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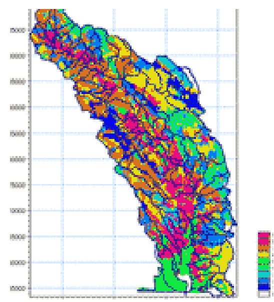
THE GREEN VISIONS PLAN

for 21st century southern california



12. Neighborhood Stormwater Quality Modeling

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THE GREEN VISIONS PLAN

for 21st century southern california

The mission of the Green Visions Plan for 21st Century Southern California is to offer a guide to habitat conservation, watershed health and recreational open space for the Los Angeles metropolitan region. The Plan will also provide decision support tools to nurture a living green matrix for southern California. Our goals are to protect and restore natural areas, restore natural hydrological function, promote equitable access to open space, and maximize support via multiple-use facilities. The Plan is a joint venture between the University of Southern California and the San Gabriel and lower Los Angeles Rivers and Mountains Conservancy, Santa Monica Mountains Conservancy, Coastal Conservancy, and Baldwin Hills Conservancy.

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INTRODUCTION

Many federal, state and local agencies, including the San Gabriel and Lower Los Angeles Rivers and Mountains Conservancy and Santa Monica Mountains Conservancy, have an interest in multiple use projects that promote water quality improvements while providing increased public open space and parks, restoration of natural habitat, and restoration of streams and wetlands. The Conservancies are especially interested in finding ways to increase the amount of interconnected natural habitat in the urban areas and have identified two types of urban park projects that support this goal:

1. Source Area Projects (Matrix/Conversion Projects) where stormwater is controlled at the source through small local devices that also allow comprehensive neighborhood/street/industrial greening efforts (e.g. bio swales, filter strips).
2. Stormwater Parks where stormwater from the surrounding neighborhood is captured at the curb (or at accessible storm drains), treated, detained and retained or infiltrated on the park site. Preferably this would include the development of natural habitat.

Stormwater pollution prevention and treatment is an important regulatory topic in southern California and the United States. The poor quality of stormwater runoff in southern California is a result of two essential environmental alterations: the conversion of soils and other pervious surfaces to concrete, asphalt, buildings, and other impervious surfaces, and the release of pollutants into residential neighborhoods and industrial areas. This increase in impervious surfaces modifies the hydrologic cycle and forces the stormwater runoff to find alternative paths to surface waters, such as streets, storm drains, and parking lots (Figure 1).

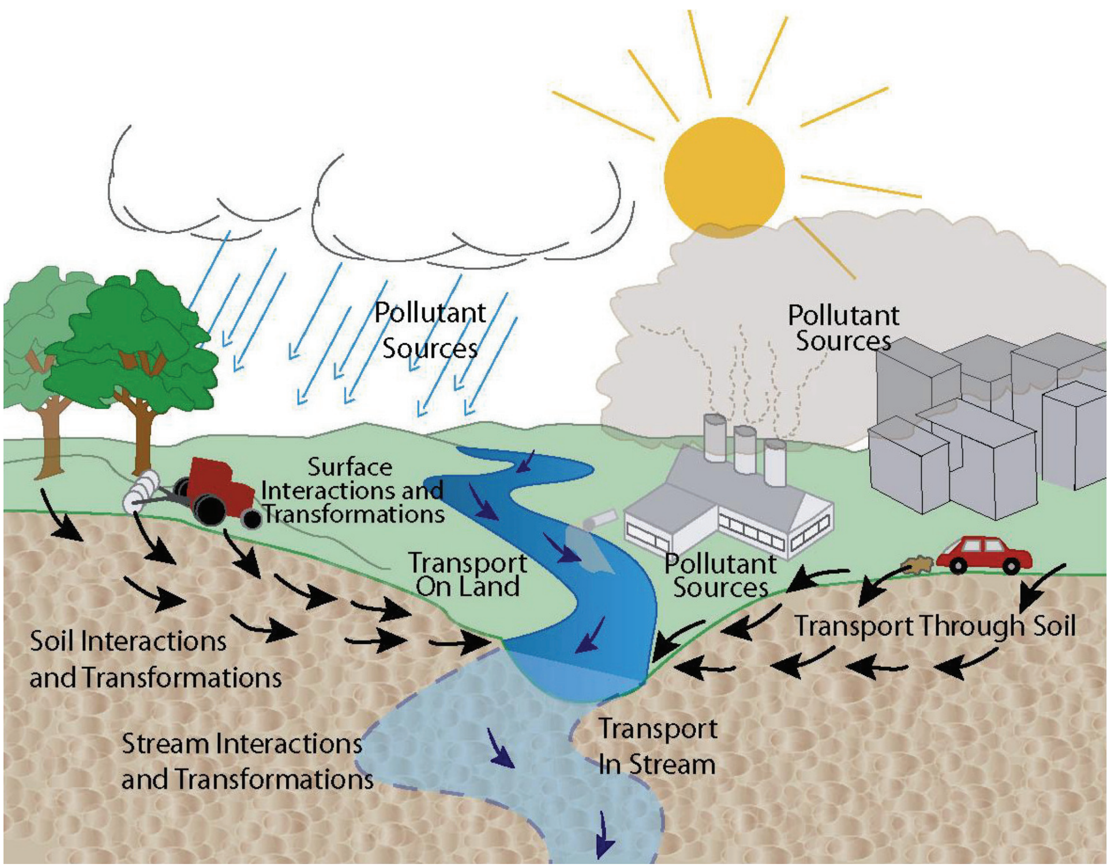

Figure 1: Water Quality Pollution Problems within the Hydrologic Cycle (Aqua Terra Consultants 2004b)

Best management practices (BMPs) have been extensively promoted and applied for the prevention and treatment of pollution in stormwater. Developed alongside BMPs, urban stormwater models are employed to calculate runoff quantity and velocity, determine pollutant “hot spots”, design treatment areas, and estimate the removal potential of BMPs. Urban stormwater models are designed to model the rainfall-runoff relationship based on meteorological data, the overland runoff of stormwater, the movement of stormwater through sewers, and the flow of water through rivers and streams.

