects, flow from sanitary side sewer lateral connections, and others.

Term	Definition
block (or census block)	A geographic area bounded by visible and/or invisible features (features may be visible, such as a street, road, stream, shoreline, or power line, or invisible, such as a county line, City limit, property line, or imaginary extension of a street or road). Generally, the boundary of a census block must include at least one addressable feature; that is, a street or road shown on a map prepared by the U.S. Census Bureau. A block is the smallest geographic entity for which the U.S. Census Bureau tabulates decennial census data.
block group (or census block group)	A statistical subdivision of a census tract (or, prior to Census 2000, a block numbering area). A block group (BG) consists of all tabulation blocks whose numbers begin with the same digit in a census tract. For example, for Census 2000, BG 3 within a census tract includes all blocks numbered from 3,000 to 3,999. (A few BGs consist of a single block.) BGs generally contain between 300 and 3,000 people, with an optimum size of 1,500 people. The BG is the lowest-level geographic entity for which the U.S. Census Bureau tabulates sample data from a decennial census.
boundary condition	Boundary condition can be most downstream discharge point of a model, most upstream point of a model, and/or adjacent point to a model. Some examples are discharge from an upstream basin, discharge from an adjacent basin, outfall to a body of water (such as creek, river, stream, Lake Washington, or Elliott Bay) as well as discharge to King County wastewater system.
calibration	The process of adjusting model parameters to have agreement between model simulation results and field data (e.g. flow monitor data, SCADA data, etc.).
combined sewer	Public combined sewers are publicly owned and maintained sewage systems that carry stormwater and sewage to a treatment facility. Treated water is released to Puget Sound.
combined sewer overflow (CSO)	A combination of untreated wastewater and stormwater that can flow into a waterway when a combined sewer system reaches its capacity.
conveyance system	A conveyance system is any natural or engineered systems that convey water from one point to another. An example of a natural conveyance system is a natural river system and an example of an engineered system is a piped sewer system.
design flow rate	Flow rate used to size infrastructure such as a pipe, creek cross-section, weir, and others
design volume	Volume of water that includes the overflow control volume plus, among other specific requirements, extra storage volume needed to allow for incidents when the facility is used to contain the overflow control volume again before the facility is completed drained while not imposing an adverse impact (e.g. local flooding) to the hydraulic system upstream of the facility. Design volume is usually calculated from long term H/H simulation results.
Discrete Address Point (DAP)	Addresses are the common way to identify specific buildings and/or property units. Discrete Address Points are intended to provide a comprehensive geographic reference for all addresses. Each point in the DAP layer represents either a building or a vacant parcel, derived from the BLDG and PARCEL layers. Linkage keys back among these geographic information system (GIS) layers are the primary DAP element attributes.
drainage	Stormwater that collects on a site through footing or yard drains, gutters, and impervious surfaces. If there is no discharge point of such stormwater into a conveyance system such as a natural drainage system, a ditch-and-culvert system, and/or a public storm drain system, such stormwater discharge may be dispersed onto the ground and be conveyed as surface runoff and/or infiltrated into the native soil as infiltration.
drainage system	A system intended to collect, convey, and control release of only drainage water. The system may be either publicly or privately owned or operated, and the system may serve public or private properties. It includes constructed and/or natural components such as pipes, ditches, culverts, streams, creeks, or drainage control facilities.
Dry-weather flow model	A mathematical model that simulates the generation and conveyance of base flow.

Term	Definition
flow assignment	Correlation of flow from tributary areas to specific nodes in the collection system model. Flow assignment nodes should be selected based on the collection system network.
flow control	Controlling the discharge rate, flow duration, or both of drainage water from a site through means such as infiltration or detention. 22.801.070 Seattle Municipal Code (SMC)
flow monitoring	Collection of data such as flow depth and velocity at a monitoring point.
green stormwater infrastructure (GSI)	Distributed best management practices (BMPs) integrated into a project design that use infiltration, filtration, storage, or evapotranspiration, or provide stormwater reuse. 22.801.080 SMC
guidelines	Advice for preparing an engineering design. They document suggested minimum requirements and analysis of design elements to produce a coordinated set of design drawings, specifications, or lifecycle cost estimates. Design guidelines answer what, why, when, and how to apply design standards and the level of quality assurance required.
hydraulics	Conveyance of water through pipes, open channels, force mains, maintenance holes, weirs, orifices, hydrobrakes, pump stations, and similar infrastructure.
hydraulic conveyance system model	A mathematical model that simulates the routing of flow through a hydraulic conveyance system. A hydraulic conveyance system model consists of link and nodes that represent physical elements in a hydraulic conveyance system (e.g. pipes, weirs, etc.).
hydrologic (hydrology)	Transport and distribution of water (such as rainfall) in an area based on top surface layer (i.e., pervious or impervious), below surface conditions (soil type), and evapotranspiration rates.
hydrologic (wet-weather) model	A mathematical model that generates wet weather flow based upon meteorological and hydrologic conditions.
hydrograph	A graphical representation of stage, flow, velocity, or other characteristics of water at a given point as a function of time. Hydrographs are commonly used in the design of surface water and sewer systems including combined systems.
infiltration and inflow (I/I)	Simulation of the component of flow from a study area attributable to surface runoff (inflow) and subsurface flow (infiltration) entering a conveyance system. Total Infiltration and inflow (I/I) is defined as the sum of Rainfall Dependent Infiltration and Inflow (RD I/I) plus seasonal Groundwater Infiltration (sGWI) as illustrated by the equation below: I/I = RD I/I + sGWI.
level of service	Performance measure of a system over time.
natural systems	A vegetated area in its natural state prior to development (such as a forest)
natural drainage systems	A form of GSI. Natural or constructed rain gardens, swales, ravines, and stream corridors. Natural drainage systems cross privately and publicly owned properties and can flow constantly or intermittently.
Operations	Generic term for SPU staff responsible for field operations.
outfall	Generally, the point of discharge from a storm drain. It can also include combined sewer flows. See also **Table 8-1** in *DSG Chapter 8, Drainage and Wastewater Infrastructure*.
overflow control volume	Overflow volume at a NPDES outfall point for a defined performance level. This usually is smaller than the design volume of an overflow control volume facility.
pump runtime	The duration of time a pump is on.
rainfall dependent infiltration and inflow (RD I/I)	During a storm event, the resulting increase in inflow and infiltration is commonly referenced as rainfall dependent inflow and infiltration (RD I/I) by literature. Then, I/I = RD I/I + sGWI. In literature, “I/I” and “Total I/I” are synonymous.

Term	Definition
sanitary sewer flow	Sewage produced by private residents, businesses, schools, hospitals, industrial users, and other sewer connections to the wastewater conveyance system. It is also called base sanitary flow [BSF]. This flow does not include drainage and only attributable to human and animal sources.
Seasonal groundwater infiltration (sGWI)	Groundwater infiltration into a conveyance system due to seasonal non-storm related fluctuation of underground water sources.
service drain (or lateral)	A privately owned and maintained drainage system that conveys only stormwater runoff, surface water, and subsurface drainage and discharges at an approved outlet as defined by the SPU Director. Service drains include, but are not limited to, conveyance pipes, catch basin connections, downspout connections, detention pipes, and subsurface drainage connections to an approved outlet. Service drains do not include subsurface drainage collection systems upstream from the point of connection to a service drain. 22.801.030 SMC. See also **Table 8-1** in *DSG Chapter 8, Drainage and Wastewater Infrastructure*.
side sewer (or lateral)	A privately owned and maintained pipe system that is designed to convey wastewater, and/or drainage water to the public sewer system or approved outlet. This includes the pipe system up to, but not including, the tee, wye, or connection to the public main. 21.16.030 SMC. See also **Table 8-1** in *DSG Chapter 8, Drainage and Wastewater Infrastructure*.
SPU engineering	Generic term for SPU staff responsible for plan review and utility system design for CIP projects.
standards	Drawings, technical or material specifications, and minimum requirements needed to design a particular improvement. A design standard is adopted by SPU and generally meets functional and operational requirements at the lowest life-cycle cost. It serves as a reference for evaluating proposals from developers and contractors. For a standard, the word “must” refer to a mandatory requirement. The word “should” is used to denote a flexible requirement that is mandatory only under certain conditions. Standards appear as underlined text in the DSG.
stormwater	Stormwater means runoff during and following precipitation and snowmelt events, including surface runoff, drainage, and interflow. 22.801.200 SMC
surcharging	A state of an underground hydraulic conveyance system that occurs when level of water in pipe (or structure) rises above the top of pipe (or structure) and therefore the pipe (structure) becomes pressurized.
tract (or census tract)	A small, relatively permanent statistical subdivision of a county or statistically equivalent entity, delineated for data presentation purposes by a local group of census data users or the geographic staff of a regional census center in accordance with U.S. Census Bureau guidelines. Designed to be relatively homogeneous units with respect to population characteristics, economic status, and living conditions at the time they are established. Census tracts generally contain between 1,000 and 8,000 people, with an optimum size of 4,000 people. A census tract, census area, or census district is a geographic region defined for the purpose of taking a census.
validation	The process of comparing simulated model results with field data (not used for model calibration) and finding agreement without adjusting model parameters.
wastewater	Wastewater is a comprehensive term including industrial waste, sewage, and other polluted waters, as determined by the Director of Health or Director of SPU. 22.16.030 SMC
wet weather flow	Flow generated during wet weather. Wet weather flow = baseflow + RD I/I.

7.2 GENERAL INFORMATION

Hydrologic and Hydraulic (H/H) modeling is a frequent component of SPU's drainage and wastewater system planning and engineering. A H/H model contains a physical description of both the hydraulic conveyance system and the hydrology of the system being modeled. A H/H model uses mathematical equations to estimate the amount of water entering the modeled systems and simulate its movement throughout the systems. Results are used to estimate and assess the hydraulic capacity of the conveyance system modeled and its response to specific changes (e.g. larger pipes, wider channels, new pumps, or new demands).

The utilization of H/H modeling and generated results are integrated into the following SPU planning, operational, and facility design activities:

- Predicting base and peak flows
- Performing system capacity assessments and Capital Improvement Program (CIP) planning
- Setting sizing criteria for preliminary engineering, pre-design, and design projects
- Planning future annexations
- Managing assets (replacement, rehabilitation, and system optimization scenario testing)
- Forensic testing of system overflows, backups, and surface flooding problems

7.2.1 Modeling Concepts

A good H/H model of a system network must adequately capture the physical characteristics of the system modeled for it to be useful in computing and assessing the hydraulic capacity of the system. To model the non-mechanical components of a system network (e.g. pipes or maintenance holes), physical characteristics of these components including elevations, geometry/diameters, friction characteristics, and connections to other system components are needed. As for the mechanical components, such as pumps stations and gates, information related to operational characteristics are also required. Generally, these required information on physical infrastructure are available from geographic information system (GIS) databases, record drawings (as-builts), and other resources (see DSG section ***7.5***).

The process of building a H/H model of a drainage or wastewater system and using it to simulate the routing of the water through the system network under different weather conditions is complex. For estimating and routing of flow during dry weather (i.e., dry weather flow), information about seasonal groundwater infiltration and sanitary flow are needed. This information is extracted from flow monitoring data and combined with user provided demographic data as needed. After this information is collected, they are input into a H/H model. A H/H model will then take this information and estimate and route the dry weather flow through the modeled system network. As for estimating wet weather flow and its routing during wet weather, additional hydrologic, hydrogeologic, and precipitation data of the modeled area are also needed. Upon input of this additional information, the H/H model will combine the dry weather flow information with the additional information and estimate and route the wet weather flow through the simulated system network.

To facilitate the H/H modeling, a representation of the hydrologic and hydraulic system of the simulated system network must be built in the H/H model. The hydraulic network in a H/H model is represented by a series of links and nodes. Nodes represent infrastructures such as maintenance holes, storage facilities, catch basins, or tee connections. Links represent conveyance such as pipes, open channels, culverts, and special structures such as weirs, gates, pumps, and hydrobrakes. The hydrologic system is usually represented by polygons with associated hydrologic and hydrogeologic parameters for flow generation. After flow is generated by the hydrologic system, flow enters the hydraulic system via pipes and/or nodes. These nodes usually represent maintenance holes in the field. During the model construction process, GIS analysis and other methods are used to allocate area from the hydrologic system to be tributary to these input nodes in the hydraulic system to mimic how laterals, curbs, drainage inlets, and possible subsurface inflow and infiltration sources could convey flow to the pipes in the field. Depending on the complexity of the modeled system hydraulics, hydraulic equations used can vary from Manning's flow equation (kinematic wave) to the full Saint Venant equations of Continuity and Momentum (dynamic wave). These equations can also be coupled with various surcharge algorithms for modeling hydraulic processes involving surcharging of pipes.

With the appropriate hydrologic, hydrogeologic, and hydraulic information entered into a model, a H/H model can generate various simulation results useful for system operation and design activities (e.g. water surface elevations in a portion of the network, pump operation sequence, and flow hydrographs, etc.).

7.2.2 Types of Models

Different types of H/H models have differing strengths and limitations and thus vary widely in complexity and requirements (e.g. quantity of input data, user training, software licensing). The design engineer should select a modeling approach with an appropriate level of complexity to address project goals (e.g. simple spreadsheet models or a more specialized H/H modeling software).

7.2.2.1 Hydrologic and Hydraulic Models

SPU characterizes its H/H models in the following three categories based on level of detail: skeletal models, planning models, and detailed design models.

7.2.2.1.1 Skeletal Model

A skeletal H/H model simulates flow in major (large diameter) sewers within a collection and conveyance system. A skeletal model is also referred to as a *trunk line model*. Typically, a skeletal model extends from a downstream outlet (e.g. a major pump station or sewer basin outlet) to upper reaches of a sewer catchment and can include multiple sewer basins. Skeletal models can also include simplifications to eliminate complexity or to improve calculation speed. The primary benefit of a skeletal model is a quick, representative evaluation of a system's major component performance. A skeletal model can be used for:

- Long-term H/H simulations for deriving performance statistics and evaluating historical events of interest
- Simulation of flows at specific locations (e.g. pump stations), where a characterization of the detailed upstream system is not of interest
- Overall assessment of a sewer basin to estimate the impact of planned re/development or annexation and/or compare alternatives for major changes to a sewer network

- Simulation of boundary conditions in larger sewers so that more detailed models of ancillary sewers can be developed using representative tail water conditions
- Design and testing of major CIP projects, where less detail is appropriate.

7.2.2.1.2 Planning Models

A planning H/H model simulates flow in most or all portions of a collection system within a specified neighborhood. These models are used when more detailed assessment is required than can be provided in a skeletal model. Planning models can be used to identify problem areas within specific portions of wastewater or drainage systems and a range of possible solutions. The level of detail included in a planning model should be balanced with the need for precision. For example, small-diameter pipes could be excluded from a planning model that covers a very large spatial extent, particularly in areas with no documented flooding history. A planning model typically is used for:

- Simulation of flows in areas excluded from a skeletal model.
- Assessment of a known problem area where a skeletal model does not provide sufficient detail.

7.2.2.1.3 Detailed Design Models

A detailed design H/H model is useful for evaluating specific areas and detailed investigation and operations. A detailed design model is usually derived from a planning model but includes an even greater level of hydrologic, hydrogeologic, and hydraulic detail and covers a more limited spatial extent. These types of models are often used in evaluating proposed solutions to improve drainage and wastewater services. These models also include infrastructure+ (e.g. weirs, orifice, sluice gate, or pump stations) that could be affected by infrastructure upgrades or modifications.

7.2.2.2 Hydrologic and Hydraulic Model Software

The standard approved H/H modeling software for SPU projects is the latest version of U. S. Environmental Protection Agency's (EPA) Stormwater Management Model (EPA SWMM) software. EPA SWMM is public domain software that can run dynamic wave simulation (i.e., St. Venant Equations) coupled with the Aldrich, Roesner et al Surcharge Algorithm to compute simultaneous flow depths (or pressures), velocities, and flow throughout any dendritic or looped conveyance system. Results generated by the software can also be post processed by third-party SWMM user-interface model processing software and exported to Environmental Systems Research Institute, Inc. (ESRI) GIS software. Examples of such third-party model processing software include PCSWMM, XPSWMM, DHI MIKE+ SWMM, and InfoSWMM. Currently, SPU uses PCSWMM.

Whenever the use of EPA SWMM cannot achieve SPU project, operation, or programmatic goals (e.g. SOPA operation, joint operation with King County, or other interagency collaboration), other public or proprietary modeling software (e.g. HEC-RAS, DHI MIKE URBAN/MOUSE) can be used. In those cases, the use of such software must be approved by the SPU LOB representative and/or project manager prior to commencement of work. Contact the SPU project manager for additional information. Currently, for drainage and wastewater operations and joint operation projects with King County, DHI MIKE URBAN/MOUSE software is used. MIKE URBAN/MOUSE software will be replaced by MIKE+ software after DHI discontinues its technical support for MIKE URBAN.

Refer to the City of Seattle Stormwater Manual for additional modeling software approved for hydrologic modeling.

For GSI modeling, refer to **Appendix 7H - GSI Modeling Methods**.

7.2.3 Codes and Regulations

For relevant codes and regulations for drainage and wastewater system modeling, see Section 8.3 of *DSG Chapter 8, Drainage and Wastewater Infrastructure* and the City of Seattle Stormwater Manual and its Appendix F Hydrologic Analysis and Design.

7.3 BASIS OF DESIGN FOR MODELING

SPU requires the creation of a modeling plan and a technical memorandum that describes key modeling goals for each modeling project. Quality assurance (QA) milestones approved by the SPU LOB representative assigned to the project must be incorporated into the modeling plan.

7.3.1 Modeling Plan

Each SPU project with H/H modeling must have a modeling plan. The modeling plan must follow the sample outline presented in **Appendix 7A - Modeling Plan & Reporting**. SPU must approve any deviations from the plan.

Each project with flow monitoring must have an approved flow monitoring plan before flow monitoring installation. The flow monitoring plan must follow the sample outline in **Appendix 7A - Modeling Plan & Reporting.**

7.3.2 Technical Memorandum on Key Goals

Key goals for modeling must be developed collaboratively between SPU and consultant staff (if applicable). Key goals of the project must be documented in a brief technical memorandum following the outline presented in **Appendix 7A - Modeling Plan & Reporting.**.

7.3.3 Quality Assurance Milestones

The QA milestones that must be incorporated into each SPU project with H/H modeling are shown in **Table 7-1**.

Table 7-1
H/H Modeling QA Milestones

Milestone	Phase (after . . .)	Review Activity
1	Modeling plan	Project team must review. Project manager should assign reviewers
2	Flow monitoring and precipitation plan (if necessary).	Plans must be reviewed by staff assigned by project manager
3	Precipitation and flow monitoring collection (if necessary)	Team must formalize a data QA process for weekly or biweekly review of monitoring data
4	Model development and construction	The QA check should be completed by an independent senior member of the project's modeling team
5	Model calibration	Completed by an independent senior member of the project's modeling team.
6	Long-term simulation and uncertainty analysis (if applicable)	Determines whether uncertainty in modeling results generates substantial risks to overall success of project. Key project team members must participate.
7	Alternative analysis	Reviewed by an independent senior member of the project modeling team
8	Model documentation	Reviewed by an independent senior member of the project modeling team

The following are SPU standards for H/H modeling QA:

1. The modeling plan must identify the key project milestones where model review and QA checks must be performed.
2. The model QA checks must be documented and compiled as part of the overall model documentation.
3. The elements and results of each QA check must be documented clearly to make QA documentation understandable to future modelers after the original project is complete.

For a detailed modeling QA checklist, see **Appendix 7B - Modeling QA/QC Checklist**.

7.4 MODEL ARCHIVING, UPDATES, AND DOCUMENTATION

Model archiving, updating, and documentation must all be considered before developing an H/H model. This section describes SPU standard methods for archiving, updating, and documenting H/H models of the SPU drainage and wastewater collection system. SPU collection system models are currently cataloged on the SPU server. For checking out an SPU model, refer to DSG Section ***7.5.9.8***.

7.4.1 Preparing Model for Archiving

SPU staff periodically access archived models to ensure that they function with the latest versions of relevant software packages owned and operable by SPU. All models that are five years or older must be compatible with the latest version of the relevant SPU-owned software or they can be discarded when updating is not practicable. SPU staff or consultants working on a H/H modeling project should first check to see whether a H/H model may be available for the study area. Refer to DSG section ***7.5.9.8*** for checking out a model. If available, those models should be used to the extent feasible or as a basis for further project refinement.

7.4.1.1 New Models

New models must follow these standards to develop an archiving package:

1. The H/H model file name can only use up to a maximum of 30 characters. The file name must be a brief version of the project name. For example, Windermere CSO Reduction project's H/H basin model file name is *Windermere*.
2. Naming model scenarios: The model scenario for existing conditions must be named *Existing*. All other scenarios must be named sequentially (e.g. *Scenario #1*, *Scenario #2*, and so on). A brief description for each scenario should be added to the first three lines of the title block in the SWMM5 input (.inp) file. An example of the title block of a SWMM .inp file can be as follows to include the scenario information:

   [Title]

   Windermere CSO Reduction project

   Scenario #1

   {SPU(JD)-2015.12.10} Replaced hydrobrake with automatic gate

   All intermediate scenarios that are not current or no longer needed must be deleted prior to submitting the model files for archiving.
3. Create separate subfolders for input and output time series data. In addition, the input time series data should be collocated with the .inp file.
4. Colocate supporting calculations in a subfolder and provide them with the modeling files.
5. Include the modeling plan, modeling report, and documentation with the modeling files.

7.4.1.2 Archive Package

A ready-to-archive model package must be provided to SPU staff when a project is completed. The model archive package must include a one-page summary README file that identifies key elements of the model for those searching the archive. The summary must include the following information:

1. Brief narrative description of model purpose, study area, and results
2. Map showing model location and boundaries
3. Model summary table that includes the following:
   a. Type of model (e.g. skeletal, planning, or detailed design)
   b. Purpose of model (e.g. planning, pump station design, CSO control)
   c. H/H model software and version number used to create the model

   d. Rainfall data sources
   e. Evaporation data sources
   f. Basin hydrologic and hydrogeologic properties data sources (e.g. percent imperviousness, soil map and properties)
   g. Infrastructure data sources (e.g. pipe properties, pump curves, RTC algorithm)
   h. Boundary condition data sources (e.g. time series at the Lake Washington level, Elliott Bay level, or King County system level)
   i. Model calibration period
   j. List of baseline/existing and scenarios completed and the names of the associated model input files
   k. Type of I/I calculations used (e.g. for the Madison Valley InfoWorks model, it would be appropriate to note that Hydrologic Simulation Program Fortran (HSPF) was used to calculate direct inflows to area catch basins instead of using EPA SWMM I/I simulation techniques)
   l. Key assumptions and work remaining
   m. List of file name(s) of associated documentation/reports/technical memoranda

4. Special Note Heading should include other important or unique information about the model that the next modeler should know about the model.
5. Final acceptance of the archived package should be reviewed by SPU.

7.4.2 Updating a Model

SPU staff must update models as new or updated information becomes available. Generally, most models are maintained and updated in response to one of two events:

- New or updated system infrastructure information and/or flow data become available
- The model can be expanded or integrated into a nearby modeling effort or integrated into SPU's system-wide modeling effort.

<u>At a minimum, updating a model must consist of the following</u>:

1. Give the model a new name and date stamp.
2. Document the sources of new information added to the model.
3. Add new or revise existing infrastructure, boundary condition, and/or flow data to the model. If applicable, recalibration. Document the revisions within the model.
4. Document all modeling updates in a technical memorandum and update the one-page summary README file of the updated model with new and/or revised information.

