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Survey and Assessment of Fate and Transport Models for Use Following a Wide-Area Urban Release to Inform Mapping, Characterization, and Site Clearance

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Survey and Assessment of Fate and Transport Models for Use Following a Wide-Area Urban Release to Inform Mapping, Characterization, and Site Clearance

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Disclaimer

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Table of Contents

1.0 Introduction 1
2.0 Background 1
3.0 Model Review Process 2
3.1 Initial Screening 2
3.2 Detailed Review and Quality Assurance 3
4.0 Results of Model Review 6
4.1 SWMM Family of Models 6
4.2 Sewershed and Sewer Network Models 7
4.3 Watershed Models 7
5.0 Discussion 7
6.0 References 9
Appendix A – Models in Initial Screening 13
Appendix B – Model Summaries 20
B.1 BASINS (Better Assessment Science Integrating point and Non-point Sources) 22
B.2 BasinSim 1.0 23
B.3 CivilStorm 24
B.4 GWLF (Generalized Watershed Loading Function) 25
B.5 GSSHA (Gridded Surface Subsurface Hydrologic Analysis) 26
B.6 HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System) 27
B.7 HSPF (Hydrological Simulation Program Fortran) 28
B.8 HydroCAD 30
B.9 InfoSWMM 31
B.10 InfoWorks ICM (InfoWorks Integrated Catchment Modeling) 33
B.11 LSPC (Loading Simulation Program in C++) 34
B.12 MapShed 35
B.13 MIDS (Minimal Impact Design Standards) calculator 36
B.14 Mike Urban 37
B.15 P8 (Program for Predicting Polluting Particle Passage through Pits, Puddles, and Ponds) 39
B.16 PCSWMM 40
B.17 SELDM (Stochastic Empirical Loading and Dilution Model) 41
B.18 SELECT (BMP System Effectiveness and Life-Cycle Evaluation of Costs Tool) 42
B.19 SHSAM (Sizing Hydrodynamic Separators and Manholes) 43

B.20 STEPL ... 44
B.21 StormNET ... 45
B.22 SWAT (Soil and Water Assessment Tool) ... 46
B.23 SWMM5 (Storm Water Management Model) ... 48
B.24 WARMF (Watershed Analysis Risk Management Framework) ... 50
B.25 WinSLAMM (Source Loading and Management Model) ... 52
B.26 XPSWMM ... 54

List of Tables

Table 1: Explanation of stormwater model survey evaluation criteria ... 5

Acronyms and Abbreviations

API	Application Programming Interface
ARM	Agricultural Runoff Management
ARS	USDA Agricultural Research Service
BMP	Best Management Practice
BOD	Biochemical Oxygen Demand
CAD	Computer-Aided Design
CSO	Combined Sewer Overflow
CSS	Conduit Storage Synthesizer
CSV	Comma Separated Values
Cu	Copper
DCMD	EPA Decontamination and Consequence Management Division
DEM	Digital Elevation Model
DNR	Department of Natural Resources
EMC	Event Mean Concentration
EPA	United States Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GenScn	A tool for the generation and analysis of model simulation scenarios for watersheds
GIS	Geographic Information System
HEC-RAS	Hydrologic Engineering Center – River Analysis System
HSP	Hydrological Simulation Program
HSPExp	Expert System for Calibration of HSPF
HSPF	Hydrologic Simulation Program Fortran
HSRP	EPA Homeland Security Research Program
IMAAC	Interagency Modeling and Atmospheric Assessment Center
LID	Low Impact Development
LSPC	Loading Simulation Program in C++
MPCA	Minnesota Pollution Control Agency
MS	Microsoft
N	Nitrogen
NERL	EPA National Exposure Research Laboratory
NHSRC	EPA National Homeland Security Research Center

NPS	Non-point Source
NRCS	Natural Resources Conservation Service
NRMRL	EPA National Risk Management Research Laboratory
P	Phosphorus
Pb	Lead
PC	Personal Computer
RAM	Random Access Memory
RDII	Rainfall Derived Inflow and Infiltration
RTC	Real-Time Control
SCM	Stormwater Control Measure
SCS	Soil Conservation Service
SED	Systems Exposure Division
SFEM	Sewer Flow Estimation Model
SUDS	Sustainable Urban Drainage system
SVGA	Super Video Graphics Array
SWMM	Stormwater Management Model
TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
TP	Total Phosphorus
TSS	Total Suspended Solids
US	United States
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
USDA	United States Department of Agriculture
VBA	Visual Basic for Applications
VIMS	Virginia Institute of Marine Science
WDMUtil	Tool to create time series data
WiLMS	Wisconsin Lake Modeling Suite
WinHSPF	Hydrologic Simulation Program for Windows
WSD	Water Systems Division
Zn	Zinc

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Executive Summary

If a terrorist event, accidental release, or natural disaster causes a wide area of land to be contaminated with chemical, biological, or radiological particulates, emergency responders need a rapid way to determine where to sample and decontaminate prior to clearing the area. A comprehensive stormwater model review does not exist that is focused on the needs of those remediating after such a release. This report summarizes a variety of modeling tools that are used for understanding the fate and transport of stormwater and associated pollutants in more routine applications. These existing modeling tools are expected to need modification from their existing formats to serve the needs of the emergency response and remediation community. Therefore, criteria specific to emergency response modeling are outlined in Section 3 of this report, and this report provides two appendices with detailed model information. The criteria include aspects such as ease of assembly during an emergency event, how prevalent the tools currently are (which would facilitate model repurposing), and if modifications to the source code are possible or if the source code is proprietary. In Appendix A, 62 models are characterized, based on their inclusion of hydrology, hydraulic, and water quality features, and rationale for exclusion is provided if they were not included in the detailed model summaries. In Appendix B, 26 summaries of models that fit the initial criteria for emergency response modeling are outlined in further detail, including features, mathematical methods, and license cost.

During the detailed model review, trends in model functionality and original application were observed. Several proprietary models and specialized frameworks were found to utilize the United States Environmental Protection Agency's Stormwater Management Model (SWMM) code to power their simulations. Another cluster of models was established to address design and operational questions like SWMM but included separately developed computational engines and accessories. Watershed models formed an additional cluster of models and, in general, were designed to address runoff pollution loading in a more lumped and wider ecological lens than the detailed hydraulic resolution of a sewer system. Finally, there was a group of tools that consisted of simple spreadsheet calculations and were focused on providing a decision support framework for green infrastructure decisions. These tools tended to lack the mathematical complexities and detail of the other models.

Overall, no one model was found to include all the components necessary for time-sensitive stormwater modeling during an emergency such as a widespread biological or radiological particulate release. However, the SWMM family of models was determined to have the most promising potential for expansion to emergency response applications due to the open source core engine code and widespread use. The other proprietary models were also found to include 2D modeling capabilities that could be used to determine the fate and transport of pollutants. Ultimately, local utilities will need to repurpose and expand their existing stormwater models to aid in protecting human health and the environment from release of biological, chemical, and radiological releases.

1.0 Introduction

This stormwater model review is part of a broader research effort by the Homeland Security Research Program (HSRP) of the U.S. Environmental Protection Agency's (EPA's) National Homeland Security Research Center (NHSRC), studying the fate and transport of contaminants that are deliberately or accidentally released into an urban environment. Under circumstances where hazardous agents contaminate a large urban area, modeling tools offer decision makers insight on where to focus sampling and decontamination efforts. For example, when the River Street warehouse fire occurred in Portland in May 2017 asbestos-containing debris was released from the fire and air dispersion modeling results were used to inform selection of sampling locations in the city. This modeling was rapidly available through the Federal Emergency Management Agency's (FEMA's) Interagency Modeling and Atmospheric Assessment Center (IMAAC) which provides 24/7 plume modeling support to state, local, and federal officials involving significant hazardous atmospheric releases. While a wide variety of stormwater tools are actively used in the urban planning and regulatory sectors for flood water control and water quality management, the use of water modeling tools during emergency response is relatively rare (*e.g.* metals transport in the San Juan River after the Gold King Mine spill) compared to atmospheric models. Many factors contribute to this air-water-emergency modeling disconnect, including the need for more cross jurisdictional infrastructure data (*e.g.*, pipe networks) and the lack of a federally managed modeling center such as the IMAAC. Since a standard resource for using stormwater models during an emergency response has not been established, many different modeling tools may be recommended for use during an incident. One objective of this report is to identify and better understand the diverse landscape of modeling tools that adequately represent—or can be modified to represent—the transport of substances analogous to particulate-bound radiological and biological contaminants in stormwater and on urban surfaces (*e.g.*, roadways and parks). An additional objective is that the model summaries supplied in Appendix B provide a quick reference for those new to stormwater modeling or well versed in only a few models. The summaries are intended to facilitate communication between sectors and assist emergency response project managers in selecting a useful stormwater model during response and recovery.

2.0 Background

Stormwater is a mature area of study in urban areas that have a large impervious area fraction and where problems such as flooding and sediment erosion may occur if stormwater is not adequately managed (Mays, 2001). Urban areas are also a source of a variety of pollutants, which may be transported through stormwater, typically through the erosion or washoff of particulates. Early documentation of the water pollution aspects of street surface contaminants is provided in Sartor *et al.*, 1974. Many pollutants adhere to particles and may therefore be transported along with the particulates. Stormwater runoff from urban areas is often associated with pathogenic and organic substances that are of public health concern.

Over the past three decades, a variety of public-domain and proprietary modeling tools have been developed for tracking stormwater hydrology, hydraulics, and quality. Hydrology-based models represent rainfall-runoff processes and routing through channels and reservoirs, focusing primarily on calculating flow volumes using formulas that preserve the conservation of mass. However, hydraulic models involve the conservation of mass and momentum and represent fluid transport processes in more detail, including characterization of water surface profiles, flow rates, and flow velocities on surfaces and in pipelines and channels. The use of a hydrology vs hydraulic model is very situation-dependent. For example, during an emergency response, if the primary question is "How much water is the concern and in what structure is the water after a rain event?" then a hydrology-based model would suffice. Conversely, if a responder wanted to know if material could be scoured out of a contaminated pipe, it would help to predict flow velocity, and a hydraulic model would be necessary. Water quality models characterize transport of dissolved or particulate pollutants and are usually coupled with hydrology/hydraulic models.

To model the quantity of stormwater, several hydrological processes need to be characterized. Precipitation falling on land surfaces is subject to evaporation and initial loss due to interception by vegetation. Excess rainfall is available for infiltration, overland flow, and depression storage. Infiltrated water may flow through the upper layer of the soil where some of this water may become interflow between adjacent soil layers or flow more deeply into the soil, reaching the groundwater. Stormwater flow is routed through land surfaces, stream reaches, and through engineered stormwater infrastructure (*e.g.*, drainage pipes, channels, catch-basins, and pump-stations, *etc*.). Representation of stormwater flow is an important element of stormwater modeling, and the representation can be analyzed at different levels of detail, from mechanistic models of physical processes to more general statistical or empirical relationships (Westphal, 2001). For modeling stormwater hydraulics, the shallow water dynamic wave equations (*i.e.,* the Saint-Venant equations) can be solved numerically to simulate unsteady one-dimensional flows in open and natural channels or in pressurized closed conduits (Zoppou, 2001). Approximations to the shallow wave equations are also used, including the kinematic wave model and diffusion wave models in one or two dimensions (Zoppou, 2001; Mays, 2001).

The ultimate goal of the modeling tools compiled in this report is to characterize the spatial extent of contamination following transport through stormwater and to inform cleanup activities in an emergency setting, including over a longer duration, as the extent of contamination is better understood. In this respect, the potential application is different from typical stormwater quality tools that are focused on more-or-less ubiquitous continuous contaminant sources, with a focus of estimating and controlling loading rates to downstream waters.

3.0 Model Review Process

3.1 Initial Screening

An initial list of available stormwater models that potentially simulate both stormwater flow and fate and transport of pollutants in the watershed was obtained from a list compiled by the Minnesota Pollution Control Agency (MPCA, 2017). This list was supplemented with additional reviews of stormwater models in the peer-reviewed literature and standard text references (Zoppou, 2001; Elliott and Trowsdale, 2007; Mays, 2001). The combined set of models screened in this work is more extensive than in any prior evaluation and is also focused on an assessment specific to the goals of modeling biological and radiological contaminants during emergency response and remediation. The models used in the initial screen are listed in Appendix A in alphabetical order. The models were first characterized based on the following criteria (denoted as "x" in Appendix A, when the characteristic applied):

- Hydrologic Model,
- Hydraulic Model,

- Combined Hydrology and Hydraulic Model,
- Pollutant Transport,
- Water Quality Model,
- Receiving Water Model,
- Simulates Best Management Practices (BMPs),
- Proprietary, and
- Developer.

Because simulation of pollutant transport on landscape surfaces is important in this study, hydraulics-only models and those models that only simulate receiving waters were excluded from detailed review after the initial screening. While there may be potential for coupling a hydraulics model with a water quality model for emergency response applications, it was assumed this would require a substantial coding effort. The initial assessment resulted in a total of 26 models for detailed review. In Appendix A, each of the screened models is identified, and the reason for exclusion of each model from the detailed review is briefly described. These models are unlikely to provide information on the transport of pollutants on land surfaces without substantial further development. All other models were characterized in greater detail as described below.

3.2 Detailed Review and Quality Assurance

For the detailed model review, a variety of sources of information were consulted, including peer-reviewed and gray literature. The information used for each model review was derived from several sources: 1) description, documentation, manuals, and factsheets listed on the model's official website; 2) literature searches based on the model's name; and 3) a review of case studies of model applications from real study sites obtained from internet searches. This work also included outreach to model developers or the company selling the model, contacts from other specialist users, and our own experience in using some of these modeling tools. Given the broad range of models considered, direct testing of each model was beyond the scope of the present review. Also, some models differed in the extent of information available in the public domain (*e.g.*, journal articles and user manuals available without purchase of the software).