These models can be applied to a watershed, city, county, stream segment, city block, or parcel. The focus here is those models that can be applied at the city block or parcel scale to describe water quality loadings and opportunities for management. This white paper includes a brief summary of previous stormwater modeling work, an overview of several candidate stormwater quality models, and a brief guide for what would be required for the Conservancies to conduct their own stormwater quality model assessments.

Previous Work

The identification, evaluation, comparison, and selection of stormwater models has been studied since the 1960s; however, stormwater models have become more readily available and user friendly with the development of more powerful computers (Gupta et al. 2003). Stormwater models are used for the simulation of precipitation and pollutant movement from catchments through pipe and channel networks, storage treatment units, and receiving waters. Both single-event and continuous simulation are used on catchments having storm sewers and natural drainage, for prediction of flows and pollutant concentrations (USEPA 2004).

A number of reviews of storm water models have been conducted. Wilson et al. (2000) evaluated the integration of storm water model outputs with geographic information systems (GISs) for water resource assessment and management. The authors suggested the use of GIS as a way of adding dimensions in watershed modeling applications, in which watersheds were conventionally defined as homogenous units with precipitation, terrain, soil, and land cover conditions described by average values. The combination of GIS and storm water models expanded the number of ways in which information can be presented and accessed, including through the Internet. This combined effort offers the best opportunity for understanding spatial processes and patterns in the movement of water through watersheds, as well as the long term impacts of land use change on water resources.

Zoppou (2004) offered a general review of stormwater models in which he identified the important features of twelve models, which represent a wide range of capabilities and spatial and temporal resolutions, and rated the models according to the urban water quality parameters that were identified and the modeling approaches used to estimate water quantity and quality. The models were categorized in terms of their functionality, accessibility, water quantity and quality components, and the temporal and spatial scales included in each model. The study was conducted to provide planners and managers with an overview of modeling approaches that have been used to simulate storm water quantity and quality and to provide a comprehensive summary of approaches and capabilities of a number of storm water models in current use.

The model calibration and validation tasks are very challenging because of the number of variables and processes in play. Models applied to urban settings must be able to predict runoff quantity, combined sewer overflow volumes, and pollutant concentrations. Any evaluation of these models should discuss the performance of the system, the uncertainty in the parameters, and any assumptions that are made.

The goal of this particular review differs from the aforementioned reviews because of its focus on the modeling of rainfall-runoff; the local routing of overland surface runoff; street and curb conveyance; routing through ditches, drains, pipes, and culverts; and open channel flow (including streams); all at neighborhood scales where source controls and BMPs might be implemented.

STORM WATER QUALITY MODELS

Stormwater computer models can be hydrologic, hydraulic, or water quality models (Table 1). Hydrologic models act to simulate rainfall-runoff processes to determine how much water and how often. Rainfall simulations and data are utilized to predict runoff characteristics such as peak flow, flood hydrographs, and flow frequencies. These models can be deterministic or stochastic, continuous or single event, and lumped or distributed. Hydraulic models use a given flow amount, which is typically the output of a hydrologic model, and determine information about flow height, velocity, direction, and pressure. These models, similar to hydrologic models, can be continuous or single event, and one-dimensional or multi-dimensional, steady or unsteady, and uniform or non-uniform. Water quality models are utilized to simulate the stormwater pollution processes and interactions, and predict various stormwater pollutant loadings (Table 2). These model components (like the underlying processes) can be very complex when simulating the cycle of pollutant build-up, wash-off, and impact. Water quality models have similar components as hydrologic and hydraulic models and often require calibration to produce credible predictions (Georgia Stormwater Management Manual 2001).

Table 1: Stormwater Models[1]

Stormwater Model	Model Developer	Model Users	Cost
HEC-HMS	US Army Corp of Engineers	City and Federal Agencies, consultants	Free
HSPF	US Environmental Protection Agency	Governmental Agencies, industries, engineers, universities	Free
BASINS	US Environmental Protection Agency	Local, regional, and state pollution control agencies, and general public	Free
MIKE 11	Danish Hydraulic Institute	City and Federal Agencies, industries, consultants, engineers, universities	$7015
MIKE SHE	Danish Hydraulic Institute	City and Federal Agencies, industries, consultants, engineers, universities	$3518
XP-SWMM	XP Software	Consultants, engineers, local and federal agencies	$3000
MIKE SWMM	Danish Hydraulic Institute	City and Federal Agencies, industries, consultants, engineers, universities	Free
SLAMM	US Geological Survey	City, Regional, State, and Federal Agencies	$200
XP-STORM	XP Software	Consultants, engineers, local and federal agencies	$3500

[1] Danish Hydraulic Institute (2005), United States Army Corp of Engineers (2005), USEPA (2003), USGS (2005), XP-Software (2005)

Table 2: Model Functionality[1]

Stormwater Model	Rainfall-Runoff Computation	Local Runoff Routing (Overland Flow/ Street and Curb Conveyance)	Ditch, Drain, Pipe, Culvert Routing	Open Channel Flow (Stream and River)	Pollutant Loading Computation
MIKE SWMM	Yes	No	Yes	Yes	Yes
HEC-HMS	Yes	No	Yes	Yes	No
HSPF	Yes	Yes	No	Yes	Yes
BASINS	Yes	Yes	Yes	Yes	Yes
MIKE-11	Yes	Yes	Yes	Yes	Yes
MIKE SHE	Yes	No	Yes	Yes	Yes
XP-SWMM	Yes	Yes	Yes	Yes	Yes
SLAMM	Yes	Yes	No	Yes	Yes
XP-STORM	Yes	Yes	Yes	Yes	Yes

[1] Danish Hydraulic Institute (2005), United States Army Corp of Engineers (2005), USEPA (2003), USGS (2005), XP-Software (2005)