For detailed information on a modeling plan, see DSG section ***7.3.1***.

7.4.3 Modeling Report

A modeling report describes the model and conclusions drawn from its use. The report also provides a record for assessing the model's suitability for future use such as during design, post construction monitoring, and on other projects.

SPU H/H modeling work must be documented in a modeling report. SPU must approve any deviations from the modeling plan and the deviations must be documented in the modeling report. At a minimum, the modeling report must include the following sections:

- Model development
- Model calibrations and validation
- Uncertainty analysis (if applicable)
- Discussion of existing system performance
- Alternatives analysis (if applicable)
- Discussion of modeling results limitations
- Discussion on model future use (e.g. post construction monitoring, informing design)
- Conclusions and recommendations

For a sample outline for a modeling report, see **Appendix 7A - Modeling Plan & Reporting**.

7.5 MODEL CONSTRUCTION

Model construction is the initial phase in building a H/H model. This section describes the five major elements required to construct a H/H model:

- Hydraulic conveyance system model
- Sub-basin delineation and flow assignment in the study area
- Boundary condition definition and modeling
- Dry-weather flow model
- Hydrologic (wet-weather) model.

7.5.1 Data Sources and Requirements

SPU H/H models have several data requirements and sources (**Table 7-2**).

Table 7-2
H/H Model Inputs and Data Requirements

Major Input	Required Data
System infrastructure data (hydraulic conveyance system model data)	• Pipes • Maintenance holes, catch basins, tee-connections • Open channel cross-sections, chainages from ditches and natural drainage systems (rivers, creeks, streams, etc.) • Pump stations • Special structures (e.g. weirs, gates, hydrobrakes) • SCADA data and RTC schemes

Major Input	Required Data
Spatial data (sub-basin delineation and flow assignment data)	• Topography – contour and LiDAR data • Impervious and pervious areas • Soil characteristics • Land use and zoning • Parcels • Lateral connections (buildings and inlets)
Precipitation and evaporation data (hydrologic wet-weather model data)	• Permanent gauges • Project-specific gauges • Evaporation monitoring stations
Flow demand model data	• Permanent and/or temporary flow monitoring data • Dry-weather flow (BSFs and sGWI) • Extraneous flow (RD I/I) • Other inflow (e.g. permitted industrial discharge)
Boundary conditions	• Lake, rivers, creeks, and marine outfalls level data • Level data from King County system or SPU facilities used as boundary condition (e.g. pump station wet well) • Discharges from basins draining to the system in the study area • Discharges from adjacent agencies to SPU system

7.5.2 Hydraulic Conveyance System Model Data

Drainage and wastewater system infrastructure data is warehoused in GIS. At the beginning of a modeling project, if the modeling project is to be done by a consultant project team, SPU project manager will provide system infrastructure data to the consultant team. The pipe and maintenance hole GIS records are mostly complete. However, if the project team discovers any missing or erroneous data that would otherwise be needed to build a model, the consultant team should check available as-built records, review available survey information, and, if needed, work with SPU project manager to coordinate field work to fill data gaps. In turn, SPU project manager will inform SPU GIS about missing or erroneous data to update SPU GIS system with the new information.

The horizontal and vertical datum of data associated with constructing a computer model must be consistent with the SPU GIS datum:

- **Horizontal datum**: NAD_1983_HARN_StatePlane_Washington_North_FIPS_4601_Feet
- **Vertical datum**: NAVD88-North American Vertical Datum of 1988

In addition to GIS databases, SPU's Special Structures Data Manager also contains attribute data of many special structures designed to regulate, divert, or otherwise control the flow of water through the conveyance system. Most common special structures are weirs, gates, pumps, and hydrobrakes. The types of special structure attribute data stored in Special Structures Data Manager include data such as weir crest elevation, weir length, and hydrobrake curve. Contact SPU GIS to obtain access to the Special Structures Data Manager. Contact SPU SOPA for Special Structure Data not available in Special Structures Data Manager.

7.5.2.1 Hydraulic Model Requirements

The following data standards must be used in H/H modeling of SPU drainage and wastewater system infrastructure:

1. SPU GIS data must be used to build basic hydraulic models of the SPU system.
2. The model structure must be clear, easy to understand, reflective of field condition, and follow the naming conventions for data format **(Appendix 7D - Data Formats)**.
3. Whenever data from other sources such as King County are needed, the request must be made through the SPU LOB representative.
4. Whenever new GIS data sets are created as a result of hydraulic model construction, the file names and coverage data fields must follow the guidelines described on the SPU GIS website.
5. If the modeling team identifies data gaps during model setup, the team must work with SPU staff to fill data gaps (e.g. review record drawings [as-builts], review available survey information, or, if needed, work with SPU staff to send survey crews to collect relevant information).
6. If discrepancies occur among GIS and other data sources such as record drawings and survey, the following data preference hierarchy must be followed:
    a. Survey data
    b. Record drawings [as-builts] – if record drawings used a datum other than NAVD 88, check with SPU Survey to obtain local conversion. For other datum conversions, refer to City of Seattle Standard Plans 001 and 001a.
    c. Field observations
    d. GIS data

7.5.2.2 GIS Point Data for Structures

Drainage and wastewater structures that occupy a single location in the SPU system (e.g. maintenance holes, catch basins, and tee-connections) are represented with GIS point coverage (i.e. feature class). For a complete list of structure types, see the SPU GIS website.

7.5.2.2.1 GIS Point Coverage

This coverage contains the following data fields, which are important for model development:

- Structure type (FEATYPE)
- Structure ID (S_ENDPT_ID (wastewater) or D_ENDPT_ID (drainage)
- Top elevation (rim elevation of maintenance hole)
- DEPTH (depth of maintenance hole)
- Invert elevation of connecting pipe(s)
- Location (easting and northing coordinates)

7.5.2.2.2 Modeling Point Data as Nodes

Most point data are modeled as nodes in a model. The following coordinating data fields used to model nodes are found in GIS:

- Node ID = S_ENDPT_ID (wastewater) and D_ENDPT_ID (drainage)
- Coordinates = X_COORD, Y_COORD
- Ground Elevation = CURVE_ELEV_FT
- If the model requires node bottom invert, use the minimum of ELEV1_FT, ELEV2_FT, ELEV3_FT, ELEV4_FT or CURVE_ELEV_FT – DEPTH_FT

Note: *The node invert can also be calculated from the lowest pipe invert connected to the node.*

7.5.2.3 GIS Pipe Data

SPU DWW pipes within City limits as well as some King County interceptors are depicted by GIS line coverage (i.e. feature class). The pipe feature class database includes fields that indicates whether a pipe conveys stormwater, sanitary, or combined sewer flows, as well as ownership.

7.5.2.3.1 GIS Line Coverage

For each pipe segment, the GIS line coverage should include the following:

- Pipe shape (circular, oval, rectangular)
- Pipe lifecycle (connected, abandoned)
- Pipe dimensions (diameter, width, height)
- Pipe length
- Upstream and downstream pipe invert elevations
- Pipe material
- Pipe installation year
- Pipe flow type (drainage, sanitary, combined)
- Upstream and downstream connecting maintenance hole IDs

7.5.2.3.2 Modeling Pipe Data as Links

For modeling pipes as links, the coordinating data fields in GIS are the following:

- Pipe ID = MAINLINE_PT_ID
- Upstream node ID = UPS_ENDPT_ID
- Downstream node ID = DNS_ENDPT_ID
- Upstream invert elevation = UPS_ELEV_FT
- Downstream invert elevation = DNS_ELEV_FT
- Pipe cross-section = PIPE_SHP
- Pipe dimensions = HEIGHT_IN and WIDTH_IN
- Pipe length = LENGTH_FT

- Pipe material = MATERIAL_CODE
- Pipe use = USE_PERMIT
- Pipe lifecycle = LIFECYCLE

7.5.2.4 Special (Ancillary) Structures

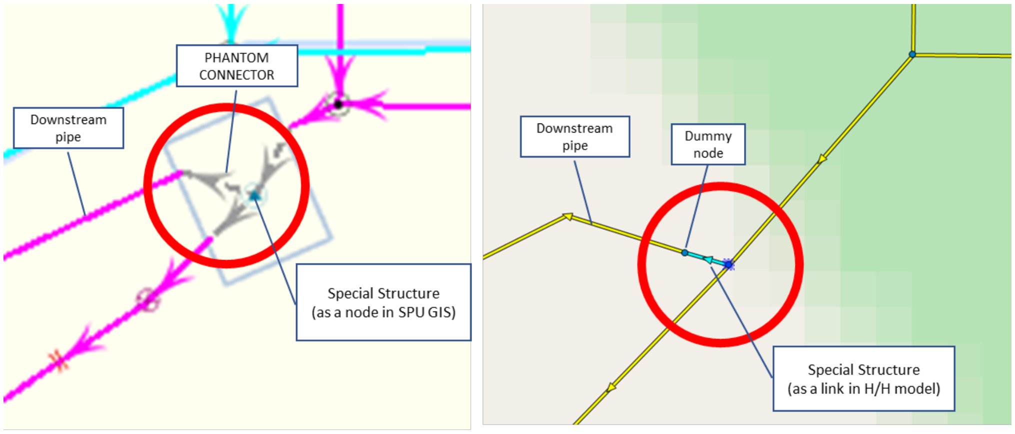
Special structures are often located in flow control areas of the drainage and wastewater system. These structures regulate flows and are designed to prevent unplanned flooding onto streets and private properties. SPU special structures include:

- Pump stations
- Weirs
- Sluice gates
- Hydrobrakes
- Orifices
- Flap gates or valves
- Storage facilities

The SPU drainage and wastewater infrastructure GIS point coverage differentiates among various ancillary structures by using the FEATYPE (structure type) attribute. However, GIS should be used only to locate ancillary structures. Layout, dimensions, and function of these devices are not defined in GIS. Please refer to the following subsections for more information.

A special structure, such as a pump, a weir, or a hydrobrake, is usually represented by a "node-link-node" configuration in a H/H model. Thus, when SPU GIS point coverage data of a special structure are transferred to a model, the data are transferred from the point coverage to the associated "node-link-node" configuration**.** **Figure 7-1** illustrates the differences in how special structures are represented in GIS and a H/H model. For naming conventions, see **[Appendix 7D - Data Formats]**.

Figure 7-1
Example of representation of special structures in GIS and H/H model



SPU GIS Representation of a Special Structure

H/H model representation of the same Special Structure

7.5.2.4.1 Pump Stations

The drainage and wastewater pump station data warehoused in GIS is limited to location, connecting maintenance hole ID, National Pollutant Discharge Elimination System (NPDES) basin number, and sometimes wet-well elevation. The locations of pump stations are provided in the SPU drainage and wastewater Mainline End Points coverage wherever the FEATYPE field has a value of “PST.” Accurately modeling the hydraulics of SPU pump station operations requires additional information beyond that available in the GIS system.

SPU staff can help the modeling team to acquire the information listed below:

- Wet-well dimensions and elevations
- Influent pipe elevations
- Force main information (length, diameter, starting and ending elevations, material)
- Force main discharge conditions
- Pump control type: VFD or constant speed
- Pump curves
- Control setting elevations
- Real-time controls or other pump control information

Typical sources are record drawings, SCADA data, technical reports, and O&M documentation.

Generally, SPU pump stations are modeled by entering pump curve data (i.e., head vs. flow) or fixed discharge rate and control specifications (wet-well pump on and pump off elevations). In almost all cases, forcemains are not represented in a SPU’s H/H model. In such cases, the pump curve data used are not those typically provided by pump manufacturers. Instead, a modified pump curve must be used. The modified pump curve correlates Total Static Head vs. flow without considering friction in the forcemain. In cases when forcemains are modeled, pump curves provided by pump manufacturers can be used.

7.5.2.4.2 Weirs

Weirs provide a method to control flow within a collection system. They are generally located in maintenance holes where flow is diverted from one section of the collection system to another. SPU drainage and wastewater system infrastructure includes several types of weirs, including transverse, trapezoidal (Cipolletti), side overflow, and leaping weirs.

The modeling team should acquire record drawings, photographs, field investigation records, and all physical dimensions for weir structures. The team should have physical dimensions field verified when possible. The DWW Mainline End Points (i.e., point) coverage indicates the location of weirs in the drainage and wastewater conveyance system with FEATYPE value of “OF” (i.e., overflow maintenance hole). Hydraulic modeling simulation results of weirs are usually very sensitive to weir dimensions, elevation, orientation, configuration, and weir coefficient. All drawings and field reports provided for a weir structure should be documented in the model.

The modeling team should determine whether the overflow structure has entrance losses to include in a weir's modeling representation. Entrance losses are the result of turbulence upstream of the weir. The sections below describe various weirs and their attributes.

(1) Common Attributes

Table 7-3 lists the common attributes of weirs found in H/H software packages. Modelers should consult the software's user manual together with other hydraulic references to determine the appropriate values for discharge coefficients. It should not be assumed that software packages use U.S. units, equations, and coefficients until verified.

If a weir can be submerged, modelers should review the weir solution method to ensure that the software can accurately simulate submerged weirs. Modelers should also review the weir solution method to determine how the software estimates surcharging upstream of a weir and whether the software automatically switches to a gate (orifice) equation solution when surcharging occurs.

Table 7-3
Weir Attributes for Modeling Software

Weir Attribute	Description
Weir type	Select type of weir: e.g. 1) sharp crested, 2) broad crested 3) transverse, 4) side flow, 5) V-notch, 6) trapezoidal (Cipolletti)
Crest	Level of the crest (or top) of the weir Software may ask for height or crest elevation
Width	Width of weir over which water spills. Some software refers to this as "length" (e.g. EPA SWMM).
Height	Roof height for the weir Weir should behave like a sluice gate orifice when water level is above roof height. In fact, some software require modeling of an enclosed weir as a rectangular orifice rather than a weir (e.g. DHI MOUSE and MIKE 1D)
Weir crest geometry	For an irregularly shaped weir, a table of values describing the shape of the weir's cross-section.
Weir (discharge) coefficient	The coefficient for the weir flow equation. This coefficient is unit and equation dependent. Modelers should confirm how the weir equation is implemented in the modeling software and use the weir coefficient appropriate for the unit and equation used.
Length	Distance across flat part of weir top measured parallel or perpendicular to flow direction depending on the type of weir. Applies only to broad crested weirs. Should not be confused with the "width" of weir. This "length" equals to zero for a sharp crest weir.

(2) Transverse Weir

Transverse weirs are installed perpendicular to the flow direction. Transverse weir structures are frequently used near CSO outfalls to allow excessive flows to exit the system to prevent surface flooding. Flows are fully conveyed within the conveyance system until water surface elevation exceeds the elevation of the weir. If the water surface elevation exceeds the weir level, flows are split between the conveyance system and outfall piping.

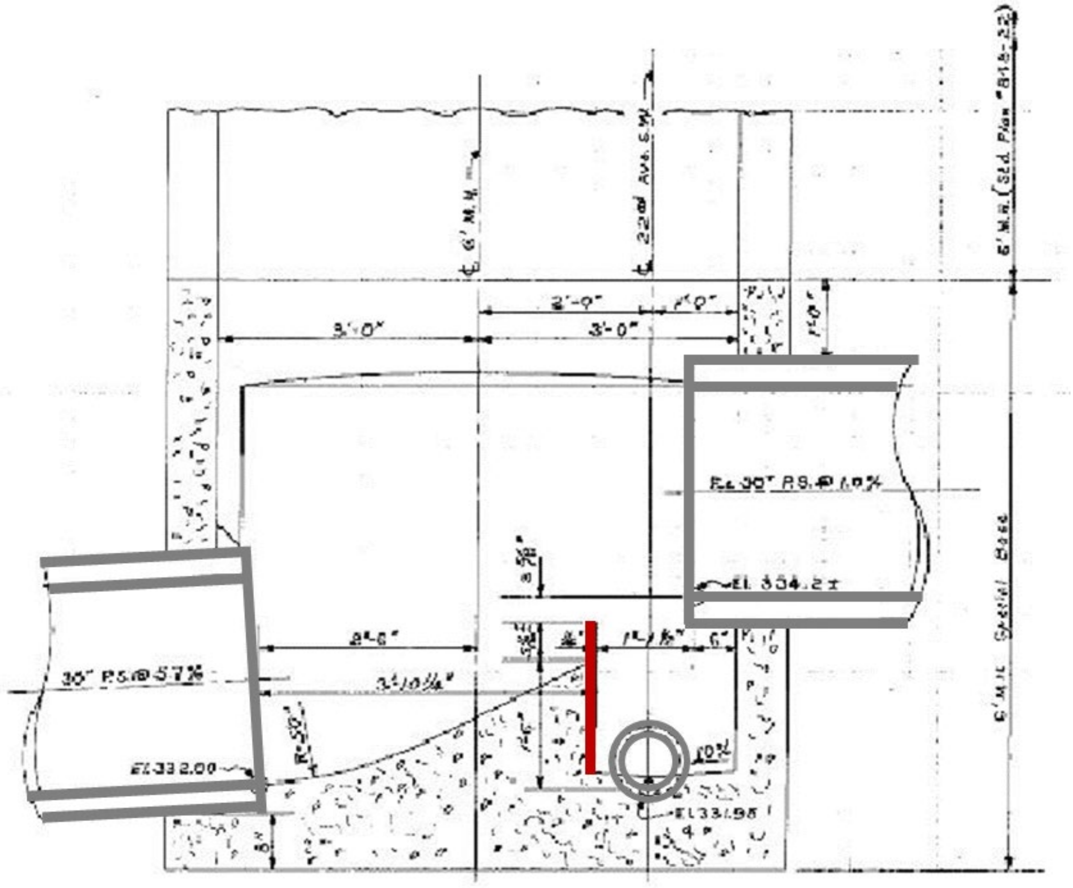
(3) Side-Overflow Weir

Side-overflow weirs are installed on the side of a pipe or main channel of a structure, parallel to the flow direction. Flows are fully conveyed within the conveyance system until a high-flow condition occurs and the water surface elevation exceeds the weir elevation. When the water surface elevation exceeds the weir elevation, flows are split between the conveyance system and the outfall piping.

(4) Leaping Weir

A leaping weir is a special case (**Figure 7-2**). A leaping weir is a transverse weir incorporated into a drop-maintenance hole. Under a low-flow condition, water will drop into the maintenance hole trough and flow out in a direction perpendicular to the entrance flow. When flow on the upstream side of a maintenance hole reaches a certain velocity, water will leap over the trough and continue to flow in the same direction as upstream flow. At intermediate or transitional velocities, the influent water will divide; a portion of the flow passes through the low-flow outlet and the remainder flows over the leaping weir. Whenever possible, the modeling team should calibrate the behavior of the weir using upstream and downstream flow monitoring. After an appropriate regression relationship is established, a leaping weir could be simulated using a user-defined relationship. Modelers should consult the user manual of the selected software to determine the most appropriate method for simulating a leaping weir.

Figure 7-2
Example of Leaping Weir



7.5.2.4.3 Sluice Gates

SPU currently implements two types of sluice gates in the conveyance system. One type is a manual operating gate to bypass flows during maintenance. Manual sluice gates consist of a vertical slide gate that can be set in an open or closed position. During normal operation, manual sluice gates are closed. Manual sluice gates must be modeled as closed unless SPU provides information that the gate has been opened for normal operation. The RTC capability of a H/H modeling software can be used to simulate the operation of a manual sluice gate if the regular maintenance schedule, when the gate is manually opened or closed, is known.

The second type is automated sluice gates used to regulate flows to the downstream system. As the water level in the conveyance system rises, flow through the gate is limited, which causes water upstream to back up into storage and/or overflow to a nearby body of water through an outfall. Using an automatic sluice gate ensures overflows occur at the designed locations instead of unplanned locations in the downstream conveyance system. The operation of automatic sluice gates is usually controlled by PLC's and SCADA system in the field. The RTC capability of a H/H modeling software can be used to simulate the field operation of these PLC's and SCADA systems. For additional information on automatic sluice gate field operation at a specific location, please contact SPU SOPA.

Table 7-4 lists common gate attributes for various modeling software packages.

Table 7-4
Gate Attributes for Modeling Software

Gate Attribute	Description
Gate type	Sluice (common for wastewater) Radial or other Some software implement sluice gates as rectangular orifices (e.g. EPA SWMM), or orifice with gate (e.g. DHI MIKE 1D). Modelers should confirm how sluice gates are represented in selected modeling software.
Maximum gate opening height	Height open when gate is fully withdrawn
Gate width	Width of flow channel through gate
Gate controls	Initial gate level and description of conditions that change gate level This is usually simulated by using the RTC capability of H/H modeling software with specific features varying widely among modeling software packages

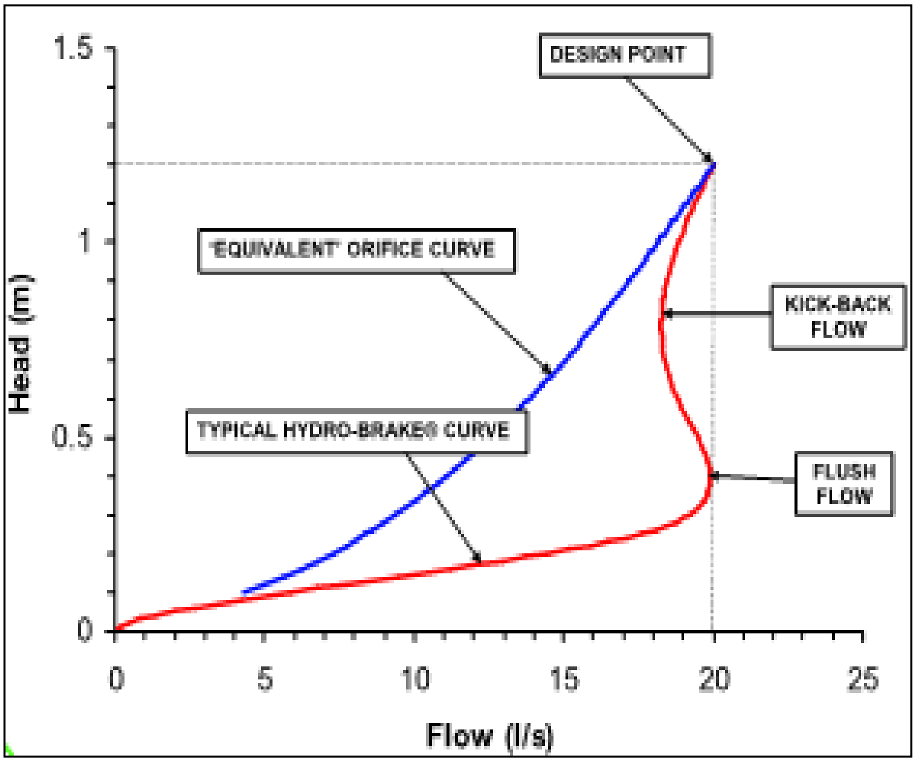
7.5.2.4.4 Hydrobrakes

Hydrobrakes, which are located throughout the SPU drainage and wastewater system, regulate flow. They are often used for implementing inline storage scheme operation during high-flow events and can protect downstream facilities from unplanned overflows at locations other than CSO outfalls. Water flows into the device through an open channel into its conical body. During low flows, water and air can flow into the conical body and through the downstream piping with minimal head losses. During high flows, water will swirl in the conical body and form a horizontal forced vortex with a center air core within the conical body and the orifice section. The vortex and associated air core are the mechanisms used by a hydrobrake to control flow. The forced vortex flow then flows through the orifice section and proceeds into the downstream system.

