Review of urban stormwater models

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Abstract

Increasing trend of urban flooding is a universal phenomenon and poses a great challenge to urban planners the world over. Proper management of stormwater drainage may be a solution to urban flooding problems but suitable selection of model for a particular watershed is a challenge. This paper reviews models for simulating stormwater quantity in an urban environment. A number of models have been developed by academic institutes, government organizations and some private agencies. Most of these models are based on conventional methods for runoff generation and routing. Some models add groundwater/baseflow component and several include infiltration component. In this paper few well known flood simulating models in current use are examined and compared in terms of their functionality and accessibility and features of all these stormwater models have been summarized. The models chosen represent a wide range of capabilities, spatial and temporal resolutions. Primarily the models are grouped as urban models which are specifically designed to simulate urban stormwater quantity and quality and non-urban models which are capable of being adapted for use in urban stormwater problems. These models are classified according to the type of modeling, availability of additional features and accessibility. This review can be helpful for the researchers and stormwater managers for choosing a model according appropriate parameter requirements of a specific urban watershed.

Keywords: Stormwater, Watershed, Urban flood, Model.

1. Introduction

Increasing trend of urban flooding is a universal phenomenon and poses a great challenge to urban planners the world over. The un-even distribution of rainfall coupled with urbanization, filling up natural drainage channels and urban lakes and their encroachment for the use of high-value urban land are the causes of urban flooding. Urban flooding is significantly different from rural flooding and so also are the strategies to deal with them. Urbanization leads to developed catchments which increases the flood peaks from 1.8 to 8 times and flood volumes by up to 6 times (NDM Guidelines, 2010). Consequently, flooding occurs very quickly due to faster flow times, sometimes in a matter of minutes. Although volume of water to be handled is not as severe as a flash flood of a river system the property damages and indirect financial losses are significant as this flooding occurs in highly populated areas. Accurate modelling of extreme urban flood events requires a better understanding of overland flow paths and the capability of representing the re-entry of surface flows into the below ground drainage network. But due to the complexity of both the underground and above ground systems within urban areas, up to now there has not been an easy way to represent both systems interactively (Andres et al., 2007).

Models capable of simulating stormwater quality and quantity appeared in the earlier 1970s and were developed primarily by US government agencies, such as the USEPA (Zoppou, 2001; Mitchell, 2001). Since then, a number of urban watershed models have been developed. Most of these models are 1D models and are based on principle of mass, energy and momentum conservation. Some models are event based models and other are continuous simulation type. These urban drainage models are able to simulate the drainage system correctly until there is no overflow from the network inlet or manhole. When such overflows occur due to insufficient drainage capacity of downstream pipes or
channels, it becomes difficult to reproduce the actual flood extents using these 1D models (Chatterjee et al., 2008). In order to overcome the deficiencies of 1D models 2D models or coupled 1D models with 2D flood inundation models i.e distributed flood models were developed. Recently, the wider availability of distributed information, ranging from soil types and land use to radar rainfall, have facilitated the production of simplified physically-meaningful distributed hydrological models (Todini, 2007). This paper gives the brief description of some of the widely used 1D and 2D models, their functionality, accessibility and features.

2. Literature review

Zoppou (2001) reviewed both quantity and quality aspects of urban stormwater models. It provided an overview of stormwater modeling approaches, with a brief mathematical description of common methods for flow routing and contaminant transport. It also described several stormwater models. Mitchell et al. (2007) compared urban stormwater models based on computational issues such as spatial and temporal resolution and representation of system dynamics through to the collection of data sets to support model development, calibration and verification. Alemseged and Rientjes (2007) studied the effects of uncertainty in the model domain in terms of selected boundary conditions, applied surface roughness values and the spatial resolution. The modeling approaches applied are 1D model (HEC-RAS) and the 2D model (SOBEK). Mitchell et al. (2007) studied various models available in order to find out the gaps in Integrated Urban Water Management (IUWM) practices. Elliott and Trowsdale (2008) focused on low-impact urban stormwater drainage systems (LID) to reduce the adverse hydrologic and water quality effects of urbanization. Chatterjee et al. (2008) compared the results of fully hydrodynamic 1D model and a coupled 1D–2D model to check the effectiveness of a proposed flood emergency storage area at the middle Elbe River, Germany.

These reviews provide a valuable background on the features of a range of models, categorizations of the models and methods for representing key hydrological processes.

3. Review process and structure

Around 40 models used for simulating urban floods have been identified from previous published reviews, journal abstracting services, internet searches, conference proceedings, and modeling practitioners. Out of which 24 well known models are listed here in Table 1 along with their latest available versions, developers, use of the model and its availability. A brief overview of the models in terms of their use, functionality and accessibility is given.