The choice of stormwater quality model for a particular project depends on user needs, desired outcomes, and the project budget. An overall assessment of the stormwater quality model should be conducted before the user starts any model construction because some models are best used for storm sewer and sewer overflow analysis, while others are best suited for overland flow and pollutant loading analysis. The inputs and required data are also important when determining which model to select. The user must be certain that the data required by the model will be available. When choosing a stormwater quality model, the overall cost of each model, i.e. license, extensions, and support, and whether a demonstration version of each model could be downloaded or requested from the company or agency should also be considered. Last but not least, all watershed models should be calibrated before they are applied. Large errors in flow and pollutant concentrations can result if the model is not adjusted as much as possible to the terrain it describes. In most cases the municipalities will not have the resources to collect the necessary flow and pollutant concentration data (USGS 2005). The following subsections take this approach and describe nine models that might generate useful outputs (knowledge) to improve water quality management decisions at the local neighborhood or parcel scale.

HEC-HMS

The Hydrologic Engineering Center of the US Army Corps of Engineers, Hydrologic Modeling System (HEC-HMS) is designed to simulate the precipitation-runoff processes of dendritic watershed systems, and designed to be applicable in a wide range of geographic areas for solving a variety of water-related problems. HEC-HMS can handle large river basin water supply and flood hydrology, as well as small urban or natural watershed runoff applications. Hydrographs produced by the program are used with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation (US Army Corp of Engineers 2005).

HEC-HMS is the USACE's updated version of this longstanding rainfall/runoff model that utilizes graphical user interfaces to build a watershed model and to set up the precipitation and control variables for simulation. Anderson et al. (2002), for example, applied this updated model to basins in the Sierra Nevada watershed: one subbasin above New Hogan Reservoir provided runoff into the reservoir, and below the reservoir, there is a routed channel reach and another subbasin that provides runoff to a sink point at Bellota. To calibrate the HEC-HMS model, a 48 hour rainfall period in February 1999 from five rain gauges in the Calaveras Basin was employed. The model utilizes the Green-Ampt infiltration/loss parameterization, the ModClark hydrograph transformation routine, and a recession base flow component. It requires point gauge calibration when using point gauge rainfall and spatially distributed rainfall when using the model to forecast runoff. HEC-HMS can also be used to model the runoff predictions across the watershed from spatially varying rainfall estimates.

HSPF

The Hydrologic Simulation Program – Fortran (HSPF) was developed by the USGS in 1996 to simulate the water quantity and quality processes that occur in a watershed, including sediment transport and movement of contaminants. It is used in hydrologic and water quality process simulations, stream flow hydrograph and pollutograph computations, pervious or impervious unit areas discharge simulation, frequency-duration analysis, and land-use change, reservoir operation, point or non-point source treatment alternative, and flow diversion assessments. HSPF can simulate interception soil moisture, surface runoff, interflow, base flow, snowpack depth and water content, snowmelt, evapotranspiration, ground-water recharge, dissolved oxygen, biochemical oxygen demand (BOD), temperature, pesticides, conservatives, fecal coliform, sediment detachment and transport, sediment routing by particle size, channel routing, reservoir routing, constituent routing, ph, ammonia, nitrite-nitrate, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton, and zooplankton (USGS 2005).

HSPF is most typically utilized for continuous or single-event simulation of runoff quantity and quality from a watershed. It is a popular model for continuous non-point water quality simulations and can model non-point sources from urban and agricultural land uses, and pervious and impervious surfaces. HSPF is a DOS-based model and does not support the user-friendly graphical interface and editing options of windows-based programs. The USEPA recommends using it for continuous simulation of hydrology and water quality in watersheds and has incorporated it into their own program, BASINS, described in greater detail in a later subsection (Georgia Stormwater Management Manual 2001).

HSPF can be considered one of the most physically based and best tested catchment quality models. However, it is complex and difficult to use (Codner 1999). HSPF has been used to: (1) simulate runoff and sediment loads in river basins; (2) predict annual volume, daily average flow, and hourly flow; (3) size large urban detention facilities; (4) predict hydrology and non-point source pollutant loads; and (5) numerically implement BMPs to determine which is best suited to the situation at hand. The model can be parameterized with land use/land cover and physical watershed characteristics (Cryer et al. 2001, Lukas and Roe 1993, Hayashi et al. 2004, Ackerman et al. 2005).

In Southern California, the Southern California Coastal Water Research Project (SCCWRP) applied HSPF to an urban watershed and tested the ability of HSPF to predict annual volume, daily average flow, and hourly flow. The model was parameterized with eight land use classes and physical watershed characteristics. The model was calibrated using rainfall and measured flow over a five year period in a predominantly undeveloped watershed and it was validated using a subsequent four year period. The process was repeated in a separate, predominantly urbanized watershed over the same time span. SCCWRP found that modeling was difficult during dry-weather periods. This was a result of the large influence of artificially introduced water from human activities, such as landscape overwatering, that can be important sources of water in urbanized arid environments. This dry weather flow was poorly accounted for in the model. Hourly flow predictions mistimed peak flows, reflecting spatial and temporal heterogeneity of rainfall within the watershed, but correlation increased when the predictions were averaged over longer time periods (Ackerman et al. 2005).

HSPF has been used to calculate stormwater contributions from typical urban residential and commercial blocks. The modeling approach using HSPF to simulate runoff from one-block sites has been shown to be a viable method to estimate the relative effectiveness of stormwater BMPs such as rain barrels, rain gardens, porous pavement, and roof gardens. The effectiveness of such measures has become an important factor in decisions concerning investment of public funds in such practices. Loucks et al. (2004) utilized HSPF to calculate stormwater contributions from typical urban residential and commercial blocks, and estimate estimate the relative effectiveness of implementing various BMPs.