These complicated hydraulic structures can be modeled as a generic structure using a user-specified *head versus discharge* curve. If flow monitoring data collection is planned for a project, data should be collected from upstream and downstream of a hydrobrake to verify whether the manufacturer’s curve reflects field operation of the structure. If not, the field data can be used to construct the necessary head verses discharge curve for use in the model. **Figure 7-3** shows a typical head versus flow curve for a hydrobrake.

The modeling team must develop site-specific hydrobrake *head versus discharge* performance curves by collecting water surface elevation data on the upstream side of the hydrobrake and flow data on the downstream side of the hydrobrake. The modeling team should not rely on the manufacturer’s curve unless there is no other option. SPU’s experience has shown that hydrobrake performance in the field may vary substantially from the manufacturer’s curve.

Figure 7-3
Head vs. Flow Performance Curve for a Hydrobrake



Acronyms and Abbreviations
l/s: liters per second
m: meter

7.5.2.4.5 Orifices

An orifice is a device for regulating flow. It is a hole of any shapes and sizes through which flow can pass. The amount of flow through an orifice is controlled by the dimensions and shape of the opening and the associated hydraulics. Typical shape of an orifice is circular or rectangular, although it can be the shape of a half circle when an orifice is formed by covering part of a circular orifice with a rectangular plate. An orifice can be a traverse, or bottom orifice.

When modeling an orifice in a H/H model, typical input requirements are limited to the orifice diameter (circular), height and width (rectangular), user-defined dimensions (custom shape orifice), invert elevation, and discharge coefficient. Orifices can be useful for modeling complex hydraulic conditions such as flow splitting or flow constraints. For example, when a maintenance hole includes two exit discharge sewers, some software cannot accurately predict the relative division of flow between the two lines. Inserting orifices at the exits will force the software to apply energy balancing orifice equations at these locations. **Table 7-5** lists common orifice attributes for various modeling software packages.

Table 7-5
Orifice Attributes for Modeling Software

Orifice Attribute	Description
Orifice type	Select type of orifice: 1) side, 2) bottom
Orifice shape	Select shape of orifice: 1) circular, 2) rectangular (RECT_CLOSED), 3) custom cross-section shape (CRS)
Invert elevation	Invert of the bottom of the orifice
Height	Height of orifice (diameter for circular orifice)
Width	Width of orifice (zero for circular orifice)
CRS ID	A table of values describing the cross-section of an irregular shaped orifice
Discharge coefficient	The coefficient for the orifice flow equation. This coefficient is unit and equation dependent. Modelers should confirm how the orifice equation is implemented in the modeling software and use the discharge coefficient appropriate for the unit and equation used.

7.5.2.4.6 Storage Facilities

A storage facility includes any type of tank or pipe system designed to detain flows. This element is typically modeled using a stage-area table and an appropriate outflow control. Representing a storage facility using a stage-area relationship neglects flow velocities within the structure, which is a reasonable simplification. Modelers should confirm how the modeling software uses the stage-area relationship in determining storage volume at specific depths. In some cases, the area requested is the plan area of the storage facility at a specific depth (e.g. as in MIKE 1D). In other cases, it is the area calculated by using Trapezoidal Rule from the stage-storage curve of the facility (e.g. as in EPA SWMM).

The method for defining the outlet control of a storage facility varies by software. The modeling team should include as much detail as possible to represent the outlet control. Often an outlet control is a combination of pipe, gates, orifices, hydrobrakes, and/or weirs. **Table 7-6** lists common storage facility attributes for various modeling software packages.

Table 7-6
Storage Facility Attributes for Modeling Software

Storage Attribute	Description
Invert elevation	Invert of the bottom of the storage facility
Ground elevation	Ground elevation of the storage facility
Stage-area curve	Curve that defines the stage-area relationship of a storage facility. Modelers should confirm how area should be calculated for the storage facility. Depending on the software, it can be plan area at specific depth or area backed calculated from stage-storage relationship by using Trapezoidal Rule.

7.5.2.4.7 Backflow Preventers

Common backflow preventers in SPU drainage and wastewater systems are flap valves. Flap valves are commonly known as tide gates and/or flap gates. Some common uses for flap valves are at the end of some outfall pipes (especially pipes that are tidally influenced), points of discharge from storage to mainline system, and to prevent fishes from swimming up pipes.

Modeling software use various methods to model backflow preventers. Modelers should consult the user manual of the modeling software package for details. For EPA SWMM, an outfall tidal gate is modeled by selecting *Yes* in the Tide Gate option of the outfall. Tide Gates cannot be controlled by Control Rules in SWMM. If the tide gate is linked to an RTC, an orifice of the appropriate shape (closed rectangular or circular) and size should be connected to the upstream side of the outfall to represent the gate. Additionally, the Tide Gate option of the outfall should then be set to *No,* because the tide gate is represented by the upstream orifice. With this configuration, Control Rules can be used to control the rate and conditions of the opening and closing of the gate. For EPA SWMM, a flap gate that is located in a part of the conveyance system not immediately adjacent to an outfall is modeled by selecting *Yes* in the Flap Gate option of the conduit where the gate is located. If the flap gate is linked to a RTC, the flap gate is configured similarly to a Tide Gate. An orifice of the appropriate shape (closed rectangular or circular) and size should then be connected to the conduit and the Flap Gate option of the conduit itself should be set to *No.* The operation of the RTC flap gate can then be simulated by operating the orifice with Control Rules.

7.5.2.5 Natural Channel Parameters

Natural conveyance systems are included in SPU's drainage model. **Table 7-7** below lists the natural channel parameters with guidelines to define their values.

Table 7-7
Natural Channel Parameters

Natural Channel Parameter	Guideline
Cross-sectional geometry	The minimum width is set by extending the left and right ends of the cross-section to one foot above the left and right floodplain (LRFP) elevation
Spacing of cross-sections	Cross-section locations should be based on sound engineering judgment. Higher density is required at tributary locations, slope changes, roughness changes, valley morphology changes, and at bridges or other structures.
Cross-section data points	A minimum of seven data points is required to describe each cross-section. The maximum number of data points is limited by software constraints.
Elevation	Elevation data in the active channel must be collected with field survey and tied to SPU current datum standard. GIS 2-ft contour mapping may be used to supplement cross-section data in the floodplain (overbanks). A licensed Land Surveyor or Professional Engineer must document the accuracy of survey information at cross-sections and structures

Natural Channel Parameter	Guideline
Bank stations	Bank stations in natural cross-sections should be placed at the geomorphic bankfull elevation.
Manning's roughness coefficient	Roughness values should be reflective of the natural variations in the bed materials and overbank vegetation. Manning's roughness values must be used to describe frictional energy losses. A listing and description of roughness values with photographs must be included in the documentation of the model development. Manning's roughness values must be included for the channel bed, left and right banks, and left and right floodplains.
Reach lengths	The distance measured along the stream thalweg for the centerline reach length. Left and right overbank reach lengths must be estimated as the center of mass of the floodplain discharge.
Expansion and contraction coefficients	Subcritical flow contraction and expansion coefficients are used to estimate energy losses caused by abrupt changes in the flow cross-sectional area. Where contraction and expansion losses are expected to occur, contraction coefficients can vary between 0.1 and 0.3, expansion coefficients can vary between 0.3 and 0.5.
Ineffective flow areas	Effective flow, in one-dimensional modeling, is the portion of the flow traveling in the downstream direction. Portions of the cross-section that are occupied by water but not flowing in the downstream direction are described as ineffective flow areas and must be specified. A definition of ineffective flow areas must be justified in the H/H report. Ineffective flow areas in urban watersheds must reflect current development.

7.5.2.6 Naming Convention for Links and Nodes

Data collected for defining nodes and links of the hydraulic conveyance model must follow the naming convention and data format defined in **Appendix 7D - Data Formats**.

7.5.3 Basin Mapping, Sub-Basin Delineation and Flow Assignment

Spatial data are used to develop basin mapping, sub-basin delineation, and flow generation, direction and assignment in a H/H model. In a H/H model, basin mapping defines the areal extent of flows tributary to various parts of the collection system (e.g. inflow to the King County system). Sub-basin delineation defines the areal extent of individual subareas within the basin and assigns their outflow to appropriate inflow nodes in the collection system. Basin mapping and delineations should be consistent with flow monitoring locations, areal granularity accuracy needs (e.g. defining subarea to individual block level versus flow monitoring level), hydraulic properties of the collection system, sewer mapping, and topography.

GIS tools can be used to automate the delineation and flow assignment process. For example, ArcMap includes network tracing tools that will identify all pipes upstream of a given location. In addition, SPU has a propriety ESRI-based network tracing tool.

7.5.3.1 Spatial Data

Five common spatial data categories are used for H/H modeling: (1) topography, (2) parcels, (3) impervious area, (4) soils (pervious area), and (5) land use and zoning. These data, available in GIS, are described in the sections below.

7.5.3.1.1 Topography

The modeling team must use either LiDAR-derived or local survey data and these data must meet the datum requirements defined in DSG section ***7.5.2***. If datum conversion is necessary, the team should obtain the conversion factor from SPU's Land Survey Section.

Topography data can be used with spatial analysis tools to determine the direction of surface water drainage and to delineate the extent of surface water basins. Topographic data sets may be available as raster (e.g. digital elevation models), triangular irregular network (TIN) or contour line files. Topography data analysis is important for projects that route stormwater into catch basins.

7.5.3.1.2 Parcels

Parcels or property data can be used for many purposes. For example, parcels can be used to map which properties drain wastewater to specific maintenance holes within a basin via information shown in the side sewers and laterals GIS coverage. Delineating wastewater sub-basins at the MH level helps SPU estimate tributary area and number of customers contributing flow to each maintenance hole in a model. In addition, parcel data could be combined with land use data to provide a preliminary estimate of impervious area. Parcel data can also be used to indicate the locations of various customer types (e.g. residential, industrial, commercial, or institutional) within a basin. Parcel data can also help identify critical public facilities that may require a higher level of protection against flooding.

7.5.3.1.3 Impervious Area

1. Impervious area data are used to estimate the rate of surface water runoff from sources such as driveway, asphalt pavement, and direct sewer inflow from sources such as roof downspouts. Impervious area data sets are usually developed from orthophotography data, land use categories, and building outlines. If impervious area data are unavailable for a project area and surface runoff calculations are needed to calibrate a model, the modeling team should consult with SPU GIS to develop the impervious area coverage for the modeled area. For more information on impervious areas, please refer to DSG section ***7.5.6.1.2(1)*** .

7.5.3.1.4 Soil Data (Pervious Area)

Soil characteristics are used to estimate infiltration potential through pervious surfaces in a watershed. For drainage and wastewater modeling projects, soil data can be used to compute surface water runoff from pervious areas and subsurface infiltration contributing to the conveyance system. Soil coverage can also help a project team to identify potential stormwater infiltration facility locations. For example, soil coverage might indicate areas of higher-infiltrating soils, which can be feasible GSI locations. Please refer to the DSG modeling library for City soil characteristics.

7.5.3.1.5 Land Use and Zoning

Land-use and zoning data can be used to estimate impervious areas when more detailed information is unavailable. For SPU projects, these data types are more useful for estimating wastewater loading for existing and future conditions.

7.5.3.2 Sub-Catchment Delineation

After the necessary data are collected and sub-catchment boundaries have been delineated, each sub-catchment must be further divided into:

1. Building (BLG_) area
2. Right-of-way (ROW_) area
3. Catchment (C_) area

Catchment (C_) area of each sub-catchment is the rest of the sub-catchment area that is not occupied by buildings or a right-of-way.

7.5.4 Boundary Conditions

A specified boundary condition is required for each of the terminus boundary nodes of a H/H model. Such terminus nodes are often referred as “Outfalls” or “Outlets” of a model. The boundary condition for these nodes may be modeled by supplying a downstream water surface elevation: static or time varying. The outlet must be accurately modeled because the water level at these nodes can affect water surface levels upstream due to backwater effects.

For the SPU drainage and wastewater conveyance system, downstream boundaries include:

- Outfalls (e.g. Longfellow Creek, Lake Washington, Puget Sound, Elliot Bay, or the Duwamish River). Please refer to ***7.5.4.1.1***.
- Discharge to King County wastewater conveyance system
- Discharge to SPU large hydraulic structures (e.g. pump station wet well)

For locations where continuous water surface elevation data are not available, the team should make a conservative assumption about the water level at these boundary nodes. For example, the modeling team can vary the elevation of the water at the boundary node based on I/I rates from the upstream basin. When the upstream SPU system receives high levels of I/I, the modeler can assume the water level at the receiving water body (e.g. King County interceptor) to be high. Alternately, the modeling team could set the water level at the boundary node to match recorded or inferred high water marks or assume the boundary node is continuously submerged. Coordination with agencies (e.g. King County) responsible for the receiving water body, boundary node, can help assess the ranges of water levels of interest in the receiving system. If consultant services are utilized in projects that involve such inter-agency coordination, all such coordination must be done through SPU.

7.5.4.1 Defining Boundary Conditions

H/H modeling software packages commonly include a graphical interface to define boundary conditions. Often, boundary conditions are defined by times series data.

7.5.4.1.1 Assigning Boundary Condition

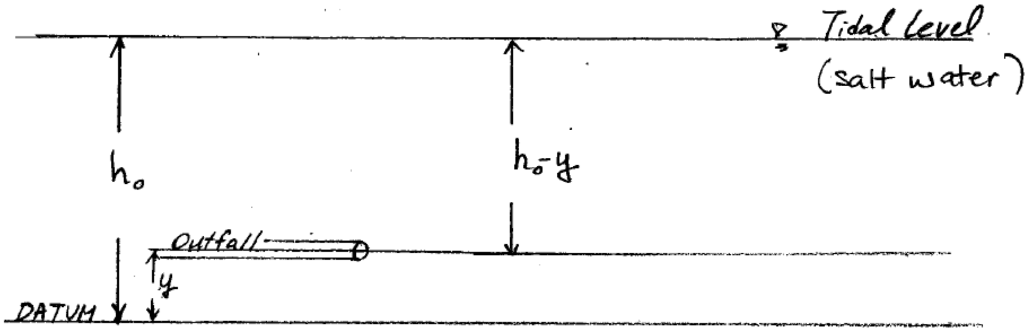
When assigning a boundary condition to a boundary node in a model, the modeler should consider how the boundary condition fits into the physical system and how the boundary conditions affect overall model results:

- In situations where the downstream boundary is likely to affect upstream modeling results, the modeling team should use the most detailed time-varying water surface elevation data available. For example, if the water level in a King County system feature could potentially backup wastewater into the SPU system, the modeler should obtain time series data for the water level in the King County system feature for the simulation time period. Time series data should always be examined for outliers, data gaps and other potential sources of error before being incorporated into a model.
- For models that are relatively insensitive to downstream boundary conditions (e.g. steep pipe or supercritical flow to an outfall), the modeling team may use simplified or average values to describe the water surface variations at the boundary nodes.

7.5.4.1.2 Availability of Time Series Data for Outfall to Water Body

The largest receiving water bodies for the City of Seattle drainage and wastewater system are Lake Washington and Puget Sound. Historically observed and estimated water surface elevation data are available for these water bodies. As a hydraulic model treats all fluid (both in the system and at the boundary) as having the same specific weight, freshwater-seawater specific weight conversion must be performed on all Elliott Bay tide level data at each Puget Sound Outfall before the data can be used to form boundary conditions. This conversion accounts for the effect of the difference between the pressure head of a column of sea and fresh water of the same height has on the boundary of a hydraulic model. The following figure illustrates this effect.

Figure 7-4
Saltwater-freshwater time series conversion



The equation for saltwater-freshwater conversion at each Puget Sound boundary condition is:

$$h_f = \frac{\gamma_s}{\gamma_f} * h_0 - \left(\frac{\gamma_s}{\gamma_f} - 1\right) * y$$

Where

h_f = equivalent freshwater level time series (ft NAVD88 datum)

γ_s = specific weight of saltwater = 64.0 lbf/ft^3

γ_f = specific weight of freshwater = 62.4 lbf/ft^3

h_0 = saltwater level time series (ft NAVD88 datum)

y = invert of outfall (ft NAVD88 datum)

Given $\frac{\gamma_s}{\gamma_f} = 1.026$,

Numerically, the above equation can be expressed as follow:

$$h_f = 1.026 * h_0 - 0.026 * y$$

Since the invert elevation of an outfall is part of the conversion equation, each Puget Sound outfall will have its own boundary condition time series. This conversion is only necessary for Elliott Bay water level data, because Elliott Bay is brackish water.

The following are SPU standards:

1. When the downstream boundary is close to a hydraulic structure, the structure must be modeled to mimic field operations so that the correct downstream boundary condition can be simulated in the model.
2. SPU must be involved throughout the process of estimating downstream boundary conditions and the results must be documented in the modeling report.

(1) Lake and Ship Canal Level Data

Refer to Appendix F Hydrologic Analysis and Design of City of Seattle Stormwater Manual. If EPA SWMM is used as the modeling software, the Lake Washington level time series in EPA SWMM external time series format (.dat) is available starting from 9/1/1977. Please refer to DSG modeling library for Lake Level data for more information.

(2) Tidal Influence/Sea Level Rise

Refer to Appendix F Hydrologic Analysis and Design of City of Seattle Stormwater Manual. If EPA SWMM is used as the modeling software, the Puget Sound saltwater tidal time series in EPA SWMM external time series format (.dat) is available starting from 12/15/1977. Please refer to DSG modeling library for Tidal level for more information. It should be noted that when the Puget Sound saltwater tidal time series is used for modeling, the time series will need to be converted to its freshwater-outfall equivalent as described above.

7.5.4.1.3 King County or Other Agencies Time Series Data

When the downstream boundary of a study area or a sub-catchment is the King County wastewater conveyance system, the modeling team should use actual historical water surface elevation data provided by King County. SPU can obtain the data from King County when data are available. When data are not available, SPU will collaborate with King County to assess boundary condition definition.

Note: *Whenever data sourced by other agencies are needed, SPU must be consulted. All these data requests must be made by SPU.*

7.5.5 Dry-Weather Flow Model Data

During the dry weather season, sewer flow includes base sanitary flow and I/I that is not attributed to rainfall. It is generally known as dry-weather flow. Base sanitary flow is sewage entering the conveyance system from side sewers and laterals. Seasonal I/I is attributed to flow entering the conveyance system from defects in the sewer system below the seasonal water table and portions of the vadose (unsaturated) zone with high subsurface flow (e.g. springs).

When dry weather flow monitoring data are available, only flow monitoring data are needed to estimate dry weather flow and the associated diurnal patterns. When dry weather flow is calculated, current and future sanitary flow can be estimated based on existing and future demographic and land use information and existing per-capita flow estimate data.

Data useful for computing dry-weather flow include:

1. Flow monitoring data collected during dry weather or available per-capita flow estimate information.
2. Demographic data. Parcel data, current and future population, and traffic analysis zone.
3. Industrial and institutional flow. Flow discharged from identified industries (e.g. food manufacturing plants) and institutions (e.g. hospitals).

As situations dictate, a combination of this information is collected and analyzed to develop dry-weather flow patterns. This section provides further description of these data sources and how they can be used for computing dry-weather flow patterns.

7.5.5.1 Dry-Weather Flow (DWF) Based on Flow Monitoring Data

When flow records are available for a basin, the modeling team should examine flows for a dry-weather period (May through June or September through October) to determine the DWF from the basin. DWF during the months of July and August should not be used, because there is a noticeable change in the temporal distribution and magnitude of DWF attributed to the demographic shift resulting from summer vacations.

The flow data collected during dry weather shows a simple diurnal pattern with peaks and troughs. To develop DWF entry for a H/H model, a seven-day period of dry weather must be selected from the flow records. The seven-day period must include data from each day of the week.

After the seven-day DWF data record are selected, the following steps should be used to calculate an average DWF and a weekday and a weekend diurnal pattern.

a. Calculate an average DWF value.
    i. If the H/H software allows **only one average DWF** value to be used at each inflow node, this calculated DWF value must be the average of the seven-day record including both weekdays and weekends. Enter the seven-day-DWF value into the inflow node.
    ii. If the H/H software allows **two average DWF values** at each inflow node – one for weekday and one for weekend, then a separate average five-day

weekday DWF value and a separate average two-day weekend DWF value should be calculated. Enter the five-day weekday DWF value and the two-day weekend DWF value into the inflow node.

b. Calculate an average five-day weekday and an average two-day weekend DWF hydrograph for the construction of weekday and weekend diurnal patterns. The average weekday DWF hydrograph must be calculated by averaging the hydrographs from Monday to Friday within the seven-day DWF record. Likewise, the average weekend DWF hydrograph must be calculated by averaging the hydrographs of Saturday and Sunday within the seven-day DWF record.

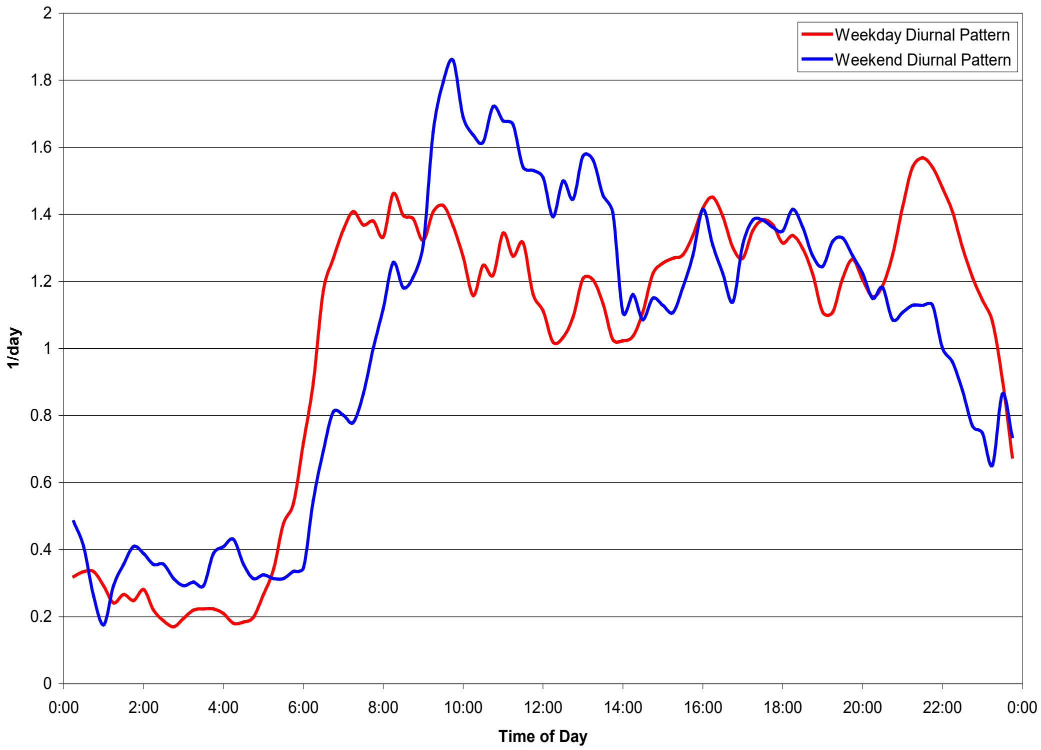
c. Divide the average weekday hydrograph by the average DWF values calculated in Step "a" to create a weekday diurnal pattern.
    i. If the H/H software allows **only one average DWF value** for each inflow node, divide the average five-day weekday hydrograph by the seven-day DWF value calculated in Step "a" to create a weekday diurnal pattern. **The area under this diurnal pattern will not and should not sum to 1.0**.
    ii. If the H/H software allows **two average DWF values** at each inflow node, divide the average five-day weekday hydrograph by the five-day weekday DWF value calculated in Step "a". **The area under this diurnal pattern will sum to 1.0**.
    iii. Depending on how many average weekday DWF value is allowed at each inflow node, enter the corresponding weekday diurnal pattern into the model.

d. Divide the average weekend hydrograph by the average DWF values calculated in Step "a" to create a weekday diurnal pattern.
    i. Likewise, for H/H software that allows **only one average DWF value** for each inflow node, divide the average two-day weekend hydrograph by the seven-day DWF value calculated in Step "a" to create a weekend diurnal pattern. **The area under this diurnal pattern will not and should not sum to 1.0**.
    ii. For H/H software that allows two average DWF values at each inflow node, divide the average two-day weekend hydrograph by the two-day weekend DWF value calculated in Step "a". **The area under this diurnal pattern will sum to 1.0**.
    iii. Depending on how many average weekend DWF value is allowed at each inflow node, enter the corresponding weekend diurnal pattern into the model.