A set of evaluation criteria was used to systematically characterize the models in the survey and is listed in Table 1. These criteria were developed by the project team based on experience working in either the stormwater or emergency response sector, or both. ***Model prevalence*** refers to the extent to which the model has been used in various applications. Several approaches were used to evaluate model prevalence, including: 1) the number of applications of the model in literature case studies, and 2) the number of model users. Information regarding extent of model use can be derived either from the model's website or from the literature. When the model was estimated to have over a hundred applications or users, we characterized the model prevalence as high. When more than 10 applications were found, we characterized the model as somewhat prevalent (moderate). If the number of the model applications was not available from the model website, we did an online search for recent individual applications. If few applications were estimated to have been reported and could not be generally quantified, the model prevalence was characterized as low. Model prevalence in peer reviewed literature and real-world applications was also included in the summaries to provide an indication as to the industry's acceptance of the model being a quality tool.

The ***Ease of use for public utilities*** was classified as easy, moderate or advanced. The ease of use was defined according to the complexity of the model and based on model case studies. When the model is a spreadsheet-type model and requires minimal inputs (*e.g.*, simple calculator type of model), the model is characterized as easy to use. If the model is more complicated with representation of watershed processes and a greater number of inputs, the model is characterized as moderate. When the model has a more complicated representation of hydrology and hydraulics processes requiring multiple input layers and adjustable parameters (*e.g*., Hydrological Simulation Program-Fortran [HSPF]) or has sewer/storm water network calculations (*e.g.*, CivilStorm), the model is considered advanced. The ease of model use was also verified by reviewing case studies of model applications for each model.

The ***Representation of uncertainty*** describes in narrative form how the model handles uncertainty in predictions, either due to uncertainty in the input, model representation of certain parameters, or in the output. Most of the stormwater models reviewed here are deterministic, with model inputs used to predict a single set of outputs (Lind, 2015). For these deterministic models, the uncertainty can be derived externally by users through uncertainty analysis of the inputs or through sensitivity analysis. The uncertainty specified in inputs by users can then be propagated through the model by running different model scenarios through the range of the inputs. Some models (*e.g*., PCSWMM) offer a tool in the model for the user to specify an input range for addressing the uncertainty in input variables, while other models may offer options to specify stochastic distribution of rainfall input (*e.g*., 100-yr rainfall, 5-yr rainfall; HydroCAD, 2011). For models that possess some inherent randomness, stochastic representations of the model inputs and its representation of uncertainty are built directly into the model (Lind, 2015). For example, the Monte Carlo method was incorporated into the Stochastic Empirical Loading and Dilution Model (SELDM) model to produce random combinations of input variable values.

The ***Ease of obtaining information and availability of technical support*** criterion for each model was evaluated using information provided on the model website or through a literature search and reported in narrative form. Another criterion for evaluation is ***Data assembly requirements*** during and after emergency response. Selected stormwater models are intended to be used during or soon after an emergency event in any arbitrary location in the country. Setting up the models beforehand is impractical, except for a few key locations. How quickly these models can be assembled during an emergency response is therefore an important evaluation criterion. Some models have built-in functions or data to simulate the required inputs (*e.g*., rainfall) or to extract data from the internet. These requirements were ranked as low. Some models are geographic information system (GIS)-based and can derive watershed data (*e.g*., slope, watershed area) from a digital elevation model (DEM), which can be obtained from national-scale databases. These models have fewer data requirements, may be assembled relatively quickly, and are rated as moderate with respect to data assembly requirements. Other models have more site-specific data requirements such as the details of a stormwater network, junctions, BMPs or low impact developments (LIDs), which may not be readily available. Therefore, the rating for data assembly requirements for these models is considered high. In addition to the criteria previously described, the detailed review also looked at stormwater LID/BMPs as well as data and software compatibility, whether the model is event-based or continuous, lumped (*i.e.*, variables in a land area are represented as aerial weighted averages) or distributed (*i.e*., variables of each homogenous land area are represented individually), empirical or physical, where the model was used, and other general features. Table 1 provides further explanation for the criteria used in the model survey. Model runtime was not included in the criteria due to its dependence on available computing power and modeling domain. Post-processing of outputs was also not included because the extent of post-processing can vary greatly depending on the parameter.

Table 1: Explanation of stormwater model survey evaluation criteria

Criterion	Explanation
Developer	Name of company/agency/individual who developed the model.
Version	The version number of the model at the time of this review
Hardware computing requirements	Specific computational requirements, if specified.
Code language	Language in which the model was coded.
Original application (*e.g*. urban, rural)	Focus of the original model, type of landscape and conditions modeled in the literature. In general, the model was considered urban or suburban if the original application was for stormwater utilities with a high population density and piped infrastructure and rural if the applications were more agriculturally based.
Public/proprietary and cost	Whether model and source code are public and modifiable, or if proprietary. Where available, specific licensing costs were reported.
Physically or empirically based	Whether the underlying formulation of the model solves mechanistic equations of flow and transport or is based on an empirical formulation. Both types of model are considered.
Mathematical method for flow routing and water quality	Mechanistic or empirical approaches used for flow routing and contaminant transport for physically based models.
Input data requirements	Typical input data needs, and difficulty of preparing these data sets from publicly-available information.
Data assembly requirements during and after emergency response	As above, but specifically considering the potential of rapidly setting up a model run to respond to an emergency
Outputs	Nature and format of outputs
Representation of uncertainty	How is uncertainty analysis integrated into the modeling framework?

Prevalence	How common is the model? Are there many known applications (not just peer-reviewed publications)?
Ease of use for public utilities	What are the barriers to the widespread use of the model in terms of training or specialized supporting hardware and software?
Ease of obtaining information and availability of technical support	Is the model actively supported with an engaged user group or commercial help desk?
Source code availability	Is the source code available for modification if needed?
Status of model development	Is the model developed and available for immediate use? This category may include models that continue to be updated.

4.0 Results of Model Review

Summaries for the models that were reviewed in detail are presented in Appendix B, with text descriptions associated with the criteria listed in Table 1. In summary, based on the review here, models were classified into four categories: the SWMM family (sewer and stormwater modeling), detailed sewer pipe-only models, watershed models, and simple empirical models (support tools). These categories are briefly described below (in no special order) and graphically in Mikelonis *et al.*, 2018.

4.1 SWMM Family of Models

One grouping that emerged during the detailed review was the SWMM family of models (EPA SWMM, PCSWMM, InfoSWMM, and XPSWMM), which offer comprehensive capabilities to simulate stormwater hydrology, hydraulics, pollutants, and LID/BMPs/control devices. The individual models differ in the quality of the user interface and GIS computer-aided design (CAD) platforms and specialized tools. The free version of EPA SWMM supports some schematic representation of the drainage areas and storm-drain network but does not have algorithms to establish a 2D flow mesh. Commercial versions that run the baseline EPA SWMM code and add additional functionality are described below:

- PCSWMM expands EPA SWMM5 with 1D or 2D urban flood modeling capabilities. PCSWMM is a stand-alone application with built-in GIS functionalities, including tools that can determine drainage areas from a digital elevation model and stream network.
- InfoSWMM is an ArcMap extension of the EPA SWMM5 model. The model is provided as an extension to the ESRI ArcGIS platform. Therefore, the ESRI ArcGIS software is required for setting up the model. InfoSWMM provides ArcGIS integration and capabilities for wastewater and stormwater modeling and a greater number of hydrology representation methods.
- XPSWMM is another interface for SWMM5 (and parts of SWMM4) for modeling stormwater, sewers and floodplains. XPSWMM also simulates both 1D and 2D overland flow. The model allows GIS and CAD integration and allows for easy setup of a site with external data.

- SUSTAIN (Shoemaker et al., 2011) is a stormwater model interface that uses the SWMM hydrology engine. In addition to predicting stormwater runoff, SUSTAIN is a decision support system for optimally selecting locations of stormwater BMPs and their costs. Since the framework for SUSTAIN is from a different lens than emergency response it would need to be reworked before being an applicable tool for recovery.

4.2 Sewershed and Sewer Network Models

The second category of models includes detailed sewer models that simulate storm sewer networks and associated catchments. These models include: InfoWorks Integrated Catchment Model (ICM), MikeUrban and CivilStorm. These models offer capabilities to simulate sewer network hydraulics, as well as 1D or 2D surface overland flow. These models may use portions of the SWMM code, but also contain their own proprietary engines for flow routing and pollutant fate and transport. Typically, they are used in urban flood management studies. They cover very comprehensive modeling features but are expensive.

4.3 Watershed Models

The third category of models includes watershed models or pollutant transport models that simulate stormwater flow and pollutant loads. These models range from simple lumped models that use the same parameter values for the entire watershed, to more comprehensive spatially distributed models such as the Soil & Water Assessment Tool (SWAT), HSPF and the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model. These models can simulate transport and reaction of pollutants across the watershed and effects of stormwater control facilities and best management practices, although several lack capabilities to simulate detailed stormwater sewer networks. These models have been used extensively in studies to characterize pollutant loads to receiving waters in watersheds with mixed land use, as part of total maximum daily load (TMDL) analyses.

The fourth category of models includes the simple spreadsheet-type calculator tools for estimating stormwater flow and pollutant load and sometimes effects of stormwater BMPs, such as BMP System Effectiveness and Life-Cycle Evaluation of Costs Tool (SELECT), the Stochastic Empirical Loading and Dilution Model (SELDM), the Minimal Impact Design Standards (MIDS) calculator, and the Spreadsheet Tool for Estimating Pollutant Loads (STEPL). These models provide simple calculations for stormwater flow and pollutant loads, can be applied relatively easily, and may have applications for stormwater modeling where rapid results with minimal data are essential.

5.0 Discussion

The model review shows that a vast number of choices exist for further development, with the following observations: (1) most commercial modeling frameworks are not open, limiting their adaptability for new types of process representation if needed; (2) some of the commonly used urban modeling packages are relatively expensive, with licensing costs of several thousand dollars per year; (3) uncertainty analysis is rarely a feature of most models, and typically such analysis is done by re-running the model with different parameters; and (4) model complexity is tied to input data complexity and user expertise.

Providing decision makers with an estimation of transport of radiological contaminants and biological agents during emergency response and recovery, are not directly addressed through currently available off-the-shelf models. No one model is readily usable for the types of applications needed, including the need for modeling small-scale prototypes and rapid application in urban areas with complex catchments. However, based on the model review presented here, and the experience and evaluation of the reviewers, the SWMM class of models is appropriate for future development as part of an effort to provide information on biological and radiological contaminants fate and transport during emergency response and recovery because of the availability of the source code, the overall robustness and prevalence of the SWMM engine, and basic capability of the SWMM model to handle the underlying flow and contaminant transport processes.

This review clearly shows that complex models have substantial data requirements that may not be readily available in an emergency. Rather than developing site-specific models in such a situation, it may be helpful to have a set of archetype models, with typical urban settings and driven by ranges of parameters (rainfall, slope, washoff, *etc.*), pre-run for use under such conditions. Ultimately, it is important to recognize that the choice of modeling software during an emergency may also be heavily influenced by the preexisting software choice of the affected municipality. Future development is recommended not only to expand the SWMM family functionality for emergency response, but also to improve the conversion and transfer between different software frameworks. Model applications originally developed in a specific SWMM family commercial framework can be challenging to transfer from one software framework to another as there are usually subtle differences between the model representation of data that prevent a straightforward transformation from one package to another, especially for complex city-scale models. It is important that tools created during future research projects be as flexible as possible in being able to interact with multiple software platforms.

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Appendix A – Models in Initial Screening [1]

Item #	Model	Description	Model Characteristic: Hydrologic Model	Hydraulics Model	Combined Hydrology and Hydraulic Model	Pollutant Transport	Water Quality Model	Receiving Water Model	Simulates BMP?	Proprietary	Developer	Included in Detailed Review?	Reason(s) for exclusion from detailed review
1	BASINS	Watershed modeling system			x	x	x	x	x		EPA	Y	
2	BasinSim1.0	Watershed modeling package based on Generalized Watershed Loading Function model (GWLF)	x			x	x				Virginia Inst. of Marine Sciences	Y	
3	Bathtub	Empirical model of reservoir eutrophication						x			United States Army Corps of Engineers (USACE)	N	Receiving water model only
4	CE-QUAL-W2	Water quality and hydrodynamic model in 2D (longitudinal-vertical) for rivers, estuaries, lakes, reservoirs					x	x			USACE and Portland State University	N	Receiving water model only
5	CivilStorm	Comprehensive stormwater modeling and analysis software.			x	x	x		x	x	Bentley	Y	
6	Culvertmaster	Hydraulic analysis for culvert design		x						x	Haestad Methods, Bentley Systems, Inc.	N	Culvert design only
7	EPD-RIV1	One Dimensional Riverine Hydrodynamic and Water Quality Model					x	x			Georgia Environmental Protection Division and EPA	N	Receiving water model only
8	FHWA Hydraulic Toolbox	Hydraulics model for transportation structures		x							Federal Highway Authority (FHWA)	N	Hydraulic model only
9	Flowmaster	Hydraulic analysis program for design and analysis of open channels, pressure pipes, inlets, gutters, weirs, and orifices		x						x	Haestad Methods, Bentley Systems, Inc.	N	Hydraulic model only