BASINS

The Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) software system was originally introduced in 1996 with subsequent releases in 1998 and 2001. BASINS facilitates examination of environmental information, supports analysis of environmental systems, and provides a framework for examining management alternatives. It was designed as a multipurpose environmental analysis system designed for use by regional, state, and local agencies in performing watershed and water quality-based studies, and users can access large amounts of point source and non-point source data from within this framework. BASINS can be utilized to assess water quality at selected stream sites or throughout the entire watershed. It integrates environmental data, analytical tools, and modeling programs to support development of watershed management and environmental protection policy, including TMDLs (USEPA 2006).

BASINS was developed by EPA for local, regional and state pollution control agencies to analyze water quality on a watershed-wide basis. It combines the ArcView GIS environment, national databases containing watershed data, and modeling programs and water quality assessment tools into one standalone program (Figure 2). BASINS can analyze both point and non-point sources with tools including TARGET, ASSESS, Data Mining, HSPF, TOXIROUTE, and QUAL2E. The core datasets of BASINS consist of DEM (Digital Elevation Model) shapefiles and grid datasets, including the National Elevation Dataset (NED), the GIRAS land use/land cover dataset, specially prepared weather data organized by state (see http://www.epa.gov/waterscience/ftp/basins/wdm_data/ for additional details), and STATSGO soils data. A version of HSPF is packaged within BASINS and is used to assign water quality parameters. The relative ease of BASINS can mask limitations and inaccuracies of the underlying datasets and prevent improved datasets from being sought and incorporated into modeling effort. BASINS has been utilized to determine whether water quality standards are likely to be violated under various flow and pollutant loading conditions. It was essentially developed to assess TMDLs. The modeling system can simulate invariant hydraulic conditions in watercourses and the steady state discharge conditions of point and non-point sources. BASINS traditionally has been applied to predict worst case scenarios, was expressly developed for modeling water quality at the watershed scale, and is most often implemented using the environmental data it contains (Georgia Stormwater Management Manual 2001; Burian et al. 2002, 2004; Rousseau et al. 2002).

MIKE 11

MIKE 11, developed by the Danish Hydraulic Institute, is a tool for modeling conditions in rivers, lakes/reservoirs, irrigation canals and other inland water systems. Typical applications of MIKE 11 include flood

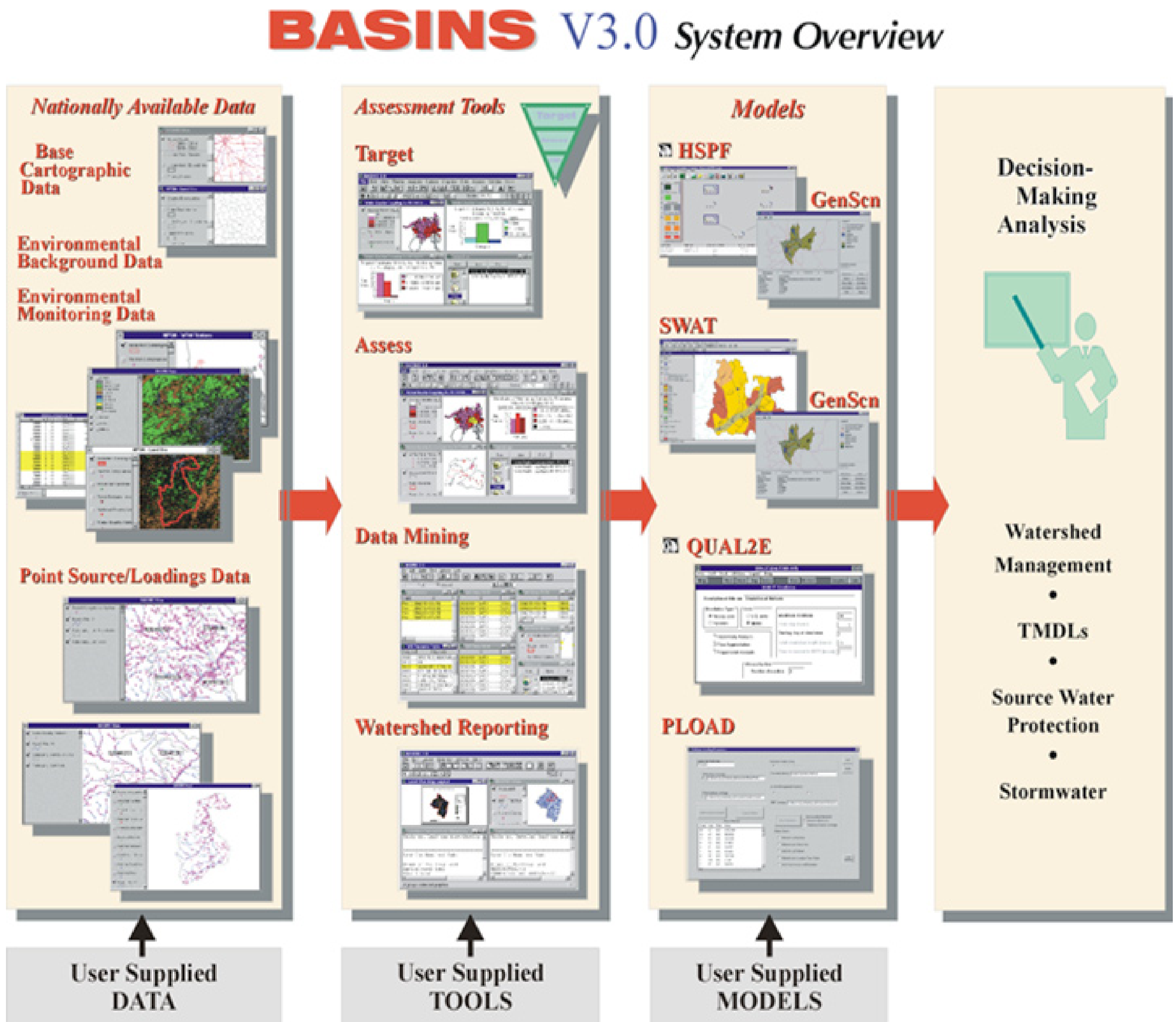

Figure 2: BASINS Version 3 Systems Overview (Aqua Terra Consultants 2004a)

risk analysis and mapping, flood alleviation systems design, real-time flood forecasting, hydraulic analysis/design of structures including bridges, drainage and irrigation studies, river and reservoir operations optimization, dam break analysis, water quality issues, and integrated groundwater and surface water analysis (Danish Hydraulic Institute 2005).

