Environmental Technology Verification Report

Evaluation of the XP-SWMM Stormwater Wastewater Management Model, Version 8.2, 2000, from XP Software, Inc.

Prepared by

NSF.

NSF International

Under a Cooperative Agreement with
EPA U.S. Environmental Protection Agency

ETV ETV ETV

**THE ENVIRONMENTAL TECHNOLOGY VERIFICATION
PROGRAM**

**U.S. Environmental
Protection Agency**

NSF International

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**STORMWATER WASTEWATER MANAGEMENT MODEL**
APPLICATION:	**WET WEATHER URBAN RUNOFF MODELING**
TECHNOLOGY NAME:	**XP-SWMM STORMWATER WASTEWATER MANAGEMENT MODEL, VERSION 8.2, 2000**
COMPANY:	**XP SOFTWARE, INC.**

ADDRESS:	**2000 42nd AVE., SUITE 214**	**PHONE:**	**(888) 554-5022**
	PORTLAND, OR 97213	**FAX:**	**(888) 554-5122**

WEB SITE:	**http://www.xpsoftware.com**
EMAIL:	**sales@xpsoftware.com**

NSF International (NSF), in cooperation with the U.S. Environmental Protection Agency (EPA), operates the Water Quality Protection Center under EPA's Environmental Technology Verification (ETV) Program. As part of the Center's activities in verifying the performance of wet weather flow technologies, NSF evaluated the performance of the XP-SWMM Stormwater Wastewater Management Model, Version 8.2, 2000 (XP-SWMM). This verification statement provides a summary of the test results for the XP-SWMM. Crawford Engineering Associates (CEA) performed the verification test under contract with NSF.

EPA created the ETV Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer-reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with testing organizations and stakeholder advisory groups consisting of buyers, vendor organizations, and permitters, and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of the stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance/quality control (QA/QC) protocols to ensure that data of known and adequate quality are generated, and that the results are defensible.

TECHNOLOGY DESCRIPTION

The following technology description is provided by the vendor and does not represent verified information.

XP-SWMM is a commercial software package used throughout the United States and around the world for simulation of storm, sanitary and combined sewer systems. It was designed based on the EPA Storm Water Management Model (EPA SWMM), but has enhancements and additional algorithms for the analysis of urban runoff and drainage. Simulation models like XP-SWMM are used for planning new systems, extending existing systems to accommodate growth, and to mitigate undesirable overflows and adverse water quality impacts. Models are also used for the study and design of wet weather facilities, including the sizing of conveyance systems, storage facilities, pump stations and treatment plants. In practice, the model selected to perform an evaluation is often chosen with little understanding of the background processes involved in producing rainfall-runoff responses or conveyance through a collection system.

XP-SWMM is a collection of computer programs that simulate rainfall-runoff processes in urban watersheds in addition to the transport of the runoff through pipes and channels. The programs are referenced by a graphical user interface (GUI) that assists the user in visualizing the system, in adding data needed to perform the simulation, and in extracting and plotting model results. The GUI assists the user to understand the processes and determine the data necessary for adequately simulating system responses. Prior to using XP-SWMM, however, model users should be familiar with basic hydrologic and hydraulic concepts such as: infiltration; conveyance of flow through pipes and channels, including open channel flow; and flow under backwater conditions.

The XP-SWMM GUI creates a 'card-image' data file that is read by a FORTRAN program that is called by XP-SWMM. The FORTRAN program (and additional subprograms that are called when referenced) performs the required analyses and produces results that are stored in text and binary output files. Additional programs called by the XP-SWMM GUI read binary output result files.

The program has many subprograms. They can be grouped into four main categories:

- UTILITIES for processing data and performing statistical analyses (such as long period rainfall event analysis)
- RUNOFF for determining flow generated from rainfall in a defined watershed or catchment. RUNOFF can use user-selected rainfall-runoff algorithms including EPA SWMM Runoff, Santa Barbara Urban Hydrograph, Soil Conservation Service (SCS) Hydrology, and the rational formula. RUNOFF also performs water quality modeling based on land-use and pollutant build-up/wash-off techniques
- SANITARY for performing collection system routing using kinematic wave routing methods
- HYDRAULIC for performing collection system routing using techniques that solve the St. Venant equations for flow continuity and momentum.

The four main categories can be linked, but RUNOFF and HYDRAULIC are the two primary categories used in most modeling studies. Each of these categories has many components, not all of which were tested in this study. The components tested during the ETV evaluation are believed to be the most commonly used components in urban modeling.

PERFORMANCE VERIFICATION

Testing of the XP-SWMM software was conducted from May through July 2002 at the offices of CEA.

In order to verify the performance of XP-SWMM in real world conditions, the software was applied to real systems and monitored data. This verification method provided insight into how the model supports the user, simulates conditions, and presents the results to the user. Since applying software to real-world situations is subject to a variety of calibration and validation parameters and a certain degree of uncertainty, this testing methodology was not intended to calibrate model parameters.

The goals of the verification were to:

- Identify components of the model (XP-SWMM);
- Review key algorithms to insure they are implemented correctly in XP-SWMM; and
- Compare the model results with off-line calculations, where applicable/possible.

RESULTS

Evaluation of the XP-SWMM components provided insight into the interaction of many 'basic' functions commonly used in building models of actual systems. Examples of basic functions include the WIDTH parameter, used in RUNOFF to determine flow rates from a watershed, and infiltration simulations. Relationships between these types of functions are generally not transparent or even recognized by many potential modelers or users of models. Some of these interrelationships were revealed and highlighted during the testing of XP-SWMM to enhance user confidence in the model.

The results from the testing conducted on the model components were comparable overall to results achieved with off-line calculations. In many instances, the model results were identical to the off-line results, as depicted in Table 1. For the model components listed in Table 1, the values in the column titled "% Comparison" reflect the degree of similarity between the results obtained from the model simulations compared to those obtained through off-line calculations. The model's performance for a particular function may or may not be appropriate given that each function is different and has a different level of inherent uncertainty as a calculation or process.

Table 1. Summary of XP-SWMM Testing

Module	Component	Process	% Comparison	Notes
RUNOFF	Rainfall	Event	100	
		Interface	>99	Small rounding errors encountered.
		Continuous	100	Raw data check recommended to ensure no deviant data values.
		Standard format	99	Standard formats are most likely changed by collecting agencies.
		Statistics	100	
	Infiltration	Horton	No value	Horton equation represented appropriately. However, infiltration and excess rainfall were influenced by value used for WIDTH parameter.
		Green-Ampt	>99	Green-Ampt equation represented appropriately. WIDTH parameter not an issue with Green-Ampt.
	Runoff	Runoff	90	Clarification on how the WIDTH parameter affects runoff volume for pervious areas is needed.
		SBUH	95	Within expected modeling technique variation.
		SCS	95	Within expected modeling technique variation.
		Calibrated model	95	Monitored results duplicated when model parameters selected with care and with proper basin definition.
HYDRAULIC - nodes	Node inflows	Diurnal pattern	99	Minor time shift (one hour).
		Gauged inflow	95	Generally appropriate but possible misrepresentation may impact some simulations.
		Interface	100	
	Node loss coefficients	Minor loss simulations	90	Calculated head loss greater than simulated values.
	Storage node	Constant area	98	Water levels predicted are dependent on volume used in upstream and downstream links.
		Depth-area	95	Time step for reporting flow results has a significant impact on spreadsheet accuracy.
		Power function	95	
	Node inlet capacity	Maximum value	99	
		Rating curve	99	
	Node control	Flooding allowed	99	
		Sealed	100	

Module	Component	Process	% Comparison	Notes
		Surface ponding	99	
	Outlet control	Free outfall	100	
		Fixed backwater	95	
		Tidal changes	90	Generation of tidal values not working in program.
		Variable water level	95	
HYDRAULIC - links	Manning's Roughness	Manning's Equation	100	
	Pressure and open channel flow	St. Venant's Equation	95-100	
	Flow direction	Upstream, downstream and free flow	100	
	Flow routing for conduit shapes	Basic and user-defined shapes	90	Misreporting of some maximums for some shapes.
	Gauged flow for calibration plots	Input of external data for comparison of results.	95	
HYDRAULIC - special links	Multiple conduits	Parallel pipes	95	
	Pump simulations	Type 1	Not tested	Not recommended. Use Type 4.
		Type 2	Not tested	Not recommended. Use Type 4.
		Type 3	100	
		Type 4	100	
		Type 5	No value	Use with caution.
	Weir simulations	Side weir	98	
		Transverse weir	99	
	Orifice simulations	Bottom orifice	98	
		Side orifice	98	

QUALITY ASSURANCE / QUALITY CONTROL (QA/QC)

During completion of this verification, CEA personnel duplicated program calculations by hand calculations, checked or duplicated data entry into the model to ensure the model data correctly compared to data used in hand calculations, and checked or duplicated entered data and calculations used in spreadsheets (e.g. checked fields referenced in formulas).

Original signed by		*Original signed by*	
Sally Gutierrez	*9/2/05*	*Thomas G. Stevens*	*9/7/05*
Sally Gutierrez	Date	Thomas G. Stevens, P.E.	Date
Acting Director		Program Manager	
National Risk Management Research Laboratory		ETV Water Quality Protection Center	
Office of Research and Development		NSF International	
United States Environmental Protection Agency			

NOTICE: Verifications are based on an evaluation of technology performance under specific, predetermined criteria and the appropriate quality assurance procedures. EPA and NSF make no expressed or implied warranties as to the performance of the technology and do not certify that a technology will always operate as verified. The end user is solely responsible for complying with any and all applicable federal, state, and local requirements. Mention of corporate names, trade names, or commercial products does not constitute endorsement or recommendation for use of specific products. This report in no way constitutes an NSF Certification of the specific product mentioned herein.

Availability of Supporting Documents

Copies of the *ETV Protocol for Verification Testing for Urban Runoff Models* dated October 2000, the verification statement, and the verification report are available from the following sources:

ETV Water Quality Protection Center Manager (order hard copy)
    NSF International
    P.O. Box 130140
    Ann Arbor, Michigan 48113-0140

NSF web site: http://www.nsf.org/etv (electronic copy)

EPA web site: http://www.epa.gov/etv (electronic copy)

(NOTE: Appendices are not included in the verification report. Appendices are available from NSF upon request.)

Environmental Technology Verification Report

Evaluation of XP-SWMM Stormwater Wastewater Management Model (Version 8.2, 2000)

Prepared for:
NSF International
Ann Arbor, MI 48105

Prepared by:
Crawford Engineering Associates
Portland, OR 97212

Under a cooperative agreement with the U.S. Environmental Protection Agency

Raymond Frederick, Project Officer
ETV Water Quality Protection Center
National Risk Management Research Laboratory
Water Supply and Water Resources Division
U.S. Environmental Protection Agency
Edison, New Jersey 08837

February 2005

Notice

The U.S. Environmental Protection Agency (EPA), through its Office of Research and Development, has financially supported and collaborated with NSF International (NSF) under a Cooperative Agreement. The Water Quality Protection Center, operating under the Environmental Technology Verification Program, supported this verification effort. This document has been peer-reviewed, reviewed by NSF and EPA, and is recommended for public release.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

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Acronyms and Abbreviations

ANSI   American National Standards Institute
ASQC   American Society for Quality Control
CANAES Canadian Environment Service
CEA   Crawford Engineering Associates
DQI   Data quality indicators
DQO   Data quality objectives
EPA   United States Environmental Protection Agency
ETV   Environmental Technology Verification
GUI   Graphical User Interface
HGL   Hydraulics gradient line
NSF   NSF International
NWS   National Weather Service
NRMRL National Risk Management Research Laboratory
ORD   Office of Research and Development, EPA
QA   Quality assurance
QAPP   Quality assurance project plan
QC   Quality control
SAG   Stakeholder Advisory Group
SBUH   Santa Barbara Urban Hydrograph
SCS   Soil Conservation Service
SOP   Standard operating procedure
TO   Testing organization
TMDL   Total Maximum Daily Load
VO   Verification Organization
VTP   Verification Test Plan
WQPC   Water Quality Protection Center
WWF   Wet Weather Flow

Acknowledgments

The testing organization, Crawford Engineering Associates, was responsible for many elements in the testing sequence, including creating the test plan, obtaining the XP-SWMM model from XP Software, data collection and analysis, data management, data interpretation and the preparation of this report.

The vendor of this software is:

Chapter 1
Introduction

1.1   ETV Purpose and Program Operation

The U.S. Environmental Protection Agency (EPA) created the Environmental Technology Verification (ETV) Program to accelerate the development and commercialization of improved environmental technologies through qualified third-party verification and performance reporting. The goal of the ETV Program is to verify performance characteristics of commercial-ready environmental technologies through the evaluation of objective and quality-assured data so that designers, potential buyers, and permitting authorities are provided with an independent and credible assessment of the technology they wish to use.

The ETV Program is made up of six centers, one of which is the Water Quality Protection Center (WQPC) that is administered by NSF International (NSF). The goal of the WQPC is to verify technologies that protect the quality of ground and surface waters by preventing or reducing contamination. The technologies evaluated by the WQPC are subdivided into several categories, among which is the verification of models that simulate urban runoff.

ETV works in partnership with recognized standards and testing organizations; stakeholder groups that consist of buyers, vendor organizations, consulting engineers, and regulators; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory (as appropriate) testing, collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

This verification report summarizes the results of the XP-SWMM Stormwater Wastewater Management Model, Version 8.2, 2000 (XP-SWMM), which was submitted to the ETV program for evaluation by XP Software, Inc. XP-SWMM is a commercial software package used throughout the United States and internationally to simulate storm, sanitary and combined sewer system conditions, and is similar to another model, EPA's SWMM.

Crawford Engineering Associates, Inc. (CEA) was selected as the testing organization (TO) to perform this evaluation.

Simulation models like XP-SWMM are used for planning new systems, extending existing systems to accommodate growth, or to assist in the control of undesirable overflows and adverse water quality impacts. Models are also used for the study and design of wet weather facilities, including sizing of conveyance systems, storage facilities, pump stations and treatment plants. In practice, the model selected to perform the evaluation is often chosen with little understanding of the background processes involved in producing rainfall-runoff responses or conveyance through a collection system.

1.2 Testing Participants and Responsibilities

1.2.1 U.S. Environmental Protection Agency

The EPA Office of Research and Development, through the Urban Watershed Branch, Water Supply and Water Resources Division, National Risk Management Research Laboratory (NRMRL), provides administrative, technical, and quality assurance guidance and oversight on all ETV WQPC activities.

The EPA's responsibilities with respect to verification testing include:

- Reviewing and approving the verification test plan (VTP);
- Performing quality assurance reviews of project data;
- Performing technical and quality assurance reviews of the verification statement and verification report
- Reviewing and approving the verification statement and verification report;
- Posting the verification report and statement on the EPA website; and
- Providing financial support for testing.

The key EPA contact for this program is:

Mr. Ray Frederick, WQPC Project Officer
Phone: (732) 321-6627
E-mail: frederick.ray@epa.gov

U,S, Environmental Protection Agency
Urban Watershed Management Branch
2890 Woodbridge Ave. (MS-104)
Edison, NJ 08837-3679

1.2.2 NSF International

The WQPC is administered through a cooperative agreement between EPA and NSF. NSF is the verification organization (VO) for the WQPC.

NSF's responsibilities as the VO include:

- Reviewing and approving the VTP;
- Overseeing quality assurance, including performing technical system and data quality audits, as prescribed in the WQPC Quality Management Plan;
- Coordinating verification report peer reviews;
- Finalizing the verification report and verification statement; and
- Preparing and disseminating the final verification report and verification statement.

Key contacts at NSF for the VO are:

> Mr. Thomas Stevens, Technical Manager
> Phone: (734) 769-5347
> E-mail: stevenst@nsf.org

> Ms. Maren Roush, Project Coordinator
> Phone: (734) 827-6821
> E-mail: mroush@nsf.org

> NSF International
> 789 North Dixboro Road
> Ann Arbor, Michigan 48105
> Phone: (734) 769-8010
> Website: http://www.nsf. org/etv

1.2.3   CEA

CEA was the TO for this verification and had primary responsibility for:

- Conducting testing in accordance with the approved VTP;
- Managing, evaluating, interpreting and reporting on data and information generated during the verification testing; and
- Preparing and reviewing the draft verification report, and addressing comments raised during review of the draft documents.

This evaluation and report was prepared by the following persons from CEA:

> David Crawford, P.E. – Project Manager, principal investigator and reviewer.
> Christine Held Crawford, P.Geol. – Data management, report preparation and auxiliary investigator.
> Phil Cheung, P.E. – Reviewer and auxiliary investigator.

The key contact for the TO is:

> David Crawford, P.E.,
> Phone: (503) 282-6831;
> E-mail: c.e.a@att.net

> Crawford Engineering Associates
> 3120 N.E. U.S. Grant Place
> Portland, Oregon 97212

1.2.4   Technology Vendor

The evaluated technology was XP-SWMM, developed by XP Software, Inc.

The vendor's specific responsibilities included:

- Applying for ETV testing;
- Providing partial funding for verification testing;
- Providing XP-SWMM to the TO;
- Providing descriptive details about the capabilities and intended function of the model;
- Reviewing and approving the VTP prior to the start of testing; and
- Reviewing and commenting on the draft verification report and draft verification statement.

The key contacts for the vendor are:

Mr. Geoff Thompson, President
Mr. Anthony Kuch, Technical Manager
Phone: (888)-554-5022

XP Software, Inc.
2000 42nd Ave., Suite 214
Portland, OR 97232

1.2.5 Technology Panel

The Wet Weather Models Technology Panel was instrumental in guiding the direction of the wet weather modeling technology area and developing a generic verification protocol for urban runoff models. The generic protocol served as the template for development of the VTP for XP-SWMM.

Representatives from the technology panel also assisted the TO in reviewing and commenting on the VTP during its development. Technical and professional support to the TO from the technology panel continued during all phases of the verification test period.

1.2.6 Stakeholder Advisory Group

The Wet Weather Flow Stakeholder Advisory Group was instrumental in approving the development of the *ETV Verification Protocol for Urban Runoff Models* that served as the basis for the development of the *ETV Test Plan for the Verification of the XP-SWMM Runoff Model* (Reference 11).

1.3 ETV Testing Location

The testing of the XP-SWMM software was performed at the CEA office in Portland, Oregon.

Chapter 2
Technology Description

The heart of the XP-SWMM model is a FORTRAN program that performs the required analyses and produces results that are stored in text and binary output files. There are additional programs that assist the user in visualizing the system, adding data needed to perform the simulation, and extracting and plotting model results. The graphical user interface (GUI) assists the user in determining the data necessary to adequately simulate the responses of the system, facilitating data input, and streamlining the data analysis processes. Before using XP-SWMM, the user should be familiar with basic hydrologic and hydraulic concepts, such as infiltration and conveyance of flow through pipes and channels, including open channel flow, and flow under backwater conditions.

XP-SWMM is based on the EPA Storm Water Management Model (EPA SWMM), but XP Software has added enhancements and additional algorithms for the analysis of urban runoff and drainage. The model has many subprograms that can be grouped into four main categories:

1. UTILITIES for processing data and performing statistical analysis (such as for long period rainfall event analysis).

2. RUNOFF for determining flow generated from rainfall in a defined watershed or catchment. RUNOFF can utilize user-selected rainfall-runoff algorithms, including EPA SWMM runoff (Reference 5), Santa Barbara Urban Hydrograph (Reference 12), Soil Conservation Service (SCS) Hydrology (Reference 1), and the Rational Method (Reference 1). RUNOFF also performs water quality modeling based on land-use and pollutant build-up/wash-off techniques.

3. SANITARY for performing collection system routing using Kinematic Wave routing methods.

4. HYDRAULIC for performing collection system routing using techniques that solve the complete St. Venant Equations (Reference 1) for flow continuity and momentum.

The four main categories can be linked, but RUNOFF and HYDRAULIC are the two main categories used in most modeling studies. Each of the categories has many components, not all of which were tested in this study. For example, the Rational Method was not tested, since an elaborate program such as XP-SWMM is not needed to produce results from this method; spreadsheets can be used to determine results for the Rational Method, which is approximate and ignores infiltration and many other hydrologic processes.

Prior to ETV participation, CEA used XP-SWMM in more than twenty municipalities to determine the effects of urban growth on runoff and flow generated due to land use changes. XP-SWMM has also been used to conduct studies for the control of sanitary sewer overflows (SSOs) and combined sewer overflows (CSOs), determination of flows and pollutant mass loadings in total maximum daily load (TMDL) studies, and in support of design for relief of flooding in storm and combined sewer collection systems. XP Software has announced that,

based on these capabilities, XP-SWMM has been approved by the Federal Emergency Management Agency (FEMA) for use in flood plain evaluations.

Chapter 3
Methods, Test Procedures and Results

3.1 Overview of test plan and procedures

Urban wet weather modeling requires the evaluation of storm water, sanitary, and combined sewer systems, which, in turn, require the evaluation of the rate of runoff from design storm events or continuous rainfall, and the conveyance of the generated runoff flow through the collection system. In addition, studies using XP-SWMM usually evaluate the effects of channel storage, conveyance capacity, flow diversions at weirs and orifices, and the effects of pump stations on flow and water levels. The verified components were determined by the TO to be the most commonly used components of XP-SWMM for urban runoff/hydraulic modeling.

3.2 XP-SWMM Runoff Evaluation

Hydrologic analysis of rainfall on surfaces, and the subsequent runoff produced, is simulated in the RUNOFF subprograms of XP-SWMM. The RUNOFF option is analogous to the RUNOFF subprogram of EPA SWMM. The subprogram simulates the filling of surface storage, infiltration of rainfall into soil profiles, and the runoff from surfaces when soils are saturated or excess water is produced because infiltration rates are exceeded. The simulation is affected by the input, which is used to indicate the type of drainage basin being modeled. The basin type is generally represented by the input parameters representing the basin's percent imperviousness (the percentage of paved or solid surfaces, such as roofs, within the basin), the type of soil, the basin slope, and the width/subcatchment width that affect overland flow routing. The RUNOFF option can also perform simple flow routing through pipes and open channels.

This section presents the results for the various functions obtained from the procedures outlined in the VTP, and the input data used in the RUNOFF subprogram of XP-SWMM. The FORTRAN code for the RUNOFF subprogram was reviewed to determine the representation of the equations or algorithms used by XP-SWMM and to cover the "black box" aspects of the verification. The review was conducted to insure that the elements of XP-SWMM, including the equations, were programmed consistently with the theory represented by that component of the model.

The following specific hydrologic capabilities were tested:

- Rainfall: This test evaluated the capability of the model to manage rainfall data. There are two main methods for introducing rainfall, both of which were evaluated. The methods are 1) by means of rainfall interface files and 2) through four types of text data sets. Testing of single event, continuous rainfall, and multiple station rainfall was performed.

- Infiltration: This test evaluated the capabilities of the two infiltration methods used in RUNOFF - the Horton and the Green-Ampt methods.

- Runoff: This test evaluated the capabilities of the generally used methods for simulating rainfall-runoff processes. Tested components were the Runoff Method and the Santa Barbara Method. Other methods available in XP-SWMM, such as SCS Hydrology or Laurenson, were not tested, since they are not commonly used.

General hydrologic tests performed included:

1. The appropriate use of basin definition data: basin area, percent imperviousness, slope, and the WIDTH parameter.

2. Runoff estimation from a variety of basin definitions.

3. Runoff estimation using the Runoff and Santa Barbara methods.

4. The flow generated from single subcatchments and multiple catchments draining to the terminus node (up to five subcatchments can drain to a terminus node with the flows combined in RUNOFF).

The file management test evaluated the capabilities of the flow file generated from RUNOFF and generally used in other XP-SWMM subprograms such as SANITARY and HYDRAULIC.

Detailed descriptions of the results obtained for each test are provided in the following subsections.

3.2.1 Rainfall input testing

The objective of this test phase was to determine that rainfall data from a referenced gauge location can be read correctly by XP-SWMM.

3.2.1.1 Testing procedures

XP-SWMM provides several options for inputting rainfall for a named or reference gauge location. This 'gauge' is then referenced to estimate runoff from subcatchments. The rainfall data input process is accessed in a utility function or global database of XP-SWMM (Figure 3-1).

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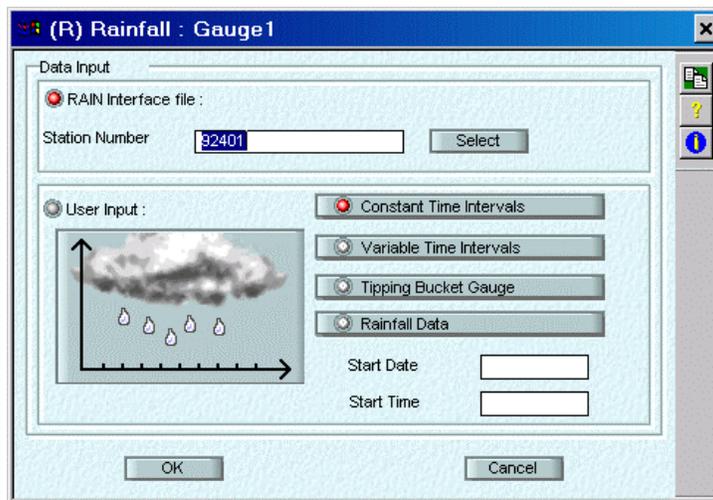
Figure 3-1. Rainfall data input utility function.

Rainfall datasets, with known time and rainfall volume distributions, were used for testing each of the rainfall input options. The datasets were extracted from records used in projects for the City of Portland, Oregon and the City of Salem, Oregon. XP-SWMM can read the data either through the Rainfall Utility or in RUNOFF. Both options were tested.

Two standard data formats from the National Weather Service (NWS) and the Canada Atmospheric Environment Service (CANAES) were used in testing. The tested formats were the NWS Post 1980 Variable format (NWS80V) from Norfolk, Virginia, and the CANAES from Toronto, Canada.

The spreadsheet format tested in the model did not require additional manipulation. Formats are subject to change by the collecting agencies, and the user should take care in specifying the required format when requesting records. In many cases, the data is now delivered in spreadsheet formats that require additional manipulation.

3.2.1.2 Testing results from several rainfall data sources

A 53-year historical hourly rainfall data series was input to XP-SWMM through a text file that specified the date, time and rainfall volume. The text file was also analyzed through the use of two additional tools, a Microsoft Excel spreadsheet and Microsoft Access database. These tools were sometimes used together and sometimes separately.

A raw data problem in the dataset was not corrected for the test. An hourly rainfall value of 6.05 inches on February 23, 1948, which most likely represents a total rainfall volume for the preceding 13-day period rather than an hourly value, was not corrected because it would have required research into the correct value. It was also left alone to emphasize the difficulties with taking raw data and accepting what a program such as XP-SWMM reads.

A comparison of rainfall volumes, intensities and rainfall distributions are provided in Figure 3-2 for the spreadsheet and XP-SWMM event file. This figure shows the raw data and XP-SWMM results in MS Excel format. Figure 3-2 illustrates the type of methods used in the evaluation to compare results. The highlighted rows show a calculated event duration of 111 hours for Event Number 4 and an inter-event duration of 130 hours (time between Event Number 3 and Number 4). An annual summary for the period of record (1948-2000 inclusive) indicates that the total rainfall volume and number of events in the dataset (1930.87 inches of rainfall and 3180 events respectively) match the results provided by XP-SWMM. Comparison of the output from the Excel spreadsheet and the XP-SWMM model showed no difference, on an annual basis, between the rainfall volume and number of events.

Since XP-SWMM calculates event volumes based on start time of the event, the rainfall volume for events that start in one year and end in the next year are counted in the starting year. Therefore, it is possible to see annual differences in total rainfall if this year-end event overlap is not considered.

Figure 3-2. Comparison of rainfall data and XP-SWMM results.

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A 24-hour rainfall distribution representing a test-l storm event (SCS-1a distribution, for example) was input into XP-SWMM using the constant rainfall input feature. The rainfall distribution was input as the percent of the total storm volume for a 30-minute period of the storm. The total volume and adjustment for the percentage data entered is also an input value. This allows application of other storm event volumes (such as 10-year, 25-year, etc.), as the underlying storm distribution is the same.

Figure 3-3 depicts the XP-SWMM representation of the SCS-1a storm event. The input rainfall volume was 3.5 inches and the volume simulated using XP-SWMM RUNOFF was also 3.5 inches. Raw rainfall data was compared to what XP-SWMM read and processed. The simulated peak intensities matched the input data. The results provided by XP-SWMM matched calculated values.
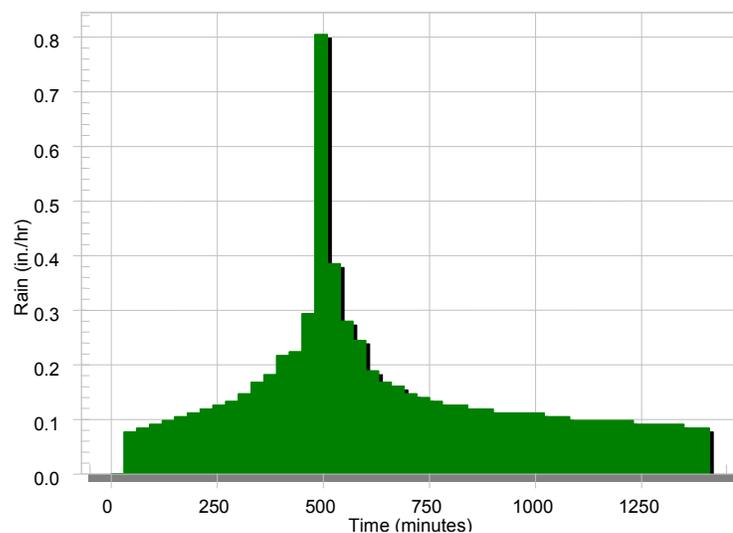
Figure 3-3. SCS-1a 30-minute rainfall intensity.

A rainfall interface file was created from the 53-year historical hourly data as described previously. The interface file was created by XP-SWMM from a text file of rainfall data. The interface file was read by XP-SWMM to determine rainfall statistics. Two periods were evaluated:

1. A winter period from November 1, 1971 through March 31, 1972 was selected to test the year-to-year reading of data and for leap years. The recorded rainfall for this winter period was 29.01 inches; XP-SWMM reported a rainfall volume of 29.02 inches.

2. A multiple year period, from January 1, 1995 through March 31, 2000 was also evaluated. The rainfall for this period was 243.53 inches and XP-SWMM reported a rainfall volume of 243.62 inches.

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The statistics reported by XP-SWMM matched the statistics determined by spreadsheet analysis of the hourly rainfall data.

The two standard rainfall data file formats, NWS80V and CANAES were read directly by XP-SWMM, and rainfall analysis was performed to produce total rainfall volumes and rainfall events. The two data file formats are illustrated in Figure 3-4 and Figure 3-5.

Data from the files were extracted into MS Excel and MS Access to determine annual and event related results. Figure 3-6 shows an example of the spreadsheet analysis and the event report file produced by XP-SWMM for the NWS80V file format, and Figure 3-7 is an example of the Canadian CANAES format.

The first highlighted event in Figure 3-6 had an event volume of 0.63 inches of rainfall in the original data (Excel spreadsheet), and 0.63 inches reported in the XP-SWMM event file (middle of Figure 3-6, screen capture). The second highlighted event had 0.16 inches calculated in the spreadsheet (Figure 3-6, Excel spreadsheet), and by XP-SWMM (bottom of Figure 3-6, screen capture).

The manually calculated values matched the values produced by XP-SWMM in this example for the NWS80V format. For instance, the first event highlighted in Figure 3-6 started on January 6, 1995 at 2000 hours and the last reading for the event was on January 7, 1995 at 0800 hours. The volume of rainfall was sixty-three units, and the storm duration was thirteen hours. The start time, volume, and duration reported by XP-SWMM matched the values determined from the input data file.

In Figure 3-7, the highlighted row shows the first event with 2 centimeters of rainfall (bottom of Figure 3-7), which corresponds to the volume of 20 millimeters of rainfall (top of Figure 3-7, Excel spreadsheet bolded figure under "Event 1" in column AE) from the original data. The storm inter-event duration was set at six hours; there was a second event on April 1, 1939. The second event had a volume of 74 mm (top of Figure 3-7, Excel spreadsheet bolded figure under "Event 2" in column AF). XP-SWMM once again produced the same results (7.4 cm below 2.00 cm. in the screen capture at the bottom of Figure 3-7) as the manually calculated values for the CANAES format.

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```
HPD44613901HPCPHI19950100010030100 00003  0200 00002  2500 00005
HPD44613901HPCPHI19950100060032000 00001 2300 00001  2500 00002
HPD44613901HPCPHI19950100070070100 00006  0200 00015  0300 00037  0400 00002  0800 00001  2100
00001  2500 00062
HPD44613901HPCPHI19950100120020700 00001  2500 00001
HPD44613901HPCPHI19950100140021500 00002  2500 00002
HPD44613901HPCPHI19950100150071300 00003  1400 00002  1500 00013  1600 00007  1700 00003  1800
00002  2500 00030
HPD44613901HPCPHI19950100160021900 00001  2500 00001
HPD44613901HPCPHI19950100180022400 00001  2500 00001
HPD44613901HPCPHI19950100190120400 00001  0500 00001  0700 00001  1300 00001  1500 00001  1700
00001  1800 00001  1900 00001  2100 00002  2200 00005  2300 00002  2500 00017
HPD44613901HPCPHI19950100200040300 00035  0400 00028  0500 00004  2500 00067
HPD44613901HPCPHI19950100280061400 00004  1500 00006  1600 00001  1800 00001  1900 00001  2500
00013
HPD44613901HPCPHI19950100290020100 00001  2500 00001
HPD44613901HPCPHI19950100300101200 00004  1300 00010  1500 00001  1600 00003  1700 00006  1800
00010  1900 00002  2000 00001  2100 00001  2500 00038
HPD44613901HPCPHI19950200010020100 00000g 2500 00000
HPD44613901HPCPHI19950200040050400 00004  0500 00001  0600 00016  0700 00008  2500 00029
HPD44613901HPCPHI19950200150150800 00004  0900 00006  1000 00007  1100 00005  1200 00005  1300
00003  1400 00002  1500 00008  1600 00006  1700 00011  1800 00004  1900 00001  2100 00001  2400 00003
```

Note: text files wrapped to fit in text box.

Figure 3-4. Example standard National Weather Service format (NWS80V).