Normally, the area under a diurnal pattern should always sum to 1.0. However, depending on how a H/H modeling software process DWF (allows only one or more than one at each inflow node), the above differences in diurnal pattern derivation is necessary for working with the parameters of the H/H modeling software so that when the H/H modeling software multiplies the average dry weather flow values by the diurnal patterns, the original average weekday and weekend hydrograph are obtained.

Figure 7-5 shows an example of dry-weather diurnal patterns generated from flow monitoring data collected in residential area adjacent to south downtown area.

Figure 7-5
Example of Dry-Weather Flow Diurnal Patterns



7.5.5.2 Demographic and Sewer Billing Data

In some cases, flow monitoring data do not provide sufficient information to determine DWF from a modeled area. For example, existing flow monitoring data do not reflect future flows attributed to planned land use densification (e.g. Upzoning) or the flow rates of the modeled area are too low for flow monitoring equipment to work properly. In those cases, other data such as demographic and sewer billing data can be used to estimate base sanitary flow. The following provides the sources of these data.

7.5.5.2.1 SPU Data

SPU can provide the following demographic and sewer billing data for the estimation of base sanitary flow:

- Parcel
- Current residential population data
- Current employment population data
- Future residential growth estimates
- Future employment growth estimates
- Statewide traffic analysis zones (STAZs)
- Sewer billing data

7.5.5.2.2 Other Agency Data

The following demographic data from other agencies may also be used in SPU modeling projects to fill in any data gaps. However, whenever data from other agencies, such as King County or Puget Sound Regional Council (PSRC), are needed, SPU must be consulted regarding to the type of data being requested. This direct involvement of SPU in the data acquisition process ensures that SPU is aware of the data source and interagency data requisition protocols, if any, are followed.

- Puget Sound Regional Council (PSRC):
  - Current household population
  - Current employment population
  - Estimated future household population growth
  - Estimated future employment population growth
  - Census tracts
  - Traffic analysis zones (TAZs)
- King County Department of Assessment (KCDOA).
- EPA. Per capita flow estimates from **Tables 3-3 to 3-6** of EPA's Onsite Wastewater Treatment Systems Manual[1]. The EPA manual lists results from urban area across the United States, including the City.

7.5.5.2.3 Dry-Weather Flow Based on SPU's Sewer Billing

When the flow rate from a modeled area is too small for flow monitoring equipment to work properly, base sanitary flow can be estimated using SPU's sewer billing data, which includes Discrete Address Point ID (DAP_ID) point coverage and an associated wastewater consumption database. The database stores sewer consumption volume in 100 cubic feet (CCF) for each DAP_ID and days of service (DOS). This information can be used to calculate the annual average sanitary sewer flow rate:

$$\text{Sanitary Sewer Flow (gallon/day)} = \text{CCF} * 748 / \text{DOS}$$

The DAP_ID point coverage can be used with the sewer system maintenance hole point coverage to associate each DAP_ID with the nearest sewer maintenance hole. Once a relationship between DAP_ID and sewer maintenance hole is established, a total sanitary sewer flow for each maintenance hole can be calculated and loaded into the corresponding nodes in the model. The sanitary sewer flow calculated using sewer billing data only includes base sanitary flow. Seasonal groundwater infiltration estimate must be added for estimating overfall DWF.

7.5.5.2.4 Estimating Population and Per-Capita Flow Values

If future base sanitary flow demand is needed (e.g. as a result of land use changes and redevelopment), the base sanitary flow rate calculated using Sewer Billing data can be normalized by population census data to determine per-capita flow rate. The

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[1] (U.S. Environmental Protection Agency - Office of Research and Development, Office of Water)

demographic data can be obtained from SPU's GIS or from SDCI. Most data are available in geospatial format (e.g. shapefile). No single data source contains all of the data needed for estimating population in a subcatchment. Thus, all of the data should be used together.

In addition, the boundaries of the geospatial polygons that accompany various data often do not align. The modeling team will need to interpolate among the data sources.

Follow these steps to estimate population and per-capita flow when needed:

1. <u>Establish initial population density range estimates</u> for each type of residential and institutional building type (see **Table 7-8**)
2. <u>Create a new set of parcel data</u> by merging the information in SPU's parcel data with corresponding parcels in KCDOA data. New parcel data are especially useful for estimating population in multi-family, mixed use, commercial, industrial, and institutional zones. The merged data give information such as the number of apartment units and square foot of office space on a parcel. When an SPU parcel does not have a corresponding KCDOA parcel, information gathered from field survey or aerial photographs can be used to estimate characteristics and use of the parcels.
3. <u>Intersect SPU's STAZ polygon data with the new parcel data</u> created in step 2. After this intersection, the total residential and commercial population estimates are established for all the parcels within each STAZ polygon. The next step is to distribute this total population back to each parcel.
4. Within the estimated residential and employment population density range established in step 1, <u>pick a value for each type of land use</u>. Distribute the population of each STAZ polygon to its parcels within the STAZ boundary based on land-use information (e.g. apartment units, schools, hospitals, office square footage). If the population is too low or too high to distribute to parcels, adjust the selected population density values within the ranges established in step 1 and redistribute the population. Iterate until the sum of residential and the sum of employment population from all parcels in the STAZ polygon equals the respective values of the STAZ polygon.
5. After this process is completed, a reasonable estimate of residential and employment population will be established for each parcel. <u>Create a new parcel layer</u> based on work completed from steps 1 to 4.
6. <u>Estimate population</u>. Intersect the polygon boundary of the subcatchment area that need estimated population with the new population-filled parcel layer created in step 5. After the intersection, an estimate is established of the total residential and employment population within the boundary of the subcatchment.
7. Establish dry-weather flow based on SPU's Sewer Billing for the whole subcatchment as described in DSG section ***7.5.5.2.3***.
8. <u>Establish a per-capita flow</u> for either the whole subcatchment or per parcel depending on the level of detail required by the model. To calculate per-capita flow at subcatchment level, intersect the Discrete Address Point ID (DAP_ID) point coverage and the resulting base sanitary flow estimates from Sewer Billing data (as described in DSG section ***7.5.5.2.3***) with the subcatchment polygon to

determine the total base sanitary flow estimate from the subcatchment. After that, divide the sanitary flow estimates in the subcatchment by the population estimates in the subcatchment established for the area in step 6.

Table 7-8
Population Density Range

Building Type	Population Density
Multi-family - apartment/condo	1 to 2 person per unit
Multi-family - townhouse/duplex/triplex	2 to 3 person per unit
Single-family residence	2 to 5 person per residence
Public school	Refer to Seattleschools.org
Private school	Refer to Schooltree.org

After this process is completed, reasonable per-capita flow estimates are established for the subcatchments of interest. With these values, future base sanitary flow can be estimated by multiplying the per-capita flow rate by the new population estimate in the area.

Census data can be obtained from SPU GIS or King County GIS. These data contain three levels of resolution: Tract, Block Group, and Block, with Block data providing the highest level of resolution.

SPU should review the final population and per-capita flow values developed for a subcatchment before that data is used for modeling. Population values should reasonably agree with SPU's overall population and employment figures for the area. The values should also be compared against any base sanitary flow data that may be available for the larger basin where flow monitoring data is available to determine whether the flows estimates is reasonable.

After all the data needed for developing a DWF model are entered into the modeling software, each piece of data must be associated with a data source. See **Appendix 7C - Data Flags** for data flags that must be assigned to each data series. When the software does not provide for the capability of using such data flags, description of the data source must be provided in the Description fields or similar fields within the model input file.

7.5.5.3 Industrial and Institutional Flows

Industrial and institutional flows behave differently from normal DWF. Often times, industrial and institutional flows exhibit their own unique repeatable patterns and volumes for set time periods due to manufacturing process and/or worker's shift schedules. The modeling team must review the flow monitoring data during dry weather to identify the portion of additional DWF contributed by industries and institutions. Flows from industries, institutions, and other non-uniform sources can be determined by two types of review:

- Flow monitoring data to identify non-residential flow patterns and volumes. These will be needed for calibration of downstream meters.
- Industrial waste treatment records from King County, as appropriate.

The modeling team must develop a strategy for creating industrial and institutional flow patterns and volumes or creating time series data profile for industrial and institutional flows. If the modeling team is unable to identify a repeatable pattern and time for the industrial and institutional flows, the modeling team must develop another strategy. This additional flow will be used to develop DWF patterns for the industrial and institutional flows to be incorporated into a H/H model.

7.5.5.4 Estimation of Seasonal Groundwater Infiltration (sGWI)

After base sanitary flow rate is determined, an estimate of the sGWI component of the dry-weather flow is to be established. A common equation used for such estimation (e.g. Northeast Power blackout of 2003, King County I/I Program) is the **Stevens-Schutzbach equation**[2] applied to the DWF flow monitoring data. After the sGWI estimate is established, it is to be added to the base sanitary flow rate to form the dry weather flow of the area.

7.5.5.5 Assignment of Dry-Weather Flow to dry weather model

After DWF and diurnal patterns are developed, whether through flow monitoring data or demographic information, they should be assigned to specific flow loading maintenance holes in the dry weather model as appropriate. The appropriate number and location of flow loading maintenance holes should be determined during the model schematic and sub-basin delineation phases of model development (see DSG section ***7.5.3***).

7.5.6 Hydrologic (Wet-Weather Flow) Model

As rain falls, a series of meteorological and hydrological processes generate wet-weather flow. During wet-weather flow, surface runoff from both pervious and impervious areas begins to drain into openings (e.g. inlets, catch basins, and leaking maintenance holes) of the conveyance systems along its flow paths. Such runoff forms the rainfall-dependent inflow (RD inflow) into the conveyance system. At the same time, as the soil in the vadose zone becomes saturated, subsurface flow consisting of a combination of preferential flow, matrix flow, and interflow (RD PMI) infiltrates into the conveyance systems through defects (e.g. cracks along pipes, cracks on maintenance hole barrels, defective pipe joints, defective pipe-maintenance hole barrel joints,

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[2] (Mitchell, Stevens and Nazaroff)

etc.) along the system. Additional groundwater infiltration can also be generated when the groundwater table rises above its dry-weather seasonal level due to rainfall and causes rainfall-dependent groundwater (RD GWI) to infiltrate into the sewer system. The sum of RD PMI and RD GWI forms rainfall-dependent infiltration (RD infiltration).

The following equations illustrate various components of wet-weather flow (WWF). As BSF also exists during wet weather, BSF is considered as part of wet weather flow.

$$WWF = BSF + sGWI + RD\ I/I$$

$$RD\ I/I = RD\ inflow + RD\ infiltration$$

$$\begin{aligned} RD\ inflow = {} & RD\ surface\ runoff\ from\ impervious\ area \\ & + RD\ surface\ runoff\ from\ pervious\ area \end{aligned}$$

$$RD\ infiltration = RD\ PMI + RD\ GWI$$

Where:

WWF = wet weather flow

BSF = base sanitary flow

GWI = groundwater infiltration

sGWI = dry-weather seasonal level of groundwater infiltration

RD = rainfall dependent

RD I/I = rainfall-dependent inflow/infiltration

RD PMI = rainfall-dependent preferential flow, matrix flow, and interflow

RD GWI = rainfall-dependent groundwater infiltration

After the DWF model is constructed (see DSG section ***7.5.5***), the hydrologic component of the H/H model must then be added to the DWF model to simulate each of the meteorological and hydrological processes for the simulation of the overall wet weather flow as defined above. The hydrologic model development process must include three components:

1. Meteorological time series (see DSG section ***7.5.6.1.1***)
2. Surface runoff (see DSG section ***7.5.6.1.***)
3. Subsurface infiltration (see DSG section ***7.5.6.1.3***)

SPU will support the collection of topographic, land-cover, subsurface, aerial photographs, soil, rainfall, and other spatial terrain data used for the model (see DSG sections ***7.5.3.1*** and ***7.7*** for information on spatial data and precipitation, respectively).

7.5.6.1 Hydrologic Model

The following are guidelines for developing each of the hydrologic model components.

7.5.6.1.1 Meteorological Time Series Model

Meteorological input into a hydrologic model primarily consists of rainfall and evapotranspiration time series. For detailed information on meteorological data, see DSG Section ***7.7***.

7.5.6.1.2 Surface Water Runoff Model

Surface water runoff modeling should be used whenever runoff directly contributes flow to a portion of the SPU drainage and wastewater collection system. Examples include site development projects and CSO projects with substantial contributions from the drainage network.

The available software, runoff generation mechanisms, and other guidelines for computing surface water runoff are described in detail in Appendix F Hydrologic Analysis and Design of City of Seattle Stormwater Manual.

The following standards must be used to develop SPU surface water runoff models:

1. At a minimum, a surface runoff model must contain two submodels: 1) *impervious area* and 2) *pervious area*. To determine whether an area drains to an impervious or pervious area, refer to **Figure 7-6**, Impervious vs. Pervious Area Flow Diagram.
2. SPU-provided GIS impervious and pervious area data must be used in the initial development of these submodels.
3. As the initial submodels are developed, the impervious and pervious area data must be verified with aerial photographs to ensure reasonableness and accuracy of data.
4. Where GIS data is not available, information inferred from aerial photographs provided by SPU or collected from field survey must be used.
5. After the extent of impervious and pervious areas are determined, the areas must be summed and compared with the total area of the catchment to ensure all areas are accounted for and are included.
6. If there are areas in the catchment not connected to the sewer system, those areas must be flagged and documented in the modeling report.

(1) Impervious Area Submodel

One or more impervious submodels must be established for the tributary area of each flow monitor. The percent of imperviousness must initially be assumed to be 100%. Documentation should be provided for impervious areas where the percent of imperviousness is determined to be less than 97% based upon field investigation. The impervious surface can be less than 100% for areas with the following conditions:

- Pavement or concrete around maintenance hole covers exhibit excessive cracks or other defects that cause inflow and infiltration.
- Miscellaneous impervious surfaces (e.g. garage roofs, decks, some sidewalks) that drain to pervious surfaces.
- Drainage ordinance has resulted in connection of roof tops or other impervious surfaces being directed to pervious surfaces or rock pockets.

For modeling surface runoff volume from an impervious area, the routing algorithm should be theoretically sound, use the fewest empirical coefficients, and have the appropriate complexity level. These algorithms are generally based on the unsteady continuity equation and wide channel approximation of the Manning’s Equation (e.g. *Surface Runoff* in SWMM, *Model B* in DHI MIKE URBAN and MIKE+, etc.). Such algorithms can be applied to areas of various sizes and rainfall hyetographs of various intensity, shapes, duration, and frequencies. Documentation should be provided for rationale and algorithm selection for modeling runoff routing from an impervious area.

Where calibrated models are available, the impervious submodel should use the calibrated values of effective imperviousness for impervious area. When a calibrated model or monitoring data for model calibration are not available, the effective impervious surface area must be calculated using the equation below and **Table 7-9**.

$$Effective\ impervious\ surface\ area = total\ impervious\ surface\ area \times SF$$

Where:

SF = Effective Imperviousness Scaling Factor (from **Table 7-9**)

Table 7-9
Estimating Effective Impervious Surface Area

Land Use	Drainage System	Effective Imperviousness Scaling Factor (SF)P
ROW	Informal[1]	61%
	Formal[2]	95%
Parcel (non-ROW)	Informal[3]	28%
	Formal[4]	56%

Notes

[1] ROW informal drainage indicates lack of a designed conveyance system (e.g. runoff travels as edge of pavement flow, or through ditch and culvert system).

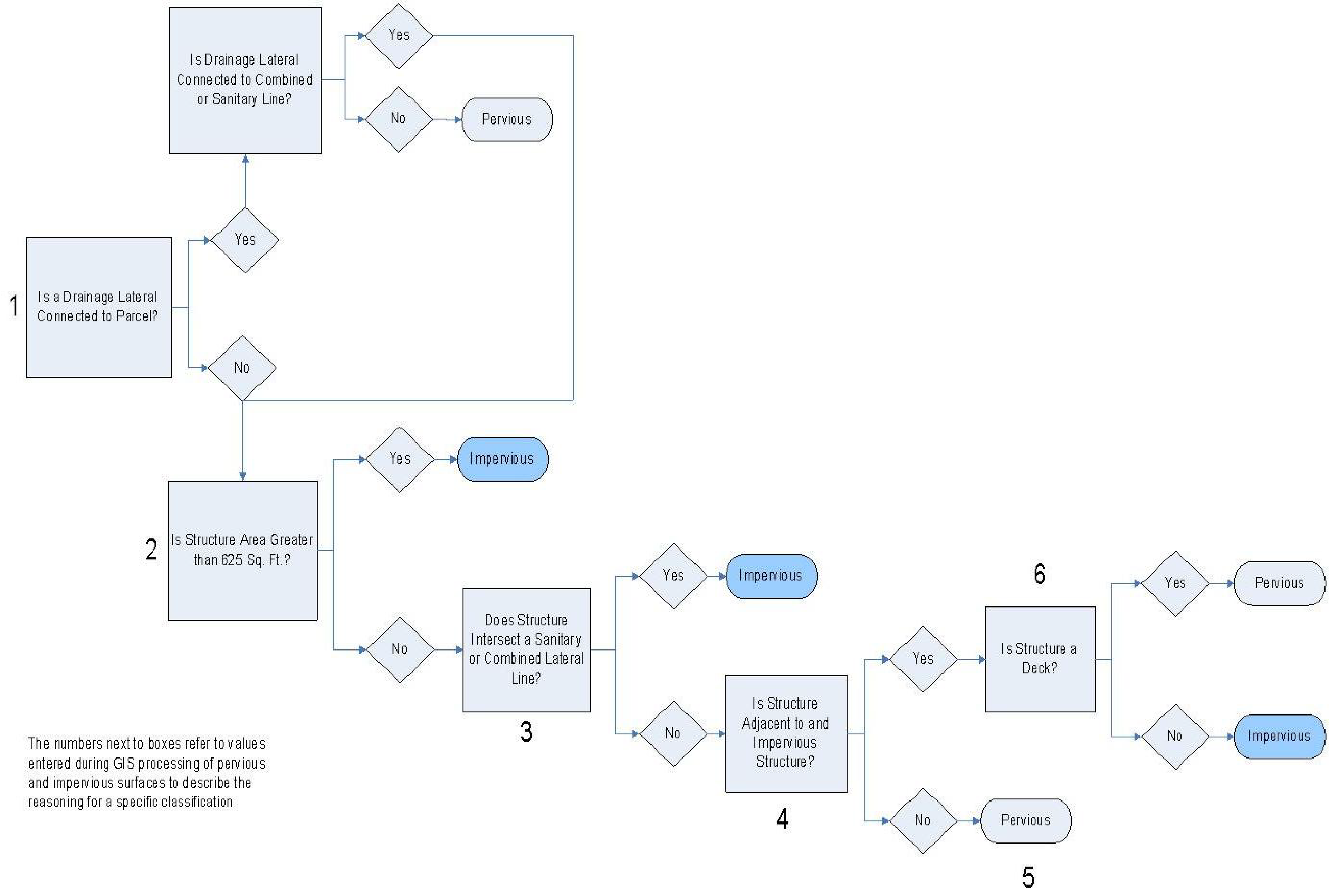
[2] ROW formal drainage indicates a piped storm drain.

[3] Parcel informal drainage indicates existing impervious surface discharges primarily to the private pervious surface or private drainage feature (e.g. rock pockets, large vegetated area).

[4] Parcel formal drainage indicates existing impervious surfaces discharges directly to the public drainage system through a pipe or surface channel).

After all data needed for developing the impervious area submodels are input into the overall H/H model, each piece of data must be associated with a data source. See **Appendix 7C - Data Flags** for data flags that must be assigned to each data value. When the software does not provide for the capability of using such data flags, description of the data source must be provided in the Description fields or a similar field within the model input file.

Figure 7-6
Impervious vs. Pervious Area High-Flow Diagram



The numbers next to boxes refer to values entered during GIS processing of pervious and impervious surfaces to describe the reasoning for a specific classification

(2) Pervious Area Submodel

<u>One or more pervious submodels must be established for the tributary area of each flow monitor</u>. For modeling surface runoff volume from a previous area, the model should be theoretically sound, use the fewest empirical coefficients, and have the appropriate complexity level (e.g. *Modified Green-Ampt Equation* in SWMM, *RDII* in DHI MIKE URBAN and MIKE+, etc.). Soil information and characteristics needed as input into the submodels can be obtained from SPU. Documentation should be provided for rationale and selection of pervious area algorithm chosen for modeling runoff volume from pervious area.

<u>After all data selected for a pervious area submodel are input into the model, each piece of data must be associated with a data source</u>. See **Appendix 7C - Data Flags** for data flags that must be assigned to each data value. When the software does not provide for the capability of using such data flags, description of the data source must be provided in the Description fields or similar fields within the model input file.

7.5.6.1.3 Subsurface Infiltration Model

<u>One or more subsurface infiltration model must be established for the tributary area of each flow monitor</u>. A subsurface infiltration model simulates the storage of rainfall-dependent subsurface flow in the ground and the subsequent routing of RD infiltration into the conveyance system. Minimum sGWI that is part of the dry-weather flow model is assumed to be constant and would not be included in this model. However, past experience in calibrating wet weather flow models in the City has shown that it takes an average of two years for the groundwater table in the City to reset itself after a wet season. As a result, when flow monitoring data shows that sGWI varies significantly from year to year, the modeling of the additional sGWI above the minimum established from dry-weather flow can be included as part of the RD infiltration modeling.

For modeling RD infiltration, the model should be theoretically sound, use the fewest empirical coefficients and/or time series, and have the appropriate complexity level. Soil information and characteristics needed as input into the model can be obtained from SPU. Whenever possible, the subsurface model should be limited to using a ***1-reservoir model*** (e.g. SWMM Groundwater-Aquifer model). The routing equation must have a sufficient number of calibration parameters so that level pool routing can be used to model the routing of RD infiltration into the conveyance system.

For areas where the groundwater table is very close to the surface, porous soil has active subsurface flow activities in the vadose (unsaturated) zone, prolonged RD GWI is observed in the flow data, or as the model project demands, a ***2-reservoir model*** (one reservoir for modeling RD PMI, one for RD GWI) may be used (e.g. *RDII* in DHI MIKE URBAN and MIKE+). <u>However, SPU must first be consulted before a 2-reservoir model is applied. Documentation must be provided for rationale and choice of the subsurface model used</u>.

After all data selected for developing a subsurface infiltration model are input into the overall H/H model, each piece of data must be associated with a data source. See **Appendix 7C - Data Flags** for data flags that must be assigned to each data value. When the software does not provide for the capability of using such data flags, description of the data source must be provided in the Description fields or similar fields within the model input file.