MIKE 11 consists of modules that allow users to specify the type of hydrologic process to simulate. It is a menu-driven model configured with a core module that includes a menu for data handling and program execution. The model includes modules to handle various data types: the catchment database manages river cross-section data, another database manages rainfall time series and water level and discharge data, computational modules control rainfall-runoff simulation and river flow, and another module manages data inputs and output graphics. The computational modules include the sediment transport module, which models sediment transport through erosion and deposition, and the resulting changes in model geometry; the transport-dispersion module that solves one-dimensional conservation of mass equation for the transport and dispersion of any dissolved or suspended material; and the water quality module, which is an extension of the transport-dispersion module and is utilized to simulate the reaction processes of multicompound systems and models a variety of biochemical interaction processes, including simple

BOD and DO computations and simulations of nutrients, macrophytes, and plankton. MIKE 11 requires hydrologic parameters, river cross sections, floodplain topography, discharge and water level records, measured or simulated rainfall (DeVries and Hromadka 1993).

Applications of MIKE 11 include modeling the transport of suspended solids, simulating channels and floodplain flows under storm surge conditions, determining alternative water level management, simulating canal flows for distributaries, evaluating the performance of the hydraulic system for different canal schedules, evaluating effectiveness of structural measures for wetland restoration, predicting peak flood stages, and forecasting the effect of pollution control schemes (Kwan 1993, Oduyemi 1994, Kazmi 2000, Gregory et al. 2001, Chowdhury and Kjelds 2002, Bennett et al. 2004, Copp and Nath 2004, Smith and West Consultants 2004, Thompson et al. 2004, Gupta et al. 2005, Zacharias et al. 2005).

MIKE SHE

MIKE SHE, another model developed by the Danish Hydraulic Institute, simulates the entire land phase of the hydrologic cycle and can be linked to ESRI's ArcView for GIS applications. The typical uses of MIKE SHE are groundwater withdrawal surface water impact analysis, wetland management and restoration, river basin management and planning, environmental impact assessments, aquifer vulnerability mapping, groundwater management, floodplain studies, land use and climate change impact studies, and agricultural practices impact studies including irrigation, drainage, nutrient, and pesticide management with daisy (Danish Hydraulic Institute 2005).

MIKE SHE has been used to evaluate the performance of physically-based, distributed and lumped models and to determine their capabilities and limitations for simulating water-related processes in mid-sized catchments. The evaluation criterion of model performance is the ability of each model to predict the time and magnitude of peak discharges, and runoff volume (Meselhe et al. 2004). MIKE SHE has simulated the inflows to a treatment plant, including groundwater infiltration into the sewer network. The results were analyzed to determine the effects from historical measures and alternative future alleviation schemes (Gustafsson et al. 1997). MIKE SHE can estimate a catchment water balance, which is an essential element for water management plan formation, and the analysis of the impacts of water level management alternatives (Thompson et al. 2004, Zacharias et al. 2005). MIKE SHE has also been utilized to evaluate the effectiveness of structural measures for restoration of the wetlands (Copp and Nath 2004).

XP-SWMM

XP-SWMM (Stormwater Management Model) is a link-node model that performs hydrology, hydraulics and quality analysis of stormwater and wastewater drainage systems including sewage treatment plants, water quality control devices and BMPs. It may be used to model the hydrologic cycle from stormwater and wastewater flow and pollutant generation to simulation of the hydraulics in any combined system of open and/or closed conduits with any boundary conditions. There are three layers in XP-SWMM: (1) the stormwater layer for hydrology and water quality generation; (2) the wastewater layer for generation of wastewater flows including storage or treatment for BMPs and water quality routing; and (3) the hydrodynamic hydraulics layer for the hydraulic simulation of open and closed conduit wastewater or stormwater systems (XP-Software 2005). Typical applications XP-SWMM include combined sewer overflow (CSO) and sanitary sewer overflow (SSO) predictions, interconnected pond analysis, open and closed conduit flow analysis, major/minor flow analysis, designs for new development, and existing stormwater and sanitary sewer systems analysis (XP-Software 2005).

XP-SWMM is divided into three blocks: EXTRAN, TRANSPORT, and RUNOFF. The EXTRAN computational block solves complete dynamic flow routing equations to simulate backwater, looped pipe connections, manhole surcharging and pressure flow. The TRANSPORT block is used to simulate open channel flow, which solves the kinematic wave equations for natural channel cross-sections. The RUNOFF block simulates hydrologic processes, computing the quantity and quality of runoff from drainage areas and routing the flow to the major sewer system lines (Georgia Stormwater Management Manual 2001).

Literature reviews show that XP-SWMM has been primarily used to develop models of storm sewer and sanitary sewer networks, to determine the frequency of CSOs, determine appropriate locations for stormwater sampling, estimate pollutant loads from various land uses, determine floodplain inundations, and analyze hydraulics and hydrology and determine detention pond sizes for stormwater management. XP-SWMM was utilized in Apalachicola, Florida to estimate the hydraulic, hydrologic, and water quality responses of the basin for short- and long-term precipitation data and determine the effect of pollution abatement procedures. The model was applied to two small drainage basins and used to predict runoff and pollutant loadings in order to evaluate existing nonpoint source controls and drainage system capacities with only a limited number of stations and storm samples (City of Apalachicola 2004). Burian et al. (2004) developed a series of XP-SWMM models for the Ballona, Sepulveda, Centinela, and Playa Vista catchments that comprise the Ballona Creek watershed in Los Angeles, California. A GIS was used assemble and manage the data and the final stormwater model was utilized to compare dry and wet weather flow discharges from the Ballona Creek watershed and as one component in a linked air-water quality modeling framework.