```
6158350937110112300000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000
6158350937110212300000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000
6158350937110312300000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000
6158350937110412300000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000
6158350937110512300000000000000000000000300000000000000000000000030003000000030000000
00000000000000000000000000000000
6158350937110612300000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000
6158350937110712300000000000000000000000000000000000000000000000000000000000000000000000
00000000005001300100008000300000
6158350937110812300050003000000000000000000000000000000000000000030000000000
00000000000000000000000000000000
6158350937110912300000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000
6158350937111012300000000000000000000000000000000000000000000000000000000000000000000000
```

Note: text files wrapped to fit in text box.

Figure 3-5. Standard Canada Atmospheric Environment rainfall format (CANAES).

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Figure 3-6. Spreadsheet and XP-SWMM event file result for NWS80V format.
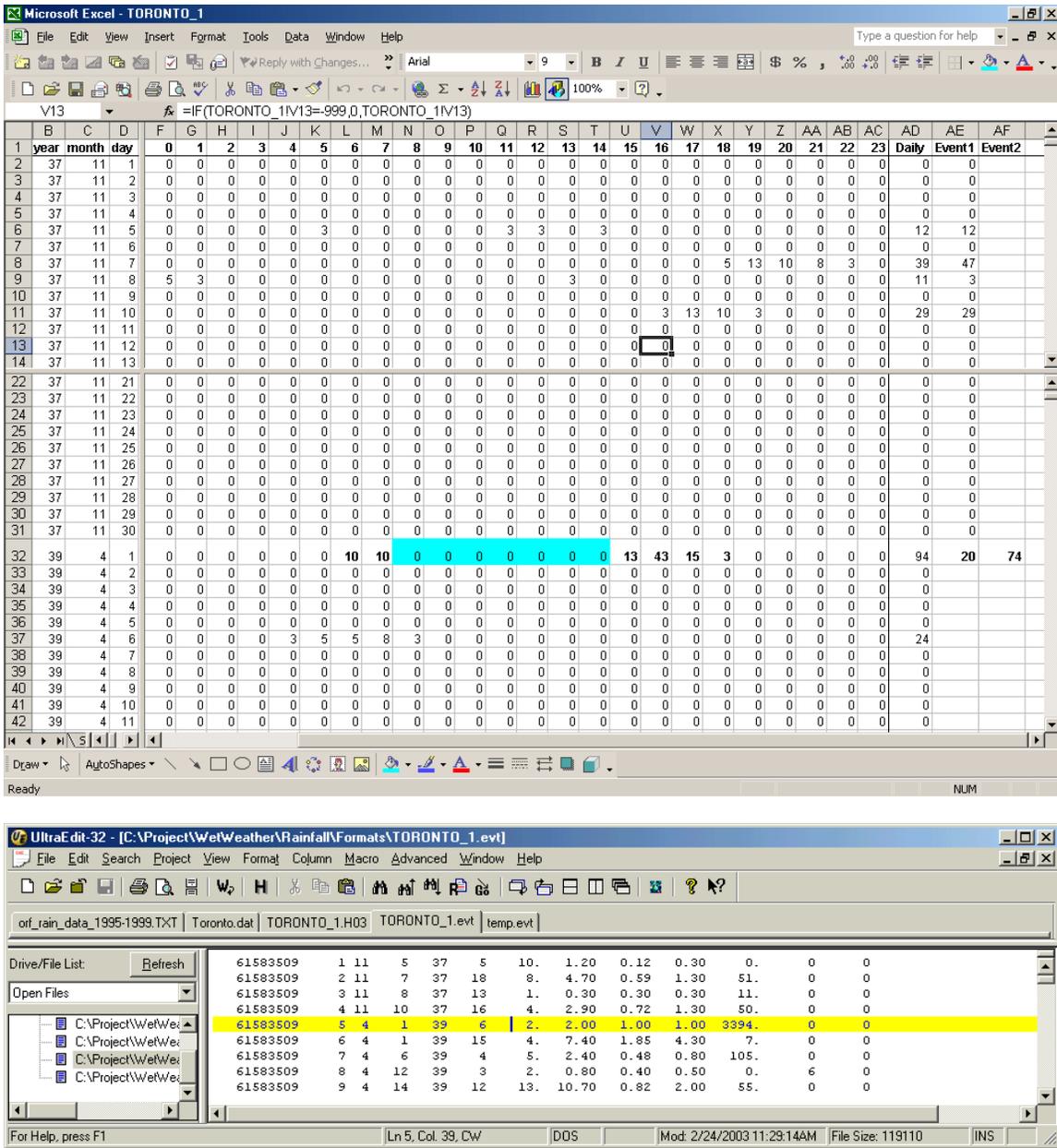
Figure 3-7. Spreadsheet and XP-SWMM result for CANAES format.

3.2.2 Infiltration testing

The objective of these tests was to determine if the estimation of infiltration and excess rainfall amounts made by XP-SWMM are consistent on the basis of the Horton Method and the Green-Ampt Method.

3.2.2.1 Testing procedure

The RUNOFF subprogram is based on the classic EPA SWMM Runoff block and gives the user an option to use either the Horton Method (Section 3.2.2.2, Item 1) or the Green-Ampt Method (Section 3.2.2.2, Item 2). Both of these methods are empirical and can be calculated by hand using spreadsheet and numerical methods. Example infiltration method set-up screens in XP-SWMM are shown in Figure 3-8.
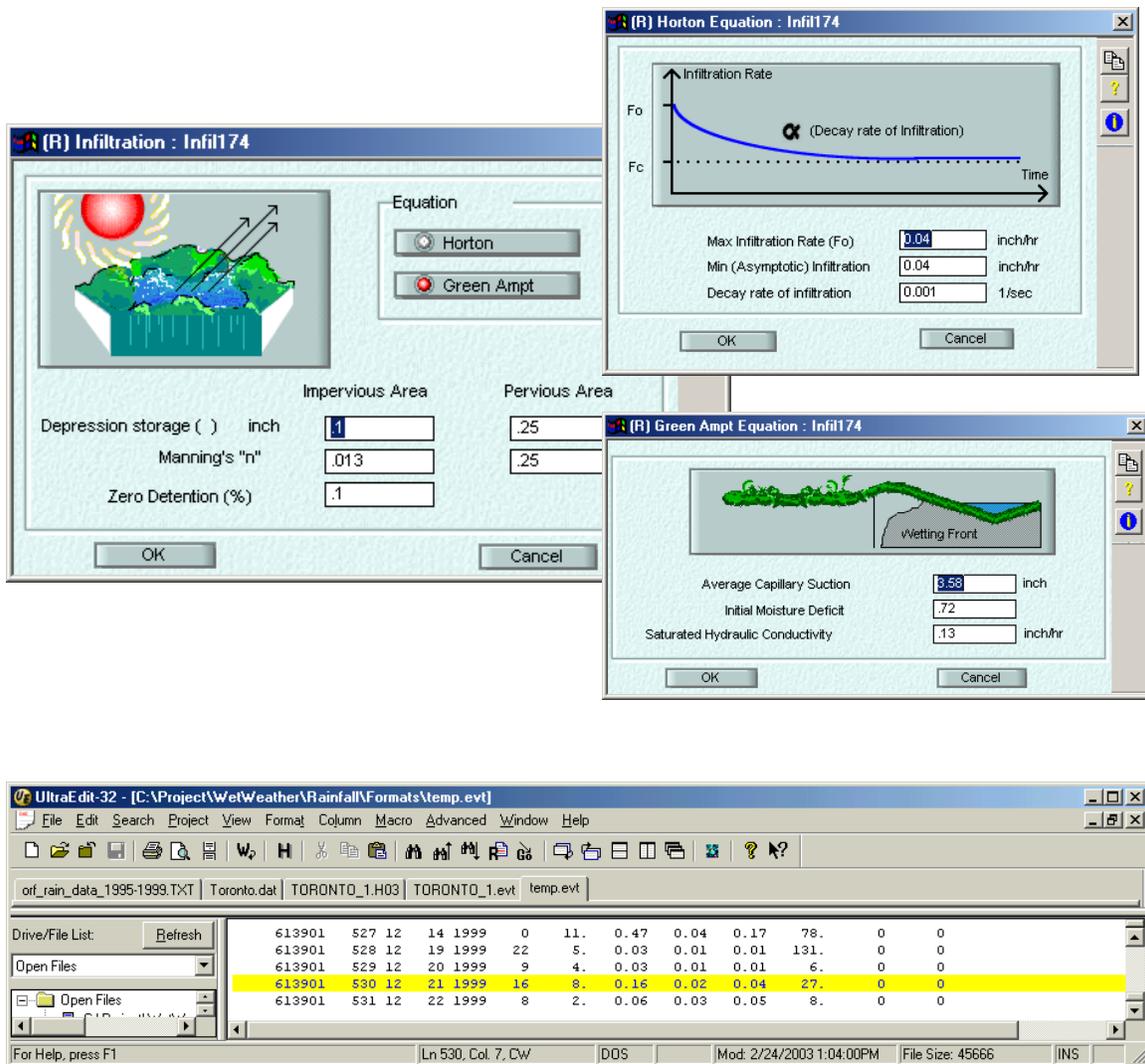
Figure 3-8. Example infiltration method set-up screens.

The testing used a series of datasets representing five different basin soil conditions ranging from clay to sand. Soil parameters for use in the two methods were extracted from literature data. Depression storage and zero detention effects on infiltration were also included in the simulations.

The testing also considered rainfall intensity using the SCS-1a distribution (shown in Figure 3-3) for design storm conditions, and two historical storms with the same volume, but with different rainfall patterns. One storm had high rainfall at the start of the storm, and the second had high rainfall at the end of the storm. The historical storms, in addition to a simulation of a week of rainfall, were used to test the effects of antecedent conditions on infiltration.

3.2.2.2 Testing results

Horton Method

Infiltration using the Horton Method was evaluated by a spreadsheet method adopted from Bedient and Huber (Reference 1). The spreadsheet calculated excess rainfall by an iterative process using the Newton-Raphson Numerical Method to determine the equivalent end time for infiltration to occur. The spreadsheet values are shown in Table 3-1. The total rainfall used in the spreadsheet and reported by XP-SWMM was 3.25 inches.

The infiltration parameters used in the Horton Method were:

- Initial infiltration capacity (f_o): 3.0 inches/hour;
- Equilibrium capacity (f_c): 0.2 inches/hour;
- Time constant (k): 1.4 hour^{-1}; and
- No initial abstraction, evaporation or depression storage used in XP-SWMM (all three of these can affect the amount of rainfall available for infiltration).

The calculated cumulative infiltration determined using the spreadsheet was 2.45 inches, while XP-SWMM reported total infiltration of 2.47 inches. The rainfall excess calculated in the spreadsheet was 0.8 inches, while XP-SWMM reported rainfall excess (surface runoff from watersheds) of 0.78 inches. The percent difference between the two results is believed to be due to internal rounding and numerical interpolation error.

The infiltration and excess rainfall produced by the program were compared with values produced using the two infiltration methods, and the series of soil conditions and rainfall datasets. Total volumes of infiltration and excess rainfall, and the time history of infiltration and excess rainfall, were compared. The comparisons are presented in Table 3-1, and graphically in Figures 3-9 and 3-10. F at t_p (inches) in Table 3-1 refers to the Infiltration (F) at the equivalent time step (t_p). F at t_p (equivalent time step) +Dt (rainfall time period) in Table 3-1 refers to the sum of these two parameters at the time at which the amount of infiltration occurs.

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Table 3-1. Horizon Infiltration Estimation

Time Interval (hr)	Rain (in/hr)	F at t_p (in)	F at t_p+Dt (in)	Potential F (in)	Rain Vol. (in)	Actual F (in)	Actual Cum. F (in)	Equivalent End Time t_p (hr)	Rainfall Excess Depth (in)	Rain Excess Intensity (in/hr)	Equivalent f (in/hr)
0-0.5	1.2	0.00	1.107	1.107	0.60	0.600	0.600	0.232	0.00	0.00	3.00
0.5-1.0	2.1	0.60	1.428	0.828	1.05	0.828	1.428	0.732	0.22	0.44	2.22
1.0-1.5	0.9	1.43	1.890	0.462	0.45	0.450	1.878	1.215	0.00	0.00	1.20
1.5-2.0	0.4	1.88	2.162	0.284	0.20	0.200	2.078	1.543	0.00	0.00	0.71
2.0-2.5	0.8	2.08	2.294	0.216	0.40	0.216	2.294	2.041	0.18	0.37	0.52
2.5-3.0	1.1	2.29	2.451	0.157	0.55	0.157	2.451	2.532	0.39	0.79	0.36
Totals	3.25				3.25				0.80		

The FORTRAN code was reviewed for representation of the Horton Equation and was found to be correctly represented. The following provides a summary of the defining equation and observations on the method used by XP-SWMM:

Subprogram: *HORTON.F90*

Defining Statement used in subprogram for Horton's Equation:

$$CUMINF (TT) = WLN*TT + (WLX-WLN)/DCY*(1.0-EXP (-DCY*TT)) \quad (3\text{-}1)$$

Where:

CUMINF (TT) = cumulative infiltration over time step TT, inches
WLN = Equilibrium infiltration capacity, inches/hour
WLX = Initial or infiltration capacity at start of time step, inches/hour
DCY = Time constant, 1/hour
EXP = natural log exponent.

Other observations:

- Equation corresponds to generally accepted Horton Equation;
- Consideration of saturated surface (groundwater at surface);
- Consideration of when no water available for infiltration;
- Regeneration of infiltration capacity during dry periods; and
- Newton-Raphson iteration used to solve for t_p.

Figure 3-9 shows rainfall and rainfall excess, calculated by the spreadsheet and produced from a simulated basin in XP-SWMM. The flow produced exactly matches the pattern and values expected from the simulated watershed for these rainfall conditions. However, selection of the WIDTH factor impacts the amount of infiltration producing excess rainfall and the subsequent hydrograph. The example given in the preceding paragraphs assumed a very large WIDTH factor of 100,000 and a watershed area of 100 acres with no impervious area. If the WIDTH factor were more typical of a developed area, with values of 500 and 10,000, the resulting XP-

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SWMM infiltration values would be 2.81 inches and 2.65 inches respectively, compared with the calculated value of 2.45 inches.
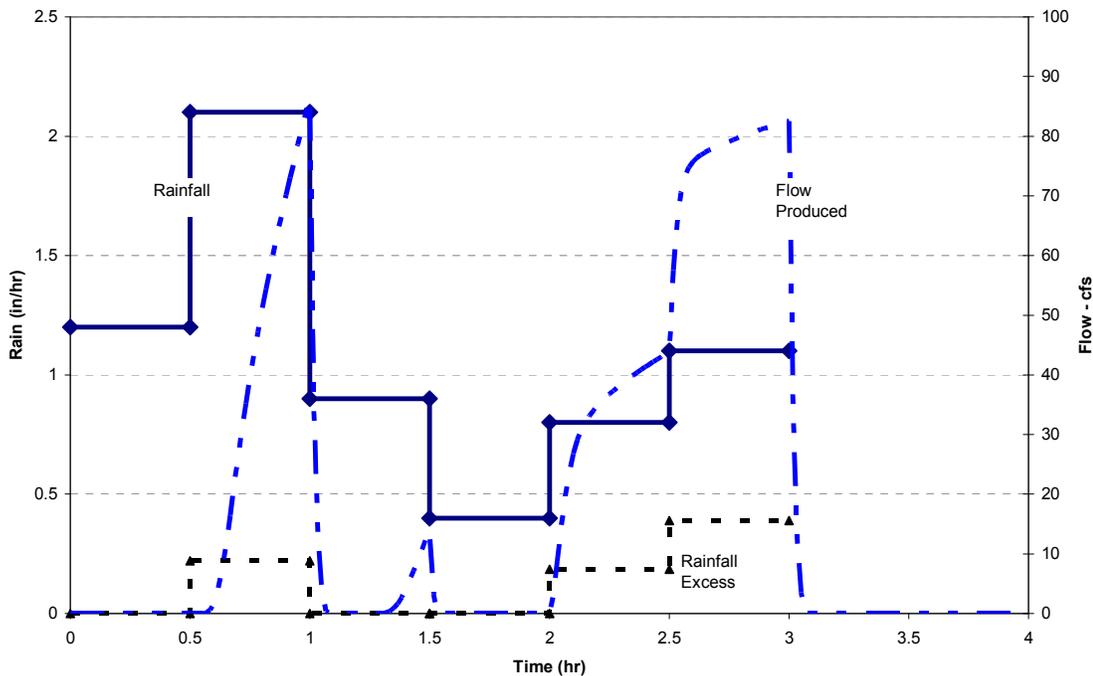
Figure 3-9. Rainfall, rainfall excess and flow produced using Horton Equation.

Green-Ampt Method

The infiltration from the Green-Ampt Method was calculated both by hand and using XP-SWMM to determine the time for soil saturation (and the start of surface runoff) and the total infiltration simulated. A constant rainfall of 7.88 inches/hour over a four-hour event period was assumed, and the following Green-Ampt parameters were used:

- Average capillary suction - 9.37 inches;
- Initial moisture deficit - 0.2 inches; and
- Hydraulic conductivity - 1.97 inches/hour.

These parameters were obtained from an example shown on pg. 58 of Reference 1.

The time for surface saturation was computed at about 4.8 minutes in the spreadsheet with XP-SWMM, showing commencement of a very small amount of runoff at about five minutes. The total infiltration over the 4 periods reported by XP-SWMM was 11.491 inches, and the calculated value in the spreadsheet was 11.496 inches. Figure 3-10 (a) shows the time when surface saturation occurs, and when measurable runoff commences. Figure 3-10 (b) shows a comparison of infiltration rate with surface runoff (flow). There is a 99.9 percent match of the

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Green-Ampt Infiltration results simulated by the spreadsheet calculations, and the infiltration results reported by XP-SWMM.
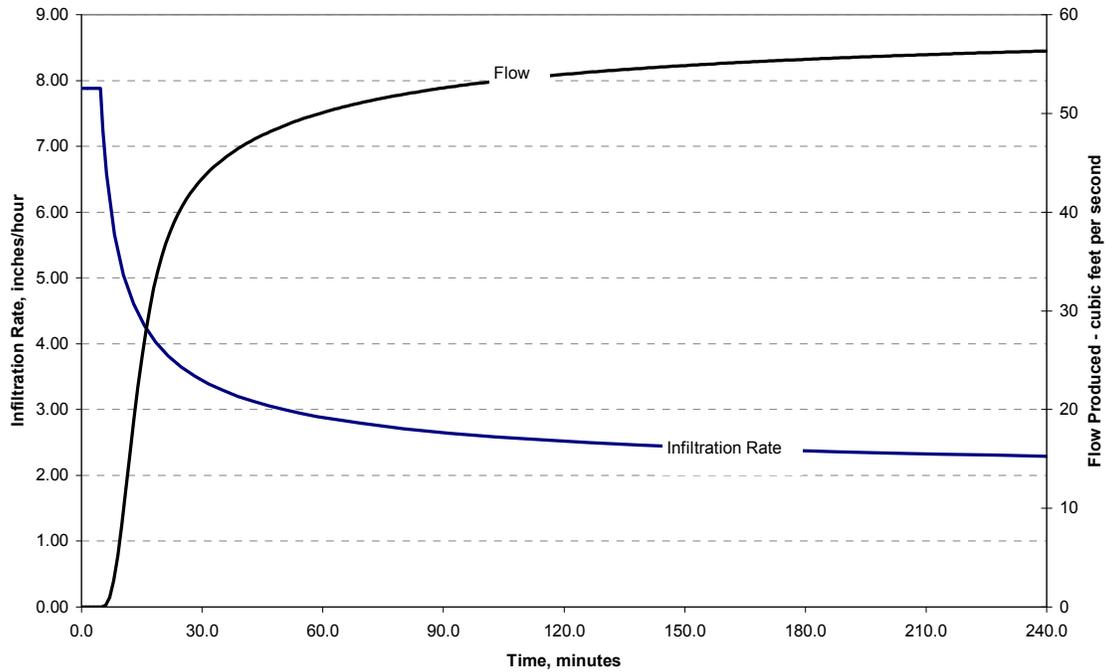
(a) Surface saturation and runoff.
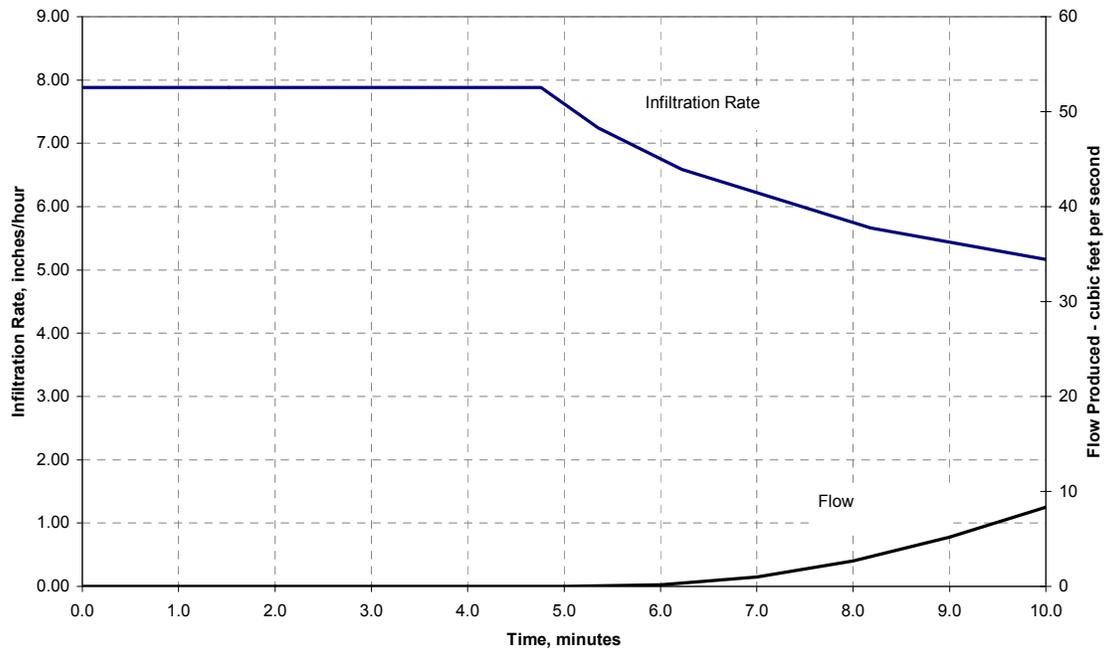
(b) Infiltration rate vs. surface runoff (flow).

Figure 3-10. Green Ampt infiltration.

The FORTRAN code in XP-SWMM was reviewed for representation of the Green-Ampt methodology and was found to be correctly represented.

The following provides a summary of the defining equation and observations on the method used by XP-SWMM:

Subprogram: *GAMP.FOR*

Function *F22*

Defining Statement used in subprogram for Green-Ampt Equation:

$$F22(X) = X - (X - F - C1 * ALOG(X + C1) + C2)/(1.0 - C1/(X + C1)) \tag{3-2}$$

Where:

X   =   Time elapsed
F22 (X) = F22 is a FORTRAN function to determine X, given infiltration and rainfall rates
C1   = Average capillary suction times soil moisture deficit, inches*fraction
F   =   Cumulative infiltration, inches
C2   =   Initial moisture deficit
ALOG = FORTRAN function that returns the log value

Other observations:

- Equation corresponds to generally accepted Green-Ampt Equations (equations 6-30 to 6-32, page 242 of Reference 5);
- Consideration is given to saturated surface (groundwater at surface);
- Consideration is given to no rain, low intensity and high intensity rainfall;
- Consideration is given to soil moisture during simulation;
- Regeneration of infiltration capacity during dry periods;
- Newton-Raphson iteration used to solve for infiltration volume; and
- Checks for non-convergence of solution for infiltration volume.

3.2.3   Runoff Testing

The objective of this test phase was to determine if the computed estimation of runoff using the Runoff or Santa Barbara Urban Hydrograph (SBUH) Methods are consistent with the XP-SWMM basis of the methods and measured data.

3.2.3.1 Testing Procedure

The RUNOFF subprogram in XP-SWMM allows five different subcatchments to attach to a terminus node. Excess rainfall on the subcatchments is routed to the terminus node through a linear reservoir routine. Routing effects are principally affected by a basin WIDTH factor, which

impacts the hydrograph shape and peak flow value. The testing procedure determined if basic parameters, such as area and percent imperviousness, were used properly, and determined the flow responses for four selected basin types. A basic set of tests included comparing results from multiple basins with the same area, but differing percents imperviousness and WIDTH parameters. The four basin types included open, residential, mixed use and fully developed basins. Example input data required in XP-SWMM for Runoff and SBUH Methods are shown in Figure 3-11.
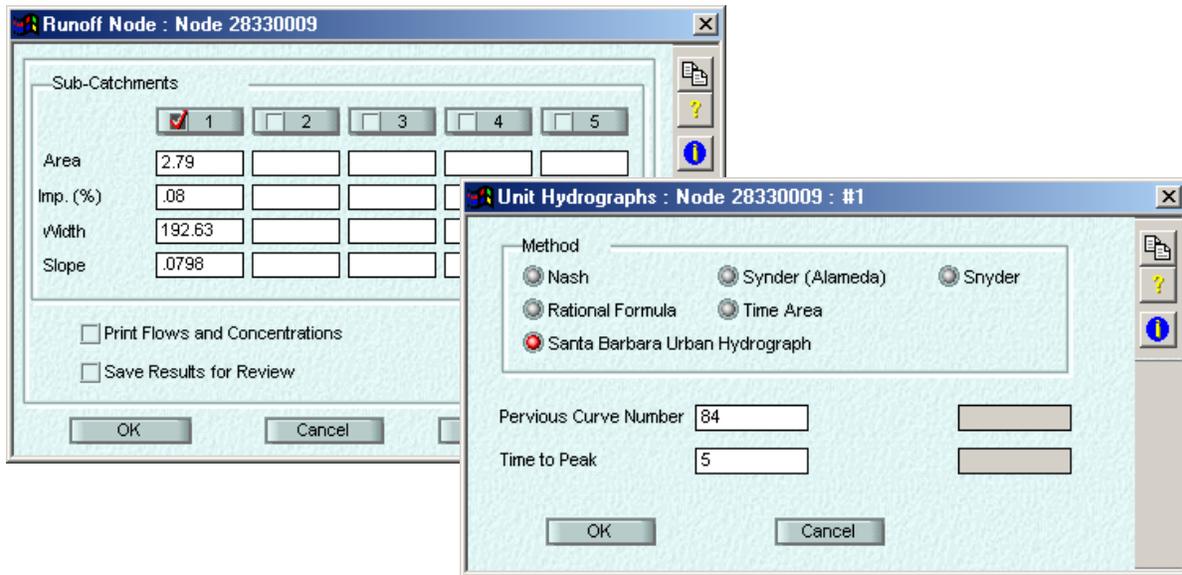
Figure 3-11. Example input data required for Runoff and SBUH methods.

3.2.3.2 Testing Results

Basic watershed representation

In general, a watershed, basin or catchment is represented by: (1) area; (2) percent imperviousness; and (3) infiltration parameters for pervious area, slope, and flow routing factors (such as the WIDTH parameter in RUNOFF, time of concentration in SCS methods, or other empirical coefficients.) This portion of the technology verification compared results from multiple basins with the same area but differing percent impervious values. Figure 3-12 shows the results generated by XP-SWMM. Results produced a reasonable match to expected peak flow rates and hydrograph shape. A basin having a high percent impervious value, as used in this case, would be expected to produce high flow rates having a fast response time.
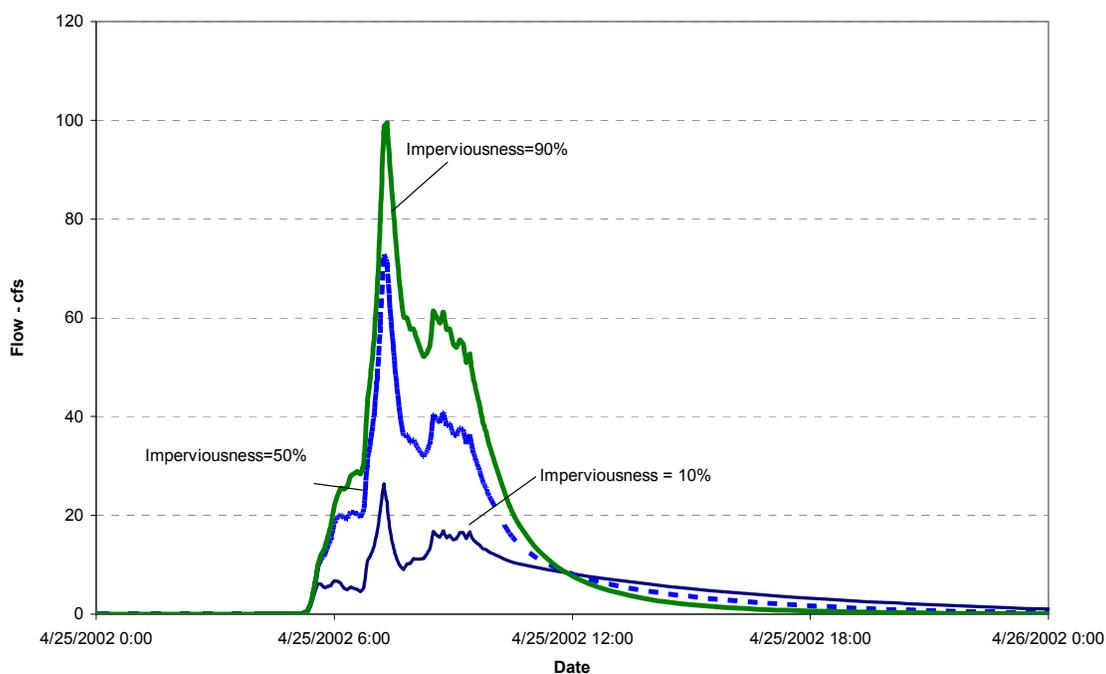
Figure 3-12. Effect of impervious percentage on generated flows.

Test of the WIDTH parameter

This test was intended to validate that XP-SWMM follows the intent of the RUNOFF representation of watersheds. Figure 3-13 shows the flow hydrographs generated from XP-SWMM. The WIDTH parameter affects hydrograph shape. Smaller WIDTHS result in low peaks but longer duration hydrographs and larger WIDTH values result in sharper peaks but shorter duration hydrographs. For the verification, a five-minute rainfall record for a storm with a total rainfall volume of 2.85 inches was input to a model of three watersheds with WIDTHs of 10,000, 1,000, and 100. The areas of the watersheds were 100 acres and 50 percent

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imperviousness. The generated hydrographs follow the expected peak flow and hydrograph shape based on the rainfall record, WIDTHS, area of the watersheds, and impervious percentage input to the model.
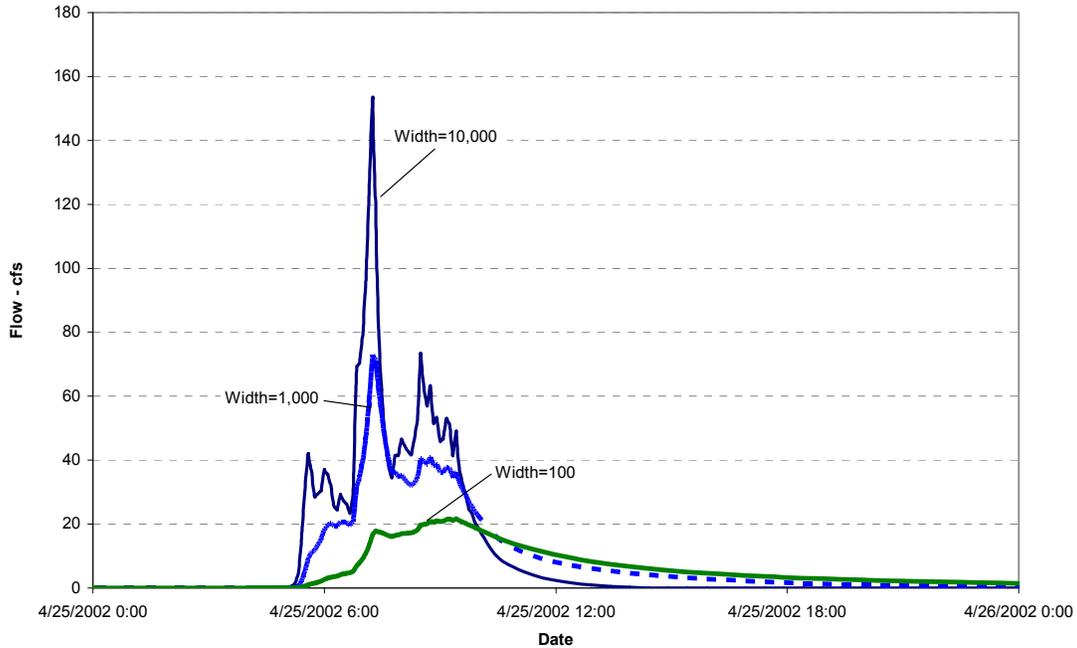
Figure 3-13. Effect of WIDTH parameter on flows generated by XP-SWMM.

Figure 3-14 shows one of the tables of results from XP-SWMM output. The table details runoff depth, peak flow rates from pervious and impervious areas, and the total peak runoff rate. Basins N1#1, N2#1 and N3#1 represent the basins with 100; 1,000; and 10,000 WIDTH values, respectively.

```
       ##################################################
        # Table R9. Summary Statistics for Subcatchments #
       ##################################################

 Note: Total Runoff Depth includes pervious & impervious area
       Pervious and Impervious Runoff Depth is only the runoff from those two
 areas.