7.5.6.2 Hydraulic Model

The following are requirements for setting up a hydraulic simulation.

1. Full *Dynamic Wave* routing method (i.e. Full Saint Venant Equations of Continuity and Momentum) must be used. This ensures that backwater effects and boundary conditions are properly modeled during a hydraulic simulation.
2. *Automatic Variable Timesteps* function must be used in a hydraulic simulation. This allows the hydraulic engine to automatically adjust time steps used during a simulation to help minimize hydraulic instability and continuity errors of a simulation.
3. Flow must not be numerically lost from the system internally during a hydraulic simulation. This can be achieved by utilizing the modeling software function(s) that either allow water to be ponded/stored on top of a node until hydraulic capacity becomes available (e.g. *Ponded Area* in SWMM, *Normal* node in DHI MOUSE and DHI MIKE 1D), or seal/pressurize the node (e.g. *Surcharge Depth* in SWMM, or *Sealed* node in DHI MOUSE and DHI MIKE 1D).

The following are recommended guidelines for setting up a hydraulic simulation.

1. Hydraulic simulation results should be saved at the same time step interval as the flow monitoring data used for model calibration.
2. The start time of a H/H simulation should be set at least two years earlier than the start time of the flow monitoring data used for model calibration. This allows components of the H/H model to be properly "wetted" before simulation results are used to compare with flow monitoring data for model calibration.

7.5.7 Operational and Observational Data

Operational information provides important qualitative and quantitative data about the performance of a drainage and sewer system. The primary sources for this information are interviews with operations staff (e.g. height of debris in surcharged maintenance holes), survey information from local residents, and maintenance logs. Operational criteria can be observed from the following changes in system operations: pump replacement, weir adjustments, control setting adjustments, locations with frequent maintenance, and sediment depths and surcharge during installation of flow monitors.

7.5.8 Conversion of Existing Models

SPU will consider converting and adapting previously developed models for a new purpose if the model was used within the past five years. Some examples include updating a model to new software version, changing model to another software platform, updating an existing model with new infrastructure data, and adding more detail to a planning level model and converting it into a detailed design model. Converting previously developed models can save time and effort. The modeling team must first confirm that the existing model contains sufficient documentation describing key assumptions and simplifications used during the model setup. The modeling team must also examine the converted model to ensure it produces simulation results consistent with previous results.

The following are key steps in model conversion:

- Confirm all pipes and nodes have successfully come through the model conversion.
- Examine dimensions and elevations to identify missing data, unit errors, or other similar data problems.
- Examine the level of conversion for other infrastructure types. If the updated version of the software contains new features for simulating other structures, the model characteristics of these infrastructure likely will not transfer. The modeling team should examine how parameters of these infrastructure are converted and verify their accuracy in the new model. The model descriptions of these special structures should be revised, as necessary.
- Determine whether the hydrologic parameters are properly converted to the updated version of the model. If calculation methods and features of the hydrologic model have changed from older to newer versions of the software, the modeling team will probably need to reenter hydrologic data and possibly recalibrate the model.
- Perform the necessary hydrologic and hydraulic simulations that compare results of the updated and previous model versions. This activity is simpler if the old version of the modeling software is available. In this case, the team can run the models side by side and compare the results. If the older version of the software is not available, the team should run the converted model and compare the results with those contained in any report prepared using the previous model's simulations. This is a quality assurance (QA) step that helps quantify the impact of new information and identifies any erroneous data or hydrologic and/or hydraulic simulation problems introduced to the model as a result of the conversion.

Note: *The steps described above also apply to converting an existing model to a new modeling platform—although the process may require more data review and correction. The modeling team should determine whether any routines have been developed by the manufacturer of the destination software to help manage the conversion. Some conversion routines include helpful reports that will inform the team about incomplete portions of the conversion.*

7.5.9 Quality Assurance/Quality Control

The modeling team should perform a series of QA tests to identify any missing or erroneous data. Identifying and correcting data errors early will help minimize the potential for inaccurate simulations and associated delays.

After the initial H/H model is constructed, the model must be checked for QA/QC according to the following guidelines.

7.5.9.1 Data Available for QA/QC

Several sources of data are available for QA/QC. Each source varies in degree of accuracy. The following data sources, in order of most to least accurate, can be considered:

- Survey (e.g. surveying field data, SPU SOPA's FOP, SCADA set points)
- As-built

- Sewer card
- SPU GIS

For SPU's system, these data can be obtained from SPU. For King County's system or systems in other adjacent agencies, these data must be obtained through the SPU DWW LOB representative for the project. SPU must be the only channel through which data of the King County system and systems of other adjacent agencies are acquired.

If missing data cannot be found from any of the above sources, the modeler can either interpolate or infer from adjacent available data using best engineering judgment. All such data must be flagged/documented in the model, reported to the SPU project manager, and documented in the Modeling Report.

7.5.9.2 Hydraulic Conveyance System Model QA/QC

The hydraulic conveyance system model requires three types of QA/QC processes: data completeness, data connectivity, and profile data, The results from each process must be documented in the Modeling Report.

The modeling team should evaluate the conveyance system infrastructure data while creating the model, identify missing or potentially incorrect data, and work with SPU staff to fill any data gaps. If any data gaps are identified, the team should work with SPU staff to verify suspect data and, if necessary, take corrective action. Often, missing data directly affect the project schedule.

7.5.9.2.4 Data Completeness

After conveyance system data are entered into the model, QA/QC for data set completeness must be conducted. Check all model links and nodes for missing data such as diameters, lengths, elevations, and any other required data. Minimum diameter of a node should be set to 4 feet unless field information indicates otherwise.

H/H modeling software typically terminate a simulation and generate *Error* messages when key data are missing in the model. Addressing the root cause of each error message is a methodical approach to achieving a complete data set.

All data values must have an associated data flag attached to document source Information. Data flags are defined in **Appendix 7C - Data Flags**. When the software does not provide for the capability of using such data flags, description of the data source must be provided in the Description fields or similar fields within the model input file. All missing data must be tabulated, reported, and resolved with SPU project manager.

7.5.9.2.5 Data Connectivity

After completing a QA/QC of data completeness and resolving missing data issues, a connectivity QA/QC must be completed on the conveyance system data. This QA/QC verifies that:

1. All elements are appropriately connected.
2. Each link is connected to an upstream and a downstream node.
3. Nodes and/or links are not disconnected from the conveyance system.

This can be done by reviewing and resolving, if possible, all *Warning* and/or *Error* messages from the modeling software. The modeler can also select the *upstream trace* and/or *downstream trace* capability, if available in the H/H software, to complete this connectivity QA/QC. ESRI's ArcGIS software has built-in network analysis tools. SPU has a propriety ESRI-based network tracing tool and software tools that can conduct such QA/QC. All data connectivity issues must be tabulated, reported, and resolved with SPU project manager. SPU project manager will in turn provide the list of issues and their resolutions, if any, to SPU GIS. SPU GIS will then judge whether the resolutions are accurate enough cartographically to be incorporated into SPU's enterprise GIS database and also make note of the unresolved GIS issues identified by the modeling project.

7.5.9.2.6 Profile Data

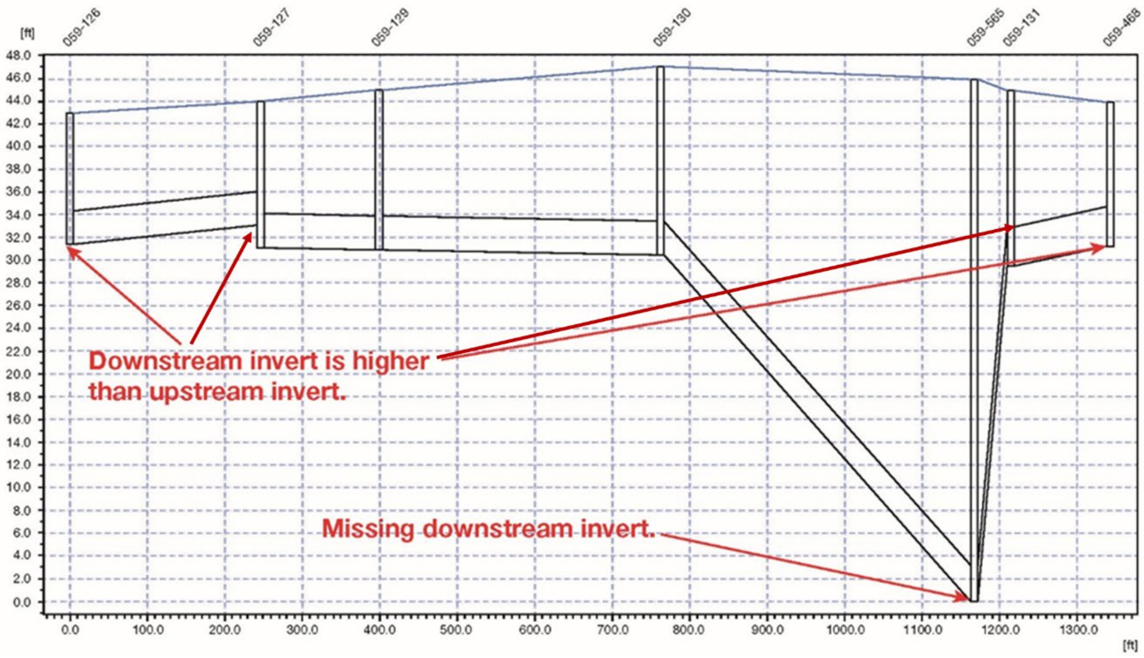
After completing data connectivity QA/QC, the profile data for the conveyance system must be verified. The following should be verified during a profile data QA/QC.

1. In general, for a section of gravity conveyance pipe, the upstream invert should be at a higher elevation than the downstream invert. Some sections of pipes in the SPU system are not gravity driven (e.g. force mains, elevated overflow pipes, or siphons). Those sections of pipes must be documented, flagged, and confirmed with SPU.
2. Obverts of a pipe should be below the ground elevation of the maintenance hole to which the pipe is connected. In parts of the SPU system, this is not the case (e.g. force mains or siphons). In such parts, the pipes must be documented, flagged, and confirmed with SPU.
3. Large vertical drop between inlet and outlet conduit at a deep maintenance hole should be verified and confirmed.
4. Vertical datum of the data must be verified to ensure that the correct datum is used in the model.
5. Examine pipe profiles or network traces to identify any areas where pipe diameters and/or capacities decrease in the downstream direction. Typically, pipe diameters and capacities should increase in the downstream direction. If such sections of sewers which decrease in capacity in the downstream direction are found in the data, they must be documented, flagged, and confirmed with SPU.

If an infrastructure elevation is incongruent with adjacent infrastructure elevation data (e.g. invert of a link is lowered than invert of the connected nodes), the H/H software typically generates warning messages. Thus, addressing the root cause of each error message is a methodical approach to complete a profile QA/QC process.

An example of the attributes of sewers that should be flagged and confirmed with SPU during profile data QA/QC is shown in **Figure 7-7**. After the QA/QC is completed, profile data issues must be tabulated, reported, and resolved with SPU's GIS department and project manager.

Figure 7-7
Sewer Attributes to Flag and Confirm during QA/QC for Profile Data



Downstream invert is higher than upstream invert.

Missing downstream invert.

7.5.9.3 Hydraulic Structure QA/QC

For all hydraulic structures, SPU data flags (**Appendix 7C - Data Flags**) and data formats (**Appendix 7D - Data Formats**) must be followed for the various structures as data is input into the model and data sources are documented. When the software does not provide for the capability of using such data flags, description of the data source must be provided in the Description fields or similar means within the model input file.

All missing data must be tabulated, reported, and resolved with SPU's GIS department and the project manager.

For hydraulic structures such as pump stations, weirs, and hydrobrakes, modeler should compare model simulation results to head discharge curves generated from flow monitoring data, field tests, manufacture curves, SCADA data, and/or information in SPU SOPA's FOP to assess and confirm that the hydraulic control structures are being simulated and functioning properly in the model.

If RTC (e.g. Control Rules in EPA SWMM) modeling software capability is used to simulate hydraulic structure operations, the logic of the model rules must be field verified. The model must reproduce the operations logic of the structure and generate the same results as actual operations. Operational data (e.g. field data) are available in several forms including SCADA data, FOP reports, SPU SOPA staff subject matter expertise, etc. Inquiry to SPU SOPA must be coordinated through SPU project manager.

7.5.9.4 Delineation of Study Area and Sub-Catchment Boundaries QA/QC

The following are QA/QC steps for delineation of study area and sub-catchment boundaries:

1. Verify that the boundary of the study area is delineated correctly within the intended area of study.
2. Verify that sub-catchments of different system types are correctly delineated by their system types and that all sub-catchment boundaries are within the study area boundary.
3. Verify that the sum of the area of sub-catchments delineated within the study area boundary includes the full extent of the study area and no area is excluded.
4. Verify that each sub-catchment drains to an outlet that is tributary to one or more flow monitors downstream to ensure that the flow from each subcatchment is captured by at least one flow monitor downstream.
5. Verify that Building (BLG_) area, Right-Of-Way (ROW_) area, and Catchment (C_) area are appropriately calculated for each sub-catchment in the study area.

7.5.9.5 Boundary Conditions QA/QC

The following are QA/QC steps for boundary conditions:

1. Verify that the unit and datum used in any user-specified input time series for defining boundary condition is the same as the corresponding unit and datum used in the model.
2. Check the magnitude of user-specified inflow data to its drain points are within physically reasonable range.
3. Check that the drain point assigned to an area in the hydrologic model corresponds to a node in the hydraulic model. All discrepancies between the hydrology and hydraulic model node assignment must be reconciled.
4. Check that sub-catchments and their associated building, ROW, and catchment area in a study area are drained to the appropriate type of system (sanitary, storm, or combined) in the hydraulic conveyance system model.
5. If a boundary condition uses tidal level time series, verify that the tidal time level series has been properly converted from saltwater level to freshwater level before it is used for setting boundary condition. The equations are shown in DSG section ***7.5.4.1.2*** and conversion procedures are available from SPU upon request.

7.5.9.6 Dry-Weather Flow Model QA/QC

The following are QA/QC steps for a dry-weather flow model:

1. A minimum of one weekday diurnal pattern and one weekend diurnal pattern are required for each subcatchment inflow node. If a modeling project requires, additional diurnal patterns can be assigned (e.g. for special events like Super Bowl, industrial and institutional discharge, sump pump discharge, etc.).
2. If flow monitoring data are used to develop input to the DWF model, verify that the sum of DWF from sub-catchments equals to the DWF of their tributary flow monitor(s). Run the DWF model and compare simulation results to flow monitoring data to confirm that simulation results closely match with the magnitude and shape of the diurnal patterns

established by the flow monitoring data. If the DWF model input data are developed correctly as described in DSG ***7.5.5***, no further calibration should be needed.

3. If demographic data are used, verify that:
    a. The sum of residential and employment population from each sub-catchment in a study area must equal the corresponding values for the entire study area. The residential and employment population values must agree with those provided by SPU for the study area.
    b. The assumed per-capita flow for each land-use is reasonable and within the limits specified in EPA's Onsite Wastewater Treatment Systems Manual **Tables 3-3 to 3-6**.
    c. The sum of base sanitary flow and sGWI of each sub-catchment equal the corresponding values for the entire study area.

7.5.9.7 Hydrologic Model QA/QC

The following are QA/QC steps for a hydrologic model:

1. Verify that the input rainfall time series used for model calibration includes at least two years of rainfall data before the start of calibration rainfall events.
2. Verify that the input rainfall time series for model validation is a continuous long-term rainfall time series of 30 years or more.
3. Verify that all field timeseries data (e.g. flow monitors and/or SCADA) used for model calibration and validation have been QA/QC'ed. Prior to using QA/QC'ed field timeseries data for model calibration and validation, data quality issues shall be resolved. Data quality resolution shall occur in collaboration with SPU staff (e.g. flow monitoring vendors and/or SPU SOPA) and coordinated by SPU PM.
4. Verify that all QA/QC'ed field data used for model calibration and validation have been correctly input into the model.
5. Verify that for each area tributary to a flow monitor, at least one impervious, pervious, and subsurface infiltration model is established.
6. After hydrologic parameters are entered into the hydrologic model, a QA/QC of the completeness of the data set must be conducted. All data values must have an associated data flag attached to document source Information as shown in **Appendix 7C - Data Flags**. When the software does not provide for the capability of using such data flags, description of the data source must be provided in the Description fields or similar fields within the model input file.
7. Verify that the sum of the impervious area in each sub-catchment equals the total impervious area of the study area. Similarly, the sum of the pervious area in each sub-catchment must equal the total pervious area of the study area. Finally, verify that the sum of impervious and pervious area equals the total study area.
8. Hydrologic parameters related to the geometric and subsurface properties of a catchment (e.g. size of area or type of soil) must be verified with GIS data.
9. Hydrologic parameters used for calibration (e.g. hydraulic conductivity of soil) must be verified for their reasonableness with available data and accepted values. Initially, modelers must establish a reasonable range for each calibration parameters based on accepted engineering and hydro-geological values. Refer to **Table 7-10**.

10. Perform simulations that compare results of updated and previous model versions.

***Note:** This QA step helps quantify the impact of new information and identifies any erroneous data or hydraulic problems introduced to the model.*

Table 7-10
Estimation of Green-Ampt Infiltration Parameters

USDA Soil Texture Classification	Suction Head (in)	Suction Head (mm)	Hydraulic Conductivity (in/hr)	Hydraulic Conductivity (mm/hr)	Porosity	Effective Porosity
Sand	1.95	49.5	4.64	117.8	0.437	0.417
Loamy sand	2.42	61.3	1.18	29.9	0.437	0.401
Sandy loam	4.34	110.1	0.43	10.9	0.453	0.412
Loam	3.50	88.9	0.13	3.4	0.463	0.434
Silt loam	6.57	166.8	0.26	6.5	0.501	0.486
Sandy clay loam	8.61	218.5	0.06	1.5	0.398	0.330
Clay loam	8.23	208.8	0.04	1.0	0.464	0.309
Silty clay loam	10.76	273.0	0.04	1.0	0.471	0.432
Sandy clay	9.42	239.0	0.02	0.6	0.430	0.321
Silty clay	11.51	292.2	0.02	0.5	0.479	0.423
Clay	12.46	316.3	0.01	0.3	0.475	0.385

Notes

[1] These values are provisional and are offered as reasonable parameter estimates for SWMM applications where more detailed soil information is unavailable. There is significant variance in these values; laboratory and field testing, sensitivity analysis, and calibration may be employed to improve upon these estimates.

[2] In the absence of a soil survey or more reliable information, the values listed above may be used.

[3] Values are derived from Journal of Hydraulic Engineering, ASCE, volume 109, No. 1, pp 62–70.

Acronyms and Abbreviations

in: inches
in/hr: inches per hour
mm: millimeter
mm/hr: millimeter per hour

7.5.9.8 Model Check In and Out

The Modeling & GIS (M&G) group within System Management (SM) division of the DWW LOB maintains all developed models, including calibrated and uncalibrated models. They are stored in a centralized network location for SPU's staff and consultants to use.

All models and associated data and documents are checked out for use and checked in after the models are completed or updated. Contact M&G Modeling staff for check-in and out requests of modeling information. Procedures for check-in and check-out of modeling information are as follows:

1. Submit a completed form to M&G Modeling staff.
2. Once received, M&G modeling staff will contact the submitter if further information is needed.
3. Modeling team will review and process the request and notify the submitter about next step(s).
4. The check in-out request forms are is in **Appendix 7F - Modeling Check In and Out Form**.

7.6 INITIAL MODEL TESTING

After the physical structure of the model is complete and all input data and boundary conditions defined, the modeler should perform initial tests to ensure the model functions as intended. These simple checks help identify setup problems before more detailed calibration and validation are performed.

While the information for initial testing will depend on the type of system modeled and the modeling software, the following initial checks are a guideline:

1. Does the model run to completion?
2. Does the model summary file(s) list specific errors or warning messages that indicate possible hydraulic or solution convergence problems? Warning messages are usually not fatal errors and models can often still be run to completion without having these messages resolved. However, warnings are often indicators of model issues (e.g. GIS and input data errors). Warning messages are often precursors for modeling errors that occur in calibration or long-term simulations, which can be harder to decipher and negatively impact modeling results and project outcomes. Thus, warning messages should be resolved prior to model calibration to eliminate the root cause of additional errors and challenges that may occur later in the modeling process.
3. Does the time series output database/selection list include data for all requested pipes, nodes, and other structures? This is an especially important verification to do before running a long-term simulation which usually takes many days to run. This verification would ensure that no needed results will be missing after the long-term simulation is complete.
4. Do the overall system inflows and outflows balance?
5. Do pump stations and other on/off or moveable structures change settings during a simulation as expected?
6. Does the model produce any overflows during low-flow test simulation?

7. Does the model simulation produce any suspicious velocities (e.g. greater than 8 feet per second [fps] or less than 0.5 fps)? High or low velocities do not necessarily indicate an error, but the system infrastructure and hydraulics in these areas should be carefully scrutinized.
8. If there are any unusual numerical oscillations in the simulation results, they should be resolved, if possible, to ensure that the model is stable. The various H/H software available use different approaches to address numerical instability. Please refer to software's user manual to resolve numerical instability issues.

The initial model test descriptions and results should be briefly documented and saved with other model plan documentation.

7.7 PRECIPITATION

This section describes the use of precipitation data for drainage and wastewater modeling projects. Drainage and wastewater infrastructure models use precipitation data to calculate stormwater flows and I/I to the conveyance system (i.e., rainfall-induced flows). During large storms (ones that generate CSOs), the rainfall-induced component of wastewater flow is usually much larger than the dry weather flow component. Rainfall-induced flows clearly affect the level of service provided by hydraulic facilities. Modelers should use appropriate and representative precipitation data to model the SPU drainage and wastewater conveyance system.

7.7.1 Permanent Rain Gauge Network

The City operates and maintains a network of 22 automated rain gauges distributed throughout the City. Many of these gauges have been operating since 1978 (**Table 7-11**). Currently, SPU SOPA manages and maintains these rain gauge locations.

Table 7-11
Permanent Rain Gauge Network Attributes

Gauge ID	Name	Address	Period of Record	In Operation
RG 01	Haller Lake Shop (SPU)	North 128th Street & Ashworth Avenue North	1978-current	Active
RG 02	Magnuson Park	7022 Sand Point Way Northeast	1978-current	Active
RG 03	UW Hydraulics Lab	Northeast Pacific Street and 15th Avenue Northeast	1978-current	Active
RG 04	Maple Leaf Reservoir	Northeast 82nd Street and 12th Avenue Northeast	1978-current	Active
RG 05	Fauntleroy Ferry Dock	4829 Southwest Barton Street	1978-current	Active
RG 07	Whitman Middle School	9201 15th Avenue Northwest	1978-current	Active
RG 08	Ballard Locks	3015 Northwest 54th Street	1978-current	Active
RG 09	Woodland Park Zoo	5500 Phinney Avenue North	1978-current	Active

Gauge ID	Name	Address	Period of Record	In Operation
RG 10	Rainier Avenue Elementary	116500 Beacon Avenue South	1978-2008	Inactive
RG 11	Metro-KC Denny Regulator	Myrtle Edwards Park	1978-current	Active
RG 12	Catherine Blaine Middle School	2550 34th Avenue West	1978-current	Active
RG 14	Lafayette Elementary School	2635 California Avenue Southwest	1978-current	Active
RG 15	Puget Sound Clean Air Monitoring Station	4401 East Marginal Way	1978-current	Active
RG 16	Metro-KC East Marginal Way	East Marginal Way and 13th Avenue	1978-current	Active
RG 17	West Seattle Reservoir Treatment Shop	8th Avenue Southwest and Southwest Cloverdale Street	1978-current	Active
RG 18	Aki Kurose Middle School	3928 South Graham Street	1978-current	Active
RG 20	TT Minor Elementary School	1700 East Union Street	1978-2010	Inactive
RG 25	Garfield Community Center	2323 East Cherry Street	2010-current	Active
RG 30	Rainier Beach Public Library	9126 Rainier Avenue South	2009-current	Active
RG 32	Beacon Telemetry Shack	3803 Beacon Avenue South	2016-current	Active
RG 33	Fire Station #38	4004 NE 55th Street	2016-current	Active
RG 34	Fire Station #39	2806 NE 127th Street	2016-current	Active
RG 35	Capitol Hill Library	425 Harvard Avenue East	2016-current	Active
RG 36	High Point Library	3411 SW Raymond Street	2016-current	Active

The rain gauges contain tipping buckets that record precipitation in 0.01-inch increments, with the timing of each bucket tip recorded to the nearest minute. All gauges include an on-site data logger for recording precipitation data and communication equipment to transmit data to the monitoring contractor’s computers for processing. Please refer to the DSG modeling library for precipitation data from the City permanent gauge network.