XP-SWMM is often selected for water quality modeling applications based on its accessibility, popularity, and reputation. XP-Software has an extensive history of verification and technical support. Several options linking SWMM and GIS have been developed and the data requirements include land use/land cover, storm drainage system, elevation, and roadway information (Georgia Stormwater Management Manual 2001, Burian et al. 2004). The major challenge associated with this model is in calibration, which is difficult because of the number of degrees of freedom within the model (Codner 1991, Barber et al. 1994, Ormond et al. 1995, Ovbiebo and She 1995, Georgia Stormwater Management Manual 2001, Gregory et al. 2001, Gremmer and Associates, Inc. 2003, Burian et al. 2004, City of Apalachicola 2004, Hettiarachchi et al. 2004).

MIKE SWMM

MIKE SWMM was developed by the Danish Hydraulic Institute to simulate hydrology and hydraulics of urban storm water and waste water systems. It is used in open-channel, closed-conduit and combination systems hydraulic analysis, CSO and SSO analysis and mitigation, storm and sanitary drainage systems hydraulic performance analysis, floodplain studies, complex flow regime analysis, water quality assessments, integrated stormwater quantity and quality assessments, and watershed-based planning (Danish Hydraulic Institute 2005).

It incorporates some of the features of MIKE 11 in the original SWMM model to capitalize on the strengths of MIKE 11 in one-dimensional unsteady flow modeling, which solves the shallow water wave equations using an implicit finite difference scheme, and utilizes this approach instead of the temperamental EXTRAN module in the original SWMM model. MIKE SWMM performs hydrologic, hydraulic, and water quality analysis of storm water and waste water drainage systems, including sewage treatment plants and water quality control devices. It models pipes, culverts, retarding and detention ponds, and overflows from sewers. MIKE SWMM calculates coliform, nitrogen, phosphorus, pesticides, and other pollutants using empirical relationships linking pollutants and water as well as sediment yield. It can estimate dissolved and suspended sediments, BOD, DO, nutrients, macrophytes and plankton. Runoff modeling calculations are based on overland and base flow. Two-dimensional overland flooding can also be simulated using the shallow water wave equation. Erosion and sediment deposition are calculated in a sediment budget. MIKE SWMM can also be used to predict flood stages (Zoppou 2001, Gregory et.al. 2001).

SLAMM

The Source Loading and Management Model (SLAMM) was developed by the US Environmental Protection Agency to understand the relationships between sources of urban runoff pollutants and runoff quality. It is most often applied to determining the impacts of BMPs such as infiltration practices, wet detention ponds, porous pavement, street cleaning, catch basin cleaning, and grass swales. SLAMM is also used for predicting stormwater flows and pollutant loads (USEPA 2005).

SLAMM was developed as a planning tool to model runoff water quality changes resulting from urban runoff pollutants. The model calculates runoff volumes and urban pollutant loadings from individual rainfall events based on land use types, and can estimate reductions in pollutant loadings from source areas due to control measures, such as detention ponds or infiltration devices. The major parameters of SLAMM include rainfall amounts, soil types, existing control practices, pollutant loading coefficients, and areas of each land use. The model is typically calibrated using a three-step procedure as follows: (1) the predicted runoff volumes are adjusted to match the values observed at the end of the pipe; (2) the predicted particle solid loads are adjusted to match, as much as possible, the observed particle solid loads at each site; and (3) the pollutant loads, such as total and dissolved sediment, nutrients, metals and organics, are calibrated against available measurements (USGS 2005).

SLAMM's main strength is in its small storm hydrology algorithms and pollutant loading coefficients (Ventura and Kim 1993). The SLAMM model, for example, has been calibrated and verified with the stormwater flow and pollutant concentration data available from urban studies conducted on Wisconsin lawns, freeways, and flat roofs. This model has been recommended by the Wisconsin Department of Natural Resources to help with the preparation of stormwater management plans and it has proven to be a reliable indicator of non-point pollution loadings in urban watersheds (USGS 2005).

XP-STORM

XP-STORM is a stormwater quantity and quality decision support system (DSS) that is used for urban or rural stormwater drainage analysis, watershed master planning, pond design and analysis, storm sewer hydraulics calculations, BMP evaluations, water quality routing, low impact development (LID) incorporating water sensitive urban design (WSUD) and NPDES compliance, urban subdivision drainage, trunk drainage and irrigation, rural stormwater, storm water quality modeling, CMOM determination, TMDL calculations, and NPDES modeling (XP-Software 2005). The XP version of STORM should not be confused with the US Army Corp of Engineers' Storage, Treatment, Overflow, Runoff Model (STORM), which was originally released in 1973 and written in FORTRAN (Nix 1994).

XP-STORM was created in cooperation with the Los Angeles County Department of Public Works (LACDPW) to serve Los Angeles County engineering and water resource professionals. This version simulates hydraulic networks using runoff generated with the LA County Modified Rational Method/F0601 (MORA) and includes six add-on modules to handle pumps and orifices, water quality, wastewater, AutoCAD files, GIS files and real time module controls (RTCs). Pumping stations and orifices are modeled as part of the drainage network in the pumps and orifices module. The water quality module calculates point and non-point pollutant loads and routes these pollutants through the drainage network, which can include a river system or other natural receiving water system. The wastewater module employs various methods for creating dry weather flows and analyzing BMPs. This module simulates pollutant flows through a sanitary sewer system and analyzes treatment processes. The AutoCAD module allows direct import of CAD files as DXP and DWG background files in real world coordinates. The GIS module links the XP-STORM model with any ODBC or OLE compliant database (shapefiles, Oracle, dbase, Access, Excel, etc.) for data import and export. The generic RTC module controls conduits, pumps, weir orifices or rating curves from an unlimited number of sensors in the form of nodes, conduits, pumps, weirs or orifices in the network. The parameters that can be controlled are flow, roughness, diameter, depth, pump start and stop elevations, pump speed factor, pump flow rates, well volumes, weir flow, weir crest elevation, weir surchange elevation, weir length, weir discharge coefficient, orifice area and orifice discharge coefficient (XP-Software 2005).