 Subcatchment...........            N1#1           N2#1           N3#1
 Area (acres)...........       100.00000      100.00000      100.00000
 Percent Impervious.....        50.00000       50.00000       50.00000
 Total Rainfall (in)....         2.85000        2.85000        2.85000
 Max Intensity (in/hr)..         2.52000        2.52000        2.52000
 Pervious Area
 -------------
 Total Runoff Depth (in)         0.32631        1.18008        1.83051
 Total Losses (in)......         1.59487        1.66903        1.01949
 Remaining Depth (in)...         0.92882        0.00089        0.00000
 Peak Runoff Rate (cfs).         1.34587       10.28685       40.65405
 Total Impervious Area
 ---------------------
 Total Runoff Depth (in)         2.36444        2.64012        2.75412
 Peak Runoff Rate (cfs).        20.36603       67.34588      114.02709
 Impervious Area with depression storage
 ---------------------------------------
 Total Runoff Depth (in)         1.76443        1.97072        2.05622
 Peak Runoff Rate (cfs).        15.21780       50.44352       85.52031
 Impervious Area without depression storage
 ------------------------------------------
 Total Runoff Depth (in)         0.60002        0.66940        0.69790
 Peak Runoff Rate (cfs).         5.14823       16.90237       28.50677
 Total Area
 ----------
 Total Runoff Depth (in)         1.34538        1.91010        2.29232
 Peak Runoff Rate (cfs).        21.71190       77.63274      154.68114
 Unit Runoff (in/hr)....         0.21712        0.77633        1.54681
```

Figure 3-14. Model results from XP-SWMM WIDTH evaluation.

The total runoff depth (third line from last in Figure 3-14) will not be the same for each sample watershed (with the WIDTH parameter as the only variable, and the area, percent imperviousness, infiltration parameters and other basic data being consistent). The pervious area runoff depth (and subsequent hydrograph volume) shows the most variation (volumes ranging from 0.33 inches to 1.83 inches for WIDTH values of 100 and 10,000, respectively). The variation for the impervious area is smaller (2.36 to 2.75 inches) but some differences occur. The differences in total runoff depth may be due to water remaining in storage in the basin. If so, it is expected that upon increasing the simulation time, the remaining depth would go to zero in all cases, and the differences between the runoff depths for the three different WIDTH values would be substantially reduced. Other reasons for the differences in runoff depth may relate to the remaining water in the reservoir at each time step being subject to evaporation and infiltration on the pervious surface.

Test of Santa Barbara Urban Hydrograph (SBUH) Method

XP-SWMM-generated flows were compared against spreadsheet-calculated flows for two basin representations (10 and 90 percent impervious). Figures 3-15 and 3-16 show the comparisons between the spreadsheet calculation of the SBUH runoff hydrograph and XP-SWMM SBUH hydrograph for 90 percent and 10 percent impervious basins, respectively.
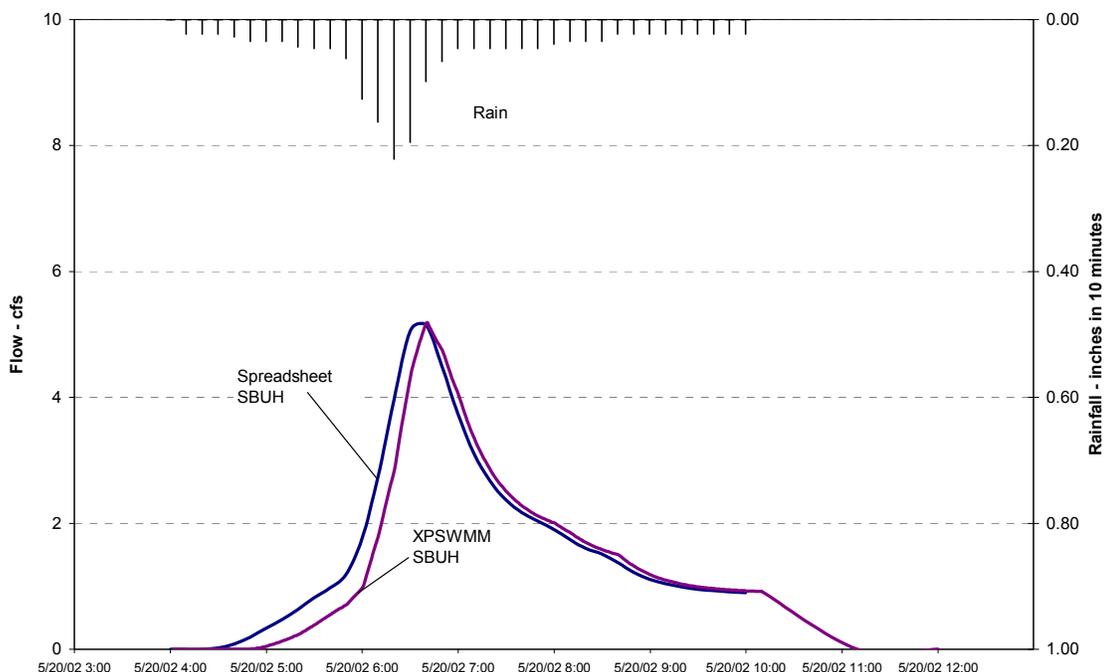
Figure 3-15. Comparison of SBUH hydrographs for 90 percent impervious area.

The hydrographs for the high percent impervious area (Figure 3-15) match well, except at the start of the storm when some time delay is observed. The peak flow and recession limb of the hydrograph match well. For the low percent impervious area, (Figure 3-16), the start of the storm is also delayed and the peak does not match as well. However, the scale of the peak flows is small and the difference in peak flows is only about 0.1 cfs. XP-SWMM generated a hydrograph comparable to the calculated hydrograph using the SBUH Method.
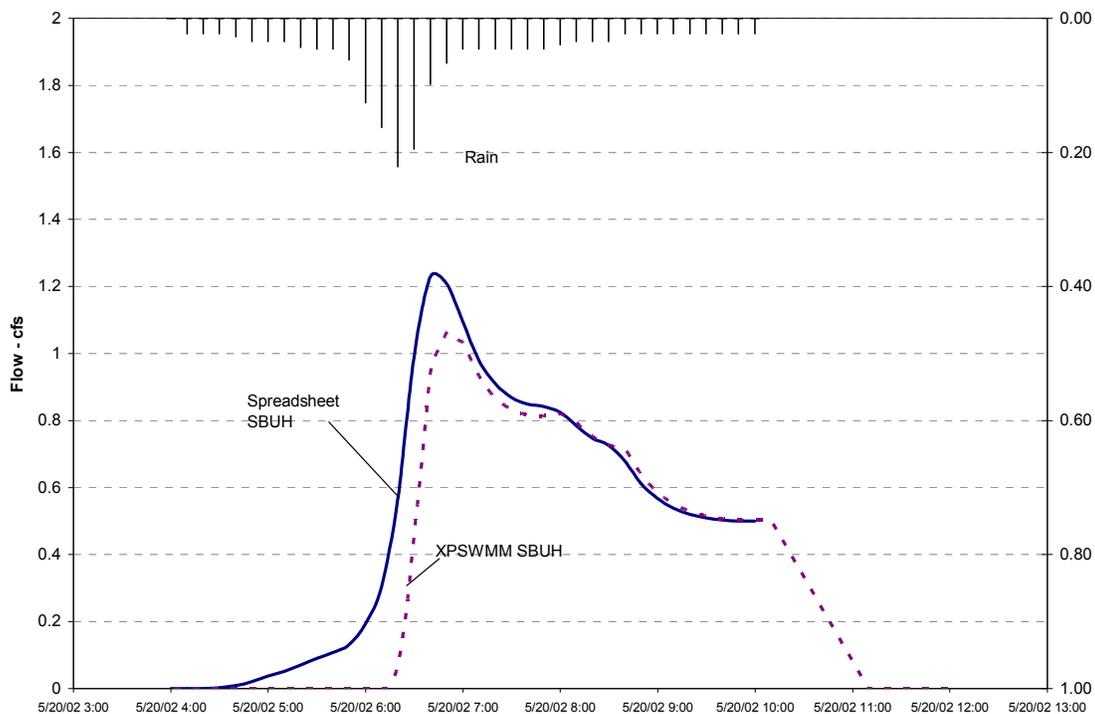
Figure 3-16. Comparison of SBUH hydrographs for 10 percent impervious area.

Comparison of flows generated from Runoff, SBUH and SCS methods

Figures 3-17 and 3-18 show results generated by XP-SWMM from three commonly used rainfall-runoff estimation methods for 10 percent impervious and 90 percent impervious basins, respectively. Area, infiltration parameters and other basin representation data were the same for each simulated estimation method. The two figures are provided to show the possible range in flows that can be generated from the techniques, and the subsequent need for care in building models and selecting a rainfall-runoff technique. Figures 3-17 and 3-18 show the expected results and relationships between XP-SWMM and the two calculated methods.
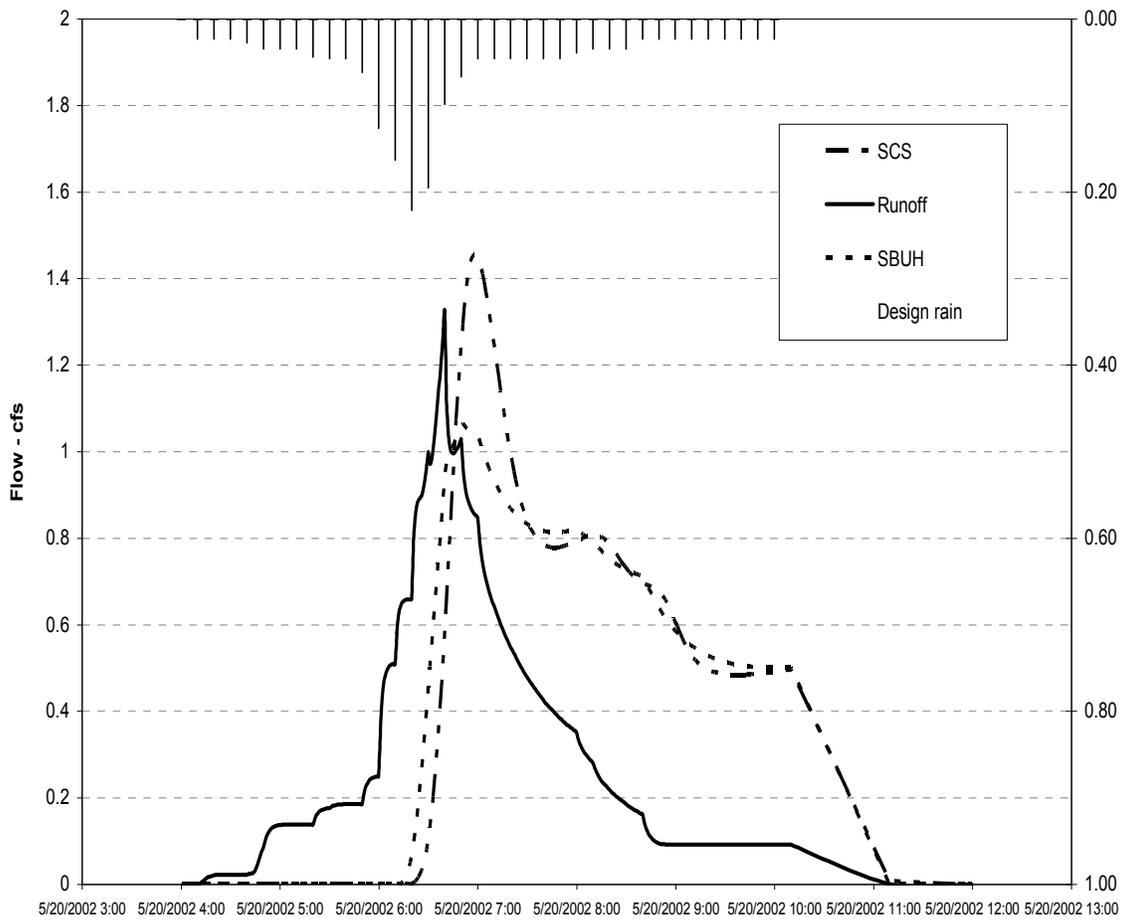
Figure 3-17. Comparison of hydrographs for low percent impervious area (10%).
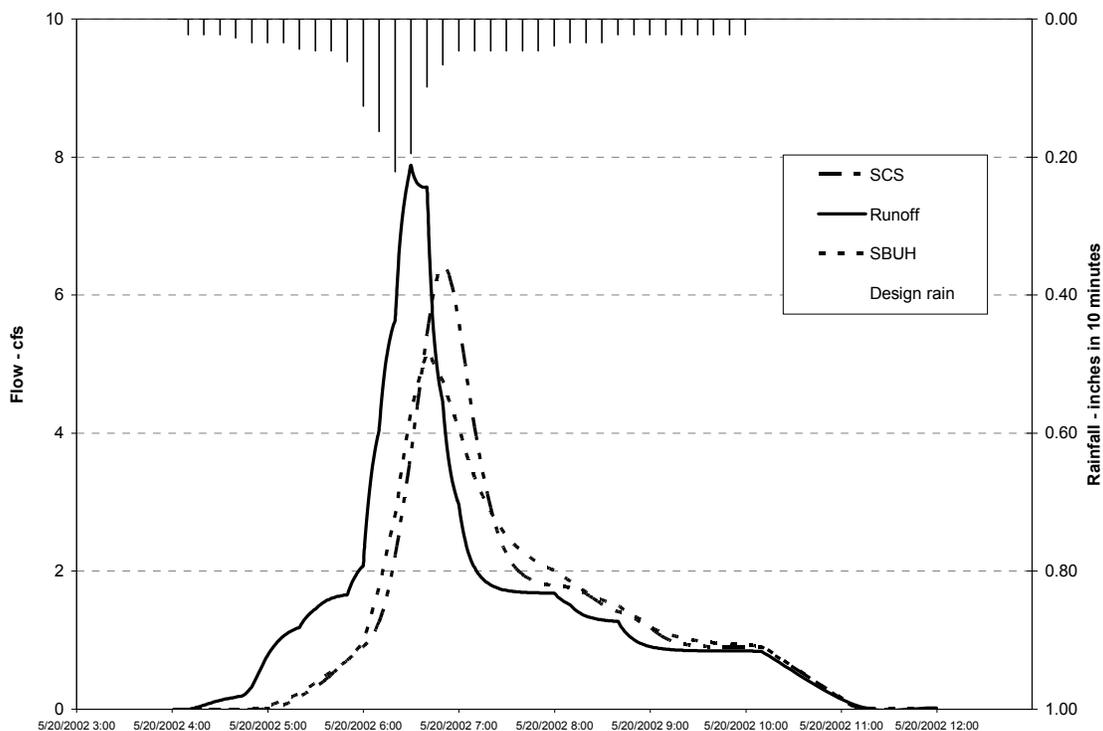
Figure 3-18. Comparison of hydrographs for 90% impervious area.

Comparison of Monitor Data and Flows from a Model Built from Detailed Data

If basin parameters are carefully and explicitly determined, then it should be possible to build models that represent the rainfall-runoff process accurately.

Portland, Oregon has such a procedure (City of Portland, 2002). Figure 3-19 shows an example area used for building a model. Figure 3-20 shows the *first* result produced from the model – that is, the first result before calibration through manipulation of runoff and collection system parameters. This example is from XP-SWMM using Green-Ampt for infiltration and Runoff for flow estimation. The calibration procedure is a lot-based approach to determine impervious areas directly connected to sewers and pervious area and impervious areas connected to the collection system via surface catchments. The results produced, as shown in Figure 3-20, are very reliable for a wide variety of basin sizes and land uses (12 different flow monitors for the selected study shows duplication of results). Based on the City of Portland's procedures to generate model data, XP-SWMM can replicate monitored data consistently.

While this testing approach may raise reader questions regarding the accuracy of the field measurements used to collect the comparison data, comparing model computed and field monitored flow hydrographs can be a useful way of observing whether model calculations reasonably match monitored events.

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Figure 3-19. Example of area detail and data to build model.
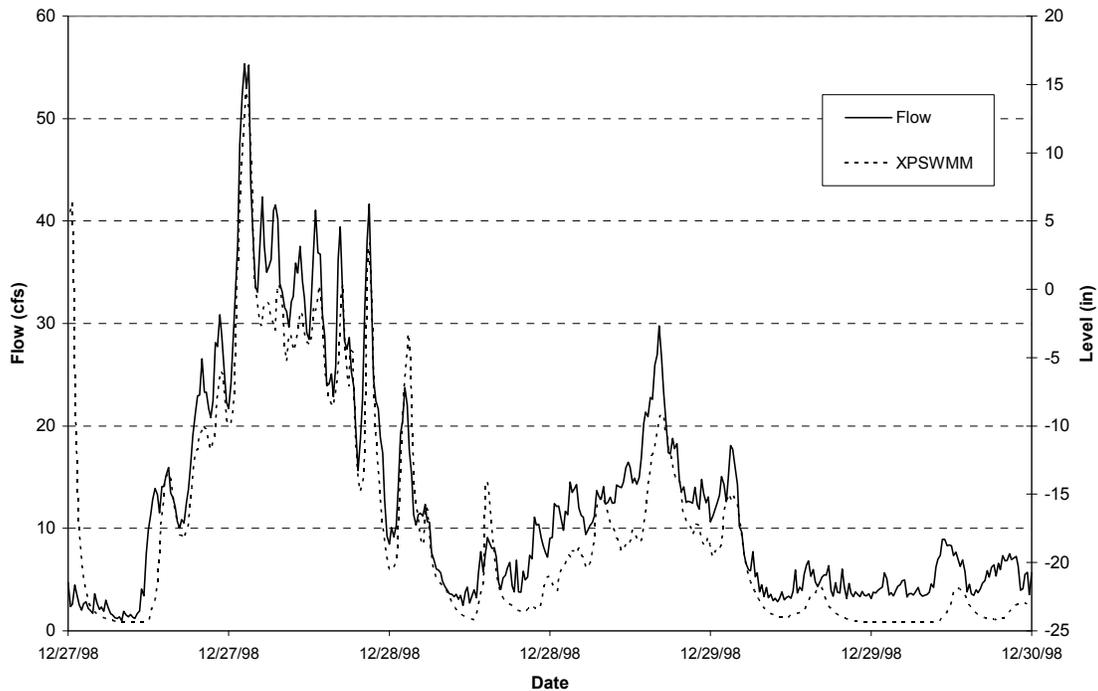
Figure 3-20. Comparison of monitor data and model results (NE 64th & Willow).

3.3   XP-SWMM Hydraulic Evaluation

Hydraulic analyses of the conveyance system are encompassed in the SANITARY and
HYDRAULIC subprograms of XP-SWMM. The SANITARY and HYDRAULIC options in
XP-SWMM are analogous with the TRANSPORT and EXTRAN subprograms, respectively, of
EPA SWMM. Flows from surface runoff normally drain to a conveyance system, such as
surface gutters on the street or sewers underneath the street, which then convey the flow to an
outlet. When flows are routed through the conveyance sewer system, their hydraulics behavior
can be simulated by either the SANITARY subprogram or the HYDRAULIC subprogram.
Compared with HYDRAULIC, SANITARY provides a simpler method of flow routing.   In
SANITARY, flow calculations are carried out without benefit from pressure flow or considering
backwater effects. Flow controls, such as weirs, parallel pipes, and storage, are simulated in a
simplified manner in SANITARY. HYDRAULIC, however, provides a more detailed analysis
of flow routing through the sewer system using dynamic equations which can account for the
dynamics of unsteady flow, forward and reverse flow, looped flow, surcharge, weirs, pumps,
orifices, and multiple parallel pipes. Since XP-SWMM recommends that flow routing be carried
out only through the HYDRAULIC routines, testing revolved around the HYDRAULIC portion
of XP-SWMM.

This section presents the results from testing the various functions and input data provided in the
HYDRAULIC subprogram of XP-SWMM. The tests included: (1) consideration of how flows

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are introduced into the collection system; (2) XP-SWMM's capabilities of routing flows in a pipe under open channel and pressure flow situations (with a variety of pipe shapes offered in XP-SWMM); and (3) through storage structures, weirs, orifices, and pump stations. The ancillary components, such as dry weather flow and RDII estimations, and the simulation of backwater at outfalls that have tidal or other tailwater conditions, were also tested.

An example network schematic of a typical testing sequence is shown in Figure 3-21. Inflow is introduced at nodes (the circles in the network schematic), and routed through the pipes (the black lines) to the terminus node (in this example at node 1625).
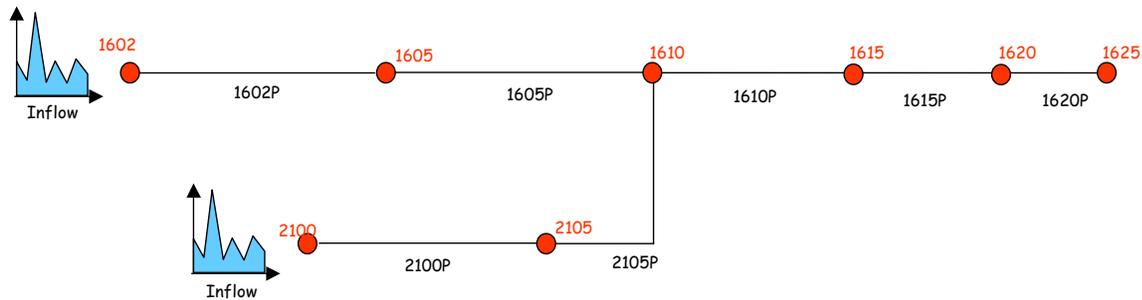
Figure 3-21. Example network schematic of a typical testing sequence.

The following are lists of the hydraulic capabilities that were tested and verified for XP-SWMM.

Testing parameters for nodes included:

- Inflow at a node (constant inflow, user inflow time series, gauged inflow, and dry weather flow at a node);
- Entrance and exit losses at nodes;
- Storage node (stepwise, linear, and power function relationships for the storage at the node);
- Inlet capacity controlled or limited at a node;
- Surface ponding at a node due to a high hydraulic grade in the pipe system resulting in flooding or flow out of the node;
- Sealed manhole, or when the hydraulic grade line is allowed to rise above the manhole rim elevation and surcharge the pipe system; and
- Tailwater specifications at an outlet node (backwater effects, high river levels, tide conditions, etc.).

Testing parameters for links included:

- Manning's Roughness coefficients;
- Pressure flow versus open channel flow (compared to friction slope in Manning's equation);
- Conduit flow simulation for free flow direction, uphill only, or downhill only;
- Routing flow through different shapes of pipe (flow depths for different shapes); and

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- Gauged flow data for calibration.

Special Links

Multiple Links

- Multiple parallel pipes (flow distribution in each parallel pipe).

Pumps

- Pump type (dynamic and steady state pumps);
- Pumping rate and pump curve representation;
- Force main representation; and
- Pump operation.

Weirs

- Weir equation and weir discharge coefficients;
- Weir overflow simulation during high flow;
- Transverse and side flow weirs; and
- Limiting reverse flow.

Orifices

- Conversion of orifices to equivalent pipes;
- Orifice simulation during dry and low flows; and
- Bottom and side orifices.

Detailed descriptions of the procedures for each test are provided in the following subsections.

3.3.1 *User Input Hydrograph Testing*

The objective of this test phase was to determine whether user inflows entered at a node are input correctly.

3.3.1.1 Testing Procedure

XP-SWMM allows several options for entering flows to the pipe system. By default, the program can read inflow at specified nodes from a flow file generated by other layers such as RUNOFF in XP-SWMM, or by other programs. The flows from the file are routed through the conveyance system by HYDRAULIC. In addition to this basic option, the program user can also enter additional flow to the sewer system by the user inflow option directly. User inflow can be in the form of a constant inflow or a time series inflow, as shown in Figure 3-22.
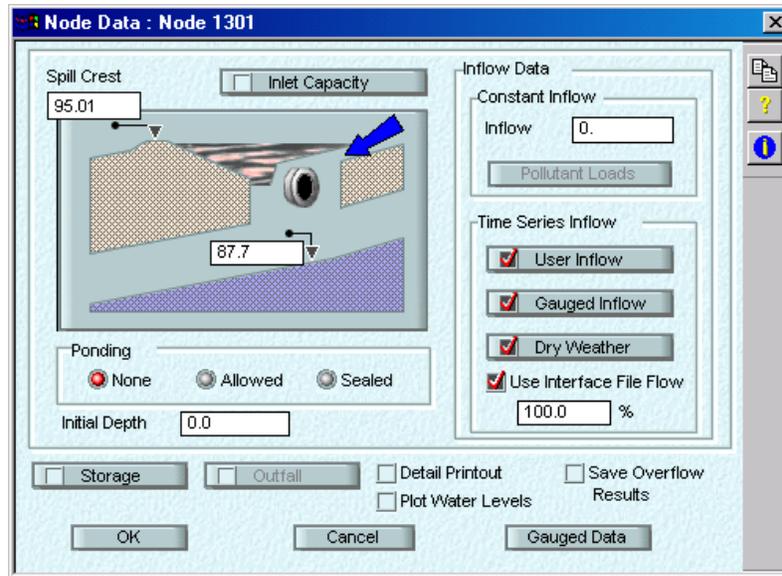
Figure 3-22. User inflow option screen.

For constant inflow, the flow entering a node will be a constant flow rate maintained throughout the simulation. Net constant flow entering (positive) or leaving (negative) the node can be specified. Using a negative value results in a withdrawal from the node.

For time series inflow, several options are available to the program user: Dry Weather Flow, User Inflow, and Gauged Inflow. A user-defined inflow hydrograph is defined by entering the simulation date and time and the flow rate at each time step. 'Gauged Inflow' allows the program user to enter the flow hydrograph in a user-specified format. Dry Weather Flow can be entered as a constant flow rate, with a peaking factor of 1.0 or higher, and can also be varied using hourly and weekly peaking factors (the flow can be multiplied by peaking factors for each hour of the day and each day of the week, for a total of 7 daily factors and 24 hourly factors). According to the manufacturer, the peaking factors usually average 1, but they can be any positive number and typically range from 0.3 for early morning flows to about 1.8 for the late morning in residential areas. In addition, the Dry Weather Flow can also be specified by a function of the area and flow per unit area, or a function of area, population density, and flow per capita. Tests of these components were individually performed with the following results:

3.3.1.2 Testing Results

Dry weather flow

Figure 3-23 shows a comparison between the hourly values inputted to XP-SWMM and the model results. XP-SWMM interpolates between hourly values to determine the flow at each individual time step during the model simulation. Hence, Figure 3-23 represents input values as points and the XP-SWMM result as a curve. The results match well except for a small lag in time. The average flow input was 1.29 cfs and flow calculated by XP-SWMM was also 1.29 cfs.

The volume of input over the simulation time was 85,137 cubic feet versus an XP-SWMM result volume of 85,257 cubic feet.