<p>| Table 1 Name and introductory information for the selected models |
|---|---|---|---|---|---|
| S. No | Program | Developed by | Version | Model type | Public domain | Comments |
| Urban Models | HEC-HMS | US Army Corps of Engineers | 2.0 and up | 1D/2D | Y | Developed to replace HEC-1 with additional capabilities such as the MOD-Clark quasi-distributed (2D) hydrologic modeling, single or multiple Storm. |
| 2 | SWMM | USEPA | 5.1 | 1D | Y | Single event or continuous simulation of runoff quantity and quality. |
| 3 | XP - SWMM | XP Solutions | - | 1D/2D | N | Comprehensive software package for modeling stormwater, sanitary and river systems, used to develop link-node (1D) and spatially distributed hydraulic models (2D). |</p>
<table>
<thead>
<tr>
<th></th>
<th>Model</th>
<th>Description</th>
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<tr>
<td>4</td>
<td>MIKE URBAN</td>
<td>A flexible system developed by DHI for modeling and design of water distribution networks, waste water and stormwater. Contain a database for storing network as well as hydraulic modeling data.</td>
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<td>5</td>
<td>HSPF</td>
<td>Lump parameter model for simulating short or long-term watershed quantity &amp; quality for small or large watersheds.</td>
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<td>6</td>
<td>DR3M-QUAL</td>
<td>Continuous simulation, daily soil-moisture accounting between storms is possible. A drainage basin is represented as a set of overland-flow, channel, and reservoir segments. Software developed in corporation with the city of Philadelphia for combined sewers drainage analysis.</td>
</tr>
<tr>
<td>7</td>
<td>Penn State</td>
<td>Uses simple runoff coefficient and depression storage method for generation of hourly runoff depths from hourly rainfall inputs.</td>
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<td>8</td>
<td>STORM</td>
<td>It enables the assessment of supply-demand balance through linking of the End Use Model software, the REALM supply system simulation software and the E2 catchment simulation framework.</td>
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<tr>
<td>9</td>
<td>Hydro Planner</td>
<td>Uses time-area methods to generate hydrographs from directly connected paved area and from the previous area.</td>
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<td>10</td>
<td>ILLUDA</td>
<td>It can perform continuous or single event simulation at five-minute time intervals and simulate flows in pipes and channels using an implicit finite difference approximation.</td>
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<td>11</td>
<td>QQS</td>
<td>Tool used for demonstrating the performance of stormwater quality treatment systems within the urban areas.</td>
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<tr>
<td>12</td>
<td>MUSIC</td>
<td>A daily urban water balance model, outputs include daily, monthly, and annual estimates of water demand, stormwater yield, wastewater yield, evaporation, imported water use, stormwater use, and wastewater use.</td>
</tr>
<tr>
<td>13</td>
<td>Aqua-cycle</td>
<td>An existing model AQUACYCLE was enhanced by extending the water balance model and introducing contaminant balance modelling.</td>
</tr>
<tr>
<td>14</td>
<td>UVQ</td>
<td>Single storm event lumped parameter model, includes several different options for modeling rainfall, losses, unit hydrographs, and stream routing.</td>
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<td></td>
<td></td>
<td>Single Storm Event lumped parameter computer program, provides a complete graphical interface</td>
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3.1 Model overview

A detailed description of the models and their capabilities is given below.

**HEC-1** was developed by Corps of Engineers Hydrologic Engineering Center. It is a lumped parameter, single storm event model capable of simulating surface runoff response of a watershed to precipitation by representing the basin as an interconnected system of hydrologic and hydraulic components (stream channels or reservoirs). Modeling results in hydrographs at points of interest. A variety of methodologies are available to input and model rainfall, losses, runoff transformation and diversion. The Corps no longer supports HEC-1. The last version, 4.1 was released in 1998.

**HEC-HMS** is the successor to HEC-1. Not all of the original HEC-1 functions are available in HMS but many of the original HEC-1 algorithms have been updated and combined with new algorithms. It is a windows based program. In previous versions, data input/output could be somewhat bulky.
Significant improvements to the interface have been made in the current version (Halwatura and Najim, 2013).

**TR-20** (Technical Release 20), like HEC-1 TR-20 is also lumped parameter, single storm event model developed by the Soil Conservation Service (SCS), formerly Natural Resources Conservation Service (NRCS). The program is a physically based event model, which computes direct runoff resulting from synthetic or actual rain events (USDA, 2004). The program uses procedures described in the SCS National Engineering Handbook, Section 4, Hydrology. This DOS program is currently out of print and is not supported by the NRCS. Its windows version is also available and is known as WIN TR-20.