APPLICATION OF STORM WATER QUALITY MODELS

The SMMC has identified numerous candidate Proposition 50 project sites which might serve water quality, habitat conservation, park and open space needs. Sayre et al. (2006) took the Pacoima Wash site and used it to show what types of water quality improvements might be achieved using porous pavement bicycle paths, stormwater infiltration basins, or some combination of these BMPs. The "back-of-the-envelope" calculations worked up by Sayre et al. (2006) were designed to illustrate the possibilities and further work, including the implementation of one or more stormwater quality models, that would be required to help the Conservancies to predict appropriate locations and designs for porous pavement bicycle paths and stormwater parks. The stormwater quality model to be useful should calculate rainfall-runoff curves at the city block scale, route runoff to the curb of a park, such as an overland flow or open channel flow component, and compute the stormwater pollutant loadings at the park influent. Two of the models reviewed in the previous section, BASINS and XP-SWMM, are described in more detail below to illustrate the level of effort and input data that would be required to implement these types of models.

BASINS

This particular model includes a data extractor, projector, project builder, GIS interface, various GIS-based tools, a series of models, and custom databases (Figure 2). The data required for BASINS can be downloaded from EPA's website (http://www.epa.gov/waterscience/basins/b3webdwn.htm) or through one of the links provided. BASINS combines the modeling power of HSPF with the visualization capabilities of the ArcView 3.2 GIS.

BASINS offers several attractive features. For example, the web-based data access tools means the Conservancies could specify the geographic area they wanted to model and BASINS will automatically download all of the appropriate data from a series of EPA, USGS, and other Internet sources. After the GIS data are downloaded, they are automatically extracted and projected to some user-specified map projection, and the ArcView project file (".apr") is built. The tool that downloaded the data would then allow the Conservancies to add additional data to the BASINS project from a variety of data sources, and to check for more recent data and updates as appropriate. This is an important option because local datasets may offer more appropriate, accurate, or updated information that will improve model performance (USEPA 2006).

HSPF predicts flow based on rainfall, land use characteristics, and stream geometry. It requires meteorological data, which can be obtained from several sources in addition to the BASINS website. Daily potential evapotranspiration can be calculated from daily maximum and minimum temperatures, and actual evapotranspiration is calculated internally within HSPF as a function of soil moisture storage and the evapotranspiration potential. The required land use data can be obtained from SCAG or LADPW. HSPF then continuously simulates the model with fixed, user-selected time steps. The model calculates the overland flow from the various land use blocks, routes the stormwater runoff along the street curbs, and determines the pollutant loading concentration when the runoff enters the park inlet. HSPF predicts loadings in mixed land use settings for various pollutant loadings, such as nutrients, toxics, bacteria, and sediment (Aqua Terra Consultants 2004a, Ackerman et al. 2005). The proposed stormwater parks could be modeled within HSPF using influent, storage and pollutant concentration changes, and effluent parameters defined by the Conservancies, and the results used with the methodology presented in Sayre et al. (2006) to quantify the pollutant concentration improvements that are likely to follow the construction of one or more stormwater infiltration basins (i.e. parks).

XP-SWMM

XP-SWMM could also be utilized to determine the best locations for a group of stormwater parks by collecting the required data and building out the TRANSPORT and RUNOFF blocks in the model. The PCSWMM decision support system could be acquired and used to manage the SWMM files and to organize the various datasets stored in the GIS for the SWMM model engine.

The data requirements are nevertheless substantial and would probably take more time and effort to organize in this model environment than was the case with BASINS. The stormwater quality model in SWMM requires land use, storm drain, elevation, road, inlet, and subcatchment data. The land use data is available through SCAG and LADPW, although XP-SWMM can only model a maximum of ten land use classes and some aggregation of the SCAG land use classes would be required here. The LADPW has storm drain data in microfiche format; it has not been completely converted to GIS format, so the size, shape, length, slope, and invert elevation of each conduit segment for the primary storm drains must be collected from the microfiche files. The storm drain inputs might be replaced with street and road data, since the streets and roads act as drains in this case, if the goal was simply to model stormwater runoff to the curb of the park. Elevation data can be obtained through USGS; roads can be accessed through US Census Bureau TIGER Lines data files; and watershed and stream characteristics can be created from some combination of the National Hydrology Dataset and the elevation data using the tools inside the GIS.

The RUNOFF block requires additional data, including the width of each subcatchment, the area, percent imperviousness, ground slope, pervious area Manning's n, impervious area Manning's n, impervious depression storage, pervious depression storage, and infiltration parameters. The RUNOFF block accounts for erosion, catch basin information, street sweeping parameters, pollutant loading concentrations, and rainfall quality (Burian et al. 2004). The TRANSPORT block is where the conduit information obtained from the LADPW storm drain microfiche files is utilized to calculate the flow in the storm drains. In this case, the TRANSPORT model could be designed to calculate the stormwater flow along the curb to the park inlet.

The RUNOFF and TRANSPORT blocks run in sequence. Pollutant loadings to the park are calculated in the RUNOFF block. Park parameters are entered into the TRANSPORT block and used to predict the influent, the treatment or change in storage, and the effluent.

DISCUSSION AND CONCLUSIONS

It is difficult to discriminate between competing rainfall-runoff models and assess tradeoffs between model performance and complexity because of the lack of widely accepted methods for addressing data uncertainty and model verification. There are typically many variables in play and most models aim to predict a range of variables, be it pollutant concentrations, rainfall runoff amounts, or combined sewer overflow volumes (Kavetski et al. 2003, Wagener et al. 2003).