Note: "x" means the model characteristic applies

Item #	Model	Description	Model Characteristic								Developer	Included in Detailed Review?	Reason(s) for exclusion from detailed review
			Hydrologic Model	Hydraulics Model	Combined Hydrology and Hydraulic Model	Pollutant Transport	Water Quality Model	Receiving Water Model	Simulates BMP?	Proprietary			
10	GWLF	GWLF is a watershed loading model developed to assess nonpoint source flow and sediment and nutrient loading from urban and rural watersheds	x			x	x				Cornell University	Y	
11	Green Values National Stormwater Management Calculator	A tool for quickly comparing the performance, costs, and benefits of Green Infrastructure or LID, to conventional stormwater practices.							x		Center for Neighborhood Technology	N	BMP only
12	GSSHA	Gridded surface subsurface hydrologic analysis	x	x		x	x				USACE	Y	
13	HEC-HMS	Hydrologic rainfall-runoff model. Computes hydrographs for a network of watersheds	x			x	x				USACE	Y	
14	HEC-RAS	River hydraulic model		x		x	x				USACE	N	River model only
15	HSPF	A watershed scale model for estimating in-stream concentrations resulting from loadings from point and non-point sources			x	x	x				EPA	Y	
16	HY8	Culvert hydraulic computations and design software		x							FHWA	N	Hydraulic model only
17	HYDRO_AS2D	2-D finite element flow modeling package		x		x	x			x	Aquaveo	N	River model only
18	HydroCAD	Civil Engineering design tool. Provides calculation for runoff hydrology, hydrograph, routing, hydraulics, culvert calculations, land use and loading			x	x			x	x	HydroCAD Software Solutions LLC	Y	

Item #	Model	Description	Model Characteristic								Developer	Included in Detailed Review?	Reason(s) for exclusion from detailed review
			Hydrologic Model	Hydraulics Model	Combined Hydrology and Hydraulic Model	Pollutant Transport	Water Quality Model	Receiving Water Model	Simulates BMP?	Proprietary			
19	ICPR	Integrated 2D surface water and groundwater flow model.			x				x	x	Streamline Technologies	N	No pollutant modeling
20	InfoSWMM	Commercial implementation of SWMM5			x	x	x		x	x	Innovyze	Y	
21	InfoWorks ICM	Integrated modeling platform to incorporate both urban and river catchments. InfoWorks ICM enables the hydraulics and hydrology of natural and man-made environments			x	x	x		x	x	Innovyze	Y	
22	i-Tree Hydro	Stand-alone application designed to simulate the effects of changes in tree and impervious cover characteristics within a defined watershed on stream flow and water quality	x				x		x		SUNY-ESF	N	No pollutant transport or hydraulics
23	i-Tree Streets	Analysis tool for urban forest managers that uses tree inventory data to quantify the dollar value of annual environmental and aesthetic benefits	x				x		x		SUNY-ESF	N	No pollutant transport or hydraulics
24	LSPC	Like HSPF			x	x	x				Tetra Tech, available from EPA	Y	
25	MapShed	A customized GIS interface that is used to create input data for an enhanced version of the GWLF watershed model	x			x	x		x		Penn State	Y	
26	Metropolitan Council Stormwater Reuse Guide	Excel-based stormwater comparison tool							x		Metropolitan Council, Twin Cities Region, MN	N	BMP only
27	MIDS calculator	Stormwater quality tool to predict annual pollutant removal and runoff volume of various LID BMPs	x			x			x		Minnesota Pollution Control Agency	Y	

Item #	Model	Description	Model Characteristic								Developer	Included in Detailed Review?	Reason(s) for exclusion from detailed review
			Hydrologic Model	Hydraulics Model	Combined Hydrology and Hydraulic Model	Pollutant Transport	Water Quality Model	Receiving Water Model	Simulates BMP?	Proprietary			
28	MIDUSS	Model for stormwater management, design and analysis. Hydrology features: storms, rainfall abstraction, overland flow routing. Design features: pipes, channels, detention pond, exfiltration trench, culvert			x				x	x	Scientific Software Group	N	No pollutant modeling
29	MIKE 11	A river model and general-purpose river modeling toolbox			x			x		x	DHI	N	River model only
30	MikeUrban	Modeling for urban catchments			x	x	x		x	x	DHI	Y	
31	MODRET	Calculates unsaturated and saturated infiltration losses from stormwater retention/detention ponds			x					x	Scientific Software Group	N	No pollutant modeling
32	National Stormwater Calculator	Tool for computing small site hydrology for any location within US and for identifying BMPs for managing stormwater	x								USEPA	N	Runoff only
33	P8	Physically-based stormwater quality model developed to predict the generation and transport of stormwater runoff pollutants in urban watersheds	x			x	x		x		W.W. Walker and J.D. Walker	Y	
34	PCSWMM	Commercial implementation of SWMM5			x	x	x		x	x	CHI	Y	
35	PLOAD	A pollutant loading model				x	x		x		CH2M HILL for EPA	N	Simplified model lacking detailed accounting of stormwater processes
36	PONDNET	An empirical model developed to evaluate flow and phosphorus routing in pond networks				x	x		x		William W. Walker	N	Receiving water model only

Item #	Model	Description	Model Characteristic								Developer	Included in Detailed Review?	Reason(s) for exclusion from detailed review
			Hydrologic Model	Hydraulics Model	Combined Hydrology and Hydraulic Model	Pollutant Transport	Water Quality Model	Receiving Water Model	Simulates BMP?	Proprietary			
37	PondPack	Program for modeling and design of the hydrology and hydraulics of storm water runoff and pond networks, for urban and rural watersheds			x				x	x	Bentley	N	No pollutant modeling
38	QHM	A continuous watershed quantity and quality simulation model intended for watershed management and stormwater design.	x			x	x		x	x	Scientific Software Group	N	Older software (for Windows XP and older). Developer indicated they had no plans for updating.
39	QUAL2E	A water quality and eutrophication model					x	x			EPA	N	Receiving water model only
40	Rainwater Harvesting Model	Simplified model for stormwater volume estimation	x						x		North Carolina State University	N	Runoff/BMP only
41	Rational method	Simple calculation of peak flow based on drainage area, rainfall intensity, and non-dimensional runoff coefficient	x								In common use for more than a century	N	Runoff only
42	RECARGA	This model is used for evaluating the performance of bioretention facilities, rain gardens, and infiltration basins.							x		Wisconsin Department of Natural Resources (DNR)	N	BMP only
43	SELDM	Planning-level estimates of event mean concentrations, flows, and loads in stormwater from a site and an upstream basin interest	x			x			x		United States Geological Survey (USGS)/ FHWA	Y	Provides only simplified estimates of loads and Event Mean Concentrations (EMCs).
44	SELECT	Planning level tool that uses long-term records to drive the model			x	x	x		x		WERF	Y	
45	SHSAM	Simulates runoff and removal of suspended sediments from stormwater			x	x	x		x		BARR Engineering	Y	

Item #	Model	Description	Model Characteristic								Developer	Included in Detailed Review?	Reason(s) for exclusion from detailed review
			Hydrologic Model	Hydraulics Model	Combined Hydrology and Hydraulic Model	Pollutant Transport	Water Quality Model	Receiving Water Model	Simulates BMP?	Proprietary			
46	STEPL	Nutrient and sediment loads from different rural land uses and BMPs on a watershed scale. Simulates watershed surface runoff, nutrient loads, BOD5, sediment delivery	x			x					EPA	Y	
47	StormNET	StormNet is software for stormwater modeling.	x		x	x	x				BOSS International	Y	
48	Stormwater Reuse Calculator	Simplified model for stormwater volume and management							x		Minnehaha Creek Watershed District	N	BMP only
49	SUSTAIN	Model for stormwater flow and BMPs on a watershed scale, based on SWMM	x			x	x		x		EPA	N	Basic stormwater processes are the same as SWMM (same engine) and covered in the review of other models
50	SWAT	A physical based, watershed scale model that predicts the impacts of land management practices on water, sediment and agricultural chemical yields	x			x	x				United States Department of Agriculture (USDA) with Texas A&M University	Y	
51	SWMM5	General stormwater model; this code underlies several commercial models			x	x	x		x		EPA	Y	
52	TR-20	Single event watershed scale runoff and routing model	x								Natural Resources Conservation Service (NRCS)	N	Runoff only
53	TR-55	Simplified procedure to calculate stormwater runoff volume, peak rate of discharge, hydrographs and storage volumes in small urban watersheds	x								NRCS	N	Runoff only
54	Virginia Runoff Reduction Method	Excel spreadsheets for regulatory compliance	x								Virginia Department of Environmental Quality	N	Runoff only

Item #	Model	Description	Model Characteristic								Developer	Included in Detailed Review?	Reason(s) for exclusion from detailed review
			Hydrologic Model	Hydraulics Model	Combined Hydrology and Hydraulic Model	Pollutant Transport	Water Quality Model	Receiving Water Model	Simulates BMP?	Proprietary			
55	WARMF	Watershed model that simulates runoff, pollutant transport, and water quality	x			x	x				Systech	Y	
56	WASP	Evaluates fate and transport of contaminants in surface waters					x	x			EPA	N	Receiving water model only
57	WinSLAMM	Stormwater quality model for evaluation of nonpoint pollution in urban areas	x			x	x		x	x	PV and Associates	Y	
58	WiLMS	The Wisconsin Lake Modeling Suite (WiLMS) model is a lake water quality-planning tool. The model includes a front-end, phosphorus prediction, internal loading and trophic response					x	x			Wisconsin Department of Natural Resources	N	Lake water quality model only
59	WMM	Estimates annual/seasonal nonpoint pollutant loads from direct runoff on watersheds and sub-basins.	x			x	x				CDM	N	Limited temporal detail in stormwater modeling
60	WSPRO	Hydraulic model for water surface profiles		x				x			USGS	N	River model only
61	WWHM	Tool developed to size stormwater control facilities to mitigate the effects of increased runoff from proposed land use changes.	x						x		Washington State Department of Ecology	N	No pollutant modeling
62	XPSWMM	Commercial implementation of SWMM5			x	x	x		x	x	XP Solutions (owned by Innovyze)	Y	

Appendix B – Model Summaries

The table below provides example references for those unfamiliar with the hydrologic equations and methods referenced in the model summaries. (The links were last referenced on August 28, 2018.)

Named Equations	Reference
Bagnold's Equation	Bagnold, 1977 (Water Resources Research)
Chezy-Manning Equation	Water Resources Engineering (Larry Mays, 2nd Edition, Eqn 5.1.2.1)
Manning's Equation	Water Resources Engineering (Larry Mays, 2nd Edition, Eqn 5.1.2.2)
Saint-Venant Equations	Desktop Review of 2D Hydraulic Modeling Packages (Defra Science Report SC080035, Section 2.1)
Universal Soil Loss Equation (USLE)	Predicting Rainfall Erosion Losses (USDA Agriculture Handbook Number 537)
MUSLE (modified USLE)	Merritt *et. al.*, 2008 (Environmental Modeling & Software)
Methods	**Reference**
Ackers-White method	Mayer et. al., 2009 (River, Coastal and Estuarine Morphodynamics, Santa Fe-Argentyna, A. Balkena Book)
Clark method	Water Resources Engineering (Larry Mays, 2nd Edition, Section 8.4.2)
Darcy's Law	Water Resources Engineering (Larry Mays, 2nd Edition, Section 4.1)
Engelund-Fredsøe method	Engelund and Fredsøe, 1976 (Hydrology Research)
Green-Ampt method	Water Resources Engineering (Larry Mays, 2nd Edition, Section 7.4.2)
Hargreaves method	Hargreaves, 1985 (Applied Engineering in Agriculture)
Horton's method	Water Resources Engineering (Larry Mays, 2nd Edition, Section 7.4.3)

Modified Horton method	Akan, 1992 (Journal of Irrigation and Drainage Engineering)
ModClark, Initial & constant loss infiltration method, linear reservoir routing method, nonlinear Boussinesq method, lag routing method, and Puls routing method	HEC-HMS Technical Reference Manual (CPD-74B, March, 2000)
Muskingum-Cunge method	Technical Paper No. 135 (USACE Hydrologic Engineering Center)
Muskingum routing method	Nash, 1959 (Journal of Geophysical Research)
NRCS-TR55 method	USDA Urban Hydrology for Small Watersheds TR-55
Santa Barbara Urban Hydrograph method	Stubchaer, 1975 (National Symposium on Urban Hydrology and Sediment Control)
SCS curve number method	USDA Urban Hydrology for Small Watersheds TR-55 (Chapter 2)
SCS unit hydrograph method	USDA Part 630 Hydrology National Engineering Handbook (Chapter 16)
Penman-Monteith method	Sumner and Jacobs, 2005 (Journal of Hydrology)
Priestly-Taylor	Sumner and Jacobs, 2005 (Journal of Hydrology)
RDII (Rainfall Dependent Infiltration and Inflow) method	Review of Sewer Design Criteria and RDII Prediction Methods (EPA/600/R-08/010)
Snyder method	Water Resources Engineering (Larry Mays, 2nd Edition, Section 8.4.1)
van Rijn method	van Rijn, 1984 (Journal of Hydraulic Engineering)

B.1 BASINS (Better Assessment Science Integrating point and Non-point Sources)

Developer: Office of Water, EPA

Description: BASINS, a multi-model system that supports watershed management and TMDL development, provides an integrated platform to conduct analysis using different environmental data, analysis tools, and watershed and water quality models. BASINS uses a GIS for organizing spatial information used in the analysis. It provides access to national datasets of DEMs, land use and soils that can be used in the analysis. BASINS also incorporates multiple watershed and water quality modeling tools into the system, including: Hydrologic Simulation Program – Fortran (HSPF), the Soil and Water Assessment Tool (SWAT), the EPA Storm Water Management Model (SWMM), Generalized Watershed Loading Function model extension (GWLF-E) Mapshed, and the Pollutant Loading Estimator (PLOAD), and water quality models including: AQUATOX and Water Quality Analysis Simulation Program (WASP). Some of these models are described elsewhere in Appendix B.

Versions: v4.1 (complete), v4.2 test version (under development)

Features: BASINS provides an automatic data download tool, such as DEM, stream network, land use, meteorology, and water quality data that can automatically download data needed for watershed modeling. BASINS provides access and tools to set up watershed and water quality models and also provides tools for watershed characterization, manual and automatic watershed delineation, WDMUtil for time series data generation, GenScn utility for post processing, and climate assessment tool (CAT) for climate change analysis.

Original Application: Urban

Mathematical method for flow routing and water quality: Depends on the watershed or water quality model selected for the application. See associated sections of this report for relevant models.