**TR-55** is a DOS program developed by the United States Department of Agriculture (USDA) using SCS methodology. It uses unit hydrographs to convert rainfall excess into runoff. TR55 is applicable to small watersheds, especially urban. TR55 is based on Technical Release 55, and incorporates SCS procedures, including procedures for calculating travel times of sheet flow, modifications to peak discharge methodology and storage routing procedure (USDA, 2004).

WIN TR-55 is the windows version of TR-55. WIN TR-20 is the driving engine for hydrograph and routing procedures.

The **EPA Storm Water Management Model** (SWMM) is a dynamic rainfall-runoff-routing simulation model originally developed by EPA. It is used for single event or long-term (continuous) simulation of runoff quantity and quality from urban areas. The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads using nonlinear reservoir methods and Horton or Green-Ampt loss functions. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period divided into multiple time steps (Rossman, 2010). **SWMM 5** is the Graphical User Interface (GUI) version of SWMM.

**SWMM-XP** is a proprietary GUI version of SWMM developed by XP Software. This version of SWMM includes a GIS interface.

**SOBEK 1D2D** is an integrated software package which enables the construction of complex models by dynamically integrating 1D components from SOBEK-Rural, SOBEK-Urban and SOBEK-River and 2D components from SOBEK Overland Flow (formerly known as Delft-FLS). SOBEK 1D (Rural, Urban and River) solves the Saint-Venant equations by means of a finite difference scheme. Breaches can be modeled by means of a complex “river weir” with time dependent properties (Vanderkimpen et al., 2009). Breach growth can be described by time series for crest width and crest level. Breach flow is obtained from weir flow equations. SOBEK 2D (Overland Flow) uses a rectangular grid and solves the shallow water equations by means of a finite difference scheme, identical to the one used by SOBEK 1D. SOBEK 2D is capable of handling flooding and drying, spatially varying surface roughness and wind friction. It also contains a “dam break” link, capable of describing breach growth by means of empirical breach growth equations.

**MIKE FLOOD** Dynamically links two independent software packages: **MIKE 11** (1D) and **MIKE 21** (2D). MIKE 11 solves the Saint-Venant equations by means of a finite difference scheme. Breaches can be modeled by means of a “dam break” structure. Breach growth can be described by time series for breach width, crest level and side slope. An erosion model based on the Engelund-Hansen sediment transport equation is also available. Breach flow can be computed by means of two sets of equations: the standard set is based on the equations for flow through a generic structure and the alternative set was obtained from the NWS DAMBRK model. The “classic” version of MIKE 21 uses a rectangular grid and solves the shallow water equations by means of a finite difference scheme.
(Vanderkimpen et al., 2009). It is capable of handling flooding and drying, spatially varying surface roughness, eddy viscosity, Coriolis forces and wind friction. The software package is able to model a complex watershed network, including unique parameters such as snow storage. The price of an unlimited structure and point HD and RR is approximately 32 lakhs, plus an annual software maintenance agreement is required.

**MIKE URBAN** is a flexible system for modeling and design of water distribution networks and collection systems for waste water and stormwater. MIKE URBAN is based on a database for storing network as well as hydraulic modeling data. The software contains GIS-based model building and management tool, integrated water quality, fire flow, real time control and water hammer simulation. Thematic mapping and integrated dynamic result visualization can be done (Graham and Butts, 2005).

**HSPF** (Hydrological Simulation Program–Fortran) is a simulation model developed under Environmental Protection Agency (EPA) sponsorship to simulate hydrologic and water quality processes in natural and man-made water systems and also may be applied to urban watersheds through its impervious land module. It is an analytical tool that has application in planning, design, and operation of water resources systems. The model enables the use of probabilistic analysis in the fields of hydrology and water quality management through its continuous simulation capability. Basic inputs to simulate the processes that occur in a watershed are time history of rainfall, temperature, evaporation, and the parameters related to land use patterns, soil characteristics, and agricultural practices. The initial result of an HSPF simulation is a time history of the quantity of water transported over the land surface and through various soil zones down to the groundwater aquifer. (Duda et al., 2010) Runoff flow rate, sediment loads, nutrients, pesticides, toxic chemicals, and other water quality constituent concentrations can be predicted. The model can simulate continuous, dynamic, or steady state behavior of both hydrologic/hydraulic and water quality processes in a watershed.