This paper presented several common stormwater quality models that might be used to calculate rainfall-runoff curves at a block scale, route runoff to the curb of a park, and compute the stormwater pollutant loadings. Two of the nine models that were reviewed – BASINS and XP-SWMM – were selected and utilized to document the level of effort and input data that would be required to model the stormwater runoff of a selected area at a neighborhood block scale, enabling them to predict appropriate locations and designs for stormwater parks. This analysis gives some guidance as to the level of effort that the Conservancies would need to invest in learning the model and collecting the required data. It would be good to clarify or prioritize the goals since no one model is likely to serve all current and future needs.

REFERENCES

Ackerman D, Schiff K C, and S B Weisberg 2005 Evaluating HSPF in an arid, urbanized watershed. *Journal of the American Water Resources Association* 41: 477-486

Anderson M L, Chen Z-Q, Kavvas M L, and A M Feldman 2002 Coupling HEC-HMS with atmospheric models for prediction of watershed runoff. *Journal of Hydrologic Engineering* 7: 312-318

Aqua Terra Consultants 2004a *Lecture 1: Introduction to BASINS and TMDLs*. WWW document, http://www.epa.gov/waterscience/basins/training.htm

Aqua Terra Consultants 2004b *Lecture 2: Introduction to HSPF and the Model Application Processes*. WWW document, http://www.epa.gov/waterscience/basins/training.htm

Barber J L, Lage K L and P T Carolan 1994 Stormwater management and modeling integrating SWMM and GIS. *URISA Journal* 6: 310-314

Bennett T H, Waltony R, Dickerson P D, and J W Howard 2004 Comparison of HEC-RAS and MIKE11 unsteady flow modeling for the Tillamook Valley. In *Proceedings of the 2004 World Water and Environmental Resources Congress: Critical Transitions in Water and Environmental Resources Management*: 1300-1307

Burian S J, McPherson T N, Brown M J, and H J Turin 2004 *Development of a Stormwater Model for the Ballona Creek Watershed*. Los Alamos, NM, Los Alamos National Laboratory Project Report

Burian S J, Brown M J, and McPherson T N 2002 Evaluation of land use/land cover datasets for urban watershed modeling. *Water Science and Technology* 45(9): 269-276

Chowdhury S and J Kjelds 2002 Simulation of coastal flooding with MIKE 11 and HEC-UNET. In *Proceedings of the Solutions to Coastal Disasters International Symposium*: 205-214

City of Apalachicola 2004 Model Development and Flow Analysis. An analysis of Stormwater Inputs to the Apalachicola Bay. Apalachicola, FL, City of Apalachicola Technical Report

City of San Fernando 2004 Pacoima Wash Project. WWW document, http://www.ci.san-fernando.ca.us/sfold/extra/pacoima_wash/overview.shtml

Codner G P 1999 Tale of two models. SWMM and HSPF. In *Proceedings of the International Hydrology and Water Resources Symposium, Part 2 (of 3)*, Perth, Australia: 569-574

Copp R S and A K Nath 2004 Verification of wetland restoration using mathematical models. In *Proceedings of the 2004 World Water and Environmental Resources Congress: Critical Transitions in Water and Environmental Resources Management*: 1476-1485

Cryer S A, Fouch M A, Peacock A L, and P L Havens 2001 Characterizing agrochemical patterns and effective BMPs for surfaces waters using mechanistic modeling and GIS. *Environmental Modeling and Assessment* 6: 195-208

Danish Hydraulic Institute, Inc. 2005 Modeling the World of Water. WWW document, http://www.dhisoftware.com

DeVries J J and T V Hromadka 1993 Computer Models for Surface Water. In Maidment D R (ed) *Handbook of Hydrology*. New York, McGraw-Hill, Inc. 21.1-21.39

Georgia Stormwater Management Manual 2001 *Volume 2: Technical Handbook*. WWW document, http://www.georgiastormwater.com

Gregory M, Walker B, Yi S, Cunningham B, and J Kjelds 2001 Case studies in automated floodplain mapping. *Urban Drainage Modeling*: 367-375

Gremmer and Associates, Inc. 2003 Manitowoc Road Stormwater Management: Final Report Prepared for the City of Menasha, Wisconsin. WWW document, http://www.cityofmenasha-wi.gov/content/government/special_studies/index.php

Gupta H V, Sorooshian S, Hogue T S, and D P Boyle 2003 Advances in automatic calibration of watershed models. *Water Science and Application* 6: 9-28

Gupta P K, Singh R, Raghuwanshi N S, Dutta S, and S Panigrahy 2005 Application of MIKE-11 to damodar 6-main canal system, India. *International Agricultural Engineering Journal* 14(2): 77-88

Gustafsson L-G, Winberg S, and A Refsgaard 1997 Towards a distributed physically based model description of the urban aquatic environment. *Water Science and Technology* 36(8-9): 89-93

Hayashi, S, Murakami, S, Watanabe, M, and X Bao-Hua 2004 HSPF simulation of runoff and sediment loads in the Upper Changjiang River Basin, China. *Journal of Environmental Engineering* 130: 801-815

Hettiarachchi S L, Luft A J, and J Onorati 2004 An innovative and multi faceted approach to reducing urban flooding. In *Proceedings of the 2004 World Water and Environmental Resources Congress: Critical Transitions in Water and Environmental Resources Management*: 3419-3424

Ho J, Grenney W J, and J J Messer 1984 Modeling Un-Ionized Ammonia with HSPF. In *Proceedings of the National Conference on Environmental Engineering*: 54-59

Kavetski D, Franks S W, and G Kuczera 2003 Confronting input uncertainty in environmental modeling. *Water Science and Application* 6: 49-68

Kazmi A A 2000 Water quality modeling of river Yamuna. *Journal of the Institution of Engineers (India): Environmental Engineering Division* 81: 17-22

Kwan R T F 1993 Modeling of river morphology using MIKE-11. *National Conference Publication, Institution of Engineers*, Australia 93(2): 117-121

Loucks E D, Garrett N, and K A Oriel 2004 Evaluating the effectiveness