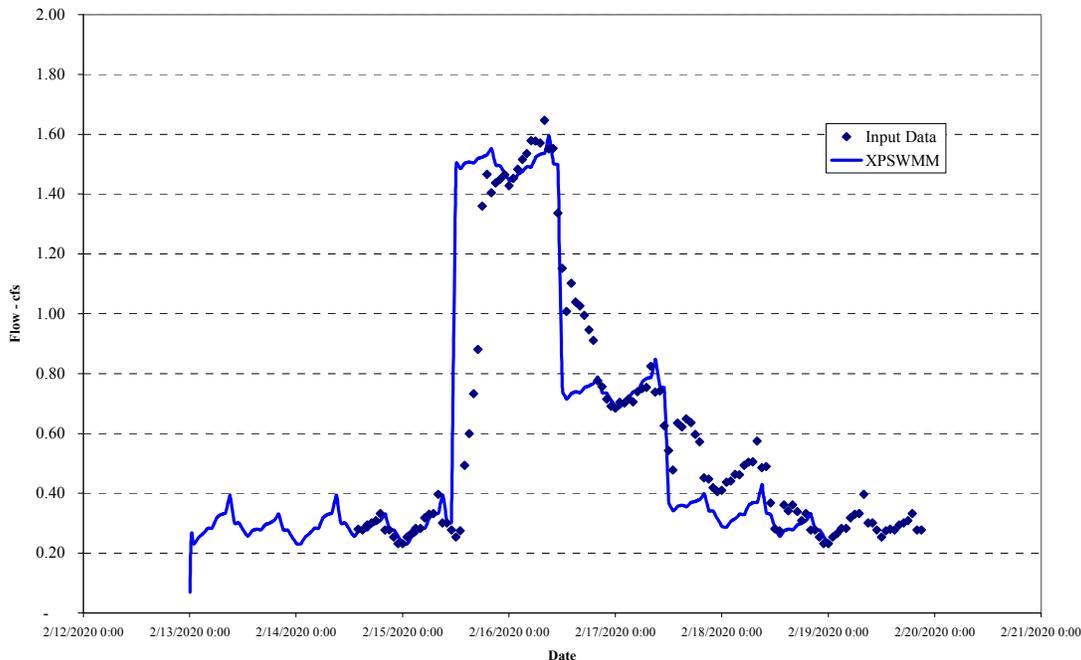
Figure 3-23. Hourly dry weather flow comparison.

Wet weather flow:

Figure 3-24 shows a comparison between hourly wet weather flow inputs in conjunction with hourly dry weather flow. XP-SWMM interpolates hourly data to determine the flow at the model time step. The model flow shown in Figure 3-24 is for the pipe immediately downstream of the input node and therefore has some storage routing effects and upstream/downstream head effects upon flow included. The peak flow generated from XP-SWMM closely matches input data (1.65 cfs for the input data and 1.60 cfs for XP-SWMM, a difference of about 3 percent). The inputted water volume was about 260,000 cubic feet, and XP-SWMM simulated 272,000 cubic feet passing through the system during a similar time period. The volume difference is about five percent, which is significant for some simulations. The sharp rise over one hour (February 25, 2002; 11 a.m. to noon) simulated by XP-SWMM represents the added volume compared with the gradual rise in flows inputted (see Figure 3-24).
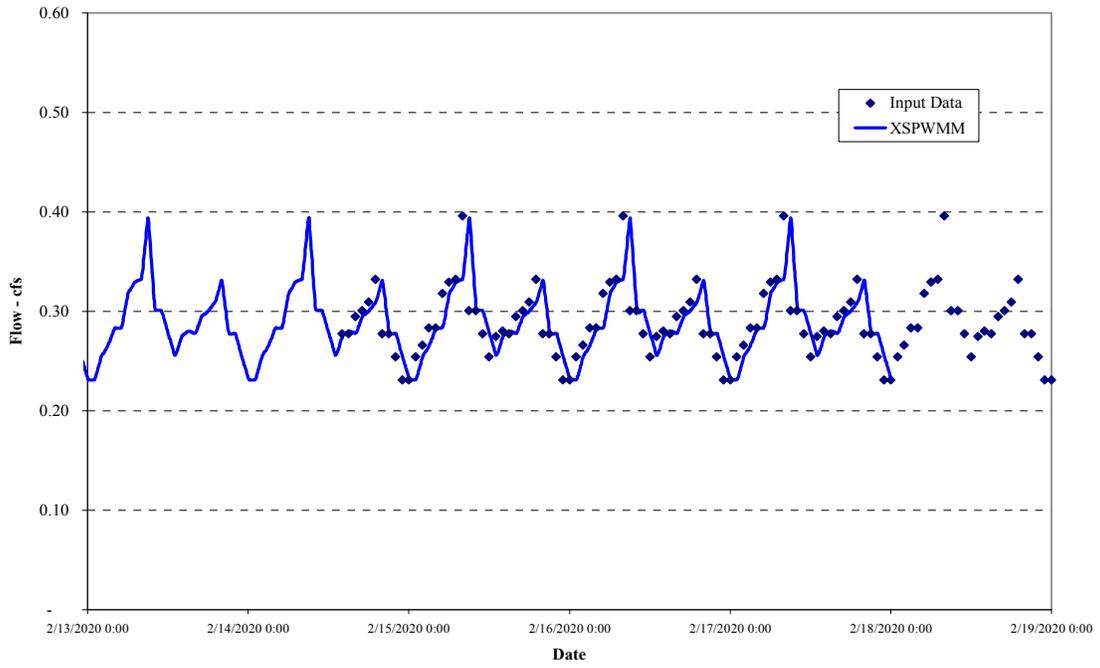
Figure 3-24. Hourly wet weather flow comparison.

<u>Interface file created in RUNOFF</u>

Figure 3-25 shows a comparison between flows created in RUNOFF and passed to HYDRAULIC through a binary interface file. Flow peaks and hydrographs match completely.
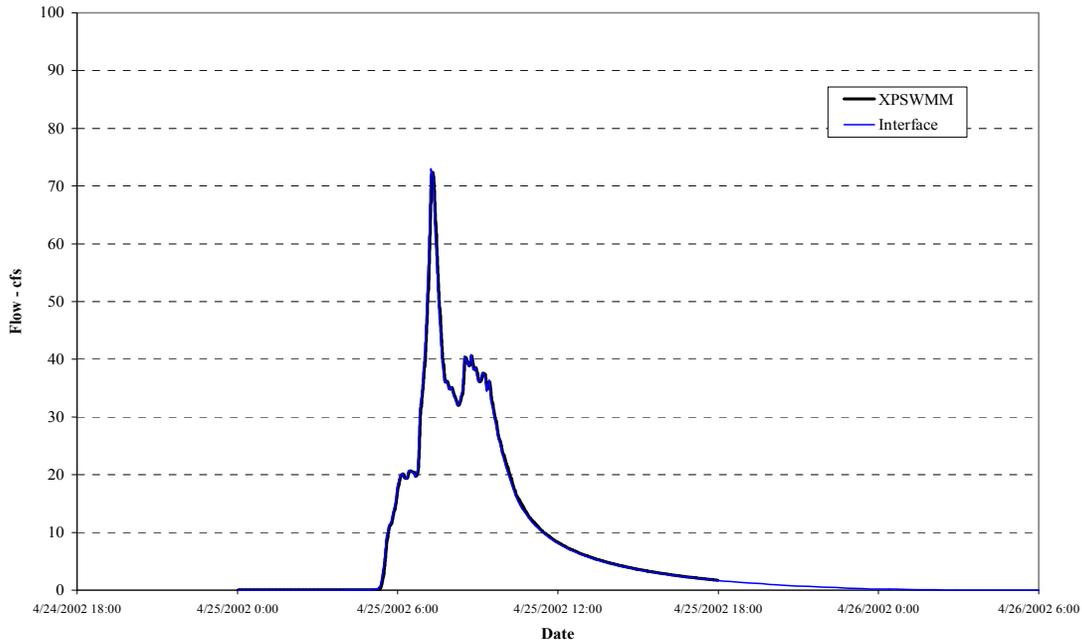
Figure 3-25. Interface file flow comparison.

3.3.2   *Node Loss Coefficient Testing*

Entrance and exit losses at a junction, and contraction and expansion losses from one conduit to the next, can be modeled in XP-SWMM by specification at individual pipes or globally for all pipes.

3.3.2.1 Testing Procedure

Entrance and exit losses are calculated by a junction head loss coefficient, which is multiplied by the velocity head at the node. The loss is modeled in the conduit momentum equation since only a continuity equation is used at junctions. The loss in velocity, due to a cross-section shape change from one conduit to the next, creates turbulence. The turbulence head loss is modeled in XP-SWMM by a contraction/expansion loss coefficient (assumed to be 1.0) multiplied by the velocity head.

Two flow regimes (hydrographs) were entered at upstream nodes of a simplified pipe network. One regime caused the system to surcharge, resulting in pressure flow through selected pipes, and the second regime resulted in open channel flow throughout.

3.3.2.2 Testing Results

Surcharge Conditions

Figure 3-26 shows the time history of water elevations at the upstream end of a pipe, at which entrance and exit losses have been applied.
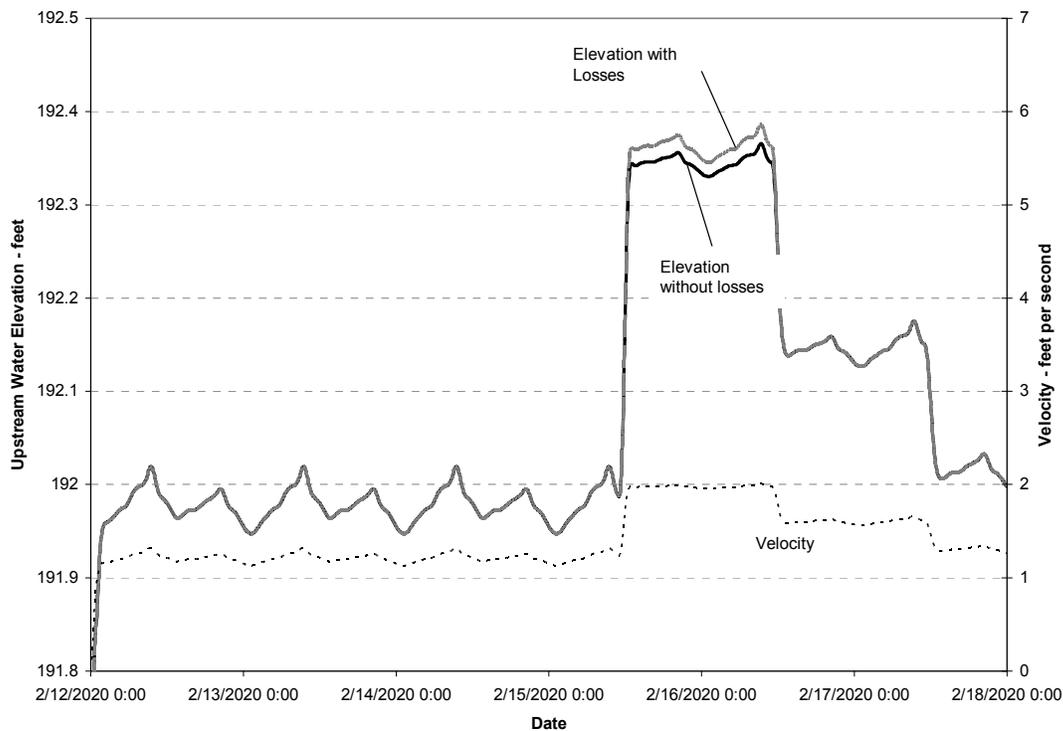
Figure 3-26. Entrance-exit head loss comparison (pressure flow).

Figure 3-27 shows a comparison of elevation differences from two simulations (one with losses applied and one without) with calculated values in feet based on pipe velocity in feet per second and entrance loss coefficient. Figure 3-27 shows that for pressure flow conditions, the head loss for entrance effects should be approximately twice that of the simulated values.   The figure illustrates that the program is including the additional head losses at exits and entrances. This additional head loss causes a rise in the water surface elevation.

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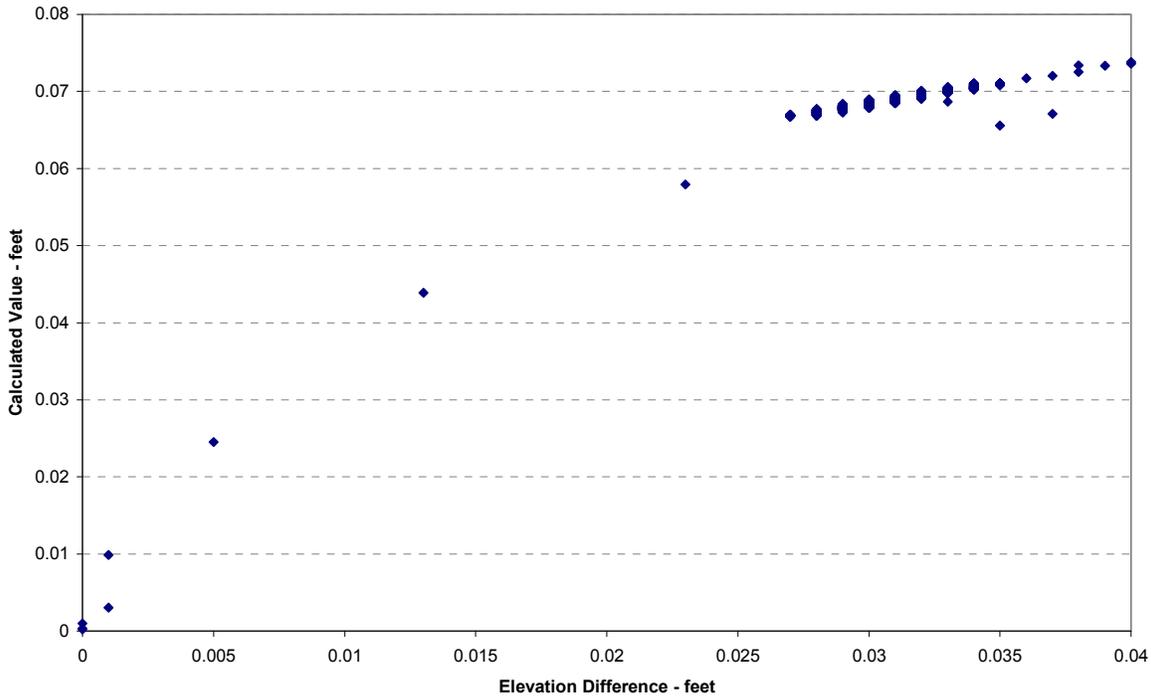
Figure 3-27. Entrance-exit loss comparison (pressure flow).

Open Channel Conditions

Figures 3-28 and 3-29 show the calculated head loss results compared to the values obtained from XP-SWMM for an open channel flow condition. Figure 3-28 shows the difference in elevations with and without entrance/exit losses at a given time, and is the source of the horizontal values in Figure 3-29. The vertical axis values in Figure 3-28 are those calculated by hand given the reported velocities in XP-SWMM at a given time.

Figure 3-29 then plots the XP-SWMM values with the calculated values. When you compare the calculated values with the simulated water level differences, the calculated values are less.

Figure 3-29 shows the differences between XP-SWMM-derived values and values calculated based on reported velocity; the simulated head losses are consistently less than calculated values. For example, compare the XP-SWMM values (horizontal axis) of 0.015 to 0.02 with the calculated values (vertical axis) of 0.059 to 0.063. Since these losses are recognized as minor losses in simulations, the percent difference may be significant. Since this is the case, it is recommended that XP Software review this portion of XP-SWMM.

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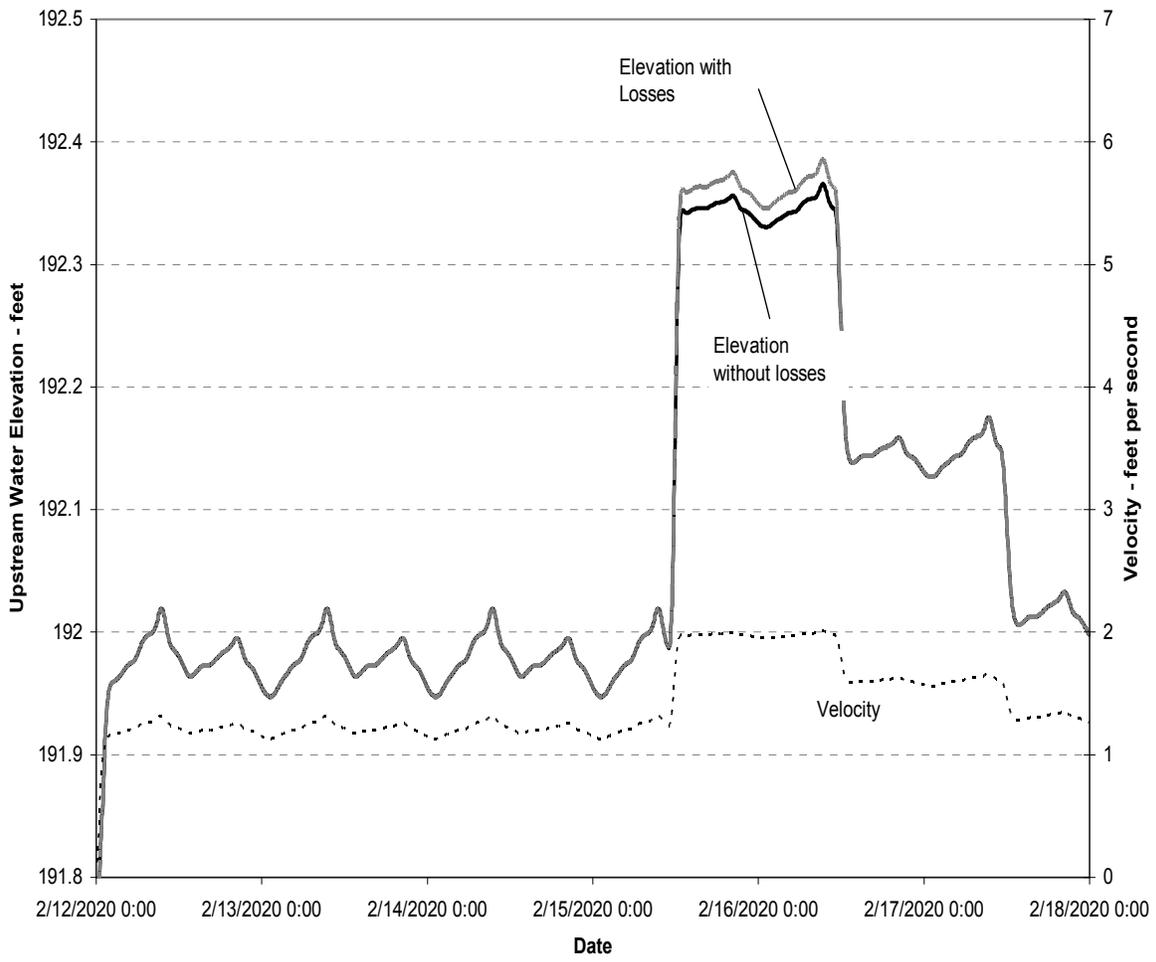
Figure 3-28. Entrance-exit head loss comparison (open channel flow).
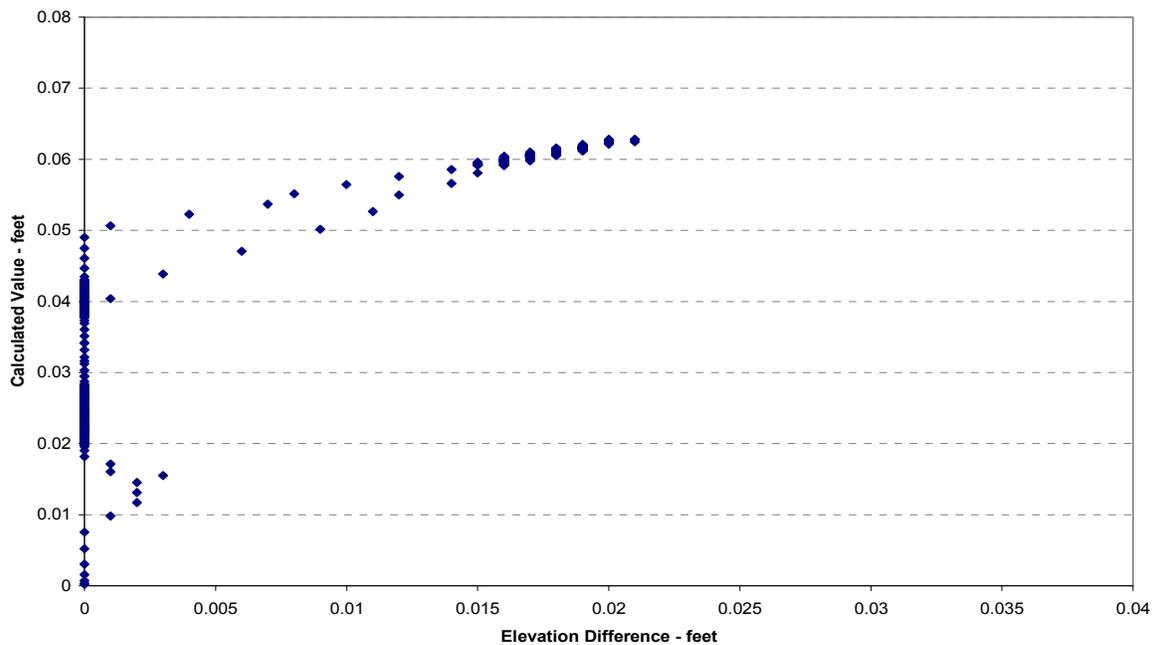
Figure 3-29. Entrance-exit loss comparison (open channel flow).

3.3.3   Storage Node Testing

The objective of this phase of the testing was to confirm that when a node is specified as a storage node, the specified storage is properly included in the hydraulic calculations under both surcharged and open channel flow conditions.

3.3.3.1 Testing Procedure

Figure 3-30 shows the various methods for including storage into a simulation: constant, stepwise linear, and power function storage methods. These methods were tested by adding a flow hydrograph to a simplified pipe network, where one node with upstream flows was a storage node. The flow magnitude was varied to create open channel to surcharged flow conditions. Because of the importance of initial conditions in simulating storage, 'wet' conditions were simulated using a hot start file. The storage node was evaluated by spreadsheet calculations using inflow and outflow values at a given time and changing storage conditions to calculate values for the flows. Flows used in the test were based on reported flows obtained from the XP-SWMM simulation. The storage use and elevation changes were calculated in a spreadsheet with reported XP-SWMM values for inflow and outflow. In all storage simulations, the time step for reporting inflow and outflow results had a significant effect on the prediction (spreadsheet) accuracy.

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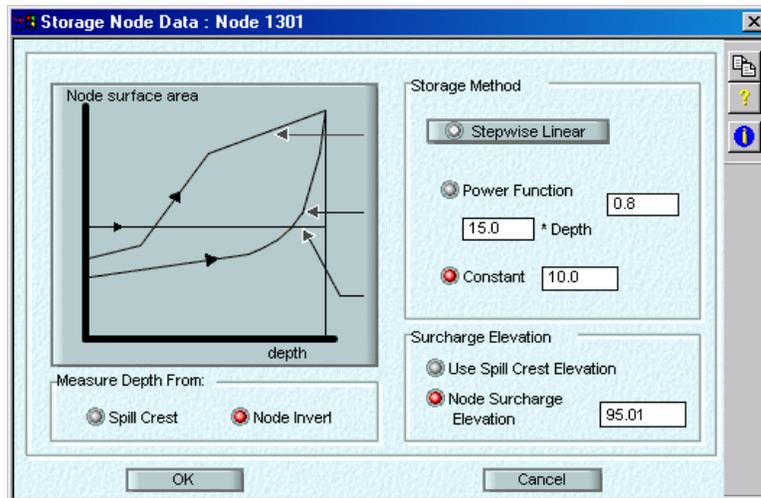
Figure 3-30. Storage node simulation screen.

3.3.3.2 Testing Results

Constant Storage Area

Constant area storage of 5,000 square feet with the bottom of the storage facility located at the invert was used in this test. Figure 3-31 shows the simulated and calculated water levels for the test. The test used the XP-SWMM reported inflow and outflow from the node. The small difference in water levels may be due to the head (or water level change) tolerance set in XP-SWMM for the simulation. The volume of storage used in upstream links impacts the test results.

Stepwise Linear

Figure 3-32 shows the result for a storage facility with surface area varying with water depth. One feature of the stepwise linear function is that surface area is in acres rather than square feet as used in other storage options. There is presently an inconsistency in the use of units in the stepwise linear function. Flows used in the test are based on XP-SWMM reported inflow and outflow from the storage facility. XP-SWMM reported lower water levels than predicted from the change in storage due to the imbalance between inflow and outflow reported in the XP-SWMM results at the facility. The difference in elevation is less than 0.2 feet. XP Software should consider review of linear storage calculations.

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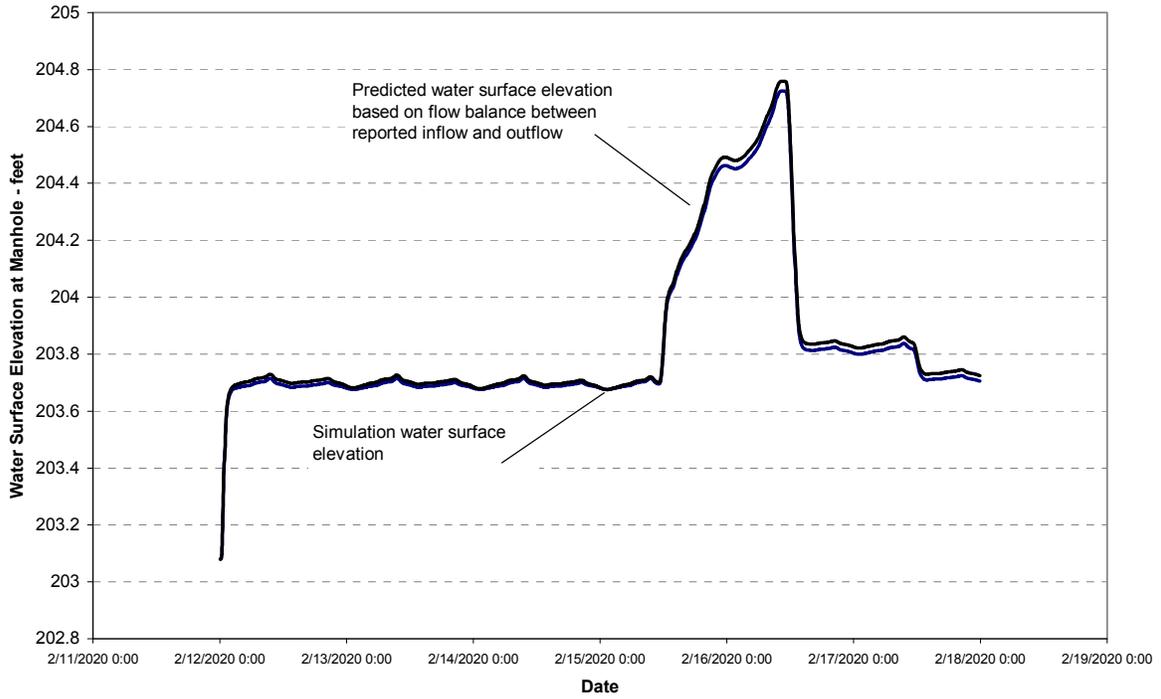
Figure 3-31. Constant storage manhole-dry conditions.

(a)
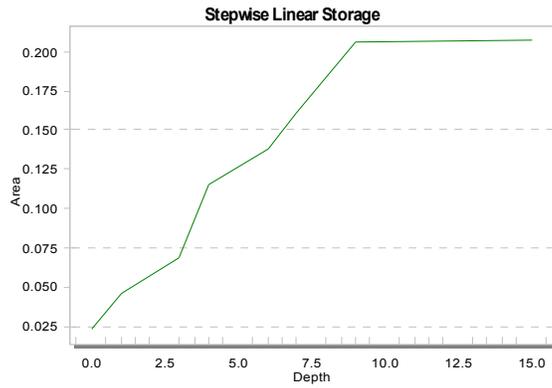
Note: Figure 3-32(a) is screen capture of XP-SWMM, Area is in acres, depth in feet.

(b)
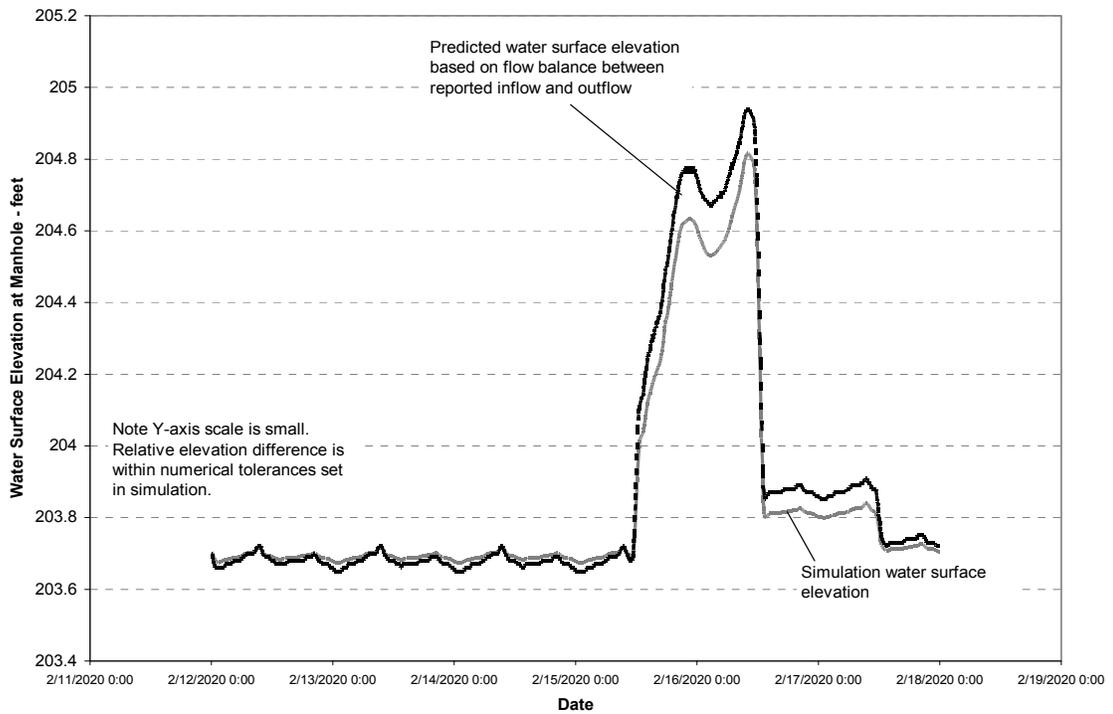
Figure 3-32. Linear storage manhole-wet start conditions.

Power Function

A power function that relates depth to storage surface area was entered into XP-SWMM. The relationship is given by:

$$\text{Surface area} = \text{Constant} \times \text{depth}^N \qquad (3\text{-}3)$$

A value of 2000 was entered into XP-SWMM for the Constant in this equation, and a power value of 5 for "N" to complete the equation. The power function used the same collection system and inflows as in the other two storage options. Figure 3-33 shows the difference between XP-SWMM-simulated (model-generated) and water levels predicted based on the reported inflow and outflow. The simulated water levels are slightly higher than the predicted water levels during the high water levels. After the storm peak, the inflow and outflow are in balance; the water level should not change significantly. The drop in water level after the storm peak is reasonably simulated. The difference in peak water levels is less than 0.2 feet, with the difference most likely due to the simulation tolerances used in the simulation and the prediction worksheet. Since the water level differences are small, the test result is acceptable given the reported flow results and difference in water levels throughout the simulation period.
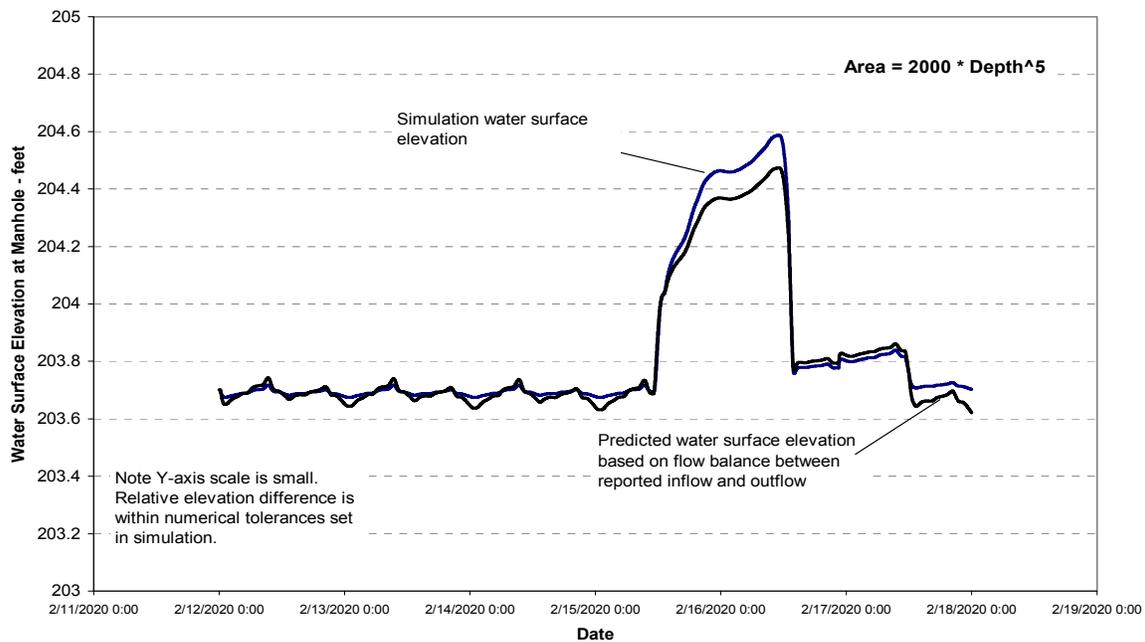
Figure 3-33. Power storage manhole-wet start conditions.

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3.3.4 Node Inlet Capacity Function Testing

The purpose of testing the node inlet capacity was to confirm that when inlet capacity at a node is specified, the maximum inflow to the node is limited to the capacity specified. Also, this test was conducted to demonstrate the fate of water stored or lost at the node when the inlet capacity specified was exceeded.

3.3.4.1 Testing Procedure

Data for a flow hydrograph was entered into XP-SWMM for the upstream node of a simplified pipe network. Inlet capacity at the node was specified so that the maximum inlet capacity is less than the peak of the hydrograph.

3.3.4.2 Testing Results

Constant Inlet Capacity

Figure 3-34 shows the inflow hydrograph and resulting flow in the downstream receiving pipe. The inlet capacity limits flow only when inflow exceeds the maximum capacity specified in XP-SWMM. The inlet maximum flow function simulation by XP-SWMM does represent the actual inlet maximum flow in the downstream receiving pipe.
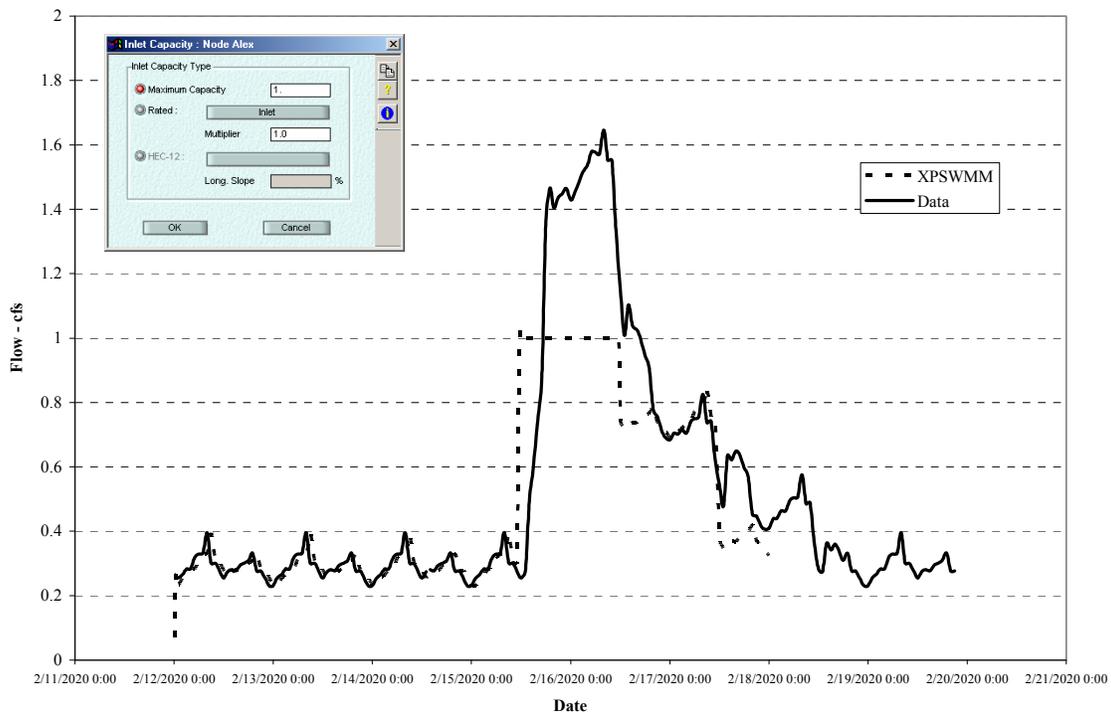
Figure 3-34. Inlet control by maximum inlet capacity.

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<u>Inlet Controlled by Rating Curve</u>

The hydrographs in Figure 3-35 show the input hydrograph and result from XP-SWMM with a flow rating curve that reduces flow based in the inflow rate. In the test, the inlet capacity was limited to 0.3 cfs if inflows were less than 0.5 cfs or greater than 2 cfs. For inflows between 0.6 and 1.0 cfs, the inlet capacity was set at 0.6 cfs. XP-SWMM interpolates inlet capacity for inflows on the two shoulders of the rating curve (for example, when inflows are in the 1.4 to 1.6 cfs range).

Figure 3-35. Inlet control by rating curve.

XP-SWMM simulations of inlet control with maximum inlet capacity or through a rating curve performed as expected. The flow was intended to be controlled to a maximum rate through a rating curve, and that is what was simulated and reported in Figures 3-34 and 3-35.

3.3.5   Surface Ponding and Other Flooding Control Function Testing

This test was performed to confirm that when surface flooding and ponding occurs at a node, the volume of water flooded or ponded at the node is correctly simulated. The volume of flow lost, ponded, or flooded should be appropriately accounted for in the water balance of the node volumes.

3.3.5.1 Testing Procedure

A flow hydrograph to cause flooding at a downstream node was entered at an upstream node of a simplified pipe network. Flooding conditions were modified to one of the following three options during testing: flooded, sealed, or ponding allowed.

3.3.5.2 Test Results

Normal node condition

The general condition in a model such as XP-SWMM is that when flooding occurs at a node, the volume of flow is lost to the collection system unless captured by another collection system and therefore maintained in the overall system. The result when the volume is not maintained is usually a reduction in flow between upstream and downstream pipes, as shown in Figure 3-36. The difference calculated from the inflow pipe hydrograph and the downstream hydrograph is 35,526 cubic feet. The flooding volume reported in the XP-SWMM output file is 33,663 cubic feet, with 1,987 cubic feet accounted for in the storage change. The difference in calculated volume and flooding/storage change is therefore about 100 cubic feet, or less than 5 percent difference.
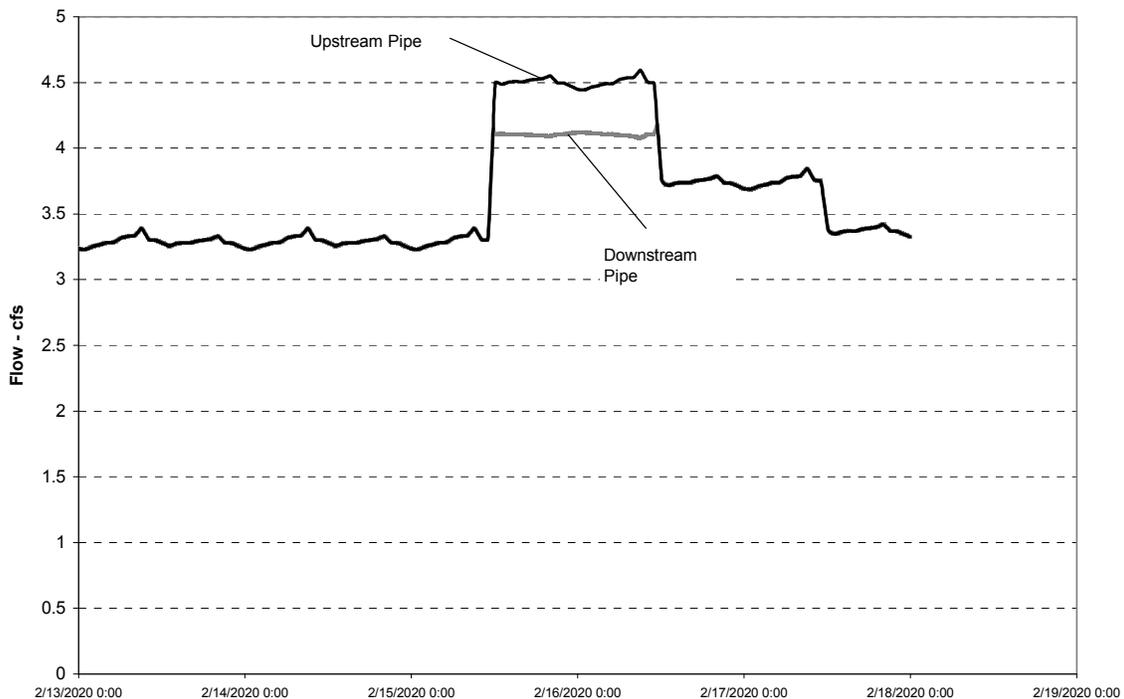
Figure 3-36. Flooding manhole with flow lost to system.

Sealed Manhole

Sealing a node will result in no flooding, but will cause a rise of hydraulic grade line above the manhole rim. Flows into and out of a manhole should be the same. Figure 3-37 shows the inflow and outflow hydrograph generated by XP-SWMM. As you can see from these hydrographs, the influent and effluent flows are the same. Figure 3-37 also contains an insert showing the water surface elevation at the sealed node, with the water level (hydraulic grade) about 1.5 feet above the manhole rim elevation.
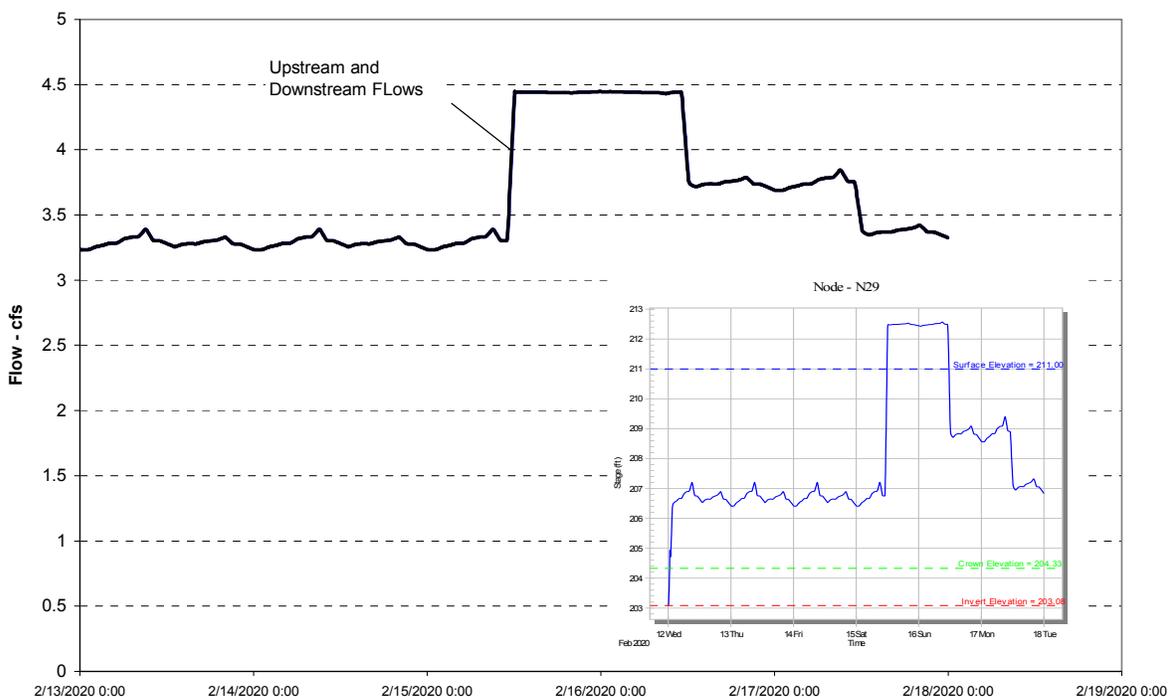
Figure 3-37. Sealed manhole hydrographs and water surface elevation (insert).