Input Data Requirements: Only the site location is necessary since data can be downloaded automatically. User specified site-specific data can also be incorporated into the model.

Data assembly requirements during and after emergency response: Moderate

Outputs: Spatial information of the watershed studied, outputs from models such as flow and water quality data. See associated one pagers for relevant models.

Representation of Uncertainty: Depends on the watershed or water quality model selected for the application

Hardware computing requirements: Minimum requirements: 1 GHz processor, 2.0 GB available hard disk, 512 MB of RAM, 16-bit color resolution monitor, internet, Windows XP, Vista, or Windows 7 and 8 operating systems. BASINS 4.1 is also 64-bit compatible.

Code language: C#

Public/Proprietary and Cost: Public, free

Prevalence: High.

Ease of use for public utilities: Moderate

Ease of obtaining information and availability of technical support: Support is available through email from EPA's BASINS Support Team. A user group mailing list is also available to answer technical questions.

Source code availability: Source code for BASINS 4 is available in the MapWindow code repository. Source codes for individual models are also available for HSPF, SWAT and SWMM.

Installation requirements/software: MapWindow

Source/Link: https://www.epa.gov/exposure-assessment-models/basins (Last accessed August 13, 2018.)

B.2 BasinSim 1.0

Developer: Ting Dai, Richard L. Wetzel, T.R.L. Christiansen, and E.A. Lewis at the Virginia Institute of Marine Science (VIMS)

Description: BasinSim1.0 is a desktop simulation system that predicts sediment and nutrient loads from small to mid-sized watersheds. The simulation system is based on the Generalized Watershed Loading Functions (GWLF) (Haith *et. al*., 1992). BasinSim 1.0 integrates the GWLF model and extensive databases, including land uses, population, soils, flow, water quality, climate, and point nutrient sources and was designed to enable resource managers to visualize and manipulate data and conduct model simulations.

Versions: v1.0

Features: BasinSim1.0 provides a user interface for the watershed model GWLF and provides extensive datasets for modeling. It can be used to create and modify input data, display data and results in maps and graphs, compare simulation scenarios and options for data manipulation, and has a capability to calculate sediment, nutrient, and pollutant loads.

Original Application: Urban

Mathematical method for flow routing and water quality: see GWLF summary.

Input Data Requirements: see GWLF summary.

Data assembly requirements during and after emergency response: Moderate

Outputs: Flow and water quality

Representation of Uncertainty: None

Hardware computing requirements: BasinSim 1.0 requires an IBM PC-compatible computer running Windows95 or above and about 20 MB of hard-drive space.

Code language: Visual Basic 6.0

Public/proprietary and Cost: Public, free

Prevalence: Low

Ease of use for public utilities: Moderate

Ease of obtaining information and availability of technical support: Not available

Source code availability: Not available

Installation requirements/software: None

Source/Link: http://web.vims.edu/bio/models/bsabout.html (Last accessed August 13, 2018)

B.3 CIVILSTORM

Developer: Bentley

Description. CivilStorm is a dynamic hydrologic and hydraulic model developed for complex stormwater systems (Bentley Systems, 2014). The model, with built-in hydraulic and hydrology tools and wet-weather calibration methods, has been used in stormwater master plan development, water quality studies, and to design, analyze, and operate stormwater systems.

Versions: v8

Features: Comprehensive analysis of all aspects of stormwater systems: rainfall, runoff, inlet capture and bypass, gravity and pressure piping, ponds, outlet structures, open channels, and culverts. Used for design of stormwater systems, simulation of hydraulics using multiple solvers, and simulation of water quality. CivilStorm can work as a stand-alone application or can be run from within MicroStation or AutoCAD.

Original Application: Urban

Mathematical method for flow routing and water quality: *Runoff/Infiltration:* SWMM and hydrograph methods (RTK, Soil Conservation Service (SCS) curve number method, modified Rational); *Flow Routing*: SWMM dynamic and kinematic solver or gradually varied flow solver (peak flow calculation uses the rational method); *Water Quality:* see SWMM summary.

Input Data Requirements: See SWMM summary.

Data assembly requirements during and after emergency response: Low

Output: Flow, depth, and water quality in junctions and outfalls that is in a format compatible with Computer Aided Design (CAD)/GIS. Micro Station V8i Select series 3, AutoCAD 2014, 2015 (32-bit/64-bit), ArcGIS 10.2, databases, ProjectWise v8i.

Representation of Uncertainty: No specific uncertainty tool.

Hardware computing requirements: Windows 8.1 (32-/64-bit)

Code language: a mix of C++, .NET, C#, SQL, and Fortran

Public/proprietary and Cost: $1,481 for 10 links (conduits and gutters) to $3,459 1000 links

Prevalence: High. 340 featured user project applications on the website

Ease of use for public utilities: Advanced

Ease of obtaining information and availability of technical support: Product information available online. Support available through user community or service request.

Source code availability: Not available

Installation requirements/software: Not specified

Source/Link: http://www.bentley.com/en-US/Products/CivilStorm/ (Last accessed August 13, 2018)

B.4 GWLF (Generalized Watershed Loading Function)

Developer: D.A. Haith and L.L. Shoemaker at Cornell University

Description: The GWLF is a model used to simulate runoff, sediment and dissolved and total loads of pollutants (nitrogen and phosphorus) from complex watersheds (Haith *et al*., 1992). The model estimates contaminant load from surface runoff and groundwater sources and calculates nutrient loads from point sources and onsite wastewater disposal systems. GWLF is a combined distributed/lumped parameter watershed model. The model is distributed in the sense that it allows multiple land use/land cover options.

Versions: v8.0

Features: The model provides monthly estimates of streamflow, soil erosion, sediment yield values and nutrient loads. A GIS-based version of GWLF, titled AVGWLF is available from Pennsylvania State University.

Original Application: Urban and rural

Mathematical method for flow routing and water quality: *Runoff:* SCS curve number method; *Infiltration:* Percolation is determined using a daily water balance, and the unsaturated zone is modeled as a simple linear reservoir; *Flow Routing:* Not applicable; *Water Quality:* Sediment erosion is modeled using the Universal Soil Loss equation. Solid-phase rural nutrient loads are calculated by taking the product of the monthly sediment yield and the average sediment nutrient concentrations. Urban nutrient loads are modeled by exponential accumulation and washoff functions. Nutrient loads from septic systems are estimated using the per capita daily load from each type of system and the number of a people in the watershed

Input Data Requirements: Daily precipitation and temperature data, land use/land cover distribution, coefficients (i.e., curve numbers, KLSCP factures, evapotranspiration coefficients, erosivity coefficients, daylight hours by month, growing season months, snow amounts, N and P point source loads, background N and P concentrations in groundwater, background P and N concentrations in soil, months of manure spreading, and population on septic systems

Data assembly requirements during and after emergency response: Moderate

Output Data: Monthly watershed runoff, monthly streamflow, sediment and nutrient (nitrogen (N) and phosphorus (P)) yields and loadings (monthly and annual), and calculated septic system loads

Representation of Uncertainty: None.

Hardware computing requirements: DOS, Windows

Code language: Visual Basic

Public/proprietary and Cost: Public, free

Prevalence: Moderate (GWLF has been applied in at least 12 states)

Ease of use for public utilities: Easy

Ease of obtaining information and availability of technical support: Technical support not available

Source code availability: Original code availability unknown, python version in development at: https://github.com/WikiWatershed/gwlf-e (Last accessed Sept. 5, 2018)

Installation requirements/software: Not specified

Source/Link: http://www.mapshed.psu.edu/download.htm (Last accessed August 13, 2018)

B.5 GSSHA (Gridded Surface Subsurface Hydrologic Analysis)

Developer: United States Army Corps of Engineers (USACE)

Description: GSSHA, a comprehensive watershed simulation and management model used for hydrologic, hydraulic, sediment, and water quality simulation and management (Downer and Ogden, 2006), is a distributed, physically-based, gridded watershed model. The model can track water, sediment, and contaminants along flow paths.

Versions: v7.0

Features: 2D overland flow, 1D stream flow, 1D infiltration, 2D groundwater, and full coupling between the groundwater, vadose zones, streams, and overland flow. Provides soil moisture, runoff and flooding predictions. Analyzes future conditions and management scenarios. Helps develop BMP and TMDL load predictions.

Original Application: Rural

Mathematical method for flow routing and water quality: *Runoff:* water balance method. *Infiltration:* Green-Ampt, Green-Ampt with redistribution, or Richard's equation; *Evapotranspiration:* Penman-Monteith or Deardorff method; *Flow Routing:* 2D diffusive wave for overland flow and diffusive wave and full dynamic wave for open channel flow; *Water Quality:* first order pollutant decay, dispersion, and reactions for uptake from land surface, uptake from soil. Sediment erosion calculation methods include: Engelund-Hansen, Kilinc Richardson, stream power, effective stream power, unit stream power, and shear stress.

Input Data Requirements: model grid size, watershed outlet slope, map of watershed elevations and shape, precipitation data, pollutant decay and dispersion coefficients, grain and sand size of particles, water temperature, porosity of channel bed sediments, manning roughness, interception coefficient and initial interception abstraction, land use, soil type, and vegetation data

Data assembly requirements during and after emergency response: High

Outputs: outflow hydrographs, overland flow depths, water surface elevations, and cumulative discharge. sediment discharge volume and load flux and particle size in specific channel locations, groundwater head and moisture data and contaminant transport

Representation of Uncertainty: It is possible to do Monte Carlo Runs and multiple optimization calibration routines.

Hardware computing requirements: Runs on Windows (32- and 64-bit), Linux, and within the supercomputing environment.

Code language: C++

Public/proprietary and Cost: Public, Free

Prevalence: Moderate. Applied in nine states of U.S.

Ease of use for public utilities: Advanced

Ease of obtaining information and availability of technical support: Product information available online. Questions should be directed to charles.w.downer@usace.army.mil

Source code availability: Available for download

Installation requirements/software: Compatible with GIS. Closely linked to WMS 6.1

Source/Link: https://www.gsshawiki.com/Gridded_Surface_Subsurface_Hydrologic_Analysis
(Last accessed August 13, 2018)

B.6 HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System)

Developer: USACE

Description: HEC-HMS is a model designed to simulate a full suite of hydrologic processes related to dendritic watershed systems. It can perform continuous and event-based simulations of precipitation-runoff and routing processes for natural and controlled systems. The program has been used in studies of urban drainage, floods, and optimizing system operations.

Versions: 4.2.1

Features: HEC-HMS includes the following hydrologic elements: sub-basins, reaches, junctions, reservoirs, diversions, sources and sinks. It also includes mathematical procedures that to account for evapo-transpiration, snowmelt, and fluxes in soil moisture content in addition to routine runoff estimation and routing of flows.

Original Application: Rural, urban, and suburban

Mathematical method for flow routing and water quality: *Runoff:* Unit hydrograph methods (Clark, Snyder, SCS, ModClark, or user specified); *Infiltration:* Initial and constant loss mode, SCS curve number loss model, Green Ampt loss model, or soil moisture accounting loss model; *Evapo-transpiration*: Monthly average values, Priestly Taylor method, or Penman-Monteith method; *Flow Routing*: Kinematic wave method, linear reservoir methods, or nonlinear Boussinesq method for baseflow contributions. A lag method, Muskingum method, modified Puls method, kinematic or Muskingum-Cunge methods for open channel flows; *Water Quality:* MUSLE for sediment, build-up/wash-off, and nutrient transformations for nitrogen and phosphorus.

Input Data Requirements: Temperature index (if modeling snowmelt), net radiation (if using the Priestley Taylor method), precipitation, reservoir/diversion discharge schedules, stage, windspeed, air pressure, humidity, altitude, crop coefficients, sediment loads, pollutant concentrations, percolation rates, and impervious area percentages.

Data assembly requirements during and after emergency response: High

Outputs: flow discharge, water volumes (loss, excess of reservoir storage, baseflows, discharge and runoff), depths of water, hydrologic element peak discharge

Representation of Uncertainty: HEC-HMS provides a probability distribution function and performs a Monte Carlo simulation to describe uncertainty in output variables

Hardware computing requirements: Windows XP, Windows Vista, Windows 7 or 10 (32-bit and 64-bit), modern 32-bit Linus x86 distributions, or 64-bit Solaris, Intel Pentium III/800 MHz or higher, minimum of 512 MB of member (at least 1 GB of memory recommended), 120 MB available hard disk space for installation, and 1024 x 768 minimum screen resolution

Code language: Java

Public/proprietary and Cost: Public, free

Prevalence: High

Ease of use for public utilities: Advanced

Ease of obtaining information and availability of technical support: hec.hms@usace.army.mil accepts bug reports from the public. Support cannot be provided by USACE to individuals outside of the USACE. Private vendors provide support for a fee (not coordinated by USACE).

Source code availability: Not freely available

Installation requirements/software: None

Source/Link: http://www.hec.usace.army.mil/software/hec-hms/ (Last accessed August 30, 2018)

B.7 HSPF (HYDROLOGICAL SIMULATION PROGRAM FORTRAN)

Developer: Aqua Terra, United States Geological Survey (USGS), Office of Research and Development EPA

Description. HSPF, a continuous simulation model developed for both natural and developed watershed and water systems (Bicknell *et al.* 2005), simulates land surface and subsurface hydrology, stream/lake hydraulics, and water quality processes. It is based upon the original Stanford Watershed Model IV and a consolidation of the Agricultural Runoff Management Model (ARM), Non-point Source Runoff (NPS) Model and Hydrological Simulation Program (HSP) (Johnson *et al*., 2003). HSPF is a lumped parameter approach (limited spatial definition) and includes a simplified representation of urban drainage system components (pipes, culverts, Combined Sewer Overflows (CSOs), etc.). The model also provides tools for data management and storage, statistical analysis, and operations. HSPF is the core watershed model in EPA BASINS and Army Corps Watershed Modeling System (WMS). The model is developed and maintained by EPA and USGS. Several user interfaces have been developed for HSPF including WinHSPF.