For more discussion on City rain gauge network and precipitation analysis, refer to the technical memorandum prepared by MGS Engineering Services, Inc. in 2004, “Analyses of Precipitation-Frequency and Storm Characteristics for the City of Seattle.” This document has been updated twice since its initial publication – once in 2013[3] and once in 2021[4].

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[3] (MGS Engineering Consultants, Inc.)

[4] (MGS Engineering Consultants, Inc.)

King County rain gauge data are also available for use by SPU when a King County rain gauge is closer than the closest SPU rain gauge. However, request for King County rain gauge data must be made through SPU.

7.7.2 Selecting City of Seattle Rain Gauge

The project team should evaluate the following local conditions when selecting a rain gauge location for obtaining appropriate rainfall data sets for a modeling project:

- Size of project area. Larger project areas are more likely to experience significant rainfall variability. To accurately capture total precipitation volume, additional gauging stations could be required.
- Proximity of the nearest permanent rain gauge site. Data from gauges located within or near the project area are more likely to correlate with flow monitoring data collected within the basin. Gauges farther from the project could present challenges during model calibration.
- Complexity of project drainage and conveyance issues. The modeling plan in **Appendix 7A - Modeling Plan & Reporting** describes the acceptable level of uncertainty.

The project team should consider the issues above when selecting rainfall data. For straightforward projects located near a permanent rain gauge, one gauge will be sufficient. For larger project areas or more complex projects, the project team should consider installing a temporary rain gauge to calibrate the model and reduce the uncertainty of the modeling results.

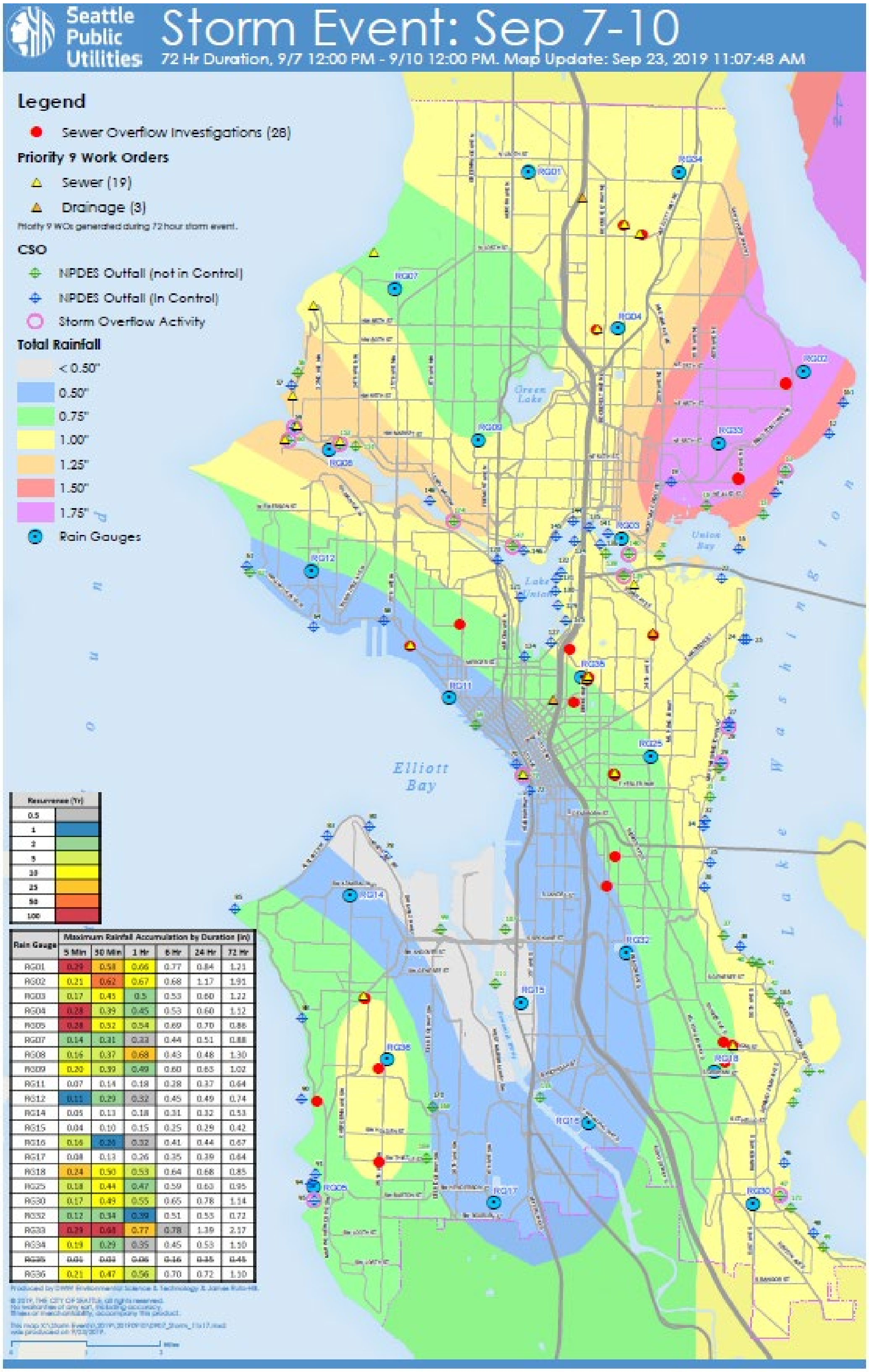
7.7.2.1 Thiessen Method

Whenever multiple rain gauges are used for drainage and wastewater system models, the Thiessen Method must be used to initially distribute rainfall throughout a basin. The Thiessen Method assumes the rainfall at a particular location is equal to the rainfall recorded at the nearest gauge. Applying the method will generate a set of polygons or sub-catchments associated with each rain gauge. Using ArcGIS built-in tools for Thiessen Method polygon generation, the SPU Modeling & GIS group created a Thiessen Polygon GIS layer for the active gauges shown on **Table 7-11**. The SPU Modeling & GIS group can provide additional information about this layer upon request.

SPU's Modeling & GIS group creates rainfall event return period maps for significant rainfall events in the City. When such maps are available for model calibration, the maps should be reviewed to refine the rainfall data and gauge(s) used for the study area.

The Thiessen Method does not consider the path that storm cells take to move across the City, and storm cells can pass over the study area without passing over the Thiessen Method rain gauge. Therefore, in some cases, data from several adjacent rain gauges, flow monitoring data and initial model simulation results may need to be analyzed together to assess the most appropriate rain gauges for model calibration. This is especially needed when observed flow monitor data are higher than the simulated flow using the selected Thiessen Polygon rain data. This is especially useful when no additional rainfall data (e.g. temporary rain gauge data) is available. **Figure 7-8** is an example rainfall event return period map.

Figure 7-8
Example Rainfall Event Return Period Map



Recurrence (Yr)	
0.5	⬜
1	🟦
2	🟩
5	🟩
10	🟨
25	🟧
50	🟧
100	🟥

Rain Gauge	Maximum Rainfall Accumulation by Duration (in)					
	5 Min	30 Min	1 Hr	6 Hr	24 Hr	72 Hr
RG01	0.29	0.58	0.66	0.77	0.84	1.21
RG02	0.21	0.62	0.67	0.68	1.17	1.91
RG03	0.17	0.45	0.5	0.53	0.60	1.22
RG04	0.28	0.39	0.45	0.53	0.60	1.12
RG05	0.28	0.32	0.54	0.69	0.70	0.86
RG07	0.14	0.31	0.33	0.44	0.51	0.88
RG08	0.16	0.37	0.68	0.43	0.48	1.30
RG09	0.20	0.39	0.49	0.60	0.63	1.02
RG11	0.07	0.14	0.18	0.28	0.37	0.64
RG12	0.11	0.29	0.32	0.45	0.49	0.74
RG14	0.05	0.13	0.18	0.31	0.32	0.53
RG15	0.04	0.10	0.15	0.25	0.29	0.42
RG16	0.16	0.28	0.32	0.41	0.44	0.67
RG17	0.08	0.13	0.26	0.35	0.39	0.64
RG18	0.24	0.50	0.53	0.64	0.68	0.85
RG25	0.18	0.44	0.47	0.59	0.63	0.95
RG30	0.17	0.49	0.55	0.65	0.78	1.14
RG32	0.12	0.34	0.39	0.51	0.53	0.72
RG33	0.29	0.68	0.77	0.78	1.39	2.17
RG34	0.19	0.29	0.35	0.45	0.53	1.10
~~RG35~~	~~0.04~~	~~0.03~~	~~0.06~~	~~0.16~~	~~0.35~~	~~0.45~~
RG36	0.21	0.47	0.56	0.70	0.72	1.10

7.7.2.2 Available Rainfall Time Series

Different types of rainfall time series are available for use in H/H modeling of the drainage and wastewater systems. The following provides a brief description of each type.

7.7.2.2.1 Active Rain Gauges

SPU's Modeling & GIS group has created a continuous rainfall time series for each of the rain gauges listed on **Table 7-11**. These time series are usually used for model calibration and long-term simulations. The start time of all of these rain gauge time series is 9/1/1976. Documentation on how these rainfall time series were developed are described in DSG section ***7.7.1***.

Two time series formats are available for each rain gauge. They are:

1. *EPA SWMM model format (.dat)*. – This is an ASCII text file in the EPA SWMM external time series format. The rainfall data is semi-parsed such that each rainfall event is surrounded by a beginning and an ending zero. This time series is in 5-minute interval.
2. *DHI MIKE format (.dfs0)*. – This is a DHI propriety format of the EPA SWMM model format rainfall time series described above. This format is created so that DHI MIKE software can use the same rainfall time series as EPA SWMM software.

These permanent gauge time series are extended as new rainfall data become available. Please refer to the DSG modeling library for the active gauges and precipitation data.

7.7.2.2.2 10-year rainfall time series

A 10-year continuous rainfall time series in 15-minutes interval has been created and is available for running simulation scenarios. This time series is available in an ASCII text file in the STORMSCAN format. Please refer to the modeling library for the 10-year rainfall time series for more information.

7.7.2.2.3 158-year rainfall time series

A 158-year parsed rainfall time series in 5-minutes interval has been created and is available for running extended long term simulation scenarios. This time series is in the EPA SWMM model external time series format. Please refer to the modeling library for the 158-year rainfall time series for more information.

7.7.2.2.4 Design rainfall time series for capacity analysis

Two 2-year continuous design rainfall time series in 5-minutes interval have been created and are available for modeling purpose. One time series is for wastewater system modeling and the other one is for drainage system modeling. These time series are in the EPA SWMM model external time series format. Please refer to the modeling library for system planning synthetic storms for more information.

7.7.2.2.5 Climate perturbed rainfall time series

In an effort to estimate climate change impact to SPU's drainage and wastewater systems, climate perturbed semi-parsed rainfall time series for each of the rain gauges listed on **Table 7-11** have been created and are available for modeling purposes. These time series are in both the EPA SWMM model external time series format and the DHI MIKE format. **As of August 2023, these time series are being updated. The updated time series will be made available after their updates are completed. During the meantime, the current versions of these time**

series are available for use as needed. Please contact SPU's *Modeling & GIS* group for more information.

7.7.3 Temporary or Project-Specific Rain Gauges

Temporary rain gauges are occasionally installed for projects without adequate local rainfall measurement coverage to meet project requirements. Reasons to install a project-specific rain gauge include:

- No nearby rain gauge
- Spatially variable rainfall and available nearby gauges do not adequately represent basin-wide rainfall

Typically, the lead modeler will determine whether to install additional rain gauges during the early phase of project planning. The timing of the new gauge is important. The gauge should be installed as early as possible in advance of temporary flow monitors for better model calibration. Temporary rain gauges must be documented in the flow monitoring plan and report.

7.7.3.1 Selecting Temporary Precipitation Monitoring Location

The project team may decide to install temporary rain gauges in a project area. These installations have the following design considerations:

- Design and install to the same standards as a permanent rain gauge as much as practical. Installation locations should allow for accurate data collection (e.g. no vertical obstructions, low-wind location), convenient access for maintenance, and good security to prevent vandalism or accidental damage.
- Locate in areas that are tributary to the study area. This will provide greater data resolution in the areas that contribute to known problems. When combined with existing gauges in the area, temporary gauges should provide a good representation of the entire project area. As discussed in DSG section ***7.7.2.1***, SPU's Modeling & GIS group creates rainfall event return period maps for significant rainfall events in the City. When such maps are available for the study area, the maps should be reviewed as they provide insights on the historical trend that storm cells have taken across the study area. When correlated with locations of study area, such information further helps in selecting suitable locations for the temporary rain gauge.
- Install the temporary rain gauge before flow monitoring data collection and model calibration. Ideally, the temporary gauges function throughout planning, design, construction, and up to five years post-construction to allow SPU staff to verify effectiveness of facility upgrades.

7.7.4 Other Sources of Precipitation Data

City permanent and temporary gauges should be sufficient for all drainage and wastewater modeling projects in the City. However, users may want to examine other nearby local precipitation data sources. Non-SPU gauges could be used for QA, to determine the spatial extent of a particular storm or to verify that an SPU rain gauge accurately recorded information for a particular storm. Other sources of precipitation data include:

- National Oceanic and Atmospheric (NOAA)/National Climatic Data Center (NCDC) sites at SeaTac Airport and Sand Point
- King County precipitation sites

7.7.5 Design Storms

For the applicable use of design storms, refer to Appendix F Hydrologic Analysis and Design of City of Seattle Stormwater Manual. Different types of readily available historical rainfall and design storm time series data are located in the modeling library as discussed in DSG section ***7.7.2.2***

7.7.6 Evaporation Monitoring Stations

If evaporation calculations are needed for modeling, the modeling team should obtain an evapotranspiration time series from a nearby location, such as the Washington State University (WSU) station at the University of Washington (UW) (Station Name: Seattle) available at WSU's AgWeatherNet website. Refer to DSG modeling library for evaporation time series data at UW.

The City does not operate long-term evaporation monitoring stations.

7.8 FLOW MONITORING

Early in the project, the project team should evaluate the need for flow monitoring data based on project goals. If flow monitoring data is needed, the project team should check first with the SPU project manager to determine whether flow monitoring data already exists for the project area. If no useable flow monitoring data is available, the following are guidelines for gathering flow monitoring data.

7.8.1 Flow Monitoring Plan

A flow monitoring plan must be developed for projects that require flow data collection. The flow monitoring plan must follow the sample outline in **Appendix 7A - Modeling Plan & Reporting**. The plan should be developed early and updated to reflect changing conditions.

The schedule outlined in the monitoring plan should be integrated with the overall project schedule, including the milestones outlined in the modeling plan (see DSG section ***7.3.1***).

7.8.2 Selecting Flow Monitoring Locations

Monitoring locations must be selected and prioritized to maximize data usefulness and to ensure proper calibration of subsequent modeling. Monitoring locations must be functional and practical. The following are basic steps for selecting flow monitoring locations:

1. Coordinate monitoring team. The project manager should coordinate with SPU staff, contractors, and consultants early in the project. Flow monitoring can be time intensive, especially when trying to capture a wide range of events or infrequent events. Flow monitoring must be initiated early to minimize impacts to project schedule.
2. Establish objectives. Data needs should be assessed. Based on data needs, specific objectives should then be established for flow monitoring. The objectives should include types of data to be collected (e.g. flow rates, flow velocities, flow depths), temporal frequency of the data, duration of data, and precision and accuracy requirements. The objectives should also indicate the geographic area of interest and specify locations of particular concern.
3. Identify constraints. Constraints should be quantified (if possible). The primary constraints on quantifying data are lack of good monitoring sites at critical locations due to poor flow monitoring conditions, budget, staff availability for O&M of flow monitoring sites, and time.
4. Select monitoring equipment based on flow monitoring objectives and constraints for the project.
5. Identify preliminary locations with alternatives. When identifying flow monitoring locations, attention should be given to both (1) areal extent of the monitored area as well as (2) suitability of localized hydraulics at the selected location within the conveyance system given flow monitoring technology constraints. When a compromise is needed between areal extent and suitability of local hydraulics, the importance of local hydraulics suitability would outweigh that of areal extent. This is because it is better from model calibration perspective to collect good data from a smaller area so that a good calibration can be achieved for the smaller area than to collect bad data from a larger area which cannot be used for model calibration at all.
6. Field-verify the suitability of local hydraulics of selected flow monitoring locations.
7. Finalize locations.
8. After the commencement of flow monitoring the monitoring team should schedule regular **weekly** to **bi-weekly** meetings to review the quality of the collected interim data. If poor data quality is observed, the location(s) and/or the technology of flow monitoring should be corrected immediately.

7.9 MODEL CALIBRATION AND VALIDATION

Model calibration consists of adjusting model input parameters to compare model simulation results with observed information (such as flow monitoring data) until the modeling team determines a reasonable agreement has been reached. Validation involves testing the model simulation against an independent set of observations that excludes the calibration period. The purpose of model calibration and validation is to replicate key H/H conditions in a project area. Model calibration and validation should give the project team a higher level of confidence in using the results to plan and design facility improvements. The criteria used for Initial Model Testing as discussed in DSG section ***7.6*** should also be used to ensure model stability during model calibration and validation.

7.9.1 Levels of Calibration

The modeling team should plan the level of model calibration approach to match project goals and available information. For example, sizing a short length of pipe may not require extensive model calibration, particularly if the project has an accelerated schedule. In this circumstance, the project team could specify a larger diameter pipe to offset any uncertainty caused by minimal calibration. By contrast, larger projects that carry significant costs and consequences of failure should receive a more thorough modeling analysis that includes calibration and validation. This may require the project team to collect additional flow monitoring data before calibration.

As part of the initial project planning, the project team should evaluate the need for model accuracy by quantifying the risks and consequences of modeling uncertainty. Would a simple, conservative approach to facility sizing suffice? Or does the project require a more thorough understanding of H/H conditions to ensure conveyance goals are adequately met?

The following types of information may be very useful for model calibration and validation.

1. **Flow monitoring data.** Continuously monitoring flow rates and depths will help the modeling team to determine the physical mechanisms by which flow enters and moves through the SPU drainage and wastewater system. Continuous flow monitoring will allow the modeler to match the rising and falling limbs of the flow hydrograph and compare flow responses to storms of different lengths and intensities and antecedent conditions.
2. **Historical anecdotal information.** Flow monitoring data may be limited in the project area, particularly if the events that triggered the need for a project occurred before any flow monitoring data was available. In some cases, historical anecdotal information may be the only type of information available for floods of interest. Available sources of anecdotal information may include the following:
    a. Interviews with local residents
    b. Photographs and/or videos of specific storm events
    c. Debris marks indicating high water within maintenance holes or above-ground flood stage
    d. Water level measurements (i.e., measure-downs) by City staff during floods.

    Anecdotal information can be particularly helpful in model validation.
3. **Permanent CSO NPDES monitoring data.** Because SPU has long, continuous monitoring records for its permanent CSO NPDES sites, these locations are a useful source of operational historical data. Modelers should use caution, however, when using permanent CSO NPDES monitoring data for calibration. NPDES CSO sites are typically difficult to monitor. The resulting data usually have a higher level of uncertainty than flow monitoring data collected in more ideal locations in the upstream collection

system. NPDES CSO site monitoring data should primarily be used to determine 1) when overflows occurred and 2) the relative magnitude of differing CSO events.

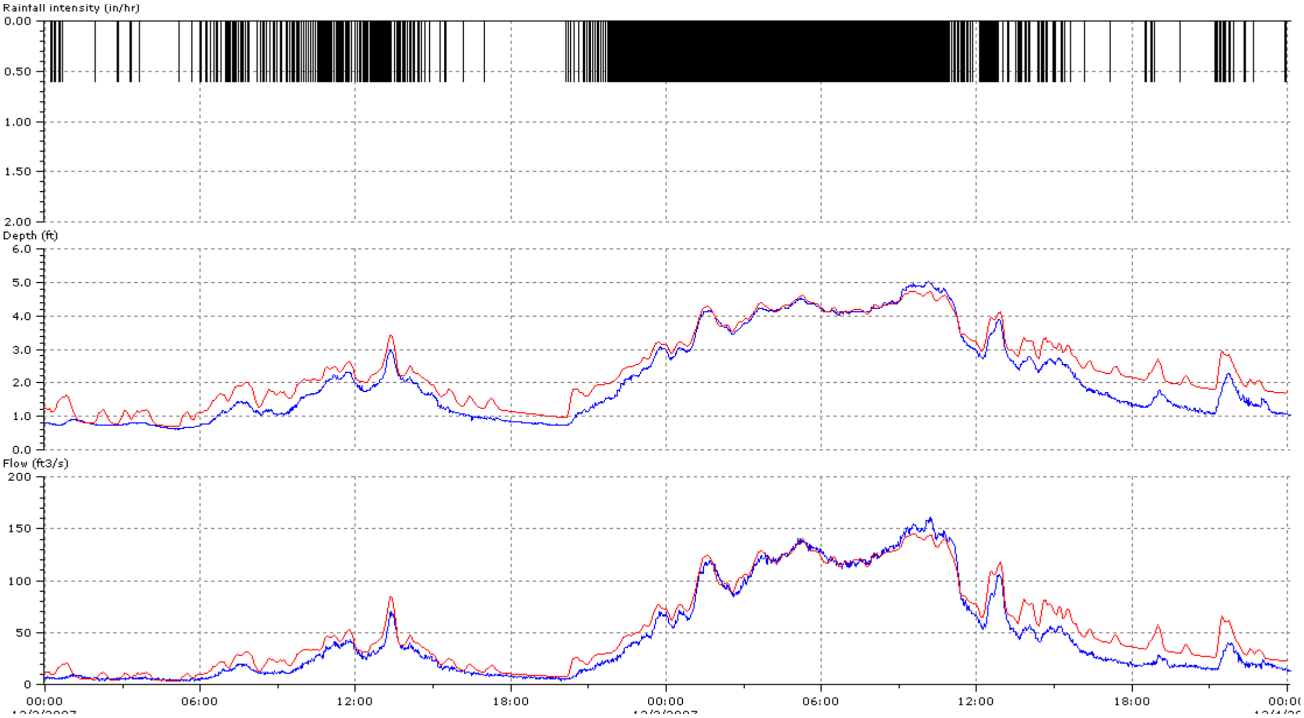
4. **SCADA data.** SCADA data such as pump station runtime data may offer a history of SPU drainage and wastewater system operational data. In addition to pump runtime data, other examples of SCADA data useful for model calibration include sluice gate positions, wet well levels, etc. Pump runtime information collected and stored in in SPU SCADA system could be converted to flow data by using the manufacturer's pump curve data or by drawdown tests performed to test the actual pump performance. The modeler should use caution when using pump runtime information to calculate pump flow for model calibration purposes, because the computed flow rates are often less accurate than actual flow monitoring data. It is preferable to use pump station runtime data as a secondary source of operational information.