Ponding-Allowed Manhole

Ponding allows capture of flows back into the collection system whenever collection system capacity is available. Storage occurs at a pre-described depth-storage-area relationship. For testing, storage was a function of depth with a relation of storage area in square feet equal to 5000 x e^1 ft^2 (e = 2.3). Figure 3-38 shows the upstream and downstream hydrographs for the simulation and an insert showing the depth of ponding above the manhole rim. Labels in this figure indicate periods when flows were stored at the node, and when flows were captured once collection system capacity was available. Inflow and outflow pipe flow volumes were within 0.1 percent (1,930 cubic feet out of a simulated total flow volume of 1,849,000 cubic feet).

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Node - N29
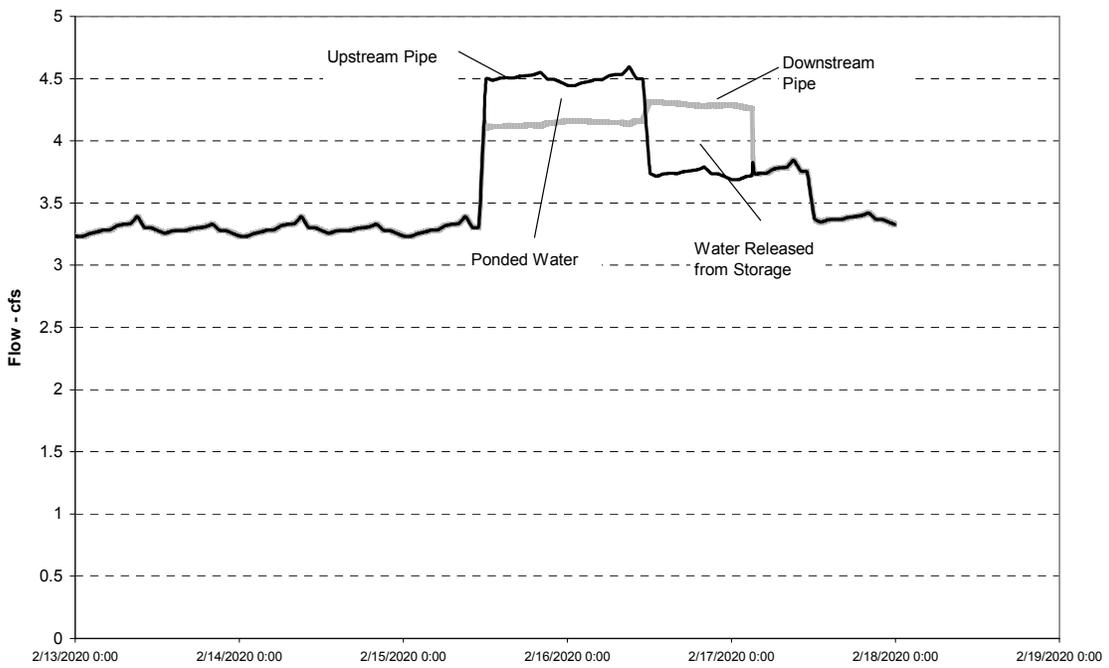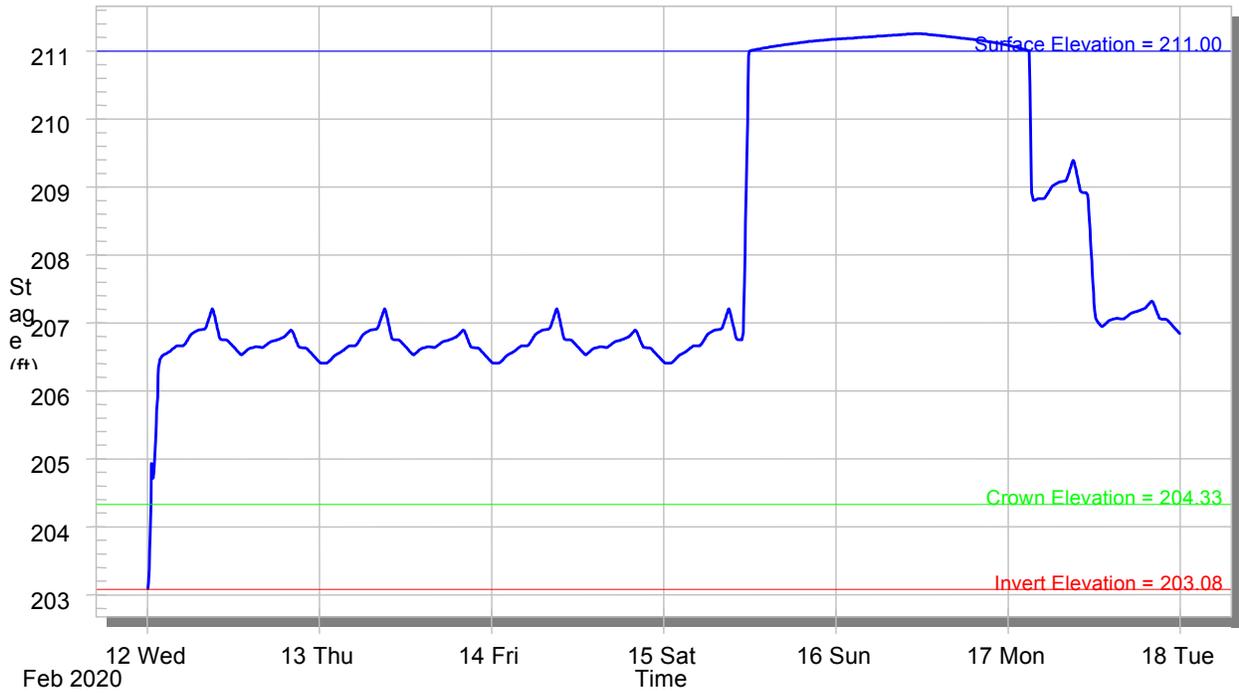
Figure 3-38. Ponding-allowed manhole.

3.3.6   Outlet Control Functions at Terminus Node Testing

3.3.6.1 Testing Procedure

Options for specifying tailwater conditions at an outlet node are shown in Figure 3-39:
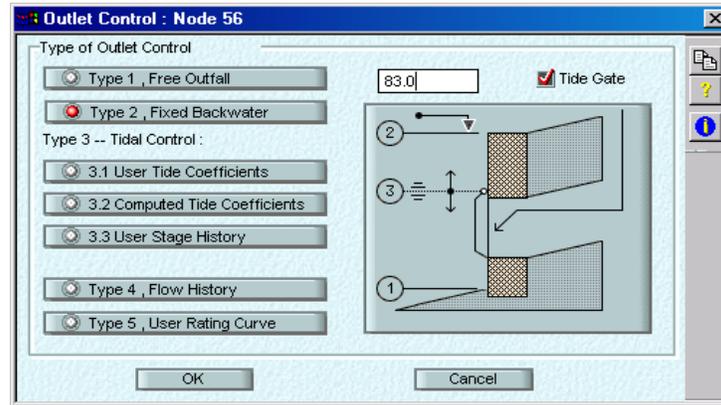
Figure 3-39. Example of specifying options for tailwater conditions at outlet mode.

The tests conducted assigned one of the following outlet conditions: free outfall, fixed backwater, tide elevations, or tidal cycles. The backwater effects and water levels reported for each of these outlet conditions were simulated in XP-SWMM and compared with calculated values.

3.3.6.2 Testing Results

Free Outfall

With a free outfall, no backwater effects are simulated. The flow 'drops' off the end of the pipe and, in most instances, the water surface profile will pass through critical depth near the outlet. This results in the water surface profile being steeper than the channel or pipe bed slope. This can occur in most instances but particularly in larger diameter pipes with low flow. To test a free outfall, the critical depth was computed for a circular pipe and the subsequent flow rate was computed based on the critical depth. This flow should match the flow given in XP-SWMM for the pipe. Figure 3-40 shows the comparison of the XP-SWMM results with calculated flow (based on critical depth) matching the simulated flow. One possible small discrepancy in the model results that is not discernable in Figure 3-40 is that the critical depth does not occur at the drop but a small distance upstream.
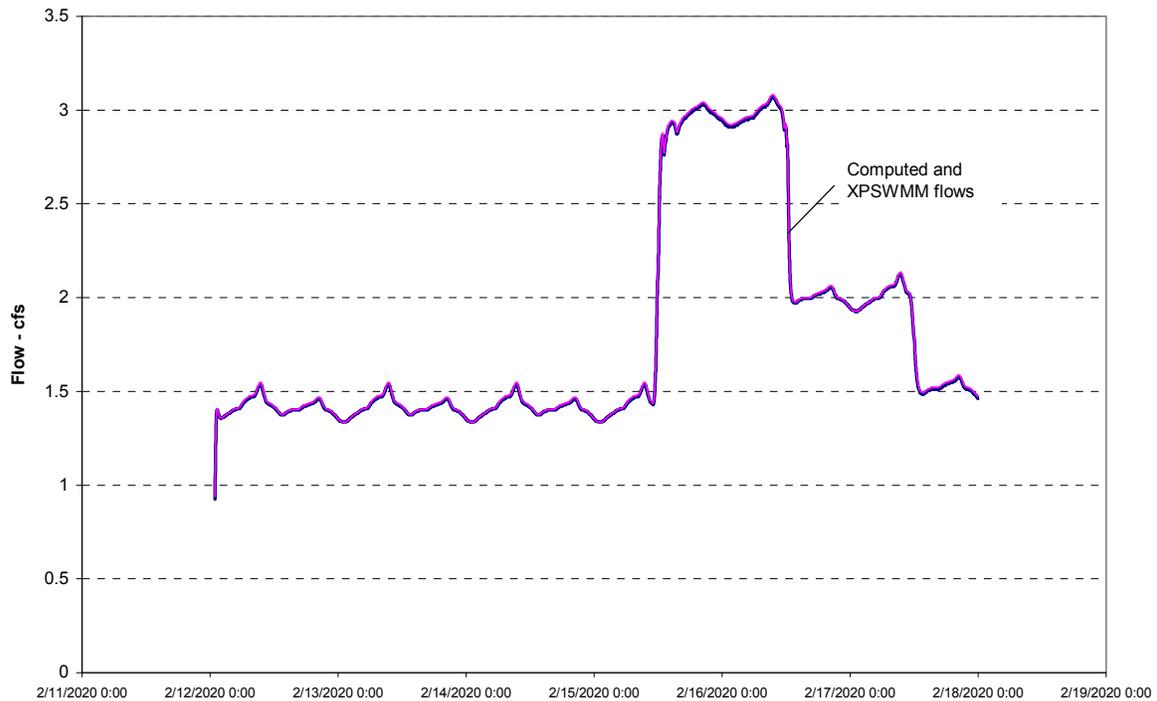
Figure 3-40. Computed and simulated flow at free outfall.

Fixed Backwater

With a submerged outfall, the water level at the outlet will be higher than the crown of the outlet pipe, thus causing backwater effects upstream in the pipe. The upstream hydraulic grade line will rise. Manning's equation was used to check the friction slope under this condition to confirm that the values simulated by XP-SWMM are correct. Figure 3-41 shows the computed head loss in a pipe subject to a submerged outlet compared with the XP-SWMM-simulated head loss (based on the difference between upstream and downstream elevations). The upper graph on Figure 3-41 shows the upstream and the fixed downstream water surface elevations and flow through the pipe.
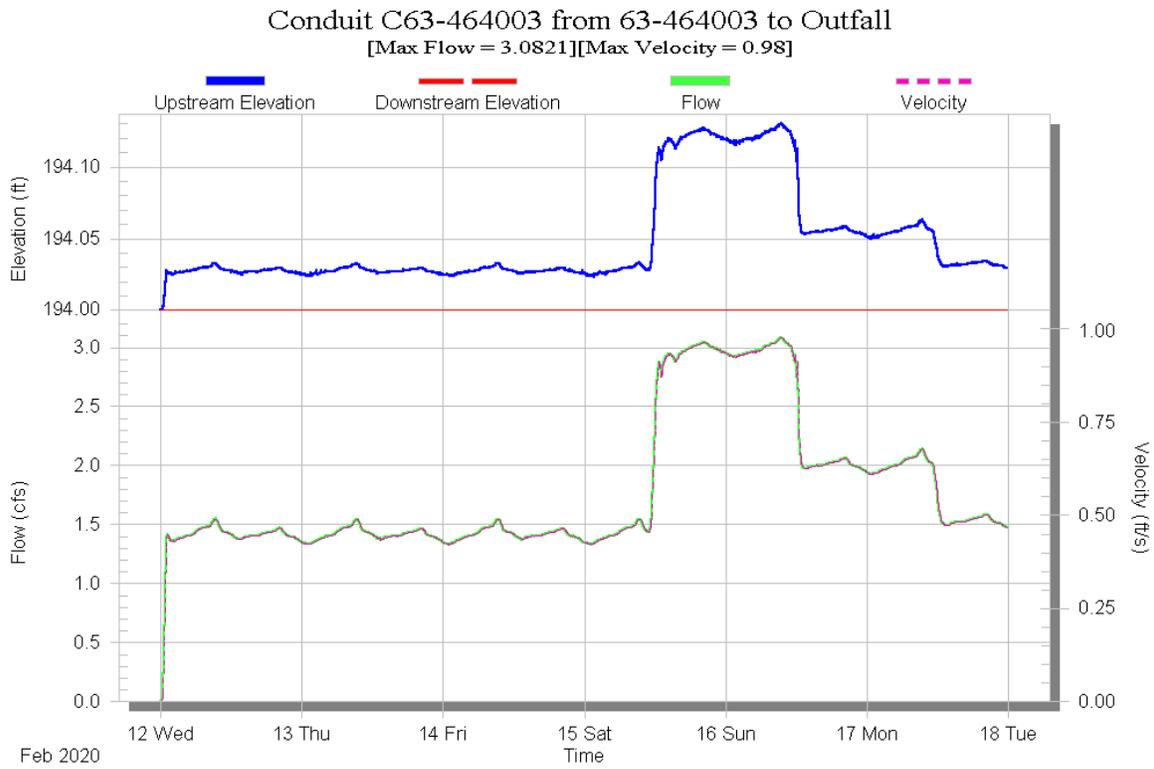
(a)
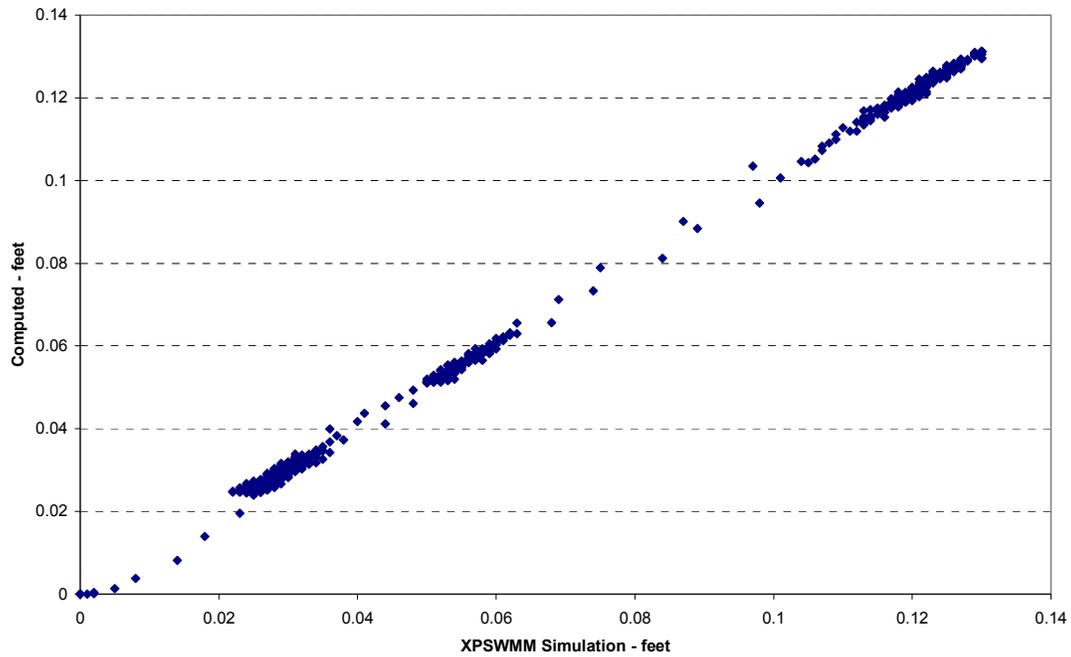
(b)

Figure 3-41. Comparison of simulated and computed head loss in pipe-fixed backwater.

Tidal Conditions

The tide level can be steady and fixed, varied according to a sinusoidal curve, or user specified pattern over time. One function of XP-SWMM allows calculation of the tidal coefficients from points describing the high and low tide cycles. This function did not work in the version supplied for testing.

Representative tidal coefficients (Astoria, Oregon) were entered into the outfall test model. Figure 3-42 shows the input screen.
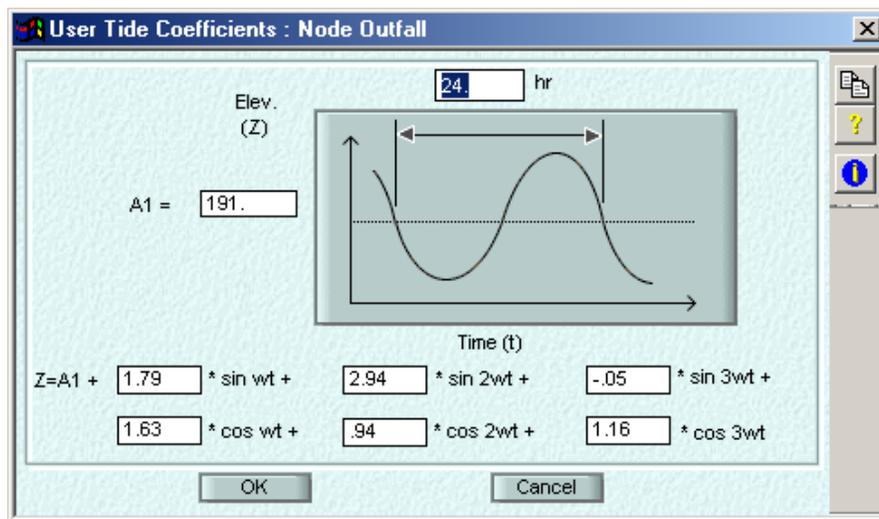
Figure 3-42. Tide coefficient input screen.

The value of A1 is a base elevation that is just above the pipe invert elevation (elevation 190 feet). This base elevation and the tidal coefficients result in a high tide elevation of about 196 feet and a low tide elevation of about 186 feet respectively. Therefore, the pipe is free flow at times and subject to tidal backwater at other times. The test model did not assume a tide gate so flow could enter the system from the tidal outlet location, resulting in flow entering and leaving the system depending upon tides and collection system flows.

Figure 3-43 shows the simulated results with tidal influenced flow reversals, and no tidal effects when collection system flow increases. Figure 3-44 illustrates a shorter time period with annotations to confirm the simulated results.
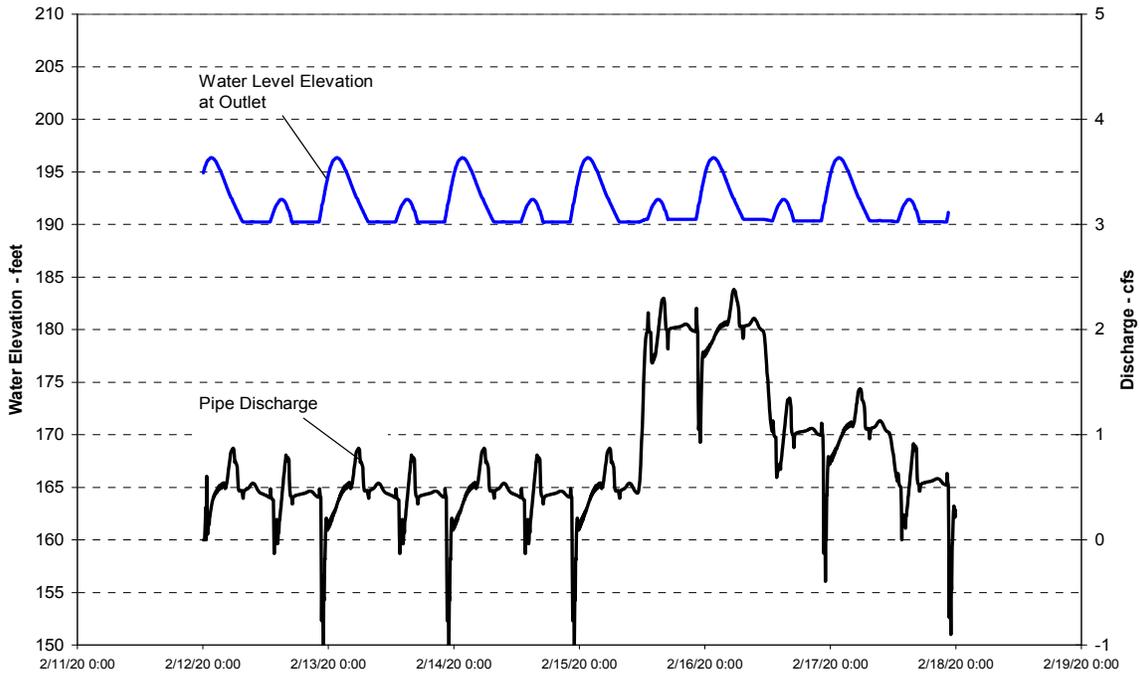
Note: The time scale is in days .

Figure 3-43. Water surface elevations and discharge with tidal outfall.
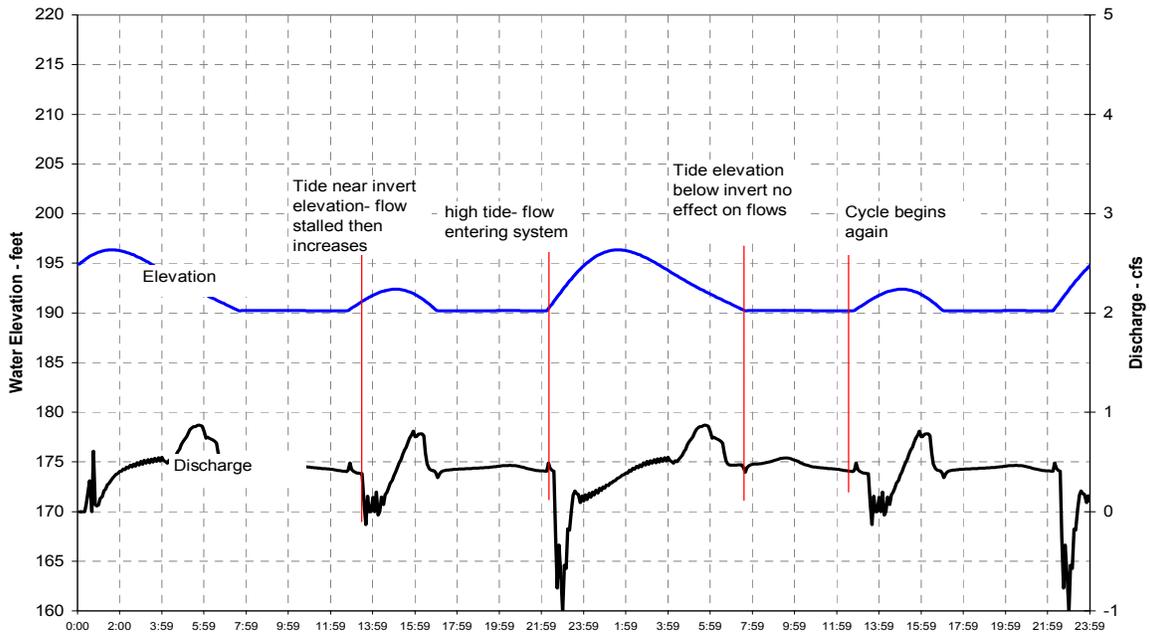
Note: The time scale is in hours.

Figure 3-44. Elevations and flow with tidal outfall.

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3.3.7 Link Specification Evaluation

3.3.7.1 Manning's Roughness Coefficient Testing

The test phase was conducted to confirm that Manning's Roughness Coefficient specified for a conduit is appropriately included by XP-SWMM.

3.3.7.2 Testing Procedure

A simple network was used with a constant 11 ft^3/sec flow to simulate both open channel and pressure flow. The pipe network consisted of three pipes with a free outfall at the terminus node. Four Manning's Roughness coefficients, ranging from 0.0075 to 0.024 were simulated. The results for the middle pipe of the network was used in the evaluation (values used are shown in Figure 3-45 below).
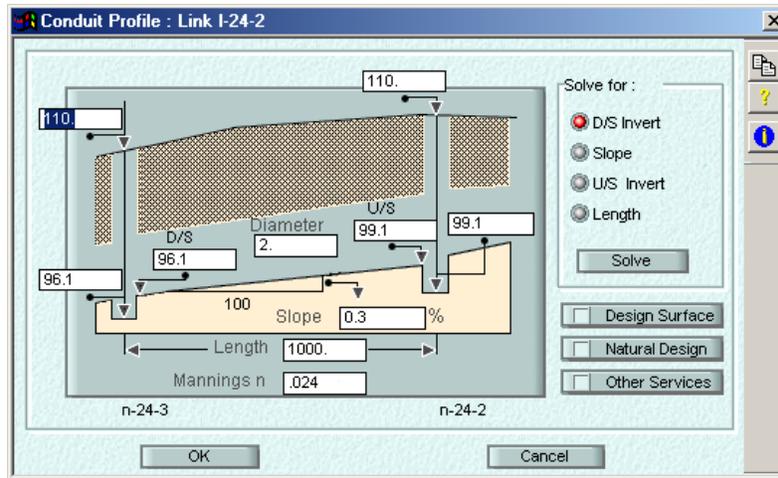
Figure 3-45. Conduit Profile data entry screen.

3.3.7.3 Testing Results

The hydraulic energy equation of flow in a pipe is equal to kinetic energy, plus pressure head (when under surcharge), friction loss, and water elevation. When a pipe has open channel flow, the slope of the hydraulic grade line (friction slope) is approximately equal to the invert slope of the pipe, because the pressure head is zero and there is little friction loss. When a conduit is under surcharge, the pressure head and friction slope will increase because of larger losses. The slope of the hydraulic grade line and the head losses calculated by XP-SWMM were compared with hand calculations using Manning's and/or Darcy-Weisbach equations for open channel flow and pressure flow, respectively.

Table 3-3 shows a comparison of XP-SWMM-simulated values to values calculated using Manning's equation derivation.   This test relates to the principle that changing roughness results in higher head losses and lower flow capacity through pipes. Calculated values are based on area

and hydraulic radius reported in XP-SWMM output. The area and hydraulic radius values reported by XP-SWMM for a pipe flowing full match the values for a 2-foot diameter pipe used in the simulation. Intermediate values for area and hydraulic radius during open channel flow conditions also match expected values. However, the results for pressure flow should have been 3.142 square feet, but were actually 3.185 square feet (for a 2-foot diameter pipe flowing full).

Table 3-2. Comparison of Simulated and Calculated Flows and Head Loss for Varying Manning's Roughness Coefficients

Values of Manning's Roughness Coefficient	Full Pipe Design Flow		Headloss	
	Simulated	Calculated	Simulated	Calculated
0.0075	21.48	21.48	3.00	3.00
0.012	13.42	13.42	2.97	2.92
0.014	11.51	11.51	2.97	2.95
0.024	6.71	6.71	7.85	7.84

3.3.8 Pressure Flow Versus Open Channel Flow Computation Testing

3.3.8.1 Testing Procedure

This testing phase was performed to confirm that the hydraulic grade line and flows are calculated correctly for open channel and pressure flow conditions. When the water surface slope is larger than the pipe bed slope, increased flow can occur. Conversely, when the water surface slope is less than the bed slope, less flow occurs. A constant flow was introduced at the upstream end of a pipe network and routed through the system. Conduit sizes were varied to create pressure and open channel flow regimes. Under pressure flow, the system was surcharged by sealing manholes. A sustained surcharge was created by maintaining a constant high peak flow to produce a stable hydraulic grade line as shown in Figure 3-46.

3.3.8.2 Testing Results

The water levels (i.e. hydraulic grade line) during pressure flow exceeded the uppermost crown of the incoming and outgoing pipes at manholes and rose above the rim elevation of the sealed manholes. The simulated fall in the hydraulic grade line over the three fully pressured reaches was 16.17 feet compared with a calculated value of 16.89 feet. The simulated value was obtained from the reported maximum water surface elevations at the upstream and downstream manholes of the three-pipe reach. The calculated value was estimated from Manning's Equation for full pipe flow. The velocity head through the system is about 0.5 feet. It was expected that the simulated head loss would be higher than the calculated values because of manhole and other minor losses.

Although the difference in head loss (about 0.7 feet in 2,300 feet of pipe length) is relatively small (about 4 percent), the relative magnitude with the simulated value being less than the calculated one implies a problem.
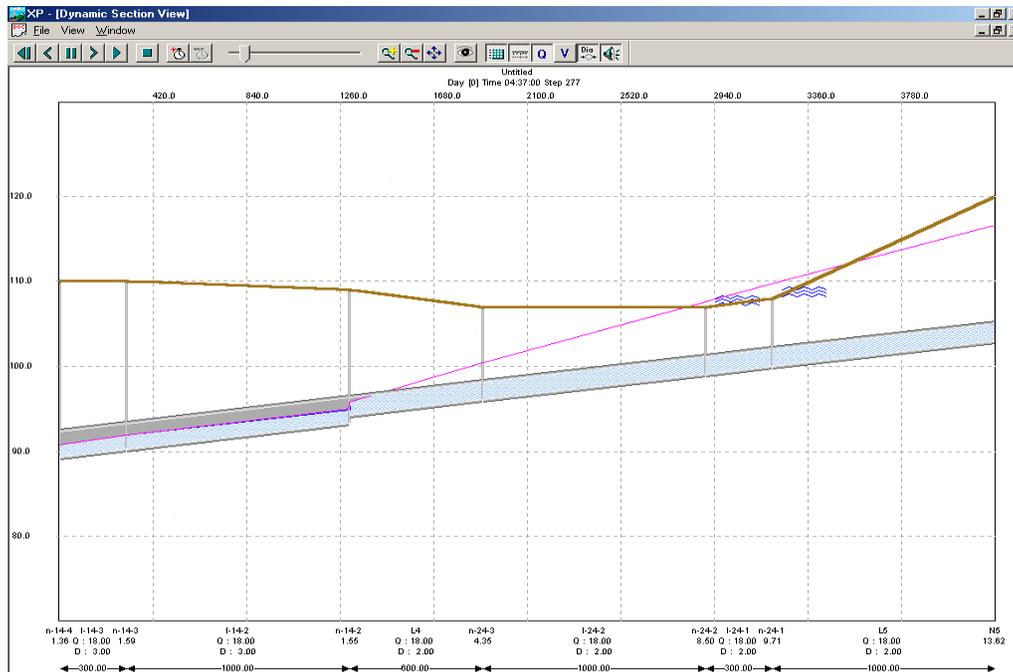
Note: Vertical axis is elevation in feet.

Figure 3-46. Pressure flow hydraulic profile.

3.3.9   Verify Flow Directions in a Conduit are Modeled as Specified

This test was performed to assure that XP-SWMM would limit flow directions in a conduit to uphill only, downhill only, or free flow. The simulations were designed to demonstrate the consequences upon simulated flows of activating pipe flow direction control within XP-SWMM.

3.3.9.1 Testing Procedure

By default, the flow direction in a pipe was set by the relative water level differences between upstream and downstream nodes. The program user specifies directional limits, as shown in Figure 3-47.
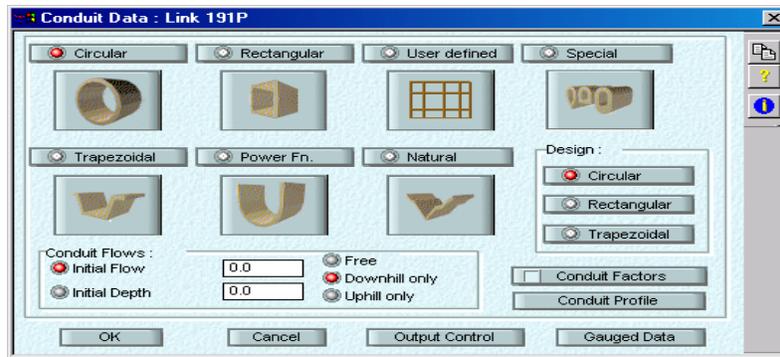
Figure 3-47. Directional limit options.

Inflow and diurnal hydrographs were entered into a pipe network and routed through the system. A pump station that caused the system to surcharge and flow 'uphill' to relieve flow at an overflow weir controlled the outlet of the collection system. This is a common configuration in collection systems.

When elevations at the downstream end of the conduit were higher than upstream elevations, reverse flow occurred as shown in Figure 3-48(a). Negative flow can occur in the conduit if the "free flow direction" (the default condition in XP-SWMM) is selected for the conduit. When the program user selects the "downhill only" option, reverse flow did not occur as shown in Figure 3-48(b). With the more extreme uphill only, reverse flow or uphill flow was allowed, but not downhill flow as depicted in Figure 3-48(c).
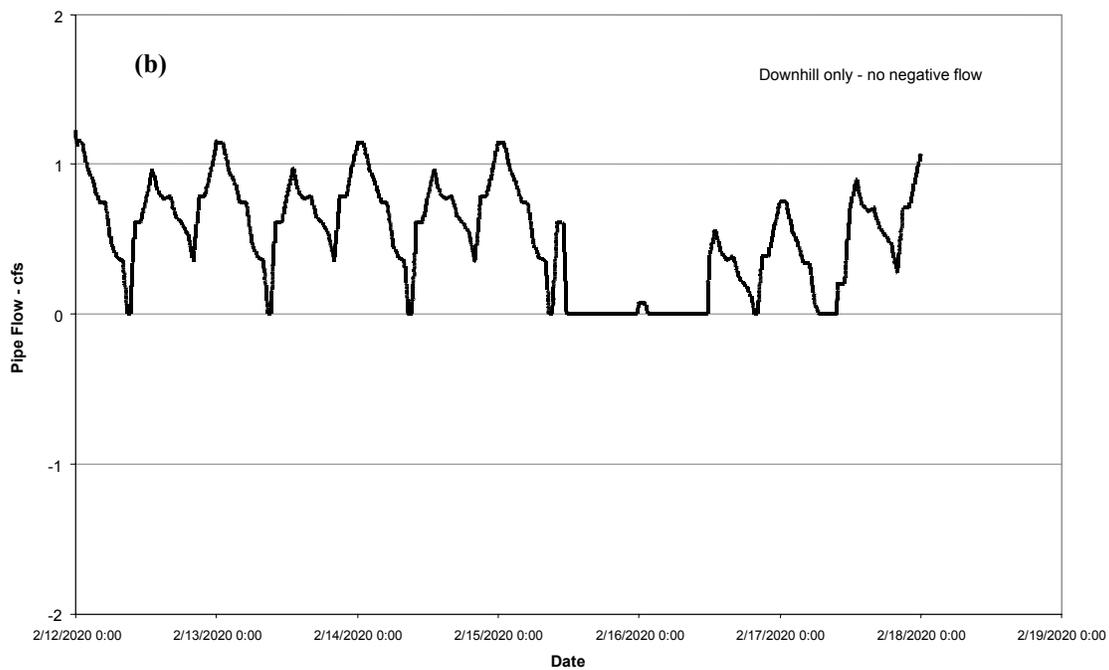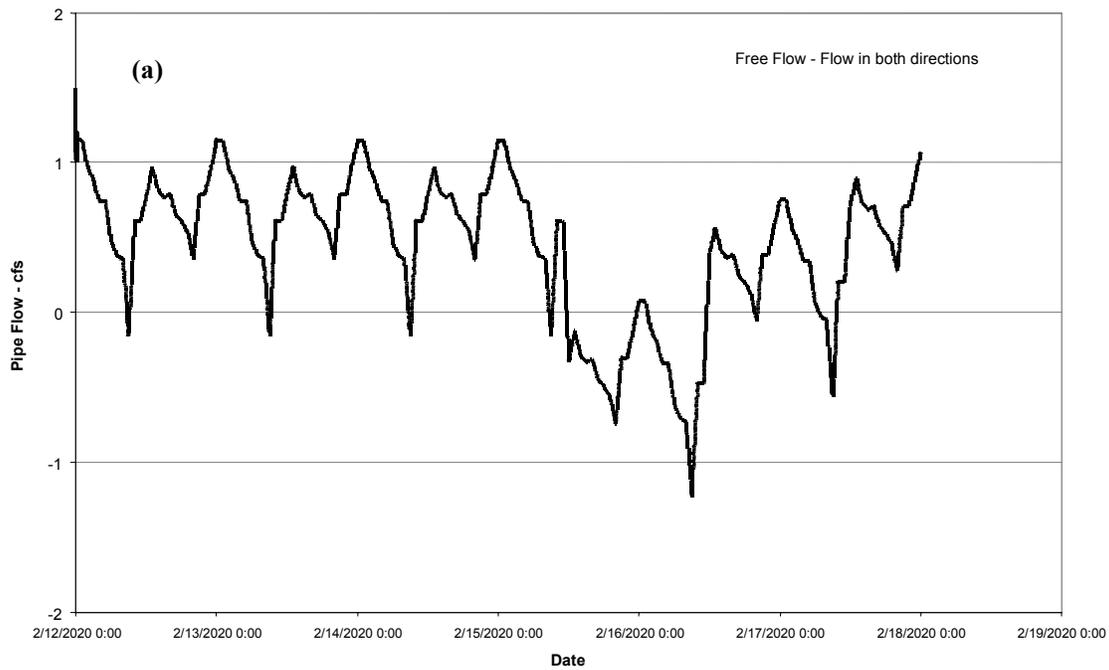
Figure 3-48. Flow direction simulations for pipes.

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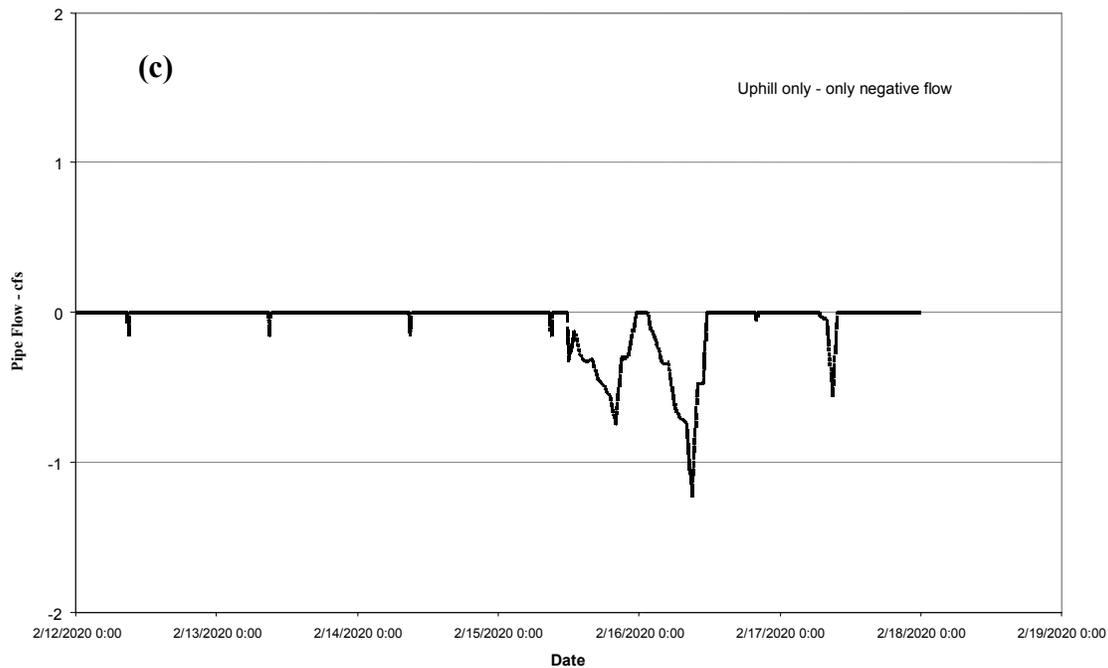
Figure 3-48 (continued). Flow direction simulations for pipes.

3.3.10 Testing of Flow Routing in Different Conduit Shapes

Testing of flow routing in different conduit shapes was conducted to determine whether flow depths and discharge are correctly simulated on a consistent basis when flows are routed through different shaped pipes, given the variations represented in depth-area-hydraulic characteristics.

3.3.10.1   Summary of Testing Procedure

Flow hydrographs were entered into a pipe network in XP-SWMM and routed through the system. Different shapes of pipes were specified, including ones that are commonly used or representative of other shapes: circular, rectangular, egg-shaped, horseshoe, and user-defined shapes.

Each pipe shape was tested with a steady flow and under open channel flow conditions. Flow was introduced into a pipe network in the model and simulated to produce steady conditions. Flow properties should follow the hydraulic properties of each shape, defined by: 1) flow depth and hydraulic radius; 2) flow depth and flow area; and 3) flow depth and velocity. Hydraulic properties for a pipe shape in XP-SWMM are pre-programmed with specific hydraulic curves in the computer program (as shown by Figure 3-49 for an egg-shaped pipe).
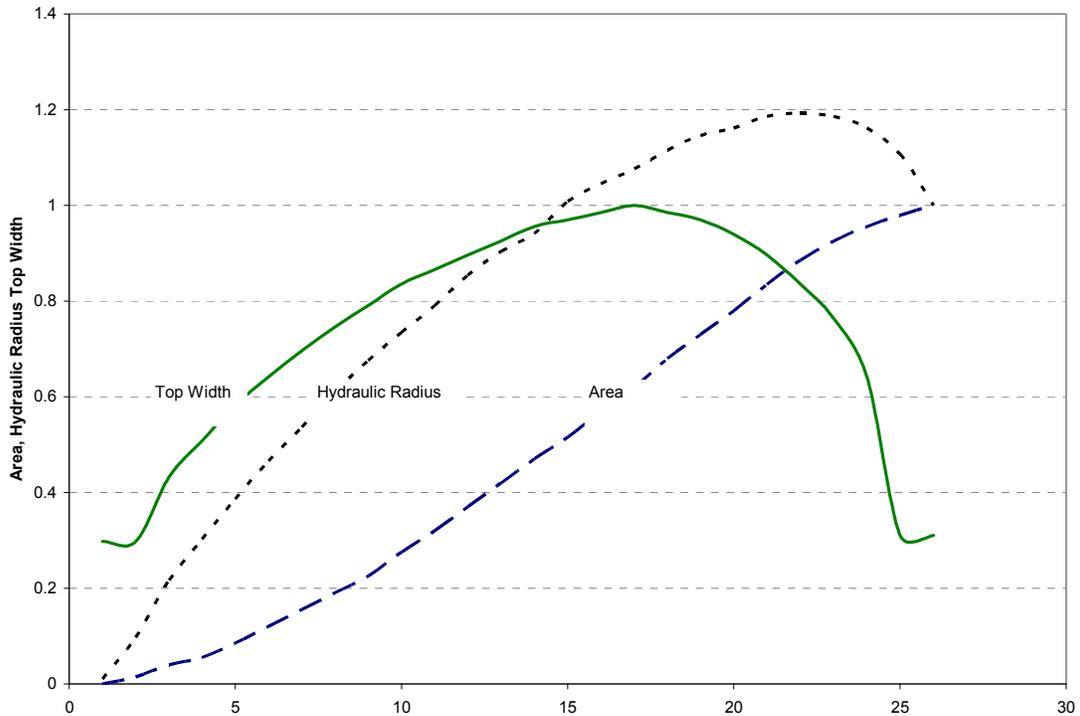
Figure 3-49. Normalized hydraulic properties – egg shaped pipe.

3.3.10.2   Testing Results

Standard Shapes

Table 3-4 shows the results of simulated and calculated hydraulic properties and flows for standard pipe shapes at a constant flow of 11 cfs. The egg-shape pipe cannot carry the flow and surcharges, and flows under pressure. The calculated flow for the pressurized egg-shaped pipe is based on the water surface profile, rather than the bed slope. Generally, the third pipe in the network is affected by the outlet (free outlet), which pulls down the hydraulic grade line. The results from simulations match with hand calculations for the pipe shape.

"Max Q" is the XP-SWMM reported value; the last column (calculated flow) in this table is the hand calculated value.

Table 3-3. Simulation and Calculated Hydraulic Properties and Flows