**DR3M–QUAL** (Distributed Routing Rainfall-Runoff model) is developed by the U.S. Geological Survey (USGS) specifically for urban hydrology. The runoff generation and subsequent routing is based on kinematic wave method using either characteristics implicit or explicit finite difference schemes with time steps as small as a minute. Rainfall excess is calculated using soil moisture, evaporation, pervious and impervious areas, length and slope of the sub-catchment and parameter optimization. Interflow and base flows are not simulated. Quality is simulated for arbitrary parameters using exponential build-up and wash-off functions. The model can be executed using any time step over any time (Zoppou, 2001). The model has been used in some of the EPA Nationwide Urban Runoff Program (NURP) studies that were conducted by USGS. The FORTRAN version of the model is also available. The model may be used for single-event or long-term (continuous) simulation of hydrographs and quality constituents. The initial result gives a WDM file which contains The information regarding computed outflow from any flow plane, pipe, or channel segment for each storm period, and a summary of the measured and simulated rainfall, runoff, and peak flows.

The **Penn State Model** Urban Runoff Model (PSURM) was developed in corporation with the City of Philadelphia for combined sewers drainage analysis. PSURM uses curve number methodology and nonlinear reservoir routing system with a user-defined lag time. A hydraulic design capability is also included in the model which helps to size pipes. No quality routines are included. The original DOS-based program is now available in a window-based version.

The first significant use of continuous simulations in urban hydrology comes with **STORM** (Storage, Treatment, Overflow, Runoff Model), a program developed by the US Corps of Engineers, Hydrologic Engineering Center (Freni et al., 2003). The model is developed for analysis of CSOs (Combined sewer overflow) and is equally useful for evaluating the effectiveness of detention facilities in reducing the frequency of runoff peaks and to simulate stormwater runoff quantity and quality. STORM uses a simple runoff coefficient and depression storage method for generation of
hourly runoff depths from hourly rainfall inputs. Water quality loads are estimated on the basis of builtup and washoff functions. The trade-off between treatment and storage options at the catchment outlet may be evaluated for economic optimization of control strategies (USACE1977). The model is no longer supported by HEC, but is available from private vendors with an enhanced graphic user interface.

**Hydro Planner** is a software tool developed as part of CSIRO’s Water for a Healthy Country National Research Flagship Program. The main purpose of Hydro Planner to understand how water, wastewater and stormwater systems interact with each other and with natural water systems in terms of water, contaminant and nutrient flows at city and regional scale. Hydro Planner enables the assessment of supply-demand balance through linking of the End Use Model software, the REALM supply system simulation software and the E2 catchment simulation framework (Mirza et al., 2013). Hydro Planner’s supply-demand balance calculations can incorporate effects of climate change, population growth, demand fluctuations, supply augmentations and land development.

**ILLUDAS** (Illinois Urban Drainage Area Simulator) evolved from the British Road Research Laboratory Model. The model uses time-area methods to generate hydrographs from directly connected paved area and from the previous area. The Horton infiltration equation is used to generate typical infiltration rates based on input of soil’s SCS hydrologic group category. A design routine is included that will resize pipes of insufficient hydraulic capacity. User defined stage/discharge/storage relationships are used to provide detention facilities anywhere in the system (Zoppou, 2001). Quality is not formally included in the model, it has been added for specific applications.

**QQS** (Quality–Quantity Simulator) can perform continuous or single event simulation using five-minute time intervals. It can simulate flows in pipes and channels using an implicit finite difference approximation of the kinematic wave equations, storage routing, backwater analysis and pipes under pressure. Looped networks, weirs and pumps can be simulated. Dry weather flow and quality based on empirical relationships have a diurnal and population dependency (Zoppou, 2001). Washoff function is dependent on the accumulation of dust and the time interval between storms and street sweeping. Quality routing through channels and pipes, storage units and receiving water is performed using plug flow.

### 4. Summary and Conclusions

Urban flooding is a universal phenomenon and poses a great challenge to urban planners of the world over. The problem may be solved by proper management of stormwater drainage by selecting proper model from the available models. Most of the urban watershed models have evolved over several years. This may be due to the complexity of the urban flow and water quality processes. Many of the models described in this review do not consider integrated stormwater, water supply and wastewater infrastructure i.e. combined drainage system. Many models except MIKE URBAN and SWMM simply consider only one component. All the urban stormwater models can be used as planning models with some as design tools and very few (MIKE URBAN, SWMM and HEC-HMS) as operational tools. All the models described here include a rainfall runoff model and use simple storage equations for overland flow estimation. MIKE URBAN, HEC-HMS and SOBEK 1D2D can solve shallow water wave equations. Risk analysis is a relatively new development in water resources models. MIKE URBAN, XP SWMM, HEC-HMS and SOBEK 1D2D which are commercial models seem to be capable of modeling two-dimensional overland flows and generate flood inundation maps.

### References