7.9.2 Calibration to Flow Monitoring Data

This section discusses methods and performance goals for calibrating to flow monitoring data. The discussion focuses primarily on sanitary and combined sewer methods. However, general goals (if not specific methodology) apply equally to drainage and creek systems.

For the City, a full wet season of flow data is needed for model calibration, because the soil moisture during winter affects the quantity of extraneous flows entering the drainage and wastewater system throughout the year. For example, October I/I flows contain much less rainfall than February I/I flows.

The quality of a model calibration and the iterative adjustment of model variables can be guided by both graphical and statistical methods. During the initial iterations, it is convenient to use a graphical comparison of modeled and observed flow, as shown on **Figure 7-9**.Figure 7-9 Example of Calibration Comparing Simulated and Observed Depth and Flow



A graphical comparison of modeled and actual flow provides a quick assessment of model accuracy. This can be used early in calibration to identify large discrepancies and make broad adjustments to the model.

Criteria for consideration during graphical analysis are hydrograph shape, peak flow rate, and the timing of peak and low values. These criteria should be applied to both base flow and I/I.

Statistical methods provide quantitative comparisons between modeled and observed flow. Calibrated models should meet the requirements in DSG section ***7.9.2.1*** for dry and wet-weather flow model calibrations. Such requirements should also be applied to the model validation process.

7.9.2.1 Measures of Calibration Success

The ability to produce an accurate calibration is affected by several factors that may be out of the modeler’s control. Calibration performance will be affected by flow monitoring data accuracy, rain gauge data accuracy and representativeness for the project area, the model’s I/I computation algorithms, and quality of model input data. While the modeling team should set calibration goals, it may need to adjust those goals during calibration phase to meet data and model limitations. The following are general guidelines for model calibration on SPU drainage and wastewater system projects.

7.9.2.1.6 Dry-Weather Flow Calibration

For dry-weather flow (i.e., base flows), the following standards should be used for calibration, in addition to matching general hydrograph shape. These standards should be met for at least two dry-weather days (weekday and weekend day):

- Estimated time of peaks and troughs should be within one hour of the observed flow
- Estimated peak flow rate should be within ± 10% of the observed flow data
- Estimated volume of flow over 24-hours should be within ± 10% of observed flow

7.9.2.1.7 Wet-Weather Flow Calibration

For wet-weather flows (base flow plus infiltration/inflow), the following standards should be used for calibration and simulation results should match the general hydrograph shape of field data. These guidelines should be met for at least five wet-weather events of varying rainfall depth, intensity, and duration:

- The wet weather model Runoff Continuity Error, Groundwater Continuity Error, and Flow Routing Continuity Error should be within -5% and +5%, ideally within -1% and +1%.
- Model results should not simulate flooding unless flooding is substantiated by field records.
- Estimated time of peaks and troughs should be within one hour of the observed flow
- Estimated peak flow rates should be within -15% and +25% of the observed flow
- Estimated volume of the wet-weather event should be within -10% and +20% of the observed volume

- Estimated surcharge depth in maintenance holes or other structures should be within -0.3 feet (ft) and +1.5 ft of the observed depth
- Estimated water surface elevations (i.e., non-surcharge depth) should be within ± 0.3 ft of the observed depth

7.9.2.1.8 Other Considerations for Calibration

Depending on the model's purpose, other parameters also require examination to ensure accurate calibration. These include, but are not limited to, the following:

- Reasonable agreement between predicted and actual pumping station wet-well level, pump run times, and discharge
- Accurate estimation of known overflow location, frequency, and volume
- Accurate estimation of duration and volume of flow equalization/storage systems
- Representative performance of flow control structures such as weirs

7.9.2.2 Automated Calibration Methods

Several software packages offer automated calibration routines that provide a quicker and less labor-intensive approach to model calibration. Automated calibration is helpful when calibrating to several different flow meters or when combined with a sensitivity analysis. Methods for automated calibration include the following:

- Minimizing the difference of squares between the model output and flow monitoring data. This method is simple but tends to optimize the fit for base flows instead of matching peak flows.
- Minimizing the difference of squares while providing additional weighting to high-flow periods. This variation of the method above seeks to provide better matching to storm data in general.
- Neural networks methods sequentially test adjustments to model parameters. They select and build on adjustments that produce a closer match between simulated and observed data. The process continues until a specified minimum level of agreement is met.

Automated calibration techniques are helpful. However, they should be used with caution. Most I/I model applications attempt to simulate the physical processes by which water enters the pipe network. When setting up an automated calibration, the modeler should use caution in selecting calibration parameters and only allow the model calibration parameters to vary within reasonable limits. Automated calibration methods increase the potential to "get the right answer for the wrong reason." For modeling studies that means producing a good calibration fit without capturing the essential physical mechanisms of the system. If a method does not capture the essential physical elements of the system, the model is unlikely to perform well in "what if" scenarios that test alternative improvement, particularly I/I removal.

For CSO projects and basin plans, ACU-SWMM is available for use with EPA SWMM. ACU-SWMM has two primary functions. The first function is automated calibration of SWMM models of urbanized basins. The automated calibration function may be used with any SWMM5 basin model. Second function is it computes Control Volumes and uncertainty bounds for CSO volumes with a frequency occurrence of once per year. For more information on ACU-SWMM, refer to **Appendix 7G - ACU SWMM User Manual**.

For SPU - King County joint projects, the software called PEST (Parameter Estimation) can be used for automated calibration with DHI MIKE URBAN software. For more information about PEST, refer to the website (www.pesthomepage.org). PEST usage for model calibration should be approved by SPU Modeling and GIS group prior to calibration.

7.9.3 Model Validation

The validation process tests that the model can rigorously reproduce a variety of H/H conditions, not only those included in the calibration period. The validation process is the final step before a model is used to simulate specific drainage and wastewater improvements.

The validation process includes the following steps:

1. Determine available data for the model validation effort. Potential sources of data (e.g. historical flow monitoring, anecdotal or operational data) are described in DSG section ***7.9.1***. When flow monitoring data is used for model validation, the data quality of the data should equivalent or better than same level as the calibration data. This helps to ensure that the validation process is properly evaluated.
2. Prepare precipitation data and any time-varying boundary conditions for the period covered by the validation data
3. Run a model simulation through the entire validation period with a simulation start date set at 2-years before the start of the validation period. The 2-year simulation period prior to the validation period allows the model antecedent moisture condition to set. After the entire simulation is complete, simulation validation period simulation results can be compared with the validation data set.

The validation data set should be independent from the calibration data set. Ideally, the validation data set would be from a different wet season with different conditions from the calibration data set.

Methods for evaluating the quality of a model validation simulation are less prescriptive than for a model calibration. Graphical and statistical comparison methods are both valid. The modeler should expect model validation simulations to match flow observations less precisely than the calibration simulations.

The model team should set specific criteria for model validation, such as matching peak flows to within 20% or volume to within 10%, to meet the project’s accuracy requirements. In the process of setting these criteria, the modeling team must consider the limitations of the model to represent the drainage and wastewater conveyance system hydraulics. The criteria should be set such that when the calibration and validation results meet the criteria, the team can assume the model is sufficiently accurate to support project goals (e.g. design pump station improvements to reduce flooding).

If the model validation simulation results do not adequately match the validation data set, the modeler should carefully examine the model input and output data. This examination may clarify the probable cause of the discrepancies (e.g. not enough direct inflow, rainfall timing does not match flood timing, or the storm cells that produce the validation flow did not pass over the rain gauge used by validation simulation run, etc.). If the model is not sufficiently robust, model calibration should be revisited. After adjusting the model calibration, model validation should be performed again with a different validation data set.

7.9.4 Flow Estimation in Absence of Flow Monitoring Data

The project team can estimate the range of peak flows in a project area by using the results of nearby studies, back-of-the-envelope calculations, or general rules of thumb. Developing a quick flow estimate is an appropriate first step in the modeling process for many reasons. For example, during the initial stages of project planning, an order of magnitude estimate of a drainage problem or capital investment project are needed, or the project schedule may not allow time for flow monitoring and model calibration and validation.

The following are examples of estimating local flows using available historical flow information.

- The modeling results from a similar, nearby basin could be used to estimate flows in the project area. For example, if estimated peak I/I flows for a variety of flow recurrence intervals (peak five-year flow, 10-year flow, 20-year flow) is available from a previous study, the modeler could convert those I/I flows into unit rates, such as gallons per acre per day (gpad), and apply those unit rates to the project area.
- Anecdotal information or historical operational data, such as those described in DSG section ***7.9.1*** could be used to help develop a quick model calibration. This would involve calibrating to a single event.
- Statistical analysis of long-term operational data measured in a nearby portion of the drainage and wastewater system can be used to estimate flow. For example, pump station runtime data could be used to develop approximate flow estimates over a wide range of conditions in the absence of more accurate flow data. These flow estimates could be converted into unit I/I rates for the project area.
- If an upper bound on the potential flow rates is sufficient for the project, the project team could perform simple runoff calculations (e.g. the rational method) to estimate the maximum amount of water that could enter the conveyance system.

The project team could expand or modify the examples provided above to meet the needs of a specific project. When estimating flows without the benefit of local flow monitoring data, the team should consult SPU staff experienced with H/H in the project area.

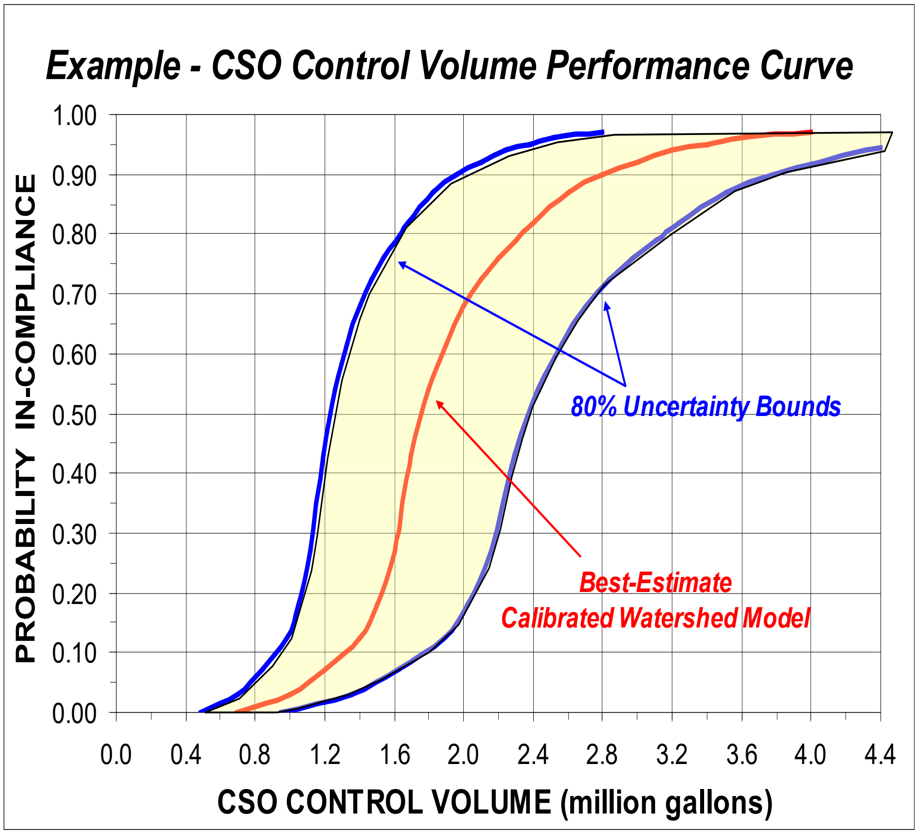
7.10 UNCERTAINTY/LEVEL OF ACCURACY

SPU has developed a risk-based approach to estimating CSO control volumes. The risk-based approach uses multiple calibrations and simulations to estimate the potential spread—or level of uncertainty—associated with CSO control volume modeling. The purpose of the risk-based analysis is to provide SPU decision makers with a way to assess risk and consequences when sizing CSO control facilities. The risk-based approach is designed to provide the information necessary to help balance the cost of over-performance against the risk of underperformance of CSO control facilities.

Figure 7-10 illustrates the relationship between compliance and level of confidence in modeling results. The curve shows the likelihood a specific CSO control volume would meet the NPDES permit requirement of one untreated overflow per year over a 20-year running average. The spread in the CSO control volumes indicates the level of uncertainty associated with the model outputs.

For example, **Figure 7-10** shows a model where the best-estimate calibration suggests that a CSO control volume of 2 million gallons would meet the permit requirements 70% of the time. Other calibration-simulation curves show CSO control volumes higher or lower than the best-estimate calibration value. Statistical analysis of the other calibration-simulation results generates uncertainty bounds (confidence levels) for other CSO control volumes. The example shows CSO control volumes of 1.4 million gallons and 2.8 million gallons at the lower and upper range of the 80% uncertainty bounds at a 70% compliance level.

Figure 7-10
Example of Risk-Based CSO Volume Curves



Acronyms and Abbreviations
CSO: combined sewer overflow

Several factors should be considered when using a risk-based methodology:

- The approach has only been applied to the combined sewer system, although the basic philosophy would apply to modeling other types of systems.
- The analyses performed to date focus on CSO control volumes. These volumes do not precisely correspond to the size of CSO storage facilities required by SPU's NPDES

permit. Other issues, such as allowable discharge rates to the downstream system, the timing of sequential rainfall events together with the time required for storage volume recovery so that Control Volume performance can be maintained without adversely affecting the upstream system (i.e. design volume vs Control Volume), will affect facility sizing.

- The approach could become substantially more complex when applied to combination of CSO control strategies, such as storage, diverting flows, and demand management (e.g. flood prevention).

At the beginning of a project, the project team should assess the feasibility of the risk-based approach, the potential benefits, and cost and schedule impacts. Larger, more sensitive projects are more likely to benefit from this approach. Smaller, more straightforward projects would not.

For estimating CSO control volumes, see the CSO Technical Guidance Manual in **Appendix 7E - CSO Technical Guidance Manual**.

7.11 CAPACITY ASSESSMENT AND ALTERNATIVES ANALYSIS

This section describes approaches for conducting capacity assessments and alternatives analyses for SPU drainage and wastewater infrastructure. SPU does drainage and wastewater capacity assessments and alternatives analyses for several purposes:

1. Private development. For some large developments, SPU may require a developer to assess the project's downstream impacts and build capacity improvements to offset them.
2. CIP planning. Capacity assessments and alternatives analyses are performed when developing basin plans and planning facility improvements to improve SPU levels of service.
3. Assessments and analyses to support City departments (e.g. Seattle Department of Construction and Inspection (SDCI)) and SPU work groups (e.g. Development Services Office (DSO) of Project Delivery & Engineering Branch (PDEB).

7.11.1 Existing System Capacity Assessment Elements

Capacity assessments should involve the following calculations:

- An estimate of stormwater and/or wastewater flows in the project area. Flow projections should be computed for the SPU level of service in the area and not just for base-flow or low-flow conditions.
- An estimate of the capacity of each conveyance element in the project area and sufficiently far enough downstream.

- A comparison of flow projections and conveyance capacities. Whatever method of comparison (e.g. sophisticated hydraulic model; pipe-by-pipe Manning's capacity calculation), the comparison should identify the conveyance elements with insufficient capacity.
- An alternative analysis that identifies specific facility improvements and/or flow reduction methods that eliminate the problems noted in the items above.

SPU does not have a standard for *at capacity* for its piped conveyance system. SPU will permit surcharging in deep conveyance pipes but not in shallow cover conveyance pipes due to the risk of side sewer backups and surface flooding. Refer to *DSG Chapter 8, Drainage and Wastewater Infrastructure.*

7.11.2 Capacity Assessments for Capital Improvement Program Projects

Capacity assessments for SPU CIP projects will usually occur in areas with known drainage and wastewater capacity problems. These problems could include excessive maintenance hole surcharging, excessive CSO frequency, or similar problems. At a minimum, the goal of the capacity assessment should be to determine the location of the capacity problem, the frequency and magnitude of the problem, the underlying cause or causes of the capacity problem, and to test alternative strategies to improve drainage and wastewater service levels.

The methodology described in this DSG should be used to develop a drainage and wastewater system model to evaluate system capacity conditions (e.g. identify specific infrastructure that result in overflows or surcharges). The following lists basic steps for conducting a capacity assessment:

1. Complete the model. The modeling plan should outline the level of detail and accuracy of the model that is necessary for a particular project (e.g. fully calibrated and validated model; simple and uncalibrated model).
2. Determine the desired level of service to test the conveyance pipe network, creek, or other conveyance assets in the model. As described in DSG section ***7.11.1***, SPU does not have a standard for *at capacity* for its piped conveyance system. Thus, the desired level of service is determined by system needs, whether any critical pipe section surcharges more than 1 feet above crown of pipe, and/or whether the system overall can achieve a specific level of service.
3. Develop time series of input flows to test for the level of service. These time series can either be generated by hydrologic models, externally provided inflow, or both. These time series should include flows up to and exceeding the level of service design flow rate. Long continuous time series are preferred when they are available. These time series should be results from continuous simulations with inflows generated by hydrologic models that are based on actual, historical precipitation data. This helps to provide system response simulation results that are based upon more realistic range of storm types, intensities, and durations, which will facilitate a more realistic estimate of the actual performance of the physical system.
4. Run the model and evaluate the results. The model outputs should be summarized graphically as much as possible (see DSG section ***7.11.2.1***). Plan view and profile plots are effective tools that illustrate key results.

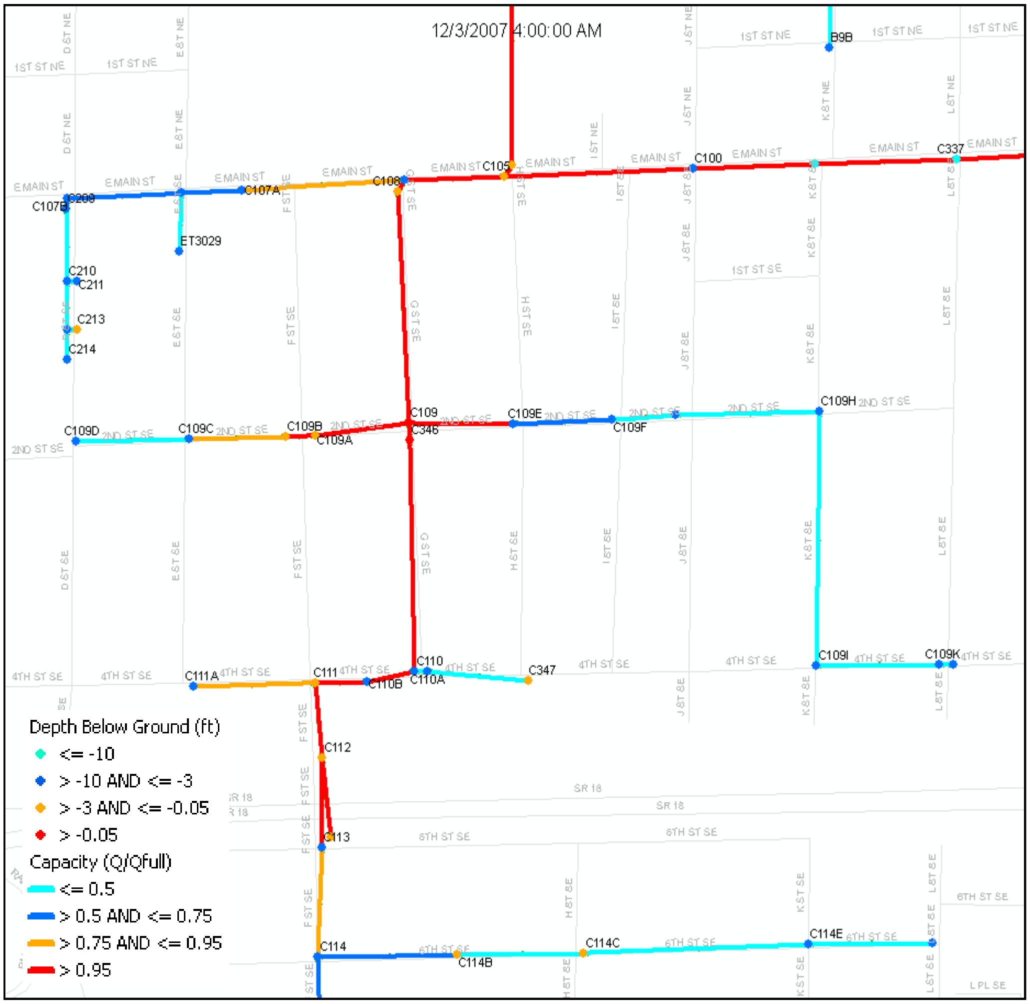
5. Generate statistical summaries that characterize the frequency and magnitude of the observed capacity problems (e.g. frequency of side sewer backups, how often does a flood occur at a specific location; what is the five-year overflow volume at a creek culvert/bridge, etc.) and compare with simulation results from proposed alternatives to evaluate the effectiveness of alternatives in improving drainage and/or wastewater system performance.

7.11.2.1 Methods for Characterizing Capacity Assessment Results

The modeling team should develop graphics that summarize the locations of capacity problems and illustrate the relative severity of these capacity problems. For example, **Figure 7-11** shows the simulated surcharge level in a stormwater conveyance system.

In this example, the pipes and maintenance holes are color coded to illustrate the maximum water surface level during the large storm event in December 2007. The red pipes flowed more than 95% full, the yellow pipes flowed between 75 and 95% full, and the blue pipes flowed 75% full or less. Dark blue, yellow, and red colored maintenance holes experienced varying levels of surcharging. Red maintenance holes show the locations of street-level overflows. This plan view summary of the capacity assessment results communicates valuable information clearly. Most hydraulic modeling software produce plan view capacity results. Software packages with GIS linkages or import/export capabilities facilitate the inclusion of other types of information including street names and locations of critical facilities (e.g. hospitals, evacuation routes) that provide additional context to the capacity assessment.