Link	Deep -feet	Width - feet	Shape	Special	Rough	Max Area – square feet	Max Hyd Radius - feet	Max Top Width - feet	Max Head Loss - feet	XPSWMM Max Q - cfs	Max V - fps	Max Depth - feet	Hand Calculated Flow - cfs
I-24-1	2		Circular		0.014	2.64	0.61	1.65	3.82	11	4.17	1.57	11.0
I-24-2	2		Circular		0.014	2.66	0.61	1.63	3.79	11	4.13	1.60	11.1
I-24-3	2		Circular		0.014	2.35	0.58	1.77	4.57	11	4.67	1.60	9.6

Link	Deep	Width	Shape	Special	Rough	Max Area	Max Hyd Rad	Max Top W	Max Head Loss	Max Q	Max V	Max Depth	Calc Flow
I-14-1	2		Special	Egg	0.014	2.09	0.39	0.01	8.01	10.484	5.01	10.000	10.49
I-14-2	2		Special	Egg	0.014	2.07	0.39	0.01	8.10	10.484	5.06	8.516	10.49
I-14-3	2		Special	Egg	0.014	1.86	0.42	0.56	8.30	10.484	5.65	3.407	10.53

Link	Deep	Width	Shape	Special	Rough	Max Area	Max Hyd Rad	Max Top W	Max Head Loss	Max Q	Max V	Max Depth	Calc Flow
I-12-1	2		Special	Horseshoe	0.014	2.64	0.61	1.77	3.83	11	4.16	1.47	11.0
I-12-2	2		Special	Horseshoe	0.014	2.67	0.61	1.75	3.78	11	4.12	1.50	11.1
I-12-3	2		Special	Horseshoe	0.014	2.37	0.58	1.84	4.59	11	4.64	1.50	9.6

Link	Deep	Width	Shape	Special	Rough	Max Area	Max Hyd Rad	Max Top W	Max Head Loss	Max Q	Max V	Max Depth	Calc Flow
I-075-1	2	3	Rectangular		0.014	2.75	0.57	3.00	3.99	11	3.99	0.92	11.0
I-075-2	2	3	Rectangular		0.014	2.82	0.58	3.00	3.82	11	3.90	0.97	11.4
I-075-3	2	3	Rectangular		0.014	2.60	0.55	3.00	4.48	11	4.22	0.97	10.1

User-Defined Shapes

Non-standard shapes are often simulated in collection systems. These non-standard shapes are defined by a table of hydraulic properties that relate depth with area, hydraulic radius (or wetted perimeter) and top width. An example of a non-standard pipe shape is shown in Figure 3-50 .
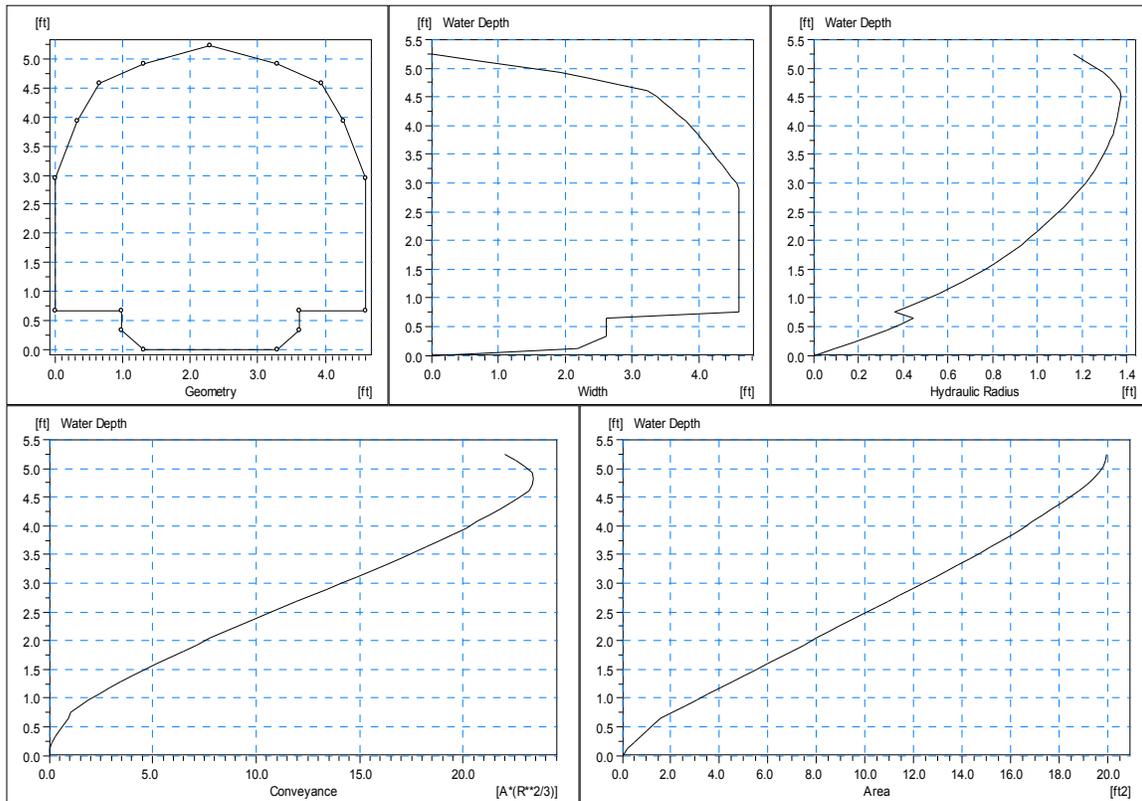
Figure 3-50. Examples of user-defined pipe shape profiles.

This user-defined pipe shape was simulated for a variety of flow conditions, and the reported area and hydraulic radius were compared with the hydraulic properties of the shape. The shape has a low flow channel and "sidewalks" that can affect the flow regime in the transitional area between the low flow channel and the pipe area above the "sidewalks." Figures 3-51 and 3-52 show the comparison between simulation results and input hydraulic properties for area and hydraulic radius, respectively, for the range of simulated flows.

 The reported values for area, hydraulic radius and top width generally match what would be anticipated based on the input hydraulic properties of the user-defined shape. The exception to this is the value for the maximum hydraulic radius when the pipe is flowing full or nearly full (refer to the 132 cfs condition in Figures 3-51 and 3-52).   The program reports higher values than anticipated for the three pipes in the network. At higher flows, when the pipe is surcharged, the maximum area and maximum hydraulic radius are reported as anticipated.

User Defined Hydraulic Radius with Depth
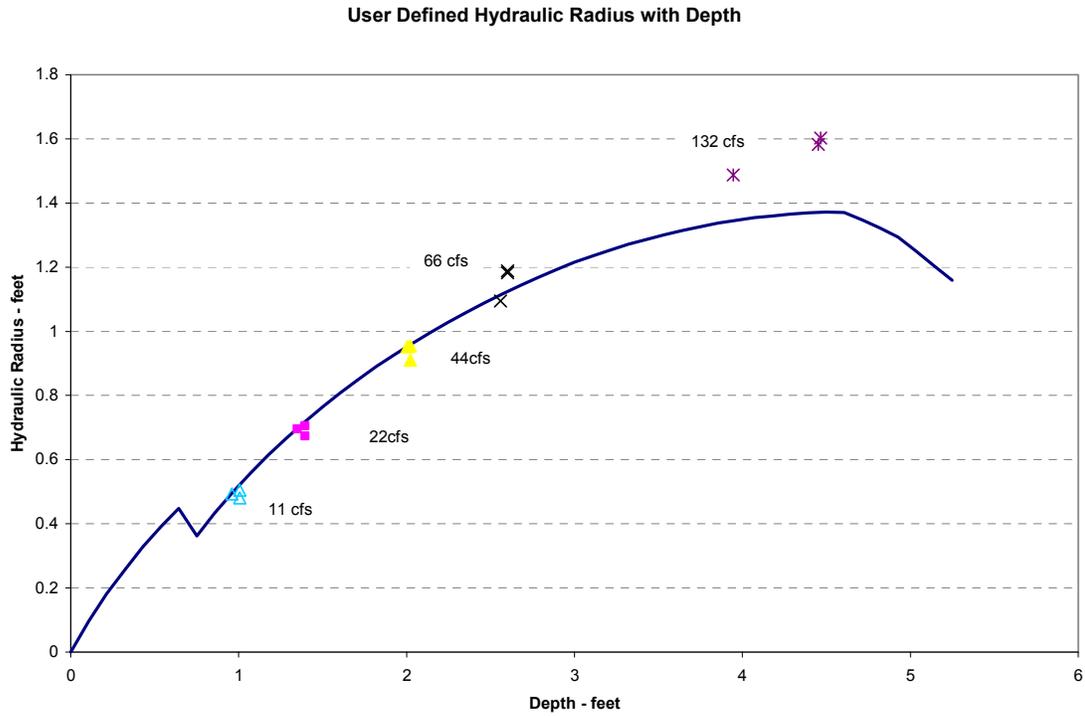
Figure 3-51. Simulated area and input pipe property with depth.

User Defined Area with Depth
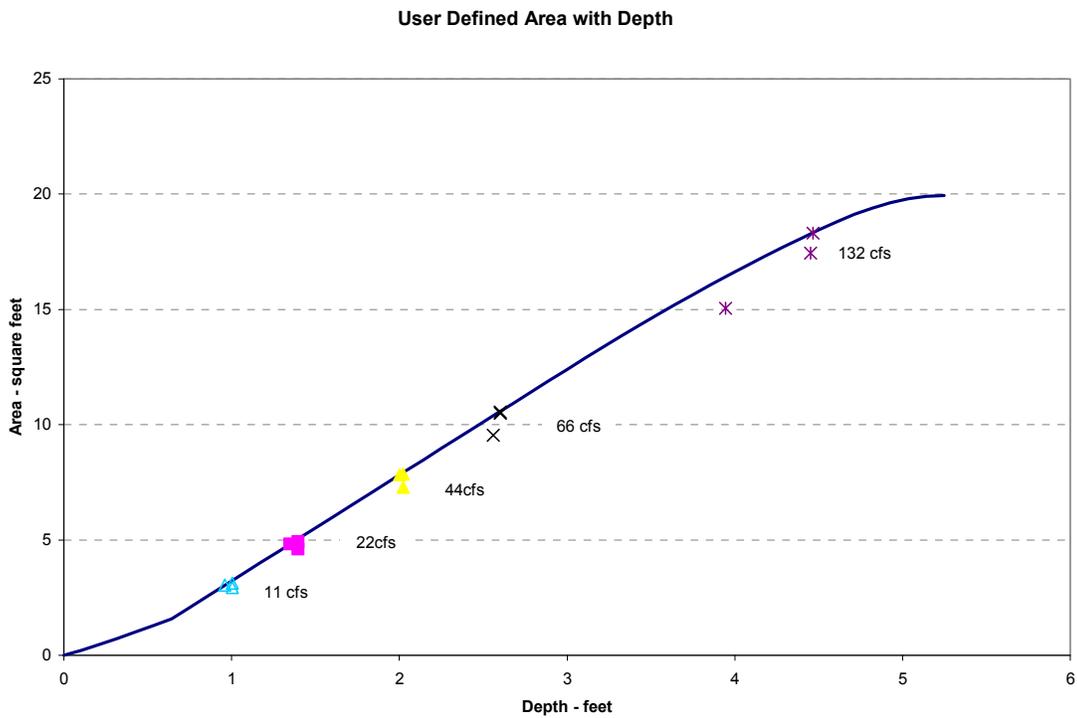
Figure 3-52. Simulated hydraulic radius and input pipe property with depth.

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3.3.11 Entering Gauged Flow Data for Calibration Testing

The purpose of this test phase was to confirm that gauging data are correctly input by XP-SWMM, and are correctly used by XP-SWMM for comparison and calibration of conduit flows.

3.3.11.1 Testing Procedure

Computer model simulation results are typically compared with gauged flow or level data. To facilitate the comparison, XP-SWMM has procedures for entering data in a user-defined format. It is important that gauge data are read and displayed correctly. A flow hydrograph from gauged data was prepared in an ASCII text file (comma separated file) that contained location, date, time and flow values. A similar file was prepared for water levels. The flow hydrograph and flow levels were collected as part of a modeling study with the pipe flow and water levels simulated in a XP-SWMM model. Gauge flow data are attached to a network link and gauged water level data to a network node.

3.3.11.2 Testing Results

Figure 3-53 shows a comparison of gauged data and simulated data from an XP-SWMM model. Testing of options in XP-SWMM allow for introduction of gauged flow to manholes for setting boundary conditions or for calibrating the hydraulics of the system. The thinner line represents the read gauged data and the heavier line the simulated data. The read data matches the raw gauge flow file and is read correctly. Similarly Figure 3-54 shows a comparison plot for water levels from a model-generated result and read gauge data. The read water level data match the raw gauge data. Figures 3-53 and 3-54 are direct output plots from XP-SWMM.
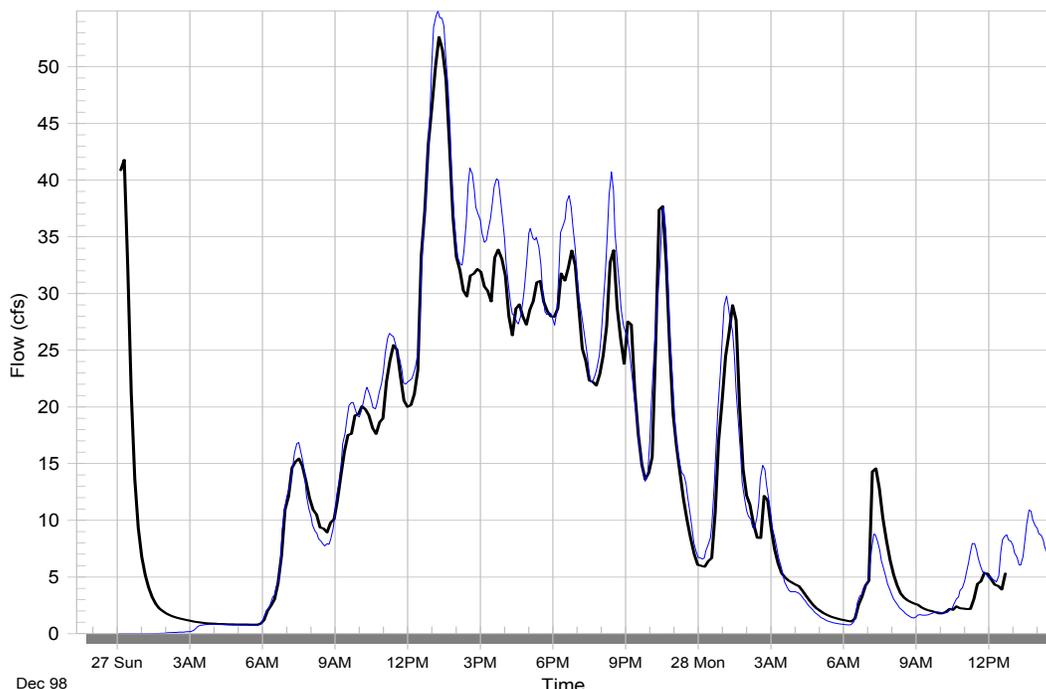
Figure 3-53. Simulated vs. gauged flow data comparison.

Figure 3-54. Simulated vs. gauged water level data read by XP-SWMM.

3.4   Testing Results of Special Links

Special links are used in XP-SWMM HYDRAULIC to model special types of connections between two junctions. Options and required data are selected and entered through the Multiple Link dialog box of XP-SWMM HYDRAULIC (Figure 3-55).

Figure 3-55. Multiple link dialog box.

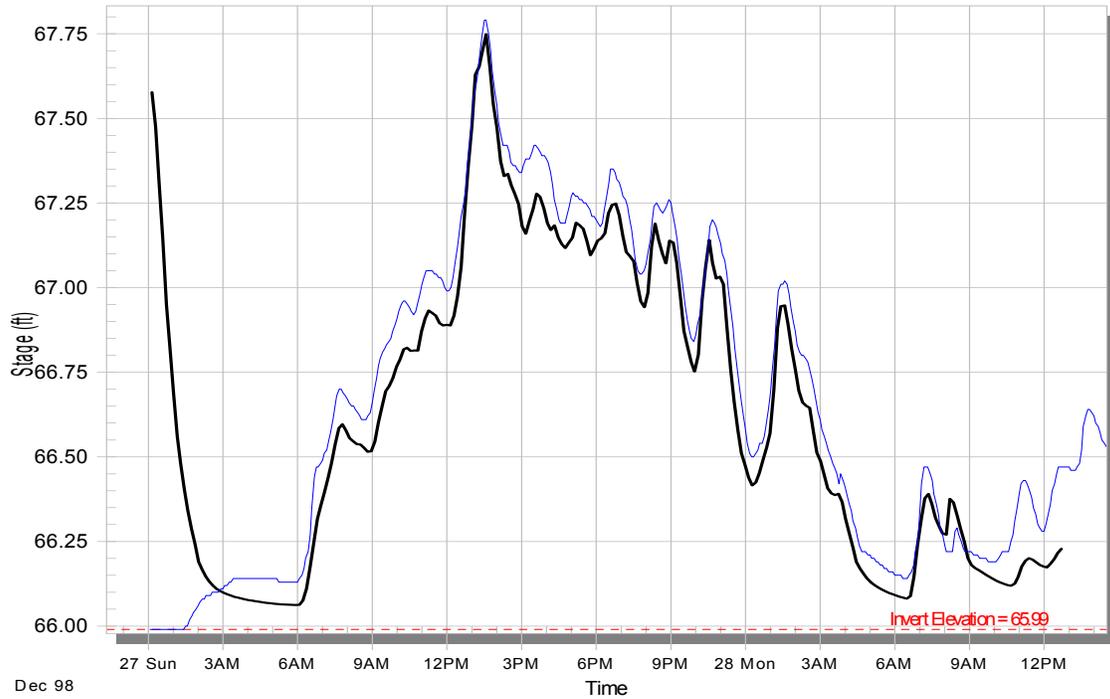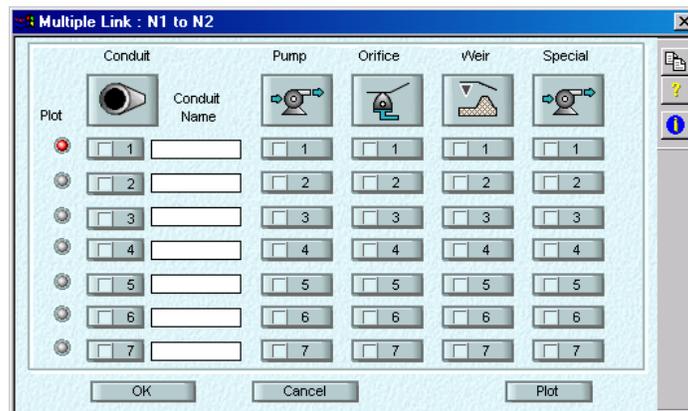Multiple parallel conduits, pumps, orifices, and weirs between two junctions are considered special links. The program user can also specify special links, such as inflatable and bendable weirs, and special pump options. Up to seven multiple links can be modeled for each type of special link. Combinations (such as a pipe overflow and pump) can also be simulated, but are not necessarily recommended.

3.4.1   Multiple (Parallel) Conduit Testing

The purpose of this phase was to test multiple parallel pipes between two junctions and confirm that flows are distributed according to the hydraulic properties of each parallel pipe.

3.4.2   Testing Procedure

A series of flow hydrographs were entered into a simplified pipe network in XP-SWMM, in which one of the links was made up of parallel pipes. To confirm that the model distributed flows appropriately to a number of parallel pipes, two, four and seven parallel pipes were simulated. The flow magnitude was varied to create open channel to surcharged flow conditions in the network.

Based on hydraulic continuity, head loss should be equal for all parallel conduits as the water levels change in the network from open channel to a surcharged condition. Head loss is a function of the length of pipe, diameter or size of the pipes, and pipe material (Manning's Roughness). Conduits that have longer lengths, smaller diameters, and higher Manning's Roughness coefficients will carry less flow, because the head loss between the two junctions must be equal. The flow hydrographs and water level time series for the parallel pipes were checked. Total flow was summed to confirm that there was no net loss of water upstream and downstream of the parallel pipes. Flow distributions in the parallel pipes were reviewed to confirm that the flows were distributed according to the hydraulic properties of the pipes in the network. Head loss between the two junctions were checked manually with Manning's equation.

3.4.3   Testing Results

A series of inflow hydrographs and diurnal flows were simulated in a simple network containing parallel pipes. The first simulation consisted of two equal sized and configured pipes (that is, the same inverts, lengths and diameters). Figure 3-56 shows that the flow produced in the two pipes was the same as the input hydrograph in the single upstream pipe (the charts of the two hydrographs overlap). Also shown in Figure 3-56 is the hydrograph from a single parallel pipe, one of the two parallel pipes. Figure 3-57 shows that the estimated flow and simulated flow in a single pipe, one of the two parallel pipes. This is shown to demonstrate that the pipe flow was equal between the two pipes. The calculation using Manning's equation is less accurate than the procedure used in XP-SWMM that uses the momentum and continuity equations, which accounts for the stepped appearance of the calculated hydrograph. The calculated hydrograph is based on the reported upstream and downstream elevations that were used to get a water surface slope. The simulated results match the calculated hydrograph.
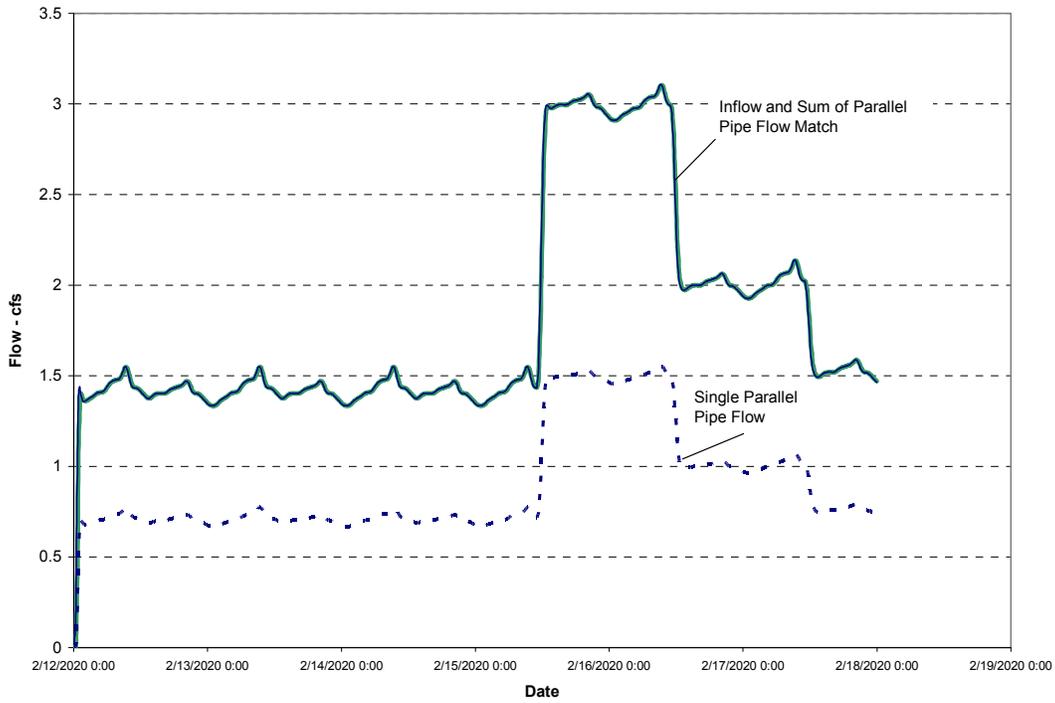
Figure 3-56. Hydrographs for two equal sized and configured parallel pipes
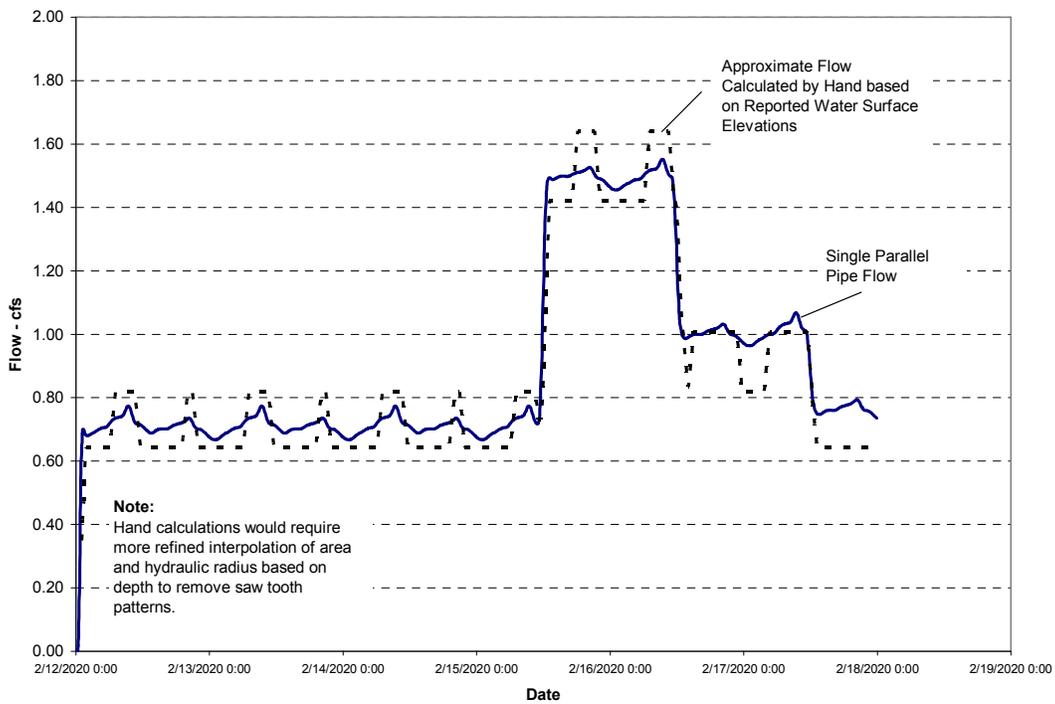
Figure 3-57. Simulated and estimated hydrographs for two equal sized and configured parallel pipes.

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The second parallel pipe simulation consists of two unequal sized pipes, with one pipe offset from the other. The offset should result in flow in only one pipe during the low flow period, and the lowest pipe flowing full under surcharged conditions. Figures 3-58 through 3-60 show the results for this simulation. Figure 3-58 shows the lower and higher flows in the two pipes and that the total flow in the two parallel pipes equals the inflow to the upstream node. Figures 3-59 and 3-60 show comparison of simulated and estimated flows in the low and high level pipes respectively. The simulated flows match those estimated from Manning's and reported water levels at upstream and downstream ends of the pipes.
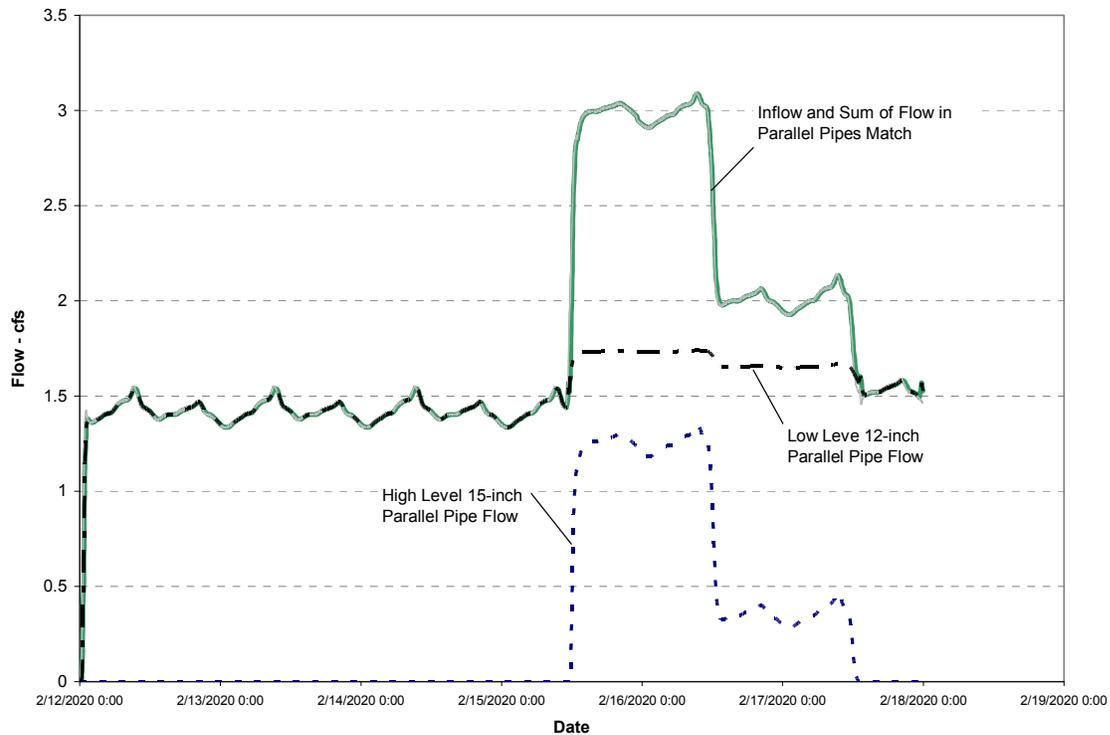
Figure 3-58. Simulated flows in two unequal sized and offset parallel pipes.
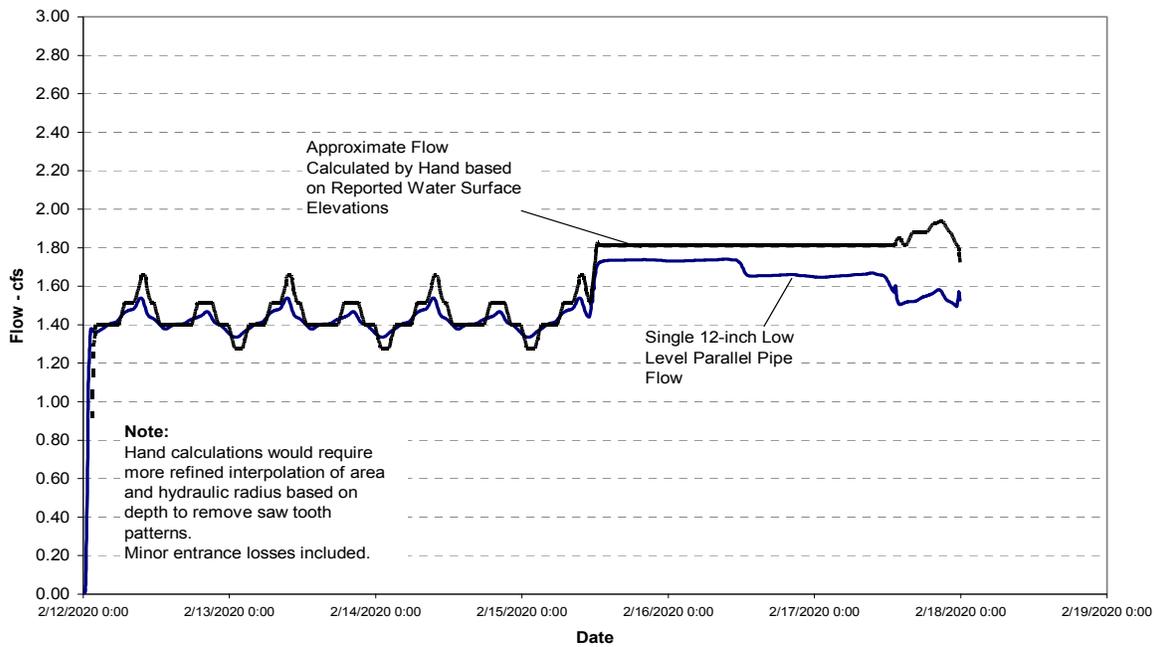
Figure 3-59. Simulated and estimated flow in offset parallel pipes -low level pipe.
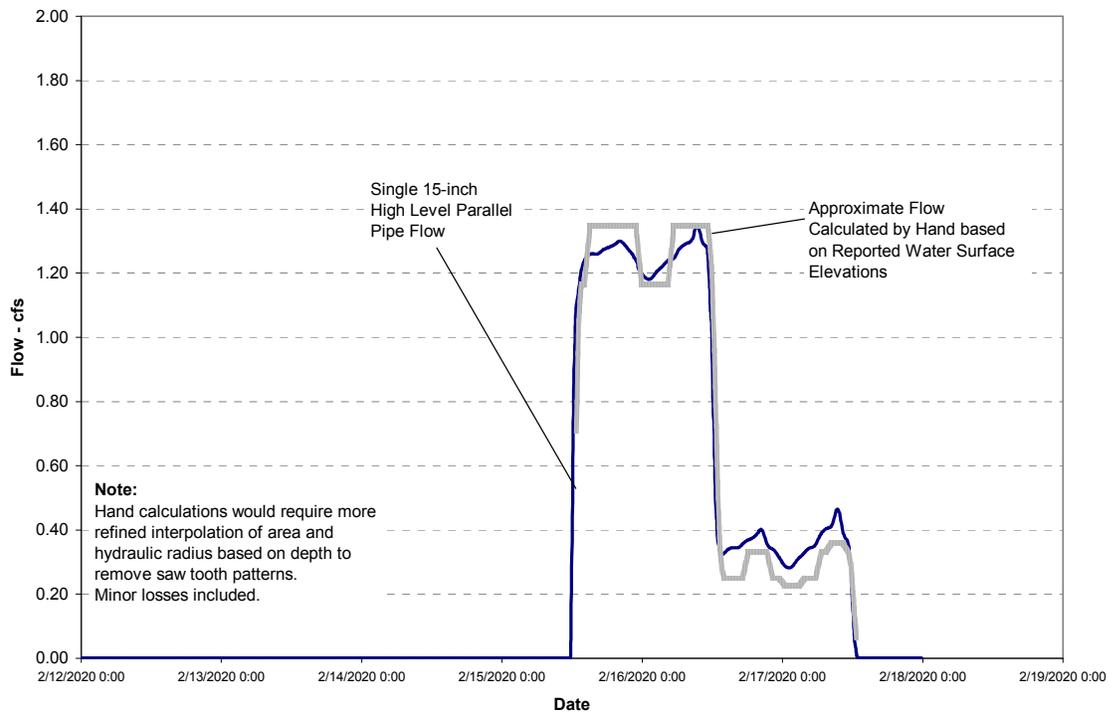
Figure 3-60. Simulated and estimated flow in offset parallel pipes-high level pipe.

The third parallel pipe simulation consists of seven 12-inch parallel offset pipes. Each pipe is offset by one foot from the next pipe, such that each successive pipe invert is at the crown of the preceding pipe. Figure 3-61 confirms that the sum of flow reported in XP-SWMM in each of the seven pipes matches the incoming flow. Figure 3-62 show an example result for the highest pipe and compares the simulated flow and calculated flow based on reported water levels at the upstream and downstream ends of the pipe. Similar results could be presented for each of the seven pipes. The simulated results match calculated results.
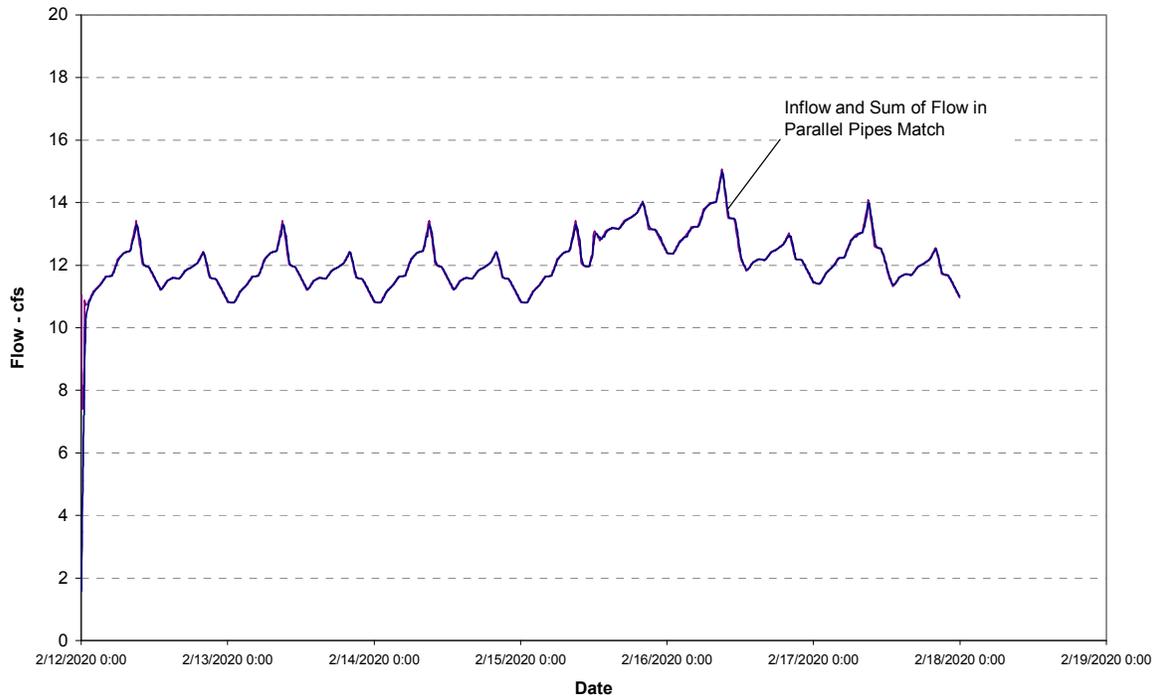
Figure 3-61. Total flow simulated in seven parallel pipes compared to inflow.
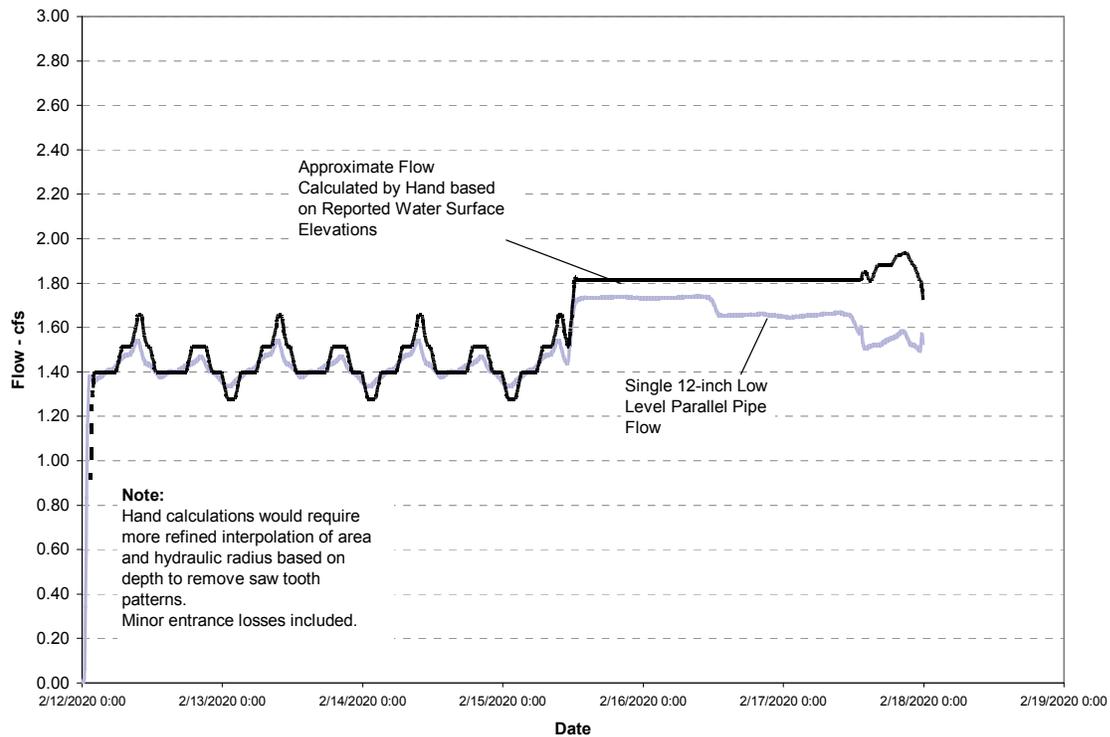
Figure 3-62. Simulated and estimated flow in a high level pipe of seven parallel pipes.

3.4.4 Pump Simulation Testing

The objective of this test was to test the pump simulation options available in XP-SWMM HYDRAULIC for modeling pumps and pump stations.

3.4.4.1 Summary of Testing Procedure

Pumps are modeled primarily by water level in the wet well (static head) versus discharge, or the head difference over the pump (dynamic head) versus discharge. A pump station is conceptually represented as either an in-line lift station, or an off-line node, representing a wet well from which the contents are pumped to another node in the system. Figure 3-63 shows how the various pumps and weirs are depicted in the model.
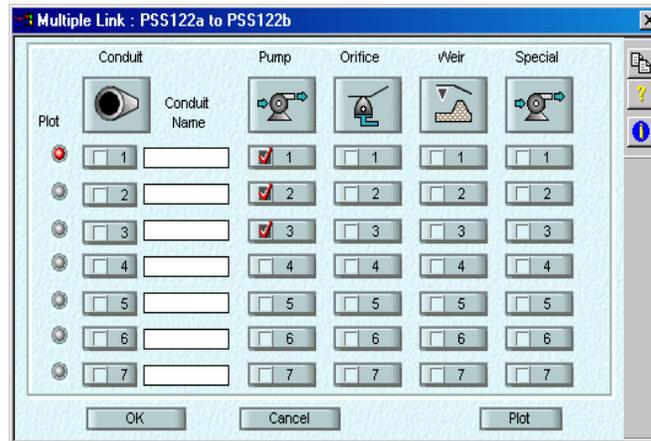
Figure 3-63. Pump and weir dialog box.

XP-SWMM HYDRAULIC can model both static and dynamic head pumps. There are five types of pump options that the program user can select:

1. Pump Rated by Wet Well Volume: An in-line or off-line pump station with a wet well; the rate of pumping depends upon the volume (or level) of water in the wet well. No on or off levels are specified.
2. Pump Rated by Depth in the Node: An in-line or off-line lift station that pumps according to the level of the water surface at the junction being pumped. No on or off levels are specified.
3. Pump Rated by Dynamic Head: An in-line or off-line pump that pumps according to the head difference over the pump, using a multi-point pump curve, and starting and stopping elevations.
4. Pump Rated by Static Head: An in-line or off-line pump that pumps according to the head at the upstream node using a multi-point pump curve and starting and stopping elevations.
5. A dynamic head pump that uses a rule curve to modify the behavior of the dynamic head pump based on the depth at either an adjacent or non-adjacent node.

For a pump station with more than one pump, the program user can specify multiple parallel pumps, and individual pump data can be entered for each pump. Multiple pumps with different characteristics may be connected to the same node to simulate more than one pump. For example, if there are three pumps at a pump station, three separate pumps and separate pump data are entered for each pump. A start and stop level is then specified for each pump. Up to seven multiple pumps can be entered.

Under most situations, the pump rate normally varies according to the head difference over the pump. This is modeled in XP-SWMM by the Type 3 pumps with dynamic head. Flows are pumped according to the head difference between the upstream and downstream node of the pump. The rate of pumping will vary by following the pump curve entered.