Versions: v12.2 (EPA), v12.4 (beta, AQUA TERRA) previous: v11.0

Features: Comprehensive representation of watershed land and stream processes as well as representation of watershed pollutant sources (including nonpoint, point, and atmospheric sources). The model offers several modules for pre- and post-processing: HSPEXP: expert system for calibrating, GenScn: software to change input, WDMUtil: tool to create time series data, and HSPFParm: a tool for organizing HSPF parameter values. HSPF simulates water quality constituents such as sediment, pesticide, nitrogen, phosphorus, and tracers for pervious and impervious surfaces, and in the stream reaches. HSPF simulates nitrogen and phosphorus through nitrogen and phosphorus cycles, and reaction processes of pesticides.

Original Application: Urban (and suburban)

Mathematical method for flow routing and water quality: *Runoff:* water balance; *Infiltration*: Green-Ampt or Maryland Method (Look-up); *Flow Routing*: kinematic wave and Chezy-Manning equation for overland flow (turbulent); *Water Quality:* Single organic chemicals and their transformation products (hydrolysis, oxidation, photolysis, biodegradation, volatilization and sorption) can be modeled. Sorption (only in reaches/streams) is modeled as a first-order kinetic process (user-specified desorption rate and equilibrium partition coefficient). Sediment transport simulated for sand, clay, or silt and washoff is modeled as an exponential function or a constant unit removal rate by overland flow. Water bodies are assumed to be well-mixed with width and depth.

Input Data Requirements: Precipitation (hourly), temperature, evaporation, wind speed, solar radiation, potential evapotranspiration, dew point temperature, cloud cover snow, soil properties, pollutant location and load, land use/cover, soil properties, DEM, hydrography, watershed characterization, channel and bed characteristics. Calibration/validation: flow, sediment, and water quality data.

Data assembly requirements during and after emergency response: High

Outputs: Flow and water quality by reach

Representation of Uncertainty: Probability distribution of inputs

Hardware computing requirements: Windows XP, Vista, Windows 7, or Windows 8

Code language: Fortran

Public/proprietary and Cost: public, free

Prevalence: High. There have been hundreds of applications of HSPF all over the world.

Ease of use for public utilities: Advanced

Ease of obtaining information and availability of technical support: Product information available online. Technical support provided by Aqua Terra.

Source code availability: Yes
Installation requirements/software: None
Source/Link: http://www.aquaterra.com/resources/hspfsupport/index.php
(Last accessed August 13, 2018)

B.8 HydroCAD

Developer: HydroCAD Software Solutions LLC

Description: HydroCAD, a CAD program for modeling hydrology and hydraulics of stormwater runoff (HydroCAD, 2011), is commonly used to generate runoff hydrographs for a given watershed and study their flow through a drainage system. HydroCAD provides many approaches for runoff hydrograph generation, time of concentration calculation, reach routing, pond routing and pond outlet hydraulics. HydroCAD has over 100 predefined rainfall distributions including SCS type I, IA, II, III storms, user-defined rainfalls, and custom synthetic rainfall distributions.

Versions: HydroCAD-10, previous versions: HydroCAD-9, 8, and 7

Features: Runoff hydrograph generation, hydrograph routing through ponds and reaches, hydraulics and culvert calculations, advanced flow simulations including pumps and float valves, land use analysis and pollutant loading calculations, and time-of-concentration calculations, including sheet flow method.

Original Application: Urban

Mathematical method for flow routing and water quality: *Runoff:* SCS unit hydrograph method, Santa Barbara Urban Hydrograph method, curve number lookup and weighting, rational method, or modified rational method; *Infiltration:* can model using elevation-dependent rating curves; *Flow Routing:* Muskingum-Cunge method or storage-indication method; *Water Quality*: pollutant load in runoff water is calculated as runoff times concentrations. Pollutant load in storage facilities is calculated as a center-of-mass detention time with plug-flow detention time.

Input Data Requirements: User defines node characteristics (subcatchment, pond, catch basin, reach, or link). Import data directly from AutoCAD for soil groups, ground covers, subcatchment boundaries or using an additional program called Carlson Hydrology (Maysville, KY, USA) for additional parameters (i.e., watershed slope and pond storage contours from .dwg files)

Data assembly requirements during and after emergency response: Moderate

Output: Runoff and water quality**.** Import or export to Comma Separated Values (CSV) format.

Representation of Uncertainty: Uncertainty can be modeled using model scenarios

Hardware computing requirements: Runs on any PC under windows 95, 98, NT, ME, 2K, XP, Vista, Windows 7, or later

Code language: Object Pascal (Delphi Compiler)

Public/proprietary and Cost: proprietary, $275 (5 nodes) - $2200 (1000 nodes)

Prevalence: Moderate

Ease of use for public utilities: Moderate

Ease of obtaining information and availability of technical support: Technical support available through user forum or service request.

Source code availability: Not available

Installation requirements/software: CD installation. Does not require other CAD software.

Source/Link: www.hydrocad.net (Last accessed August 13, 2018)

B.9 INFOSWMM

Developer: Innovyze

Description: InfoSWMM is a modeling system that simulates hydrologic, hydraulic, and water quality in urban and rural areas and uses EPA's SWMM5 computational engine. InfoSWMM is built on top of the ArcGIS platform as an extension to ArcGIS. InfoSWMM models a variety of hydraulic, hydrologic, and water quality processes for any number of user-defined constituents, including conservative and reactive substances, and load reduction due to BMPs, LIDs, and sustainable urban drainage systems (SUDS).

Version: v14.6

Features: Includes all the features of EPA SWMM5 as well as offers an advanced real-time control (RTC) scheme for the management of hydraulic structures. InfoSWMM has several extensions, including InfoSWMM Calibrator for model calibration, InfoSWMM DWF allocator for dry weather flow analysis, InfoSWMM Conduit Storage Synthesizer (CSS), InfoSWMM Suite for Subcatchment delineation, InfoSWMM Risk Assessment Manager (RAM) for overflow and flooding risk analysis. In addition, several add-on tools are available, including InfoSWMM2D for 2D flood modeling, InfoSWMM SFEM (Sewer Flow Estimation Model) for wastewater master planning, and InfoSWMM Sustain for evaluating BMP, LID, and SUDS.

Original Application: Urban (and suburban)

Mathematical method for flow routing and water quality: *Runoff:* water balance/SCS curve number method and a number of hydrograph methods including NRCS, Clark, Snyder, Santa Barbara, Delmarva, Espy, and triangular; *Infiltration:* Over 17 hydrology methods including Horton's method, Modified Horton method, Green-Ampt method, Modified Green-Ampt method, and the SCS curve number method; *Flow Routing*: steady flow routing, kinematic wave routing, or dynamic wave routing; *Water Quality:* pollutant build-up is simulated using a power function, an exponential function, a saturation function, or an external time series. Washoff of pollutants is simulated using an exponential function, rating curve, or an event mean concentration approach.

Input Data Requirements: Like EPA SWMM but also requires a DEM and boundary layer information for 2D modeling extension

Data assembly requirements during and after emergency response: High

Outputs: Subcatchment variables (*e.g*., rainfall, runoff), node variables (*e.g*., water depth, hydraulic head), link variables (*e.g.,* flow rate, water depth), system-wide variables (*e.g*., air temperature, evaporation, total rainfall, snow depth)

Representation of Uncertainty: Although no uncertainty module is provided, uncertainty can be propagated through the model by using distributions of input variables or by using alternative scenarios

Hardware computing requirements: Windows server 2008 R2, Windows 7 Pro or above, Windows Server 2012, Windows Internet Explorer 7 or later, ArcGIS 10.0-10.6, Microsoft Visual C++ 2008 or 2010. CPU speed: 2.2 GHz minimum or higher, Processor: Intel Pentium 4, Intel Core duo, or Xeon processors, SSE2. Memory/RAM: 2 BG or higher. Screen resolution: 1024 x 768 recommended or higher at normal size. Disk Space: 500 Mb of free space Video/Graphics Adapter: 64 MB RAM minimum, 256 MB RM or higher. Network Hardware: simple TCP/P.

Code language: Microsoft Visual C++ 2008

Public/proprietary and Cost: Proprietary, $1,000- $25,000 depending on application (also need ArcGIS)

Prevalence: High

Ease of use for public utilities: Advanced

Ease of obtaining information and availability of technical support: Product information available online. Formal customer support and software maintenance offered by Innovyze.

Source code availability: Code available to licensee for the open source components only

Installation requirements/software: Compatible with ArcGIS 10.0 to 10.6

Source/Link: http://www.innovyze.com/products/infoswmm/ (Last accessed August 13, 2018)

B.10 INFOWORKS ICM (INFOWORKS INTEGRATED CATCHMENT MODELING)

Developer: Innovyze

Description: Infoworks ICM (Integrated Catchment Modeling) is a 1D and 2D simulation model for above- and below- ground drainage networks (Walker, 2012). The model simulates 1D hydrodynamics of flows in rivers, open channels, and pipe networks and 2D hydrodynamics of surface flooding in urban environments and river floodplains. The model can import Hydrologic Engineering Center – River Analysis System (HEC –RAS) channel geometry and perform surface flow routing using 2D modeling. The model has been used in river, drainage, and sewerage master planning studies, development of surface water management plans, implementation of SUDS and BMPs, and to assess the impact of intermittent discharges from sewerage systems (sanitary sewer overflows and combined sewer overflows; CSOs) on river environments.

Versions: v9.5.2

Features: Full 2D surface flood modeling can be employed across both the wastewater and river components of the model. Real-time control allows control structures to be programmed into the system during a simulation. Water quality and sedimentation studies can be carried out across both 1D and 2D areas. The 1D river channels are linked to 2D floodplains.

Original Application: Urban

Mathematical method for flow routing and water quality: ICM has its own proprietary implicit solution and over 35 different hydrology and infiltration methods that are used globally. Components from SWMM5 include SWMM5 Runoff, Green Ampt and SWMM Horton Infiltration, LID components called SUDS, snowmelt and Rainfall Dependent Infiltration and Inflow (RDII).

Input Data Requirements: Like EPA SWMM (B.1) but also requires a digital elevation model and boundary layer information for 2D modeling extension

Data assembly requirements during and after emergency response: High

Output: Flood flow velocity, depth, debris potential, flood risk map, property flooding. Seamless exchange of data and result to and from GIS, Excel and Access, data exchange via Open Data Import/Export Centre.

Representation of Uncertainty: Can be modeled using comparison of different model scenarios

Hardware computing requirements: Designed for Windows 10/8/7, Windows Vista and Windows XP. Supports all 64-bit operating systems.

Code language: Unknown

Public/proprietary and Cost: Proprietary, estimated to be $50,000- $75,000 (5000 nodes – unlimited nodes) from online sources

Prevalence: Moderate. Ten case studies, many testimonials on developer's website

Ease of use for public utilities: Advanced

Ease of obtaining information and availability of technical support: Support from Innovyze available

Source code availability: Not available

Installation requirements/software: ESRI ArcGIS 9.3, 10.0-10.6. MapInfo Professional 10.5 or above.

Source/Link: http://www.innovyze.com/products/infoworks_icm/ (Last accessed August 14, 2018)

B.11 LSPC (LOADING SIMULATION PROGRAM IN C++)

Developer: Tetra Tech, under contract to National Exposure Research Laboratory, Office of Research and Development (EPA)

Description: LSPC, Loading Simulation Program in C++, is a watershed modeling system that incorporates HSPF algorithms for simulating hydrology, sediment and water quality on watersheds and water bodies. The LSPC model provides a GIS- integrated user interface for HSPF. LSPC was a primary watershed model for the EPA TMDL modeling toolbox. The in-stream model of LSPC has been expanded to include HSPF GQUAL components and the HSPF RQUAL module for simulating dissolved oxygen (DO), nutrients and algae (Tetra Tech, 2009). LSPC has been customized to simulate other pollutants such as nutrients and fecal coliform. LSPC uses a Microsoft (MS) Access database to manage model input files and an editable weather text file for managing the weather data.

Versions: v3.1

Features: Land surface and subsurface hydrology and quality. Stream/lake hydraulics and water quality. Sediment production and removal. GIS integration. MS Access database to manage model configuration and parameterization data. Output linked to other models such as EFDC, WASP, and CE-QUAL-W2.

Original Application: Mixed land use

Mathematical method for flow routing and water quality: See HSPF model (B.7)

Input Data Requirements: Same as in HSPF model, but streamlines user input interfaces (B.7)

Data assembly requirements during and after emergency response: moderate

Outputs: Flow and water quality by reach. Output from LSPC linked to EFDC, WASP and CE-QUAL-W2. Microsoft Access and Excel

Representation of Uncertainty: Probability distribution of inputs

Hardware computing requirements: IBM-compatible personal computers (PCs). Processor: Pentium II-500 MHz. Hard drive space: 500 MB. Random access memory (RAM): 128 MB, compact disc drive: CD-ROM 4x, operating system: Windows 98, 2000, or NT.

Code language: MS Visual C++

Public/proprietary and Cost: Public and free

Prevalence: High. Widely applied applications throughout the US (desert, alpine, temperate)

Ease of use for public utilities: Advanced

Ease of obtaining information and availability of technical support: User manual available online with EPA contact information.

Source code availability: Yes

Installation requirements/software: ArcGIS, Microsoft Access/Excel

Source/Link:https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=75860&CFID=22884508&CFTOKEN=98267566 (Last accessed August 14, 2018)

B.12 MAPSHED

Developer: Penn State Institutes of Energy and the Environment (PSIEE)

Description: MapShed is a GIS version of the GWLF model (Evans and Corradini, 2012). MapShed duplicates the functionalities from another GIS version of the GWLF (AVGWLF, Evans et al., 2002). The GIS interface of MapShed is provided by a free MapWindow GIS software package, while AVGWLF uses the ArcView 3.x GIS package developed by ESRI. Like AVGWLF, MapShed provides a link between the GIS software and the enhanced version of the GWLF watershed model.