Figure 7-11
Plan View: Capacity Assessment Simulation Results

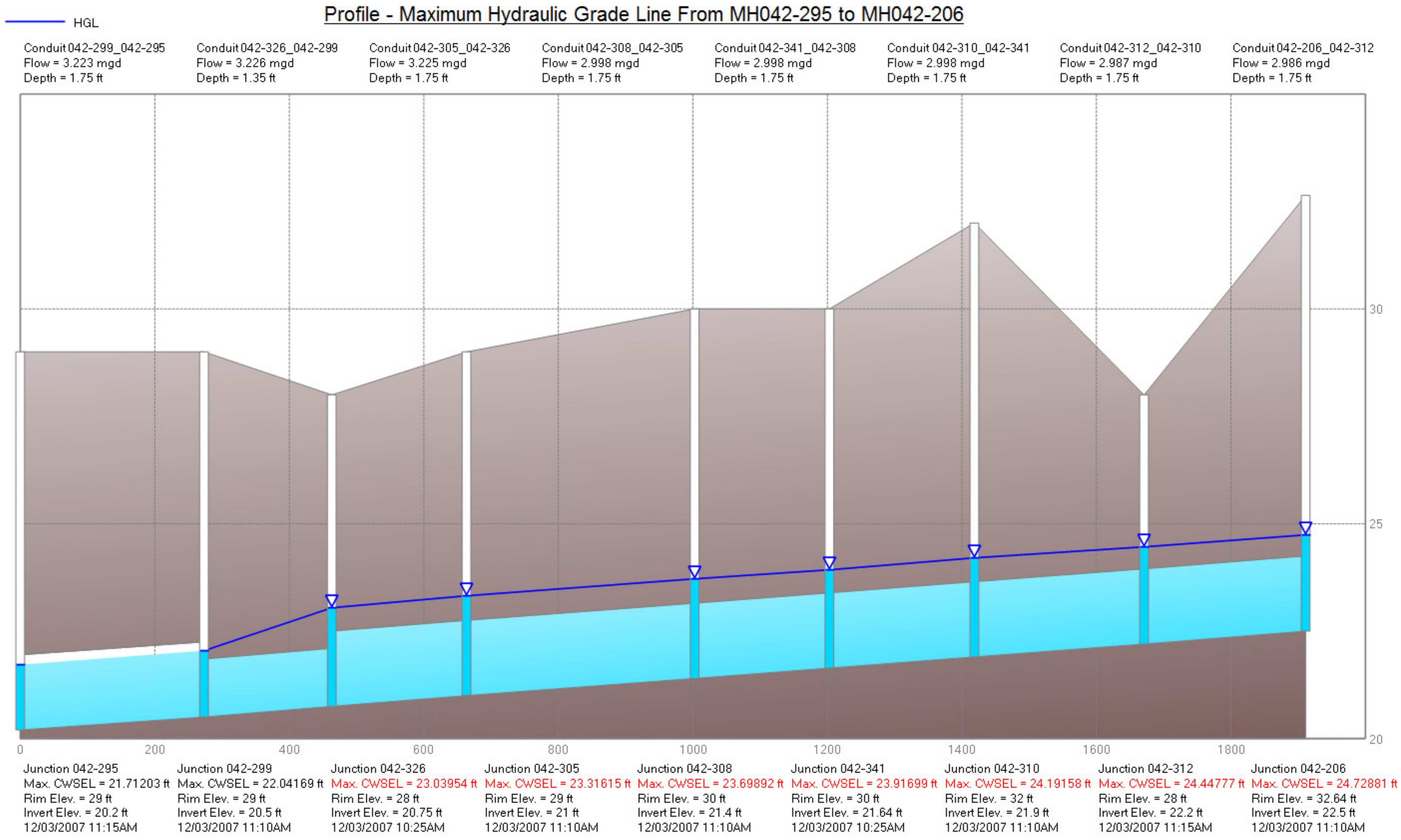


After identifying the locations of capacity problems, the modeler should produce supplemental graphics that focus on these areas to aid in determining the underlying cause of the problem. For example, a Profile Plot can illustrate common causes of flooding such as:

- Decreasing flow capacities (e.g. smaller or flatter pipes) in the downstream piping.
- Hydraulic restrictions due to special structures, such as gates and weirs.
- Large flows joining the system without a corresponding increase in conveyance capacity.
- Local low spots that only allow for shallow bury pipes.

Figure 7-12 is a Profile Plot showing the pipe diameters, hydraulic grade line, and ground surface elevations of a pipe network. Note that the surcharge level is modest through the pipe. For this case, the H/H model results shown on a profile plot, identifies that flooding is attributed to a shallow pipe in a localized low spot.

Figure 7-12
Profile View: Capacity Assessment Simulation

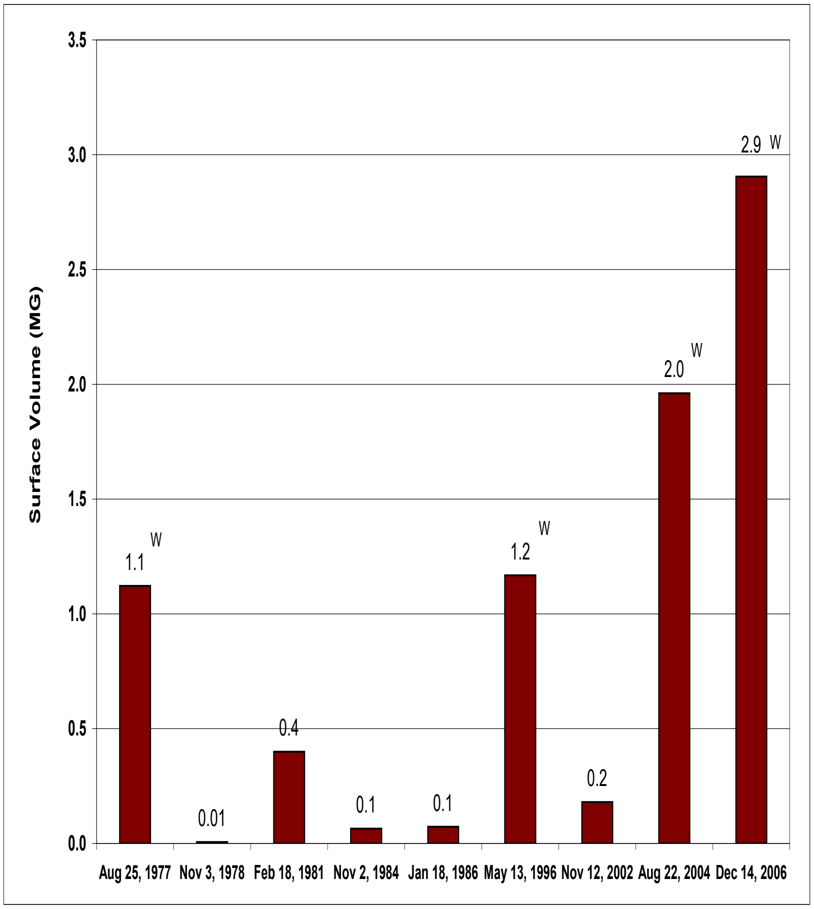


Hydraulic software packages that are used to evaluate natural drainage systems, such as HEC-RAS, can also produce Profile Plots. Floodplain analysis tools, such as HEC-GeoRAS, can extend the water surface profile simulations across the flood plain to map inundation for various storm magnitudes.

Model simulation results for large areas can be reported for a single time step or for worst-case conditions as depicted in the preceding graphics. Equally useful graphics depict hydraulic conditions or facility operations for specific locations over a long duration. For example, **Figure 7-13** depicts the frequency and magnitude of simulated overflows at a particular location over a 30-year simulation period. From this analysis, the size of flood controls required to meet specific service levels at this location can be assessed. This type of graphic effectively communicates capacity assessment results.

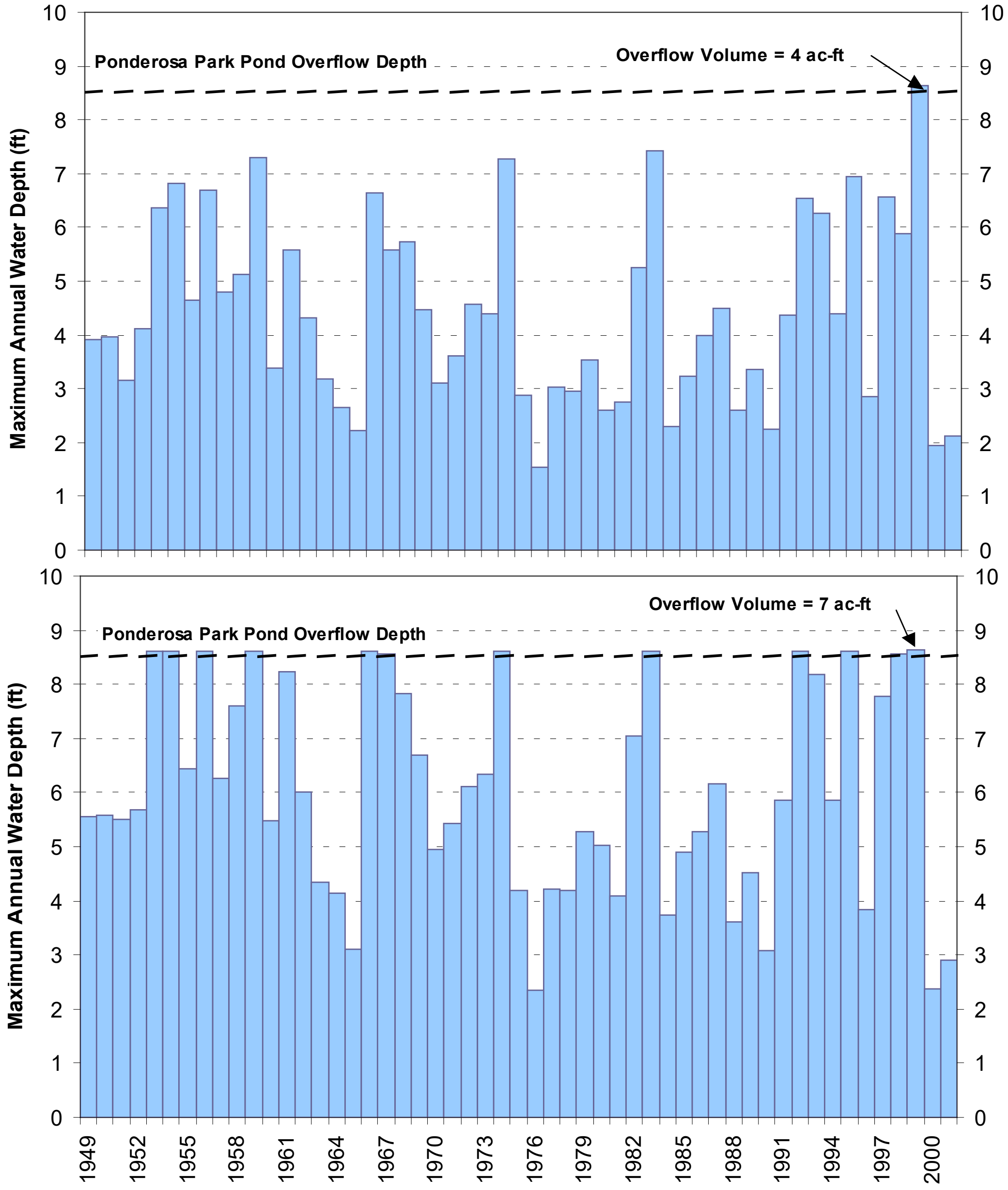
Figure 7-14 shows the maximum detention pond depth for each year in a 50-year continuous simulation for existing and future development levels. The type of “before and after” comparative graphics effectively summarize the capacity implications of land use changes.

Figure 7-13
Long-Term Continuous Simulation Overflow Occurrences and Volumes



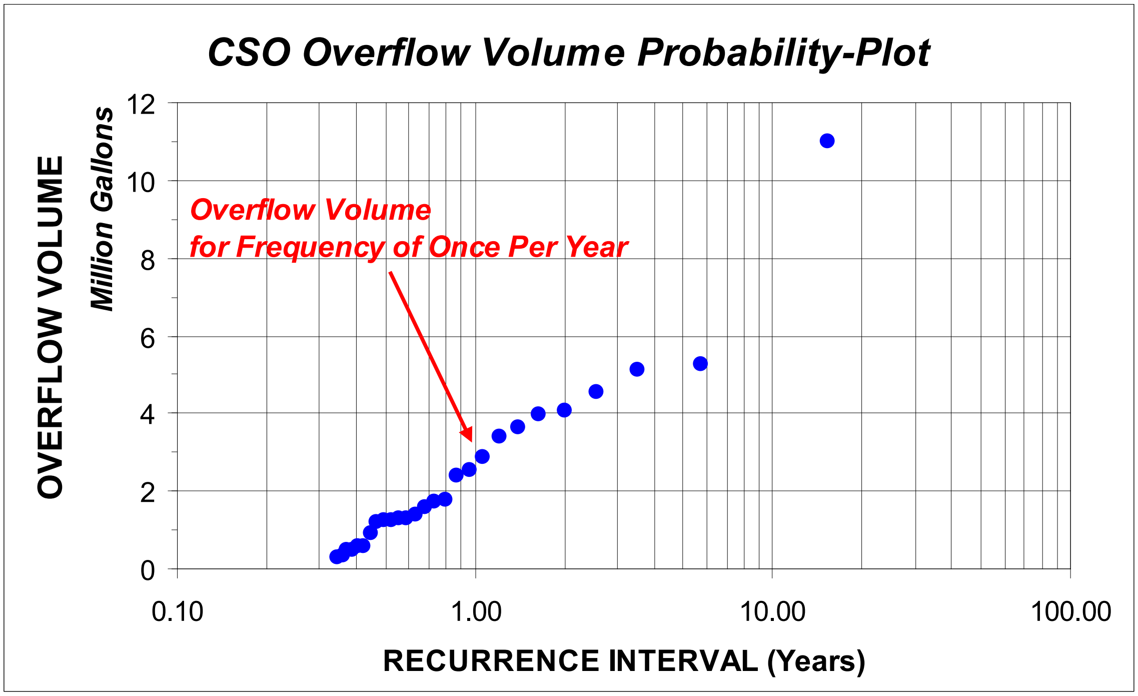
Acronyms and Abbreviations
MG: million gallons

Figure 7-14
Simulated Maximum Annual Detention Pond Depth for Existing and Future Land Use



The peak flow and/or overflow volume frequency and magnitude from long-term simulations can be summarized using statistical methods that estimate the recurrence interval for specific events in a continuous model output time series (**Figure 7-15**). By matching the peak flow and/or overflow volume to SPU's level of service for a particular drainage and wastewater infrastructure component, the appropriate design flow or overflow control volume can be estimated and solutions can be developed.

Figure 7-15
Frequency-Volume Distribution of CSO Events



The modeling team should produce peak flow or overflow volume versus recurrence interval curves as follows:

1. Parse the long-term model simulation output time series into a group of discrete events (e.g. peak flow and/or overflow volume), using either the peak annual series or the partial duration series.
2. Compute the plotting position for each event in the series. This will generate a recurrence interval for each event (e.g. largest event = 35-year recurrence; second largest event = 14-year recurrence). Results from several plotting position formulas that minimize bias (e.g. Gringorten, Blom) should be compared to obtain the best estimate of the recurrent interval of each event.
3. Plot and fit peak flows or overflow volumes against theoretical distributions (e.g. Log Pearson Type III or Extreme Value Type I (Gumbel)) to extend the series to estimate the series at the desired recurrent intervals or level of service, if the recurrent intervals from numbers 1 and 2 above do not cover the desired recurrent intervals or level of service.

7.11.3 Options Analysis

The capacity assessment should identify areas that do not meet the required level of service. After identifying the problem locations, modeling results should be reviewed to assess the underlying causes of the capacity constraints, if possible. Alternative strategies to eliminate the conveyance problems should be developed. Potential solutions often fall into these general categories:

1. Conveyance Improvements: Installing larger conveyance or parallel conveyance infrastructure

2. Flows Attenuation: Installing detention or storage to reduce peak flows until the downstream system has available capacity
3. Demand Management: Reduce flows to key facilities by installing flow diversions or reducing the amount of runoff and/or inflow and/or infiltration (e.g. via GSI projects).

When developing a model for Options Analysis, the rehabilitated or new facilities under consideration should be represented as closely as possible within the model. For example, a storage facility should be represented with explicit outlet structures with the logic that simulates when the tank is allowed to drain. Including an appropriate level of detail will provide the team with means to evaluate and refine operational alternatives that optimize system operations. Examples of such options include minor adjustments to storage facility operations to manage release rates to the downstream system or evaluating the feasibility of installing a larger pipe to address both current and future capacity constraints resulting from anticipated future growth. For GSI alternatives, refer to DSG section ***7.12*** for evaluation.

Continuous long-term simulations are advantageous when evaluating complex options, because such simulations track the performance of alternative options in storms of various intensities and durations with different inter-storm periods. Assessment of this performance is critical to simulate the effect of long-duration winter storms typical in the City. If the runtime of a long-term simulation is too long, the modeling team should consider creating synthetic input time series that condenses the long-term time series by removing the parts of the time series that are insignificant to the long-term simulations (e.g. low-flow conditions). For example, a synthetic inflow file can be condensed to only contain flow time series resulting from large storms (e.g. storms surpassing a three-month threshold) and sufficient inter-storm periods (i.e., non-flood or CSO generating flows) to allow the system to reset. In the process of condensing time series, the critical antecedent conditions for water quality projects must be maintained.

7.11.4 Characterizing Future Conditions

The future performance of a DWW system is largely related to the change in flow demands and condition of the conveyance infrastructure (or natural system) over time. Future conditions are usually evaluated over a specific horizon, such as 20 years for comprehensive planning or 50 plus years to reflect the useful life of new infrastructure. The following items are most likely to change over a planning period:

- **Flow Projections:** Base flows and storm flows could change over the planning horizon as a result of new development, densification of urban areas, and climate change. These changes add new wastewater customers and impervious areas that affect site runoff. Climate change affect the intensity, frequency and/or volume of rainfall events which impact surface runoff and groundwater infiltration. The model should include population and development forecasts, and synthetic rainfall time series that assess the effect of climate change. They should also consider how revisions to the City of Seattle Stormwater Manual could affect total runoff and groundwater infiltration.
- **Infrastructure Condition:** Sanitary and combined sewer infrastructure generally degrades over time and allows larger quantities of I/I to enter the system. These impacts may be counteracted with an aggressive sewer inspection and rehabilitation program. Some municipalities assume a 7% increase in I/I flow per decade. Others assume no I/I increase while committing to maintain the quality of conveyance infrastructure. The

change in future performance of conveyance elements in natural systems are more difficult to quantify. However, for creek systems, the project team could assess whether a stream reach is aggrading or degrading when assessing the future probability of flooding.

- **Capital Improvement Projects:** The existing conditions model can be updated to incorporate any future infrastructure upgrades. The preferred alternative model created during the alternatives analysis for future condition analysis should include the preferred capital improvement scenario. When evaluating the impacts of capital improvements on future conditions, the project team should be mindful of any planned upgrades outside of the immediate project area that could influence the project area (e.g. removing downstream bottlenecks to lower model boundary conditions; removing upstream bottlenecks to increase inflows to the model, etc.).
- **Programmatic Efforts:** Future flow projections should incorporate the expected results of any programmatic initiatives at SPU. The increased use of low-flow water fixtures and efforts to reduce water consumption could reduce per capita wastewater generation. Low-impact landscaping methods, downspout disconnection, infiltration galleries, permeable pavement, bioretention, rain gardens, rain barrels, and other green stormwater infrastructures have the potential to reduce the effective imperviousness of the City's urban watersheds.
- **Changes in Service Area:** The SPU drainage and wastewater systems are largely built out. Only small pockets of unsewered area remain within the City limits. Any changes to the SPU service area are likely to occur for one of the following reasons:
  - A redevelopment project results in a change to the location of flow discharge from the project site (i.e., site flow discharges to a different pipe).
  - Annexation areas are added to the City.

Redevelopment projects that modify the site discharge location can be easily incorporated into an existing model by adjusting the DWW system network model. Any changes in the network should also be reported to SPU GIS so that the appropriate drainage and wastewater databases are updated. Increases in sanitary flow from densification redevelopment, land use changes and residential and commercial population increases should be estimated and included in the model.

Annexation areas are more complex to evaluate. When a potential annexation is under consideration, SPU engineering staff may be asked to assess the potential impacts of extending drainage and wastewater services into the annexation area. Providing service into a new area can potentially have dual impacts: 1) contributions from the annexation area could stress the capacity of existing infrastructure and 2) the City could be required to upgrade annexation area infrastructure to meet the City's level of service guidelines.

The contributions from the potential annexation area should be computed by using the base flow and I/I flow projection methods for sewer flows and/or hydrologic methods for drainage flows. In many cases, a modeling team can estimate contributions from a potential annexation area without creating a detailed model of the conveyance network. Computing flows basin-by-basin is usually sufficient. These new inflow sources should be incorporated into the existing City system-wide model to assess specific capacity impacts, if any.

Assessing the level of service provided by existing facilities in a potential annexation area is more complex. This effort would usually require compilation of a full infrastructure data inventory and any flow monitoring and/or operations records, and the subsequent construction of an H/H model. The project team would need to determine whether the existing information is sufficient for model calibration and validation, and for performing capacity assessments. The process could involve additional data collection.

7.12 GREEN STORMWATER INFRASTRUCTURE MODELING

GSI projects use small and distributed stormwater management practices to control flow into drainage or combined sewer systems and improve stormwater quality. Initial modeling setup and calibration are anticipated to follow the procedures identified within this manual. Modeling methods and procedures for evaluating impacts of GSI best management practices (BMPs) within CIP project alternatives evaluation require focused procedures for GSI elements because:

- GSI projects are comprised of numerous facilities distributed across a basin rather than centralized facilities (such as storage facilities).
- Modeling approaches must be able to simulate the natural physical processes (e.g. filtration, infiltration) of GSI practices.

For information on GSI modeling, refer to GSI Modeling Methods guidelines in **Appendix 7H - GSI Modeling Methods**.

7.13 CLIMATE CHANGE

The modeling team must consult with the DWW LOB representative and Modeling & GIS section to develop an approach for assessing climate change.

For more information on sea level rise due to climate change, refer to Appendix F Hydrologic Analysis and Design of City of Seattle Stormwater Manual.

7.14 RESOURCES

Documents

- MGS Engineering Services, Inc. (2004). Description of SPU’s Precipitation Measurement and Data Collection System (Technical Memorandum)
- SPU’s Sewer and Drainage GIS Physical Database Design (version October 25, 2000)
- Wastewater Planning Users Group (WaPUG). Code of Practice for the Hydraulic Modeling of Sewer Systems. United Kingdom, 2002. www.wapug.org.uk
- Washington State Department of Ecology. Criteria for Sewage Works Design, 2008

- American Society of Civil Engineers. Gravity Sanitary Sewer Design and Construction. ASCE Manuals and Reports on Engineering Practice No. 60. ASCE, 1982.
- Merrill, S., Lukas, A, et al. Reducing Peak Rainfall-Derived Infiltration/Inflow Rates – Case Studies and Protocol (WERF 99-WWF-8). Water Environment Research Foundation, 1999.
- Rawls, W. J., Brakensiek, D. L., and Miller, N., Journal of Hydraulic Engineering, ASCE Volume 109, No. 1, 1983

Bibliography

MGS Engineering Consultants, Inc. "UPDATE OF 2003 PRECIPITATION-FREQUENCY STUDY FOR THE CITY OF SEATTLE." Seattle, 15 January 2013. Technical Memorandum.

—. "UPDATE OF PRECIPITATION-FREQUENCY INFORMATION FOR THE CITY OF SEATTLE." 31 January 2021. Technical Memorandum.

Mitchell, Paul S, Patrick L Stevens and Adam Nazaroff. "Quantifying Base Infiltration in Sewers - A Comparison of Methods and a Simple Empirical Solution." n.d. *ADS.* Portable Document File. 17 February 2023. <https://www.adsenv.com/sites/default/files/whitepapers/wef_determining%20base%20infiltration%20in%20sewers%20wef%20coll%202007final.pdf>.

U.S. Environmental Protection Agency - Office of Research and Development, Office of Water. "Onsite Wastewater Treatment Systems Manual." February 2002. *U.S. Environmental Protection Agency.* Portable File Document. 17 February 2023. <https://www.epa.gov/sites/default/files/2015-06/documents/2004_07_07_septics_septic_2002_osdm_all.pdf>.

Websites

- SPU GIS
- SPU Vault
- City of Seattle Stormwater Manual
- SPU CSO Program
- King County Wastewater Treatment Division
- NOAA National Weather Service Forecast Office
- WSU AgWeatherNet

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