Type 1, Type 2, and Type 4 pumps are linear static pumps as the pump rate does not depend on, and the model does not check for, downstream conditions. Flows are pumped to the downstream node at the specified pump rate regardless of the hydraulics downstream. Pump rate depends only on the volume or depth of water in the wet well upstream. These types of pumps are suitable if the gravity pipe downstream has sufficient capacity to receive the pump discharge. If the forcemain is modeled, the dynamic head pump (Type 3) will be a more suitable choice because the pressure head within the forcemain can be simulated in the pump calculations. The recommended option for these types of pumps is Type 4 with on and off levels set by the user.

Type 5 pump is a dynamic pump that is controlled by the water depth at another node in the system. The pumping system uses a dynamic head pump and a pump curve to modify the behavior of the dynamic head pump, based on the water depth at either an adjacent or non-adjacent node. This capability has an advantage in modeling actual systems. The flow through the pump will be the minimum of the flow calculated by the dynamic head pump or the flow calculated using the special pump. If this option is selected, a dynamic head pump must also be entered within the multi-link dialog box.

Type 3, Type 4 and Type 5 pumps were tested in this evaluation.

3.4.4.2 Testing Results

Type 3 Pumps - Dynamic Head Pumps

A real open channel drainage network with a dynamic head pump station as one of the links between two junctions was used to simulate dynamic head pumps. Inflow to the network was derived from historical storms, and the model was calibrated to these storms. A forcemain downstream of the pump (with negative slope) was included to receive flows discharged from the dynamic head pump. Pumping rates and pump curve data, start-stop elevations, and initial water depth at the wet well, were entered according to the dialog boxes for pump data. Figure 3-64 shows example model results from two of five pumps in the simulated system.

The operation of the pumps in the simulation performed with XP-SWMM follows the expected patterns of pumps falling in capacity, as directed by the user inputted rating curve. Other pump operations (not shown herein) turn on and off by the described on and off elevations. Figure 3-65 shows a plot derived from reported upstream and downstream water levels and flows. The dynamic head (upstream elevation minus downstream elevation) versus pumped flow, and a screen capture of the user input rating curve, as shown in Figure 3-65. The simulation of Type 3 pumps produced results as expected, based on rating curves inputted to XP-SWMM.

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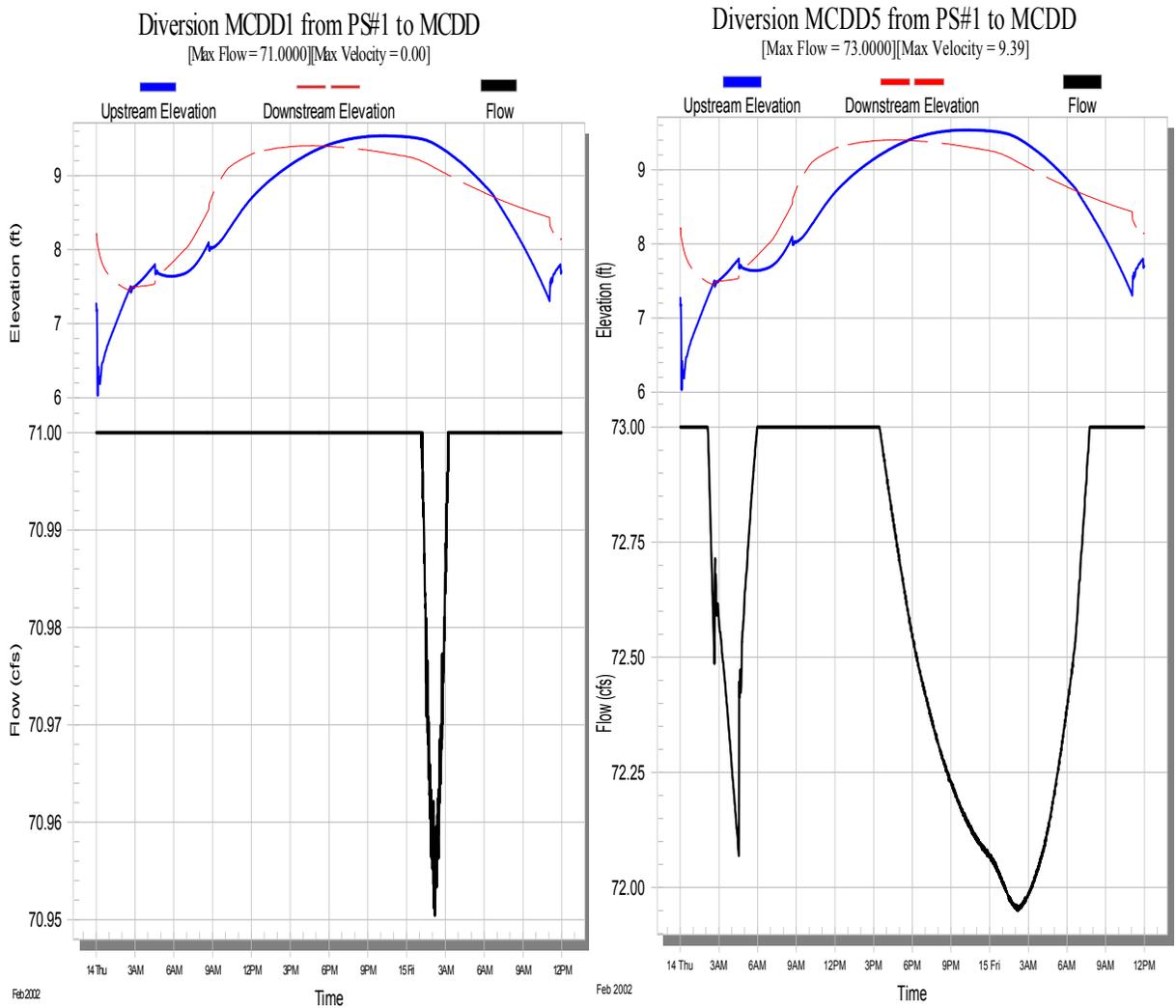
Figure 3-64. Example results from XP-SWMM for dynamic head pumps.

Type 4 Pumps – Static Head Pumps

Static head pumps are pumps that do not depend on, or check for, downstream conditions. Testing was confined to Type 4 as this option is recommended because of the ability to set on and off levels. On and off levels are not specified in Types 1 and 2. Five pumps with different pumping rates and on and off levels were simulated. The pump capacity is based on upstream depth at the node where the pump is located.

Figure 3-66 shows a typical result from the simulation for one of two low flow pumps. The lower part of the curve shows the hydrograph, and the upper two graphs the upstream and downstream water elevations.

(a)

Note: Figure 3-65 (a) Screen capture of XP-SWMM simulation of dynamic head pump.

(b)
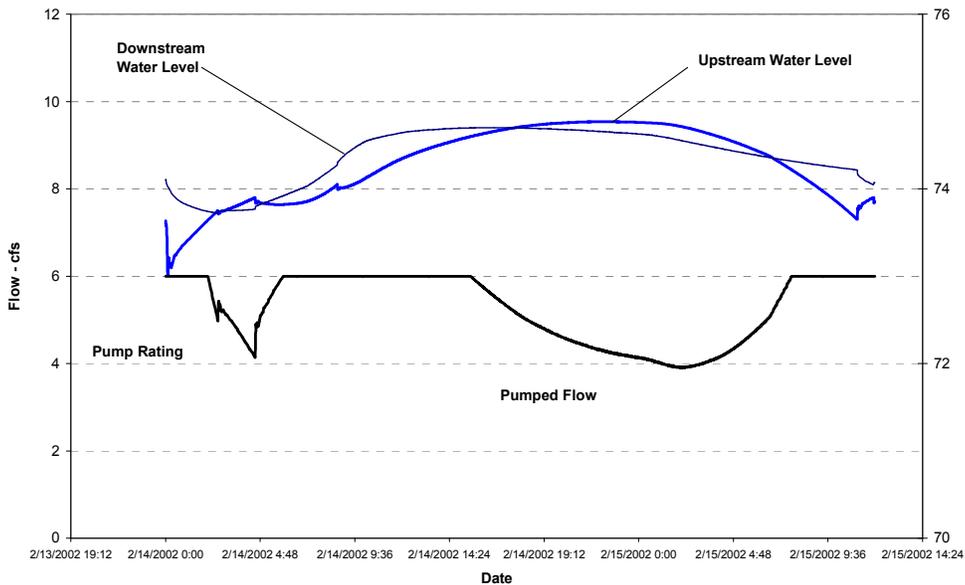
Figure 3-65. Simulated dynamic head and flow for dynamic head (Type 3) pumps.
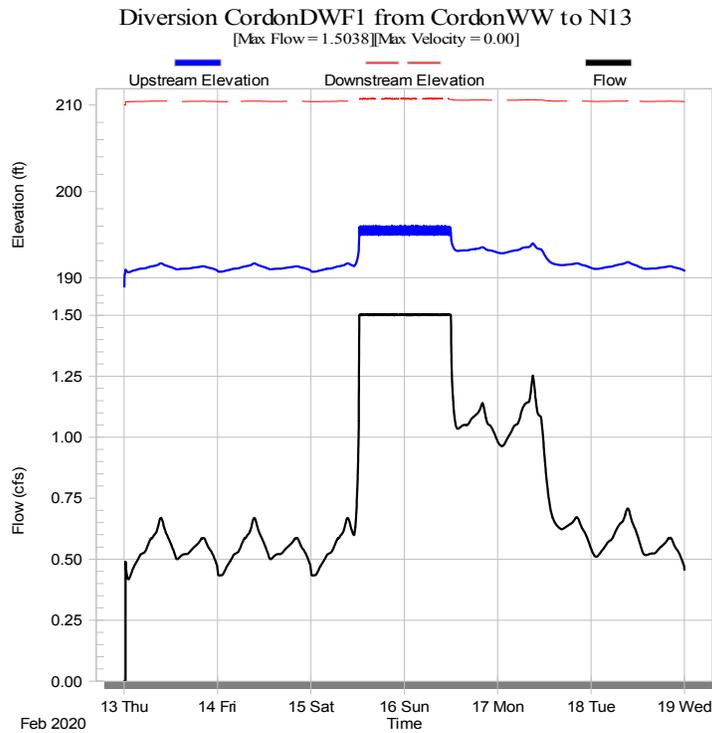
Figure 3-66. Hydrograph from a low flow pump test.

The pump rating allows the incoming flow to be pumped out at the same rate (a variable speed pump) until inflow exceeds the pumping capacity. When inflow exceeds pumping capacity, then the upstream nodes fill and the pump pumps at the specified maximum capacity.

Figure 3-67 shows two charts illustrating the operation of a pump with set on and off levels. The left hand chart shows the water level at the pump station node with a very variable level change between elevation 195 and 196, which corresponds with the on and off levels of the pump. The pump 'cycling' is illustrated by the changing flows on the right hand chart in the figure. When the pump is on, the water level drops as the pumping rate (which includes other pumps in operation) exceeds the inflow to the pumped node. When the water level reaches 195 (the off level for the pump), the pump stops and the water level begins to rise again until elevation 196 is reached and the pump starts.

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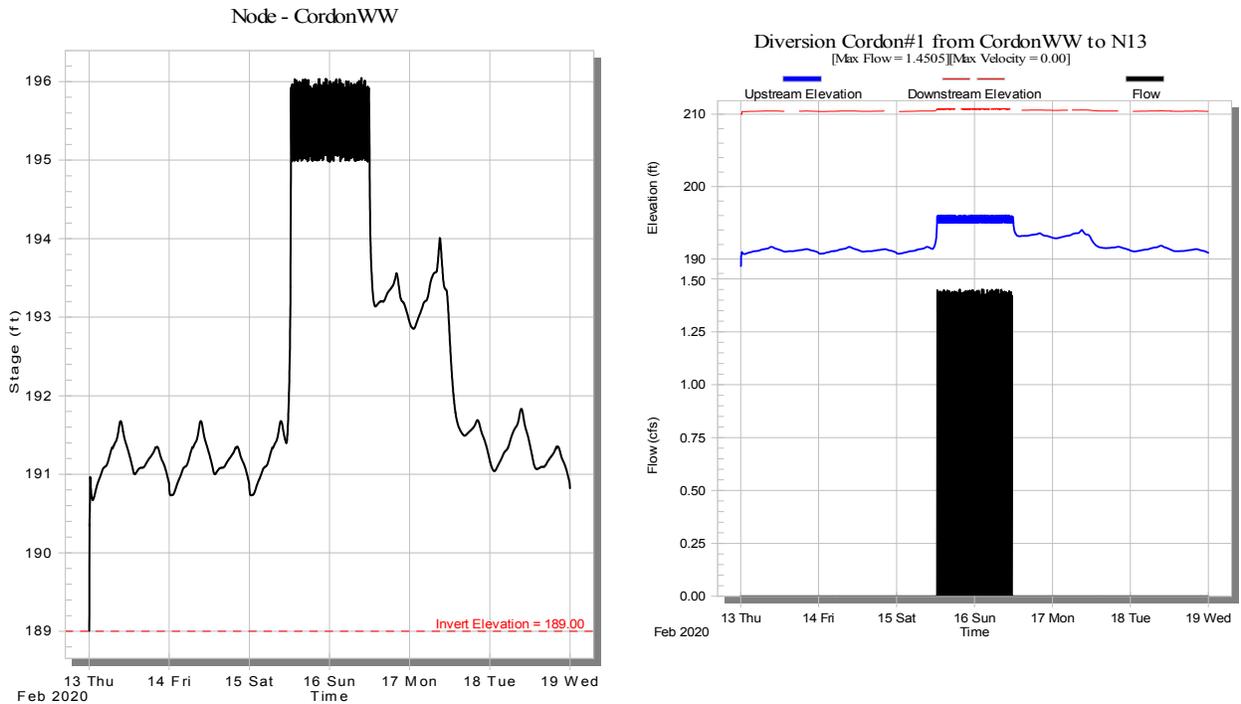
Figure 3-67. Simulation of on and off levels for Type 4 pumps.

The Type 4 pumped volume matches the incoming volume. The incoming hydrograph and the total pumped flow deviate in pattern due to storage effects at the node and in the immediately upstream collection system. The simulation of Type 4 pumps by XP-SWMM is as predicted for the operation of a pump with set on and off levels.

<u>Type 5 Pumps – Dynamic Head Pumps with Remote Control</u>

A Type 5 pump is a pump that uses a rule curve to modify the flow rate of the pump based on the depth at either an adjacent or at a remote node located somewhere in the network.

Depth at the nominated node versus flow in the special pump is used to determine the flow through the pump (the flow through the link is actually simulated). The depth in the nominated node is used to look up the corresponding flow. Figure 3-68 shows the change in the remote node water level with a major input source controlled through a Type 5 pump. Figure 3-69 shows the change in flow at the upstream link. The selected link and example flows produce an extreme example for the Type 5 simulation.

Figures 3-68 and 3-69 show the Type 5 pump working as expected. When the nominated node elevation indicates control is needed, the Type 5 pump reduces flows according to the elevation top depth relationship entered for the system. When elevations are appropriate, the Type 5 pump will revert back to the standard pumping rate specified for the non-controlled pump. The Type 5 pump performs as expected under these depth and corresponding flow conditions. However, use of the available real time control modules is recommended, which may be more appropriate for simulations involving Type 5 pumps.

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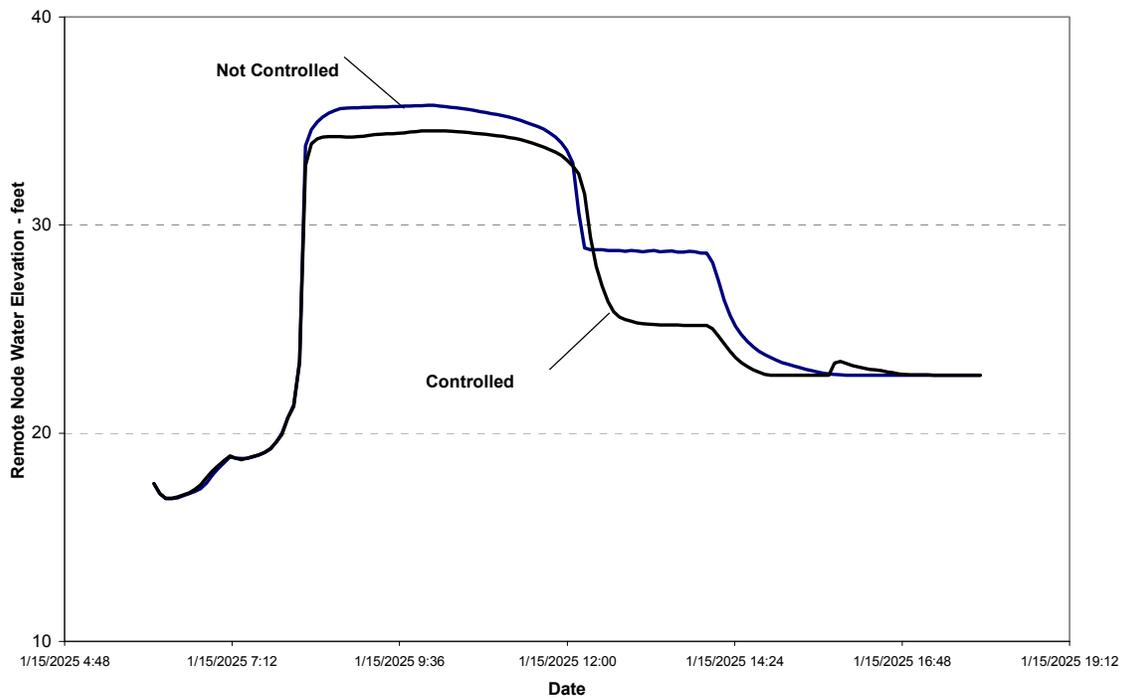
Figure 3-68. Change in elevations at a remote node controlled by a Type 5 pump.
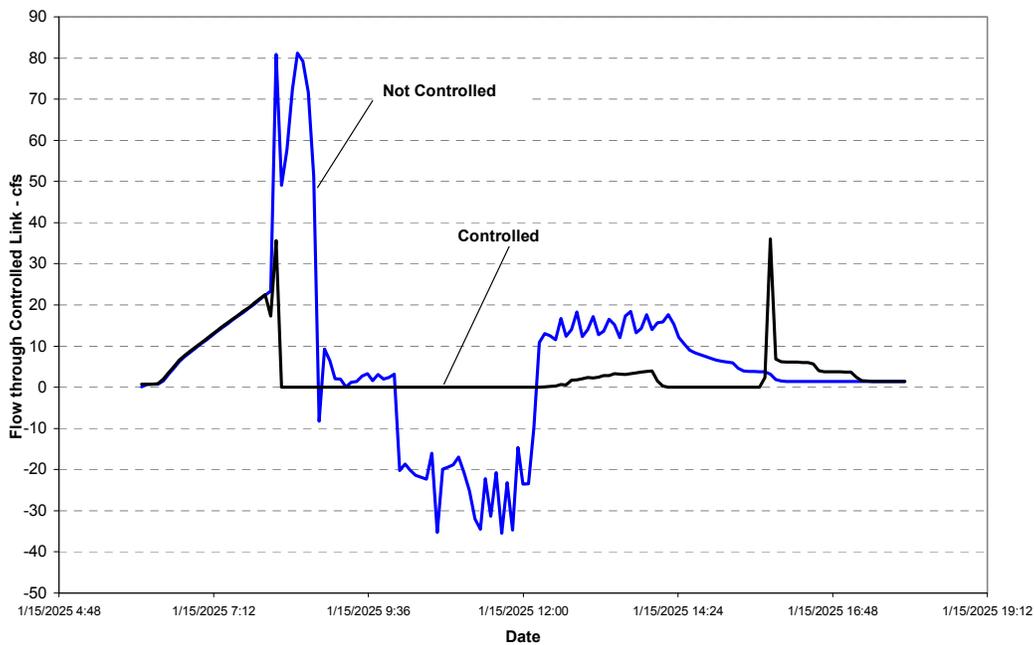
Figure 3-69. Flow change in upstream control link of a Type 5 pump.

3.4.5   Weir Simulation Testing

The objective of this phase was to test the application of weir data and simulations in XP-SWMM to determine that flow diversions over the top of the weir are correct.

3.4.5.1 Testing Procedure

Weir diversions provide relief to the drainage system during periods of high flow. XP-SWMM HYDRAULIC can simulate the following types of weirs:

- internal diversions (from one junction node to another via a transverse or side-flow weir); and
- outfall weirs that discharge to the receiving waters (these weirs may be transverse or side-flow types, and may be equipped with flap gates that prevent backflow).

The weir equation, C x L x H^k, is used, where: (3-4)

> H is the hydraulic head used to calculate weir discharge.
> C is the weir discharge coefficient with typical values of 3.0 to 3.3 (imperial units),
> L is the length of the weir,
> and k is a power exponent.

Figure 3-70 shows the input dialogue for transverse and side weirs. Weir flow is determined by the following relationship:
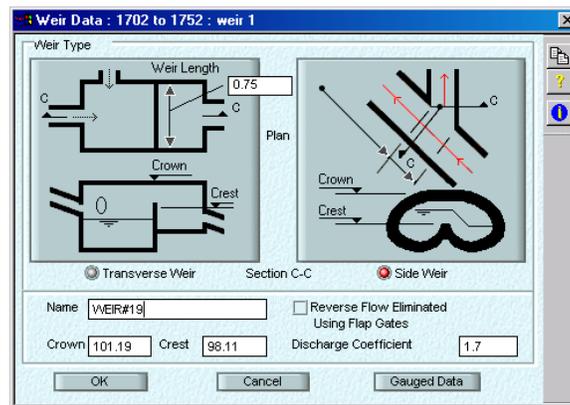
Figure 3-70. Input dialogue for transverse and side weirs.

$$Q = C_w W H^{3/2} \text{ for transverse weirs and} \tag{3-5}$$

$$Q = C_w W H^{5/3} \text{ for side weirs} \tag{3-6}$$

Where:

Q = Discharge
C_w = Weir coefficient
W = Weir length
H = Hydraulic head over the weir crest

When the water depth at a weir node exceeds a specified surcharge level, the weir functions as an orifice and the weir equation is no longer used to calculate flow. An equivalent pipe automatically replaces the weir for the duration of surcharge.

3.4.5.2 Testing Results

Weir simulations were tested by specifying one of the links between two junctions in a network as an internal weir link. Flow hydrographs and diurnal flows were entered upstream so that the weir passes flow when water levels exceed the weir crest. Transverse and side flow weirs were tested to confirm that flows were diverted properly in both cases. Figures 3-71 and 3-72 show a comparison between simulated and calculated flows for transverse and side flow weirs, respectively. The calculated flow was based on the weir equation and XP-SWMM-reported water levels. The simulated and calculated flows matched.
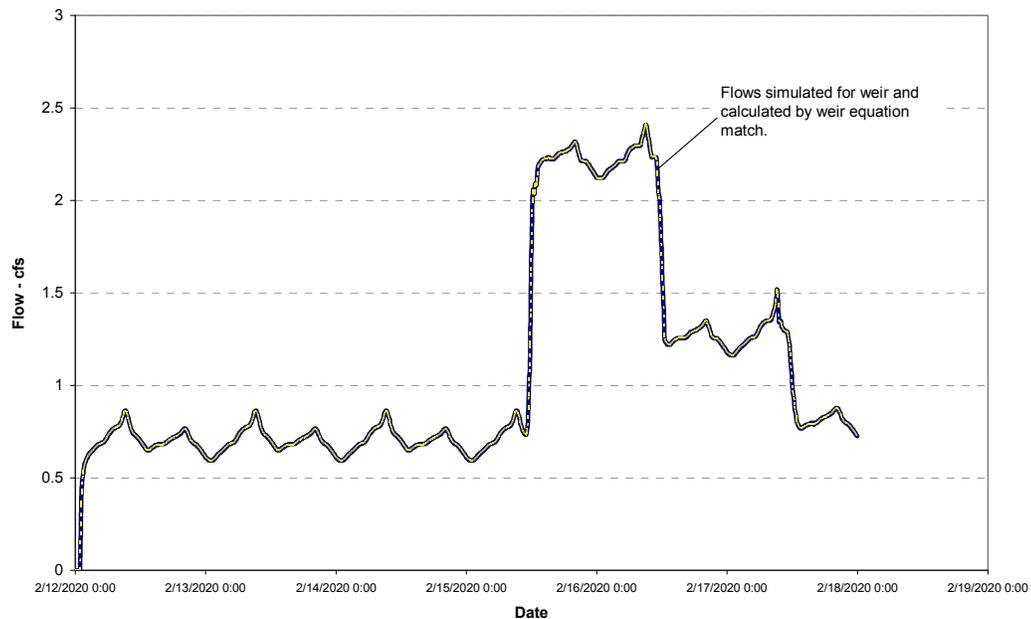
Figure 3-71. Simulated and calculated flows for transverse weir.
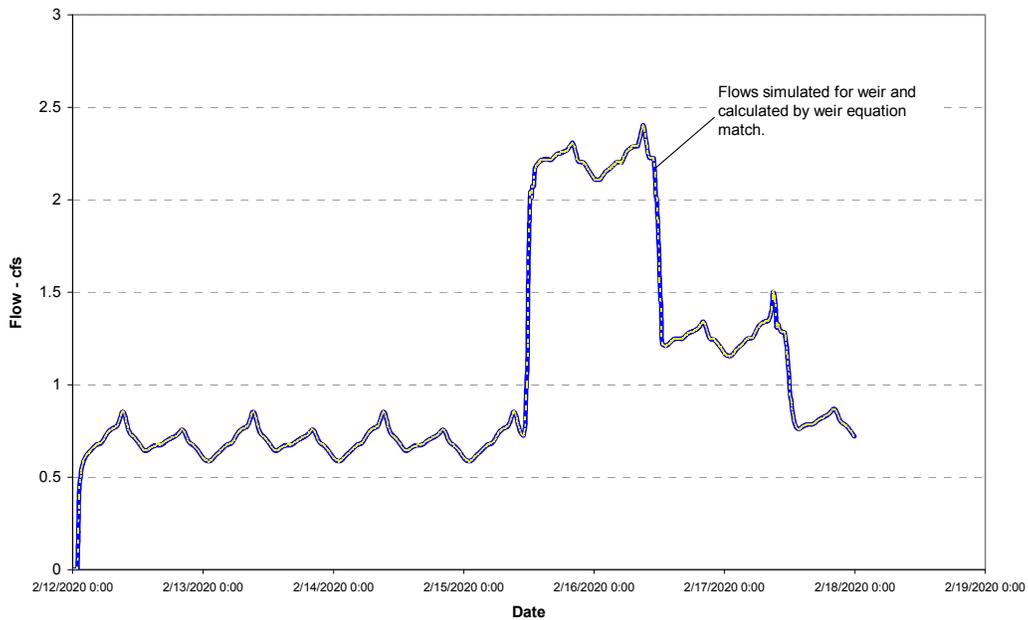
Figure 3-72. Simulated and calculated flows for side weir.

3.4.6   Orifice Simulation Testing

The objective of this phase was to test the application of orifice data and simulations in XP-SWMM to determine if flow restrictions created by an orifice are correct.

3.4.7   Testing Procedure

An orifice can be applied to restrict flows to a downstream pipe and divert the excess flows to another location such as another pipe, a pumping station, or an off-line storage tank. Bottom outlet and side orifice types were tested.

Figure 3-73 shows the input dialogue and the required information needed to simulate orifices.
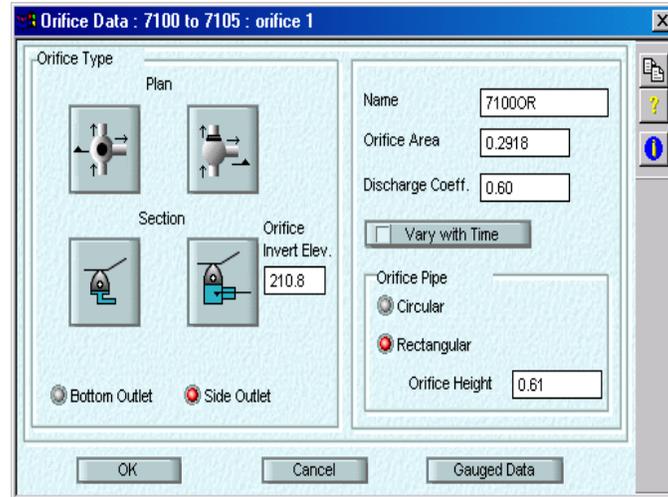
Figure 3-73. Input dialogue for orifice simulation.

XP-SWMM HYDRAULIC simulates both types of orifices by converting the orifice to an equivalent pipe. The equivalent pipe is calculated internally by XP-SWMM by equating the orifice discharge equation to Manning's equation, and used in the model as a replacement. The general orifice equation is given by:

$$CA\sqrt{2gh} \tag{3-7}$$

Where:

        C = the orifice discharge coefficient;
        A = the opening area of the orifice;
        h = the hydraulic head over the orifice; and
        g = gravitational acceleration.

For a bottom outlet orifice, the pipe invert is set by the program to be 0.96D (where D is the diameter of the orifice opening) below the junction invert, so that the orifice pipe is flowing full before any outflow from the junction occurs in any other pipe. For side outlet orifices, the user specifies the height of the orifice invert above the junction floor. Both orifice types require that the orifice area and discharge coefficient data be entered. The orifice outlet may be circular or rectangular. If rectangular, the depth of the conduit (in feet or meters) must be entered.

Bottom and side orifice simulations were tested by specifying one of the links between two junctions in a network as an orifice link. Wet weather flow hydrograph and diurnal flow was entered upstream into XP-SWMM for a location of the orifice. Flow ranges were entered such that the orifice would surcharge. While orifice settings may be varied with time to simulate external controls, this feature was not tested.

3.4.7.1 Testing Results

The equivalent pipe calculated internally by XP-SWMM was checked to confirm that the equivalent pipe diameter, length, and inverts were correctly converted, and that they corresponded to the orifice applied data.

Bottom and side orifices are converted to an equivalent pipe with the following relationship:

$$\frac{m}{n} AR^{2/3} S^{1/2} = C_0 A \sqrt{2gh} \tag{3-8}$$

Where:

m = 1.486 for US customary units and 1.0 for SI units;
n = Manning's Roughness coefficient;
A = Area;
R = Hydraulic radius;
S = Slope of equivalent pipe;
C_0 = Discharge coefficient (a function of the type of opening and the length of the orifice tube);
g = gravitational acceleration; and
h = hydraulic head on the orifice.

The equivalent pipe assumes a set diameter and slope, and calculates a Manning's Roughness Coefficient to produce a pipe with the same hydraulic characteristics as the orifice. The Manning's n value is determined using the following equation:

$$n = \frac{m}{C_0 \sqrt{2gL}} (D/4)^{2/3} \tag{3-9}$$

Where:

D = diameter;
L = length of pipe (calculated as the maximum of 300 feet or by $L = 2\Delta t \sqrt{gD}$);
Δt = simulation time step;
C_0 = Discharge coefficient (a function of the type of opening and the length of the orifice tube);
g = gravitational acceleration; and
m = 1.486 for US customary units and 1.0 for SI units.

With the values used in the simulation: (C_0=1; A=1.227 square feet; Δt=20 seconds):

L = maximum (253, 300) = 300
n = 0.00492

The calculated Manning's n value matches that given in the XP-SWMM output file for the simulated orifice. Figure 3-74 shows an abstract from the simulation output file showing the

simulation calculation of an equivalent pipe. Figure 3-75 shows the simulation water elevation results with an orifice and a simulation having a pipe with the equivalent pipe characteristics determined above. The bottom orifice (and the simulated equivalent pipe) was set 0.96 times diameter below the node invert, hence the lower water level shown in Figure 3-75 for the bottom orifice. Figure 3-76 shows the simulated flows for a bottom orifice, equivalent pipe and side orifice. All produced the same flow results.

The XP-SWMM simulations of orifices match calculated values.