Versions: v1.3

Features: GIS-based derivation of model input data with enhancements of the original code to include urban best management practice modeling including detention basin, infiltration, bioretention, vegetative buffer strips, constructed wetlands, streambank stabilization, impervious surface reduction, and street sweeping.

Original Application: Rural

Mathematical method for flow routing and water quality: See GWLF (see B.17)

Input Data Requirements: See GWLF (see B.17)

Data assembly requirements during and after emergency response: Moderate

Outputs: See GWLF (see B.17)

Representation of Uncertainty: None.

Hardware computing requirements: PC with Pentium or higher, 24 MB RAM, Windows 98/98SE, ME, 2000, XP or newer, 2003 server, 1024 x 768 pixels or higher resolution screen and >200 MB disk space, with > 4GB preferred

Code language: VB.net

Public/proprietary and Cost: Public, free

Prevalence: Low (applied in several states)

Ease of use for public utilities: Easy

Ease of obtaining information and availability of technical support: Email support available for questions on the model

Source code availability: http://www.mapshed.psu.edu/download.htm

Installation requirements/software: MapWindow Ver. 4.6

Source/Link: http://www.mapshed.psu.edu/index.htm (Last accessed August 14, 2018)

B.13 MIDS (Minimal Impact Design Standards) calculator

Developer: Minnesota Pollution Control Authority (MPCA)

Description: The MIDS BMP calculator is a spreadsheet-based tool designed to manage stormwater using a low-impact development approach (Barr, 2014, 2011). The MIDS model determines volume and pollutant reduction capabilities of various LID BMPs.

Versions: v2

Features: MIDS includes design specifications for a variety of green infrastructure BMPs, a credit calculator, and model ordinances for communities that support clean water goals. MIDS can model 16 green infrastructure BMP types including green roofs, bioretention basins, infiltration basins, permeable pavement, tree trenches, swales, cisterns, sand filters, constructed stormwater ponds, constructed wetlands, and several other user defined reductions.

Original Application: Urban

Mathematical method for flow routing and water quality: *Runoff/Infiltration:* SCS runoff curve number method; *Flow Routing:* Not applicable; *Water Quality:* Pollutant load calculations use event mean concentrations.

Input Data Requirements: Site information such as area, percent area impervious surface, land cover classifications, soil type, precipitation, and pollutant (e.g., phosphorus and TSS) event mean concentrations.

Data assembly requirements during and after emergency response: Low

Outputs: Runoff volume removed by specified BMP, additional volume removal needed to meet local ordinance, and annual and percentage phosphorous and total suspended solid loading removed.

Representation of Uncertainty: None.

Hardware computing requirements: Not specified

Code language: Visual Basic (VB)

Public/proprietary and Cost: Public, free

Prevalence: Low. Several applications in MN and MI.

Ease of use for public utilities: Easy

Ease of obtaining information and availability of technical support: A “super users” contact list available for questions at link provided below.

Source code availability: Yes

Installation requirements/software: Microsoft .Net Version 4.0 framework. Requires Excel 2003 or later

Source/Link: http://stormwater.pca.state.mn.us/index.php/MIDS_calculator
(Last Accessed August 29, 2018)

B.14 MIKE URBAN

Developer: DHI

Description: MIKE URBAN is an urban water software model with GIS integration (DHI, 2017). MIKE URBAN models all aspects of water networks in the city, including water distribution, stormwater drainage, and sewer collection in separate and combined systems. The model can be used for drinking water management including master planning, flow analysis, water quality risk analysis, and wastewater. MIKE URBAN is also used for stormwater analysis, evaluation of storm water BMPS and LIDs, and design and optimization of real-time controls. MIKE URBAN's water distribution components are based on the EPANET engine and DHI's engine for transient flows, allowing simulation for modeling water distribution networks. Collection System (CS) modules are based on DHI's MOUSE, MIKE 1D or SWMM engines. MIKE URBAN combines overland river and pipe flow modeling, allowing modeling floods in the urban environment. The model combines groundwater and pipe flow modeling, allowing modeling infiltration to and leakage from pipes.

Versions: MIKE URBAN 2016

Features: Flood modeling in urban areas. CSO analysis and flood mitigation in urban areas. Coupling of 1D sewer model with 2D overland flow model. Dynamic linkage to rivers, lakes, streams and estuaries. Sustainable planning of urban infrastructures. Groundwater modeling (2D/3D).

Original Application: Urban

Mathematical method for flow routing and water quality: MIKE URBAN includes the SWMM5 engine (see B.1). It also includes DHI's proprietary MOUSE engine which uses the following options: *Runoff:* Unit Hydrograph method (Rational method or SCS curve number method), time area curve characteristic method, linear reservoir, or a non-linear reservoir approach; *Infiltration:* Horton method or Integrated Horton method; *Flow Routing:* an implicit finite-difference numerical solution of the Saint Venant (dynamic flow) equations; *Water Quality:* The MOUSE engine includes four sediment transport models (Ackers-White, Engelund-Fredsøe, Engelund-Hansen, and van Rijn) as well as correction factors for graded sediments and thin layers of sediment in pipes. It also uses a one-dimension, vertically-integrated equation for conservation of mass of dissolved substances and solves the advection-dispersion equation for pipes, manholes, pumps, and weirs. Biological processes of water quality components can be modeled using ECO Lab coupled to the Mike 1D hydraulic engine.

Input Data Requirements: DEM, rainfall, drainage network, nodes and structure geometries: manholes, pipes, canals, orifices, weirs. Buildup, washoff, detachment rate.

Data assembly requirements during and after emergency response: High

Outputs: Hydraulic modeling results (velocity, flow rate, depth of water) for overland flow, sewer flow, and groundwater as well as water quality data. The outputs can be integrated with other DHI standalone products such as MIKE 21, MIKE 11, and MIKE SHE for mapping and visualization.

Representation of Uncertainty: Specified in input variable (*e.g.* rainfall) using the stochastic method can be propagated through the model (Rene et al. 2012)

Hardware computing requirements: Windows 7 Professional Service Pack 1 (32- and 64-bit), Windows 8.1 pro (64-bit), Windows 10 Pro (64-bit), and Windows Server 2012 R2 Standard (64-bit). X86 or x64, 2.2 GHz (or higher), 2GB memory Random Access Memory (RAM), 40 GB hard disk, 64 MB RAM, and Super Video Graphics Array (SVGA) monitor, resolution 1024 x 768 in 16-bit color

Code language: C++ and C#

Public/proprietary and Cost: Proprietary; $18,000 - $25,000

Prevalence: High. 11 references on the website. Many applications in the literature.

Ease of use for public utilities: Advanced

Ease of obtaining information and availability of technical support: Product information available online. Client care team available for technical assistance, installation, producing updates and licenses, and software maintenance.

Source code availability: Not available

Installation requirements/software: .Net Framework 3.5 SP1 and .Net Framework 4.0. ArcGIS 10.3

Source/Link: http://www.mikebydhi.com/Products/Cities/MIKEURBAN.aspx
(Last accessed August 14, 2018)

B.15 P8 (PROGRAM FOR PREDICTING POLLUTING PARTICLE PASSAGE THROUGH PITS, PUDDLES, AND PONDS)

Developer: W.W. Walker and J.D. Walker

Description: P8 simulates the generation and transport of stormwater pollutants in urban watersheds. The model uses water balance and mass balance summations to simulate drainage elements of watersheds, control devices, particles, and water quality components. P8 simulations are based on hourly precipitation and daily air temperature time series. The model was developed for designing and for evaluating runoff for existing or proposed urban developments. P8 has been used by state and local agencies as a framework to evaluate proposed developments. Predicted water quality components of the model include total suspended solids (TSS), total phosphorus (TP), total Kjeldahl nitrogen (TKN), copper (Cu), lead (Pb), zinc (Zn), and total hydrocarbons. Simulated BMP types include detention ponds (wet, dry, extended), infiltration basins, swales, buffer strips, or other devices. A simple water budget algorithm is used to estimate groundwater storage and stream base flow.

Versions: v3.5

Features: Predicted water quality components include TSS, TP, TKN, Cu, Pb, Zn, and total hydrocarbons. Simulated BMP types include detention ponds, infiltration basins, swales, buffer strips, or other devices.

Original Application: Urban

Mathematical method for flow routing and water quality: *Runoff:* SCS curve number method; *Infiltration*: difference between rainfall and runoff (rainfall –runoff); *Flow Routing:* Not applicable; *Water Quality:* Pollutant washoff is simulated using an exponential function ($dB/dt = -aBr^{C}$, where a = washoff coefficient, B = buildup or accumulation on impervious surface, r = runoff intensity, and c = washoff exponent.

Input Data Requirements: Precipitation, temperature, watershed data: land use, total area, impervious fraction, impervious depression storage, impervious runoff coefficient, street-sweeping frequency, SCS runoff curve number for pervious portion. Devices: dimensions, outlet configuration, infiltration rates, slope, roughness. Specific inputs vary with device type: detention pond, infiltration basin, swale/buffer, pipe/manhole, splitter, and aquifer. Particle inputs: accumulation/washoff parameters, runoff concentrations, street-sweeper efficiencies, settling velocities, decay rates, filtration efficiencies to account for removal via infiltration.

Data assembly requirements during and after emergency response: Low

Outputs: Flow, TSS loads, concentrations, particle loads, concentration. Compatible with Microsoft Excel

Representation of Uncertainty: Not specified.

Hardware computing requirements: PC with Microsoft Windows 10 operating system

Code language: Visual Basic 2005

Public/proprietary and Cost: Public, free.

Prevalence: Moderate. P8 has been used by state and local agencies for evaluating proposed developments.

Ease of use for public utilities: Moderate

Ease of obtaining information and availability of technical support: Product information available online. Technical support is available for a fee.

Source code availability: Unknown

Installation requirements/software: Microsoft Excel. Microsoft .Net Version 4.5

Source/Link: http://www.wwwalker.net/p8/ (Last Accessed August 29, 2018)

B.16 PCSWMM

Developer: CHI

Description: PCSWMM is a spatial modeling system that supports hydrology and hydraulic modeling. The model uses EPA's SWMM5 computational engine (www.chi.com; James et al. 2012; James et al. 2013). PCSWMM is a stand-alone application that provides a GIS engine and expanded code and tools to work with spatial data for model development and analysis. Of note, PCSWMM expands EPA SWMM5 for flood modeling. The model provides simulation of 1D and 2D overland flow. PCSWMM is commonly used in drainage and green infrastructure design, floodplain delineation, sewer overflow mitigation, water quality and catchment analysis, and 1D-2D modeling.

Versions: v7.1

Features: Includes all the features of EPA SWMM5 as well as supporting popular open standard and proprietary GIS/CAD formats and numerous specialized tools to aid in model auditing, connectivity, and calibration. PCSWMM can perform 2D modeling whereas EPA SWMM5 cannot.

Original Application: Urban (and suburban)

Mathematical method for flow routing and water quality: *Runoff:* water balance; *Infiltration:* Horton's method, Modified Horton method, Green-Ampt method, Modified Green-Ampt method, Curve number method; *Flow Routing*: steady flow routing, kinematic wave routing, or dynamic wave routing; *Water Quality:* pollutant buildup is simulated using a power function, an exponential function, a saturation function, or an external time series. Washoff of pollutants is simulated using an exponential function, rating curve, or an event mean concentration approach.

Input Data Requirements: Like EPA SWMM but also requires a DEM and boundary layer information for 2D modeling.

Data assembly requirements during and after emergency response: High

Outputs: Subcatchment variables (*e.g.,* rainfall, runoff), node variables (*e.g.*, water depth, hydraulic head), link variables (*e.g*., flow rate, water depth), system-wide variables (*e.g*., air temperature, evaporation, total rainfall, snow depth).

Representation of Uncertainty: Specified for input variables, and input range can be used in model calibration.

Hardware computing requirements: Requires the Microsoft Windows 10, 8, 7, Vista, or XP (SP2) operating system, with the Microsoft .NET 4.5 framework installed. Minimum screen resolution of 1024x768 pixels (XGA), a minimum of 2 GB of physical memory and 100 MB of disk space.

Code language: C# for .NET, utilizing many new techniques (*e.g*., Google Earth, Web documentation)

Public/proprietary and Cost: SWMM engine code is public, PCSWMM specific code is proprietary; Professional: $120/per user/month, professional 2D: $180 per user/month, Enterprise: $4,000 per year + $40 per user/month

Prevalence: High**;** 5,000+ users

Ease of use for public utilities: Moderate/advanced

Ease of obtaining information and availability of technical support: Knowledge base online, technical support from professional engineers of CHI.

Source code availability: Hydrology/Hydraulics engine is in public domain, source code viewer for the engine available online

Installation requirements/software: No third-party software is required

Source/Link: https://www.pcswmm.com/ (Last Accessed August 29th, 2018)

B.17 SELDM (STOCHASTIC EMPIRICAL LOADING AND DILUTION MODEL)

Developer: USGS/Federal Highway Administration (FHA)

Description: The Stochastic Empirical Loading and Dilution Model (SELDM) is a stochastic spreadsheet model designed to estimate event mean concentrations, flows, and loads in stormwater from a site of interest and from an upstream basin (Granato, 2013; Granato and Jones, 2014). These derived values are planning-level estimates that can be used to evaluate alternative management measures and are subject to large uncertainties. SELDM is a lumped parameter model because each site or lake basin is represented as a single homogeneous unit. It was developed as a Microsoft Access database software application.

Versions: v1.0.3

Features: SELDM is a stochastic empirical loading and dilution model that uses site information and data associated with receiving water basin, precipitation events, stormflow, water quality and mitigation measures to calculate a stochastic population of runoff-quality variables. The model uses Monte Carlo methods to produce random combinations of input variables that are used to generate the stochastic population of values of interest.