```
 *═══════════════════════════════════════════════*
 |        Orifice Data          |
 *═══════════════════════════════════════════════*


 Conduit   From      To          Area  Depth  Discharge  Height Above
  Name    Junction  Junction Type (ft2)  (ft)  Coefficient Junction (ft)
 --------  --------  --------------- ---------------   ----   -----   -----   -----------
 15inch    N30       N21     Circ Sump   1.23   0.00   1.000   0.000

 ====> EQUIVALENT PIPE INFORMATION FOR ORIFICE              1
       CONDUIT NAME...........................      15inch
       Upstream node..........................      N30
       Downstream node........................      N21
       PIPE DIAMETER........................       1.25
       PIPE LENGTH..........................     300.00
       MANNINGS ROUGHNESS...................          0.0049
       INVERT ELEVATION AT UPSTREAM END.....         199.5601
       INVERT ELEVATION AT DOWNSTREAM END...         199.5501
```

Note: For a bottom-outlet orifice the invert elevation of the downstream node would be adjusted to accommodate the equivalent conduit. Conduit grades are not affected.

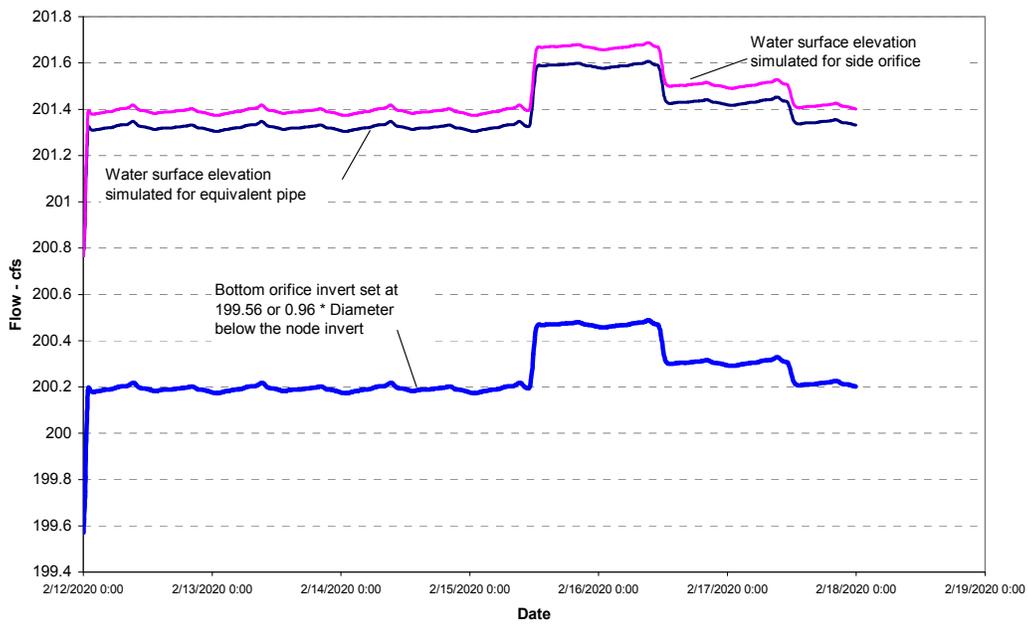**Figure 3-74. XP-SWMM output showing calculation of equivalent pipe.**

Figure 3-75. Simulated and estimated water levels for orifices.
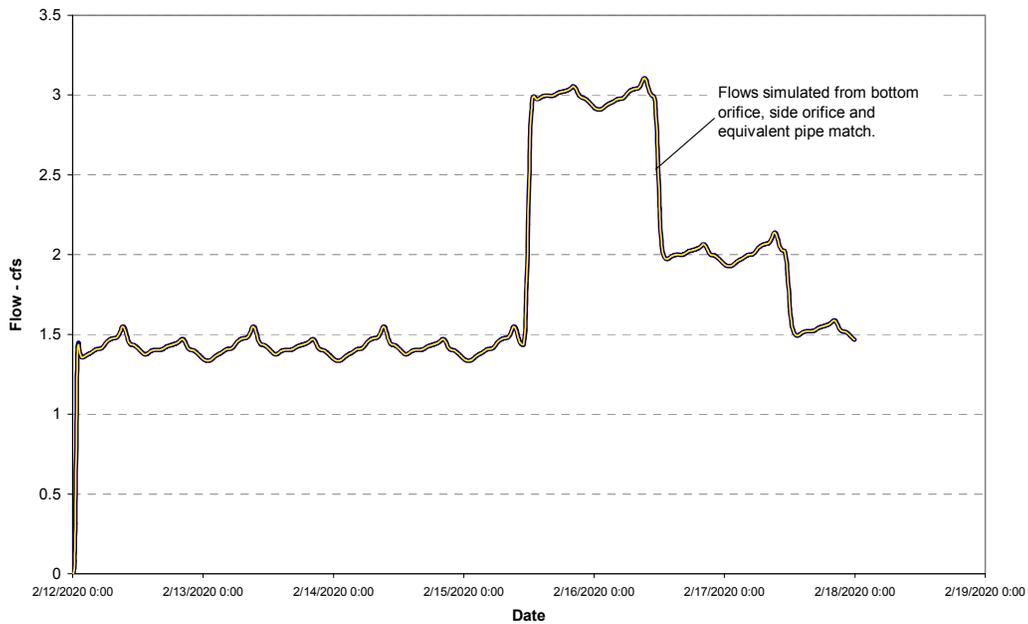

Figure 3-76. Simulated and calculated flows for orifices.

Chapter 4
Summary

Evaluation of the XP-SWMM components provided insight into the interaction of many 'basic' functions commonly used in building models of actual systems. Some basic functions include the WIDTH parameter, used in RUNOFF to determine flow rates from a watershed, and infiltration simulations. Relationships between these types of functions are generally not transparent or even recognized by many potential modelers or users of models. Some of these interrelationships were revealed and highlighted during the testing of XP-SWMM to enhance user confidence in the model.

Individuals with training in hydrology and hydraulics can use XP-SWMM with ease for simulation of storm, sanitary and combined sewer system conditions. Building simulation models requires an understanding of the quality of the underlying defining data (for example, pipe network data and hydrologic parameters), how models are calibrated and verified, and how to interpret the results. Users of XP-SWMM should be able to think critically in order to use the model to draw valid conclusions that can then be used to make engineering decisions. Users of XP-SWMM would also benefit from working through the tutorials provided by XP Software.

XP-SWMM may be the appropriate model to select if the science demands the type of calculations that XP-SWMM incorporates for the simulation of storm, sanitary and combined sewer systems. XP-SWMM provides a framework for the user to input data consistently, build models efficiently and review results effectively. This allows the user to concentrate on the results of the simulation and the conclusions that can be drawn from such results.

The results from the testing conducted on the model components outlined in the XP-SWMM VTP were comparable to results achieved with off-line calculations. In many instances, the model results matched the off-line results, as depicted in Table 4-1.

Quantifying the performance of a procedure in XP-SWMM, or any other model "simulation", is problematic in many instances because of the necessity to use other calculated "simulations" to compare results. In some cases, the performance is quantifiable (such as a known input rainfall volume versus what is reported in XP-SWMM). Table 4-1 provides a summary of the testing, including:

- The tested component;
- An indication of how closely the model results matched with off-line calculations used for comparison;
- Whether the computer algorithms were reviewed or not; and
- Brief comments, when appropriate.

Table 4-1. Testing Summary

Module	Component	Process	Percent Comparison	Discussion
RUNOFF	Rainfall	Event	100	
		Interface	>99	Small rounding errors encountered.
		Continuous	100	Raw data check recommended to ensure no deviant data values.
		Standard format	99	Standard formats are most likely changed by collecting agencies.
		Statistics	100	
	Infiltration	Horton	No value	Horton Equation represented appropriately. However infiltration and excess rainfall were influenced by value used for WIDTH parameter.
		Green-Ampt	>99	Green-Ampt Equation represented appropriately. WIDTH parameter not an issue with Green-Ampt.
	Runoff	Runoff	90	Clarification on how the WIDTH parameter affects runoff volume for pervious areas is needed.
		SBUH	95	Within expected modeling technique variation.
		SCS	95	Within expected modeling technique variation.
		Calibrated model	95	Monitored results duplicated when model parameters selected with care and with proper basin definition.
HYDRAULIC - nodes	Node inflows	Diurnal pattern	99	Minor time shift (one hour).
		Gauged inflow	95	Generally appropriate but possible misrepresentation may impact some simulations.
		Interface	100	
	Node loss coefficients	Minor loss simulations	90	Calculated head loss greater than simulated values.
	Storage node	Constant area	98	Water levels predicted are dependent on volume used in upstream and downstream links.
		Depth-area	95	Time step for reporting flow results has a significant impact on spreadsheet accuracy.
		Power function	95	

Module	Component	Process	Percent Comparison	Discussion
	Node inlet capacity	Maximum value	99	
		Rating curve	99	
	Node control	Flooding allowed	99	
		Sealed	100	
		Surface ponding	99	
	Outlet control	Free outfall	100	
		Fixed backwater	95	
		Tidal changes	90	Generation of tidal values not working in program.
		Variable water level	95	
HYDRAULIC - links	Manning's Roughness	Manning's Equation	100	
	Pressure and open channel flow	St. Venant's Equation	95-100	
	Flow direction	Upstream, downstream and free flow	100	
	Flow routing for conduit shapes	Basic and user defined shapes	90	Misreporting of some maximums for some shapes.
	Gauged flow for calibration plots	Input of external data for comparison of results	95	
HYDRAULIC - special links	Multiple conduits	Parallel pipes	95	
	Pump simulations	Type 1		Not recommended, use Type 4.
		Type 2		Not recommended, use Type 4.
		Type 3	100	
		Type 4	100	
		Type 5	No value	Use with caution.
	Weir simulations	Side weir	98	
		Transverse weir	99	
	Orifice simulations	Bottom orifice	98	
		Side orifice	98	

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Chapter 5
Quality Assurance Project Plan (QAPP)

The TO had primary responsibility for ensuring that the verification data sets, tests, related calculations and compilation of data conformed to the quality assurance and quality control requirements of the VTP. The general processes outlined in the QAPP were followed by the TO staff members. This included duplication of hand calculations by staff to check calculations, duplication or checking of data entry into XP-SWMM to ensure that model data compared correctly to data used in hand calculations, and checking or duplication of data entered and calculations (checking of fields referenced in formulas for example) used in spreadsheets.

Abnormal data used in the tests were minimal – the only occurrence was in rainfall data when a daily total was incorrectly included as an hourly value. This abnormal data point was found prior to input to XP-SWMM, but was not corrected to determine how and if XP-SWMM would handle such abnormalities. XP-SWMM in this case assumed that the hourly data point was correct.

Chapter 6
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Glossary

Abstraction – A possible source of loss to rainfall before it reaches the ground. For example, the wetting of trees abstracts rainfall before it reaches the ground (then it can drip to the ground for infiltration.)

Accuracy - a measure of the closeness of an individual measurement or the average of a number of measurements to the true value and includes random error and systematic error.

Bias - the systematic or persistent distortion of a measurement process that causes errors in one direction.

Comparability – a qualitative term that expresses confidence those two data sets can contribute to a common analysis and interpolation.

Completeness – a qualitative term that expresses confidence that all necessary data have been included.

Precision - a measure of the agreement between replicate measurements of the same property made under similar conditions.

Protocol – a written document that clearly states the objectives, goals, scope and procedures for the study. A protocol shall be used for reference during Vendor participation in the verification testing program.

Quality Assurance Project Plan – a written document that describes the implementation of quality assurance and quality control activities during the life cycle of the project.

Representativeness - a measure of the degree to which data accurately and precisely represent a characteristic of a population parameter at a sampling point, a process condition, or environmental condition.

Standard Operating Procedure – a written document containing specific procedures and protocols to ensure that quality assurance requirements are maintained.

Technology Panel - a group of individuals established by the VO with expertise and knowledge in wet weather flow models.

Test 1 Storm Event – One of a series of typical rainfall distributions developed by the SCS (Soil Conservation Service) for use in hydrology studies. The storms developed have various intensities and frequencies. SCS-1a with 30 min. rainfall intensity was used in this verification testing.

Testing Organization – an independent organization qualified by the Verification Organization to conduct studies and testing of wet weather flow models in accordance with protocols and test plans.

Verification – to establish evidence on the performance of wet weather flow models under specific conditions, following a predetermined study protocol(s) and test plan(s).

Verification Organization – an organization qualified by USEPA to verify environmental technologies and to issue Verification Statements and Verification Reports.

Verification Report – a written document containing all raw and analyzed data, all QA/QC data sheets, descriptions of all collected data, a detailed description of all procedures and methods

used in the verification testing, and all QA/QC results. The Verification Test Plan(s) shall be included as part of this document.

Verification Statement – a document that summarizes the Verification Report and is reviewed and approved by USEPA

Verification Test Plan – A written document prepared to describe the procedures for conducting a test or study according to the verification protocol requirements.