Original Application: Rural

Mathematical method for flow routing and water quality: SELDM is an empirical model based on data and statistics rather than theoretical equations. *Runoff/Infiltration*: SCS curve number method and triangular runoff hydrographs; *Flow Routing:* Not applicable; *Water Quality:* Loads from highways and the upstream basin are simulated using stochastically generated random runoff concentrations and flows.

Input Data Requirements: SELDM requires the latitude and longitude of the study site, area, imperviousness, main channel length, main channel slope, and basin development factor for the highway site and the site of interest. Also requires representative event mean concentrations for water quality parameters for the site of interest and the upstream basin.

Data assembly requirements during and after emergency response: Low

Outputs: Stochastic population of flows and pollutant loads

Representation of Uncertainty: Monte Carlo methods are used to produce random combinations of input variable values

Hardware computing requirements: Limited to Windows operating systems. The graphical display forms require a screen resolution exceeding 1024 x 768 pixels.

Code language: Visual Basic for Application

Public/proprietary and Cost: Public, free

Prevalence: Moderate. Tested and reviewed by 43 professionals and 16 state agencies.

Ease of use for public utilities: Easy

Ease of obtaining information and availability of technical support: Questions on the model can be emailed to ggranato@usgs.gov

Source code availability: Yes

Installation requirements/software: Microsoft Access

Source/Link: https://newengland.water.usgs.gov/dev/g1/Software/SELDM/index.html
(Last accessed August 14, 2018)

B.18 SELECT (BMP SYSTEM EFFECTIVENESS AND LIFE-CYCLE EVALUATION OF COSTS TOOL)

Developer: WERF

Description: The SELECT model is a simple planning and screening tool developed to evaluate alternative BMP scenarios (WERF, 2013; Moeller, 2010). It is an Excel spreadsheet tool that is comprised of: 1) a simulation module that simulates pollutant load expected in receiving water using BMP performance data, and 2) a cost analysis module based upon WERF's Whole Life Cycle Model for BMPs. The goal of the model is to link the BMP control effectiveness to cost information to improve selection and design of BMP systems. The model provides life cycle costs of BMPs including: capital costs, operational and maintenance costs, and replacement costs.

Versions: v2.0

Features: Simulated BMPs: extended detention, bioretention, wetland basin, swale, permeable pavement, and filter and generic BMP. Simulated water quality parameters: TSS, TKN, TP, Zn, Cu, fecal coliform.

Original Application: Rural

Mathematical method for flow routing and water quality: *Runoff/Infiltration:* SCS curve number method; *Flow Routing:* Not applicable; *Water Quality:* Pollutant loads are calculated using event mean concentrations (EMCs). Land use EMC values come from the National Stormwater Quality Database and BMP EMC values from bmpdatabase.org.

Input Data Requirements: Local rainfall data, local evaporation data, watershed area, watershed land use type, BMP type, BMP drawdown time. Inputs to improve accuracy: land use characteristics, water quality capture volume, local stormwater characteristics, local BMP performance parameters, local BMP costs. The model provides default values for watershed parameters for each land use (% impervious, runoff coefficient, depression storage, average phosphorus), default BMP parameters (% loss, average phosphorus, average nitrogen concentrations).

Data assembly requirements during and after emergency response: Low

Outputs: Total runoff volume, annual pollutant loads by watershed, pollutant load frequency curves with uncertainty estimates, whole life cost of BMPs

Representation of Uncertainty: Pollutant load frequency curves with uncertainty estimates

Hardware computing requirements: Windows 10 preferred (XP or windows 7 generally work, but the software is not optimized for these platforms)- either 32 - or 64-bit; Office 2007 or Office 2010 - must be 32-bit

Code language: VBA

Public/proprietary and Cost: Public, free

Prevalence: Moderate (SELECT has been used in 12 case studies in the US)

Ease of use for public utilities: Easy

Ease of obtaining information and availability of technical support: A SELECT user support website is available to assist users.

Source code availability: Yes

Installation requirements/software: Microsoft Excel 2010 32-bit version (Generally performs well with Excel 2007 32-bit version, but not optimized for this platform)

Source/Link: http://www.werf.org/i/c/Tools/SELECT.aspx (Last accessed August 29, 2018)

B.19 SHSAM (SIZING HYDRODYNAMIC SEPARATORS AND MANHOLES)

Developer: Barr Engineering

Description: SHSAM is a computer program written to specialize in predicting the effectiveness of stormwater control measures (SCMs) in removing sediment loads from stormwater runoff. SHSAM is based on data collected at the Saint Anthony Falls Laboratory at the University of Minnesota on full-scale testing of different flow-through structures.

Versions: v6.60

Features: SHSAM can model the following SCMs: BaySaver (1K), CDS (PMSU20_15), Downstream Defender (6-ft), ecoStorm (Model 3), Envronment21 (V2B1 Model 4), Stormceptor (STC4800), Standard Sumps 6x6, 6x3, 4x4, 4x2, Standard Sumps with SAFL Baffle (6x3, 4x4), Vortechs System (Model 2000), SciClone (SC-4). SHSAM does not simulate snowfall, snowpack, and snowmelt in runoff hydrographs

Original Application: Urban

Mathematical method for flow routing and water quality: *Runoff:* SCS curve number method with S-hydrograph; *Infiltration:* Implements an abstraction term; *Flow Routing:* not applicable; *Water Quality:* SHSAM uses a generic sediment removal response function based on experimentally collected data and a washout function (Vogel et al. 2013; Bonnema et al. 2014).

Input Data Requirements: climate data (precipitation, temperature), watershed data (drainage area, percent impervious, hydraulic length, average slope, curve number), particle information (particle size, sediment percent finer, specific gravity) and influent concentration of suspended solids.

Data assembly requirements during and after emergency response: Low

Outputs: Particle size fraction removal summary, runoff volumes, total suspended solids removal

Representation of Uncertainty: None

Hardware computing requirements: None specified

Code language: C

Public/proprietary and Cost: Public, free

Prevalence: Low. (SHSAM has been applied to several lakes in Minnesota)

Ease of use for public utilities: Low

Ease of obtaining information and availability of technical support: Low, limited information available

Source code availability: Not available

Installation requirements/software: Not specified

Source/Link: https://www.barr.com/WhatsNew/SHSAM/SHSAMapp.asp
(Last accessed August 14, 2018)

B.20 STEPL

Developer: EPA

Description: The Spreadsheet Tool for Estimating Pollutant Loads (STEPL) is a customized MS Excel spreadsheet model designed to support planning level decision-making (Tetra Tech, 2011). The model uses simple algorithms to calculate nutrient and sediment loads from different land uses and aggregates them by watershed. The model also calculates load reductions because of implementing BMPs. The land use types that can be modeled in STEPL include urban, cropland, pastureland, feedlot, forest, and a user-defined option. STEPL also offers a data server for deriving land use data based on location and weather data for each state.

Versions: v4.3

Features: Runoff calculation, sediment erosion and pollutant load, load reduction by BMPs. STEPL offers capabilities to simulate many types of BMPs for cropland, pasture land, urban land, and septic systems.

Original Application: Rural

Mathematical method for flow routing and water quality: *Runoff:* SCS curve number method; *Infiltration:* The SCS coefficients are adjusted by soil group; *Flow Routing*: Not applicable; *Water Quality:* The annual nutrient loads are calculated based on runoff volume and pollutant concentrations in the runoff water as influenced by factors such as the land use and management practices. The annual sediment load is calculated based on the Universal Soil Loss Equation (USLE) and the sediment delivery ratio.

Input Data Requirements: Local precipitation, land use distribution, agricultural animal population numbers, number of months manure applied, number of populations using a septic system, septic tank failure rate, direct wastewater discharges, irrigation amount/frequency, BMP type and % area applied.

Data assembly requirements during and after emergency response: Low

Outputs: Runoff volume, groundwater volume, sheet/rill erosion loads, and pollutant load by land use and load reductions by watershed of N, P, Biochemical Oxygen Demand (BOD) and sediment at watershed level.

Representation of Uncertainty: None

Hardware computing requirements: Windows 7 or 10, Microsoft Excel 2013 or 2016, 40 MB hard disk space

Code language: Visual Basic (VB)

Public/proprietary and Cost: Public, free

Prevalence: Low. Several applications.

Ease of use for public utilities: Easy

Ease of obtaining information and availability of technical support: Product information available online. Email support available.

Source code availability: Unknown

Installation requirements/software: Microsoft Excel 2010 or 2013

Source/Link: http://it.tetratech-ffx.com/steplweb/models$docs.htm (Last accessed August 14, 2018)

B.21 STORMNET

Developer: BOSS International

Description: StormNET is a dynamic hydrology and hydraulic model that can analyze highway drainage systems, stormwater sewer networks, automatic sizing and designing of detention ponds, bridge and culvert modeling, water quality studies, and sanitary sewers. The model is AutoCAD- and GIS-integrated. StormNET uses a rainfall designer that provides design storm rainfall for any location within the United States (US). The model has been renamed Storm and Sanitary Analysis in AutoCAD Civil 3D developed by AutoDesk

Versions: Part of AutoCAD Civil3D 2017

Features: Full-dynamic hydrology and hydraulic model that can analyze both simple and complex stormwater systems. Integration with AutoCAD land desktop and Civil 3D. Automated detention pond design. Incorporates BMPs. Based upon an enhanced version of the latest USEPA SWMM. Includes bridge and culvert modeling

Original Application: Urban (and suburban)

Mathematical method for flow routing and water quality: *Runoff/Infiltration:* EPA SWMM 5.0 approach, SCS curve number method, rational method, modified rational method, DeKalb rational method and hydrograph methods: Santa Barbara Unit Hydrograph, Delmarva Unit Hydrograph; *Flow Routing:* Kinematic and dynamic wave methods; *Water Quality*: pollutant build up and washoff via exponential, rating curve, or EMCs.

Input Data Requirements: hydrology data: rain gauges, sub-basin data, groundwater aquifers. Hydraulic data: Nodes (junctions, outfalls, flow diversion, inlets, storage nodes) and links (conveyance links, pumps, orifices, weirs, outlets) data. Water quality data: pollutants and land uses. Curve data: storage curves, flow diversion curves, outfall tidal curves, pump curves, outlet rating curves.

Data assembly requirements during and after emergency response: Moderate

Outputs: flow rates, velocities, hydraulic grades, water quality concentrations.

Representation of Uncertainty: None.

Hardware computing requirements: CPU: 1 GHz or faster 64-bit processor, 4 GB memory, 1360 x 768 display resolution, display card: 1360 x 768 with true color capabilities, disk space: 10.0 GB

Code language: AutoCAD .NET Application Programming Interface (API), .Net API, .COM API, Custom Draw API (in C++).

Public/proprietary and Cost: Proprietary: $2,100/year, $3,990/2 years, $5,670/3 years, $265/month for Civil 3D.

Prevalence: Moderate

Ease of use for public utilities: High

Ease of obtaining information and availability of technical support: Product information available online. Email or phone support available.

Source code availability: Proprietary

Installation requirements/software: Microsoft Windows 10, .Net Framework Version 4.6

Source/Link: http://www.bossintl.com/html/stormnet-overview.html (Last accessed August 14, 2018)

B.22 SWAT (Soil and Water Assessment Tool)

Developer: USDA Agricultural Research Service (ARS) and Texas A&M AgriLife Research

Description: SWAT is a watershed and river basin model developed by the USDA Agricultural Research Service (ARS; Neitsch et al. 2009). SWAT was developed to predict impacts of land management practices on water, sediment and pollutant yields from watersheds. The model simulates physical processes associated with water movement, sediment erosion, crop growth and nutrient cycling. The pathways of water movement simulated by SWAT include: canopy storage, infiltration, evapotranspiration, lateral subsurface flow, surface runoff, ponds, channels and return flow. SWAT also tracks the movement and transformation of several forms of N and P in the watershed.

Versions: ArcSWAT 2012.10.19 for ArcGIS or MWSWAT or SWAT2012 rev. 664 stand alone

Features: SWAT is a physically based model that uses readily available inputs and simulates impacts of land management practices. Simulated BMPs include filter strips and grassed 1D waterways. There are many versions of SWAT depending on user interface: ArcSWAT based on ArcGIS, QSWAT based on QGIS interface, MWSWAT based on MapWindow, and AVSWAT based on ArcView GIS. SWAT also offers tools for model output visualization and analysis such as IZSWAT and SWAT Check. SWAT-MODFLOW links SWAT with MODFLOW.

Original Application: Agricultural, rural

Mathematical method for flow routing and water quality: The hydrologic cycle simulated by SWAT is based on the water balance equation. *Runoff:* Runoff rate is estimated by a modified rational method/the NRCS TR-55 method; *Infiltration:* Green Ampt; *Evapotranspiration:* Penman-Monteith, Hargreaves, or Priestly-Taylor; *Flow Routing:* Manning’s equation is used for flow and average velocity calculations in channels, Muskingum routing method for reservoirs; *Water Quality:* Nutrient components are modeled through nitrogen and phosphorus cycles. For pesticides, washoff, degradation, and leaching processes are modeled. Bacteria are modeled through washoff, die-off and regrowth, and leaching processes. Sediment erosion is modeled through the modified universal soil loss equation (MUSLE) and Bagnold’s equation to predict degradation of stream linings.

Input Data Requirements: Watershed input files with routing and land parameters defined, precipitation, temperature, solar radiation, wind speed, relative humidity, potential evapotranspiration, weather forecast, land cover/plant growth, pesticide, fertilizer, urban pollutant buildup/washoff, septic, subbasin, pond/wetland, water use, soil chemical and physical characteristics, and main water channel parameter files. The model also requires water quality files associated with QUAL2E transformations in main channels and streams.

Data assembly requirements during and after emergency response: High

Outputs: Flow (surface runoff, lateral flow contribution to streams, groundwater, water percolation, drainage tile, stored soil water, actual and potential evapotranspiration, water yield) and water quality (sediment yield, nitrate loadings, plant uptake of N, soluble and organic phosphorus loadings, ammonia distributions in flow and solids and changes in bacterial loadings) by sub-catchbasin.

Representation of Uncertainty: Offers automated method for uncertainty analysis/auto-calibration. Use SWAT-CUP as a calibration, uncertainty, or sensitivity program.

Hardware computing requirements: 2 GB free space if using 32-bit system.

Code language: FORTRAN

Public/proprietary and Cost: Public, free

Prevalence: High. One of the most widely used models, with hundreds of applications reported.

Ease of use for public utilities: Advanced

Ease of obtaining information and availability of technical support: Product information available online. User support available from user groups and development team.

Source code availability: Yes. Source code available for download.

Installation requirements/software: ArcGIS, .Net Framework 2.0, ArcGIS .Net support or MapWindow

Source/Link http://swat.tamu.edu/ (Last accessed August 14, 2018)

B.23 SWMM5 (STORM WATER MANAGEMENT MODEL)

Developer: Water Supply and Water Resources Division, EPA

Description: The EPA's SWMM is a dynamic stormwater runoff model that simulates runoff quantity and quality in urban areas (Rossman, 2015). The model simulates runoff from a single rainfall event or long-term (continuous) rainfall. Stormwater generated from subcatchments is then routed through a network of pipes, channels, junctions, storage, treatment and control facilities. EPA's SWMM also has the capability to evaluate effects of LID controls. SWMM simulates various hydrologic processes that produce runoff, including time-varying rainfall, evaporation, snow accumulation and melt, rainfall interception, infiltration, percolation, interflow, and nonlinear reservoir routing of overland flow. SWMM contains a set of hydraulic modeling capabilities to handle networks of unlimited size and production of pollutant loads associated with stormwater runoff. SWMM also provides an integrated environment for running hydrologic, hydraulic, and water quality simulations, and viewing results in color-coded maps, time series graphs and tables, profile plots, and statistical frequency analyses.

Versions: SWMM 5, previous version: SWMM 4

Features: Hydrology and hydraulics, pollutant loads associated with stormwater runoff. Hydrologic processes: rainfall, snow, interception, infiltration, percolation, interflow, reservoir routing, runoff reduction via LID controls. Hydraulic features: drainage networks, kinetic wave or full dynamic wave flow routing methods. Pollutant loads features: dry weather pollutant buildup, pollutant washoff, street-cleaning, BMPs.

Original Application: Urban (and suburban)

Mathematical method for flow routing and water quality: *Runoff:* water balance; *Infiltration:* Horton's method, Modified Horton method, Green-Ampt method, Modified Green-Ampt method, SCS curve number method; *Flow Routing*: steady flow routing, kinematic wave routing, or dynamic wave routing; *Water Quality:* pollutant build-up is simulated using a power function, an exponential function, a saturation function, or an external time series. Washoff of pollutants is simulated using an exponential function, rating curve, or an EMC approach.

Input Data Requirements: Rainfall data, subcatchment data: assigned rain gauge, outlet node, land use, imperviousness, slope, manning's n, depression storage, groundwater parameters, storm drain pipe network information; invert elevation, depth to ground surface; inputs for outfall, storage units, flow dividers, conduits, orifice, pumps, LID control information, pollutant characteristics (washoff coefficients)

Data assembly requirements during and after emergency response: High

Outputs: Subcatchment variables (*e.g.*, rainfall, runoff), node variables (*e.g.*, water depth, hydraulic head), link variables (*e.g.*, flow rate, water depth, velocity), system-wide input variables (*e.g.*, air temperature, evaporation, total rainfall, snow depth)

Representation of Uncertainty: Although no uncertainty module is provided, uncertainty can be propagated through SWMM using distributions of input variables and external analysis.

Hardware computing requirements: Designed to run under all versions of the Microsoft Windows PC operating systems

Code language: C

Public/proprietary and Cost: Public, free

Prevalence: High. (SWMM has been used in thousands of studies worldwide)

Ease of use for public utilities: Moderate

Ease of obtaining information and availability of technical support: Information on EPA website. No formal support offered. An active SWMM user's listserv was created by University of Guelph. Questions on the model can be sent to EPA contact.

Source code availability: Yes

Installation requirements/software: None

Source/Link: https://www.epa.gov/water-research/storm-water-management-model-swmm (Last accessed August 14, 2018)

B.24 WARMF (WATERSHED ANALYSIS RISK MANAGEMENT FRAMEWORK)

Developer: Electric Power Research Institute (EPRI), currently supported by Systech Water Resources

Description: WARMF, a decision support system designed to inform watershed analysis and TMDL calculations (Herr et al. 2001), simulates watersheds as a network of linked land catchments, river segments, and lakes. WARMF uses meteorological data to dynamically simulate runoff and nonpoint source loads from land. The model predicts daily hydrology and water quality of rivers and lakes. The model uses spatial information from a DEM file, land use and soils data, and displays spatial distributions of point and nonpoint loading using GIS map format. WARMF contains five modules: an engineering module to simulate the hydrology and water quality for the landscape of a river basin, a consensus module to guide stakeholders to a consensus on a watershed management plan, a data module for editing the input data, a knowledge module that includes reservoir operation rules, water quality standards, rate coefficients, and a TMDL module for TMDL calculation.

Versions: v6.2

Features: WARMF contains a graphic user interface for various analyses including displaying spatial information of the watershed, editing model inputs, model simulation, and TMDL calculation. The model predicts daily flow and many water quality variables including pH, temperature, dissolved oxygen (DO), ammonia, nitrate, phosphate, suspended sediment, bacteria, cations, anion, algal species, periphyton, and metals such as iron, zinc, manganese, and copper. For stratified lakes, WARMF provides two options: 1D (vertically stratified) and 2D (using CE-QUAL-W2).

Original Application: Urban

Mathematical method for flow routing and water quality: *Runoff:* mass balance of precipitation, interception, evapotranspiration, infiltration, and percolation; *Infiltration:* modeled as a function of the available water in the layer (difference between soil moisture and field capacity) and accounts for exfiltration based on Darcy's Law; *Flow Routing*: unknown; *Water Quality:* pollutant buildup and washoff calculations are adapted from SWMM code, sediment erosion from ANSWERS model code and the universal soil loss equation. Algorithms in the model also account for water quality changes due to atmospheric chemistry of tree canopy interception and through fall, snow chemistry, pollutant transport with sediments, organic matter decay, fertilization, septic systems, biological and chemical reactions in soils and water bodies.

Input Data Requirements: Spatial data: DEM, stream network, soil, land use, septic systems, and point sources. Flow and water quality data for calibration. Coefficient data for physical data, meteorology (snow, evaporation), land use, land application, irrigation, sediment transport, BMPs, septic systems, chemical and biological reactions of pollutants, soil layers, mining, and CE-QUAL-W2.

Data assembly requirements during and after emergency response: Moderate

Outputs: Flow and water quality, pollutant loads.

Representation of Uncertainty: Stochastic simulation based on uncertainty in inputs is possible, using a stochastic simulation tool

Hardware computing requirements: None.

Code language: Visual C++, Fortran

Public/proprietary and Cost: Public Domain, Free upon request

Prevalence: Moderate

Ease of use for public utilities: Moderate

Ease of obtaining information and availability of technical support: Technical support available from Systech Water Resources.

Source code availability: Not available in entirety (Fortran code available for review upon request)

Installation requirements/software: None

Source/Link: http://wqt.epri.com/watershed-model.html (Last accessed August 14, 2018)

B.25 WINSLAMM (SOURCE LOADING AND MANAGEMENT MODEL)

Developer: PV and Associates, LLC

Description: WinSLAMM, the Source Loading and Management Model, is a tool that relates sources of pollutants to runoff quality in urban stormwater runoff (PV and Associates, 2014). The model is useful in identifying pollutant sources and evaluating effectiveness of control practices and management strategies. WinSLAMM calculates pollutant loads and runoff from different land uses and rainfalls and was designed to provide relatively simple outputs such as pollutant mass and control measure effects for a large variety of potential conditions. One unique feature of WinSLAMM is that it represents each land use from each source area separately and does not lump all land uses together for one subcatchment or lump all the areas for a single land use together. WinSLAMM is mostly used as a planning tool. The model focuses mainly on smaller rainfall events and particulate runoff. It represents many stormwater controls and is based on field data, therefore incurring minimum reliance on theoretical processes.

Versions: v10.3.4

Features: Runoff and pollutant transport. The model considers six land uses: commercial, freeway, industrial, institutional, other urban, and residential. Each land use is further defined by source areas: roofs, sidewalks/walks, other impervious areas, pave parking/storage, street, freeway lanes/shoulders, unpaved parking/storage, undeveloped areas, large turf areas, playgrounds, small landscaped areas, large landscaped areas, driveways. Control devices: biofiltration, catch basins, cisterns, filter strips, grass swales, green roofs, hydrodynamic devices, media filters, other control devices, porous pavements, street cleaning, wet detention ponds. WinSLAMM generates stormwater data at the outfall to a catchment only and does not route through a pipe network or combine hydographs or pollutant loads from multiple watersheds. Currently, storm sewer and overland flow options are not available in the model.

Original Application: Urban

Mathematical method for flow routing and water quality: *Runoff/Infiltration*: SCS curve number method and hydrographs; Flow Routing: Not applicable; *Water Quality:* Particulate solids loading (lbs) = runoff volume (ft^3) *particulate solids concentration (mg/L) * unit conversion

Input Data Requirements: Rain data, pollutant probability distribution, runoff coefficient, particulate solids concentration, particulate residue reduction, street delivery parameters, particle size distribution

Data assembly requirements during and after emergency response: Low

Outputs: Runoff volume, particulate solids, pollutant, junction and outfall output, output from control practices: runoff volume, particulate solids

Representation of Uncertainty: WinSLAMM uses stochastic analysis procedures to represent uncertainty in model input parameters, to better predict the actual outfall conditions. Probability information for the concentrations found in different source areas was used to predict probability distributions of the concentrations.

Hardware computing requirements: Compatible with Windows XP, Vista, and 7 (limited testing on Windows 8 and 10). Processor – 32-bit or 64-bit; Hard Drive Minimum 120 MB. No minimum RAM requirements.

Code language: Visual Basic for Applications (VBA)

Public/proprietary and Cost: Private, $375 site license (free upgrade within one year), not annually recurring.

Prevalence: Moderate. Approved in stormwater design manuals in Delaware, Georgia, Minnesota, New York, Wisconsin and by different government agencies.

Ease of use for public utilities: Moderate

Ease of obtaining information and availability of technical support: Product information available online. Technical guidance not provided. Limited email support on how to model various applications.

Source code availability: Source code is not distributed, but algorithms are described

Installation requirements/software: Microsoft Access, ArcGIS

Source/Link: http://winslamm.com/ (Last accessed August 14, 2018)

B.26 XPSWMM

Developer: XP Solutions (acquired by Innovyze)

Description: XPSWMM is a comprehensive software package for modeling of stormwater systems, sanitary or combined sewer systems, and river systems (XP Solutions, 2014). XPSWMM is based on the EPA SWMM5 model. The model can be used for single event or continuous rainfall-runoff simulation. The model combines 1D modeling of channels and pipes with a 2D surface grid for flood modeling and mapping. XPSWMM is a link-node and spatially distributed model that can be used for analysis and design of stormwater and wastewater systems. The model can be used in floodplain mapping and hazard maps, culvert and bridge analysis, sanitary and combined sewer systems, and stormwater management analysis. The model simulates buildup and washoff of pollutants from the watershed, pollutant and sediment transport, as well as impacts of BMPs and LIDs. XPSWMM is integrated with GIS and CAD.

Versions: Version 2018, 19.1, previous version: version 2017, 18.1

Features: Includes all the features of EPA SWMM4 and some features of SWMM5 as well as offering GIS and CAD integration. XPSWMM has several modules that expand the XPSWMM package, including XP2D for 2D modeling, multiple domain (reduces cell numbers in 2D modeling), XPVIEWER, real time control, and XPWSPG (Water Surface Profile Gradient). The model offers several bundle options including the Stormwater and River modeling bundle options.

Original Application: Urban (and suburban)

Mathematical method for flow routing and water quality: *Runoff:* water balance/SCS curve number method and a number of hydrograph methods including NRCS, Clark, Snyder, Santa Barbara; *Infiltration:* Horton's method, Modified Horton method, Green-Ampt method, Modified Green-Ampt method, and SCS curve number method; *Flow Routing*: steady flow routing, kinematic wave routing, or dynamic wave routing; *Water Quality:* pollutant build-up is simulated using a power function, an exponential function, a saturation function, or an external time series. Washoff of pollutants is simulated using an exponential function, rating curve, or an event mean concentration approach.

Input Data Requirements: Like EPA SWMM (B.1) but also requires a DEM and boundary layer information for 2D modeling extension

Data assembly requirements during and after emergency response: High

Outputs: Subcatchment variables (*e.g.,* rainfall, runoff), node variables (*e.g.*, water depth, hydraulic head), link variables (*e.g*., flow rate, water depth), system-wide variables (*e.g*., air temperature, evaporation, total rainfall, snow depth)**,** complete model data, computational details and results, profile/cross section plots, flood mapping. Compatible with GIS files, CAD files, EPA SWMM files

Representation of Uncertainty: None. Uncertainty can be modeled by running multiple model scenarios

Hardware computing requirements: Minimum Pentium processor, 512 MB RAM, Windows XP, 7 or 8, 8.1, or 10- 32- or 64-bit, 50 GB hard disk, display 1024 x 768 24-bit color, 64 MB RAM.

Code language: Fortran and C++

Public/proprietary and Cost: Proprietary, estimated to be $5,000-$25,000 from online sources

Prevalence: High

Ease of use for public utilities: Advanced.

Ease of obtaining information and availability of technical support: Product information available online. Technical support offered through "InfoCare" support portal from Innovyze Inc.

Source code availability: None. Only SWMM engine part is available.

Installation requirements/software: None

Source/Link: http://www.innovyze.com/products/xpswmm/ (Last accessed August 14, 2018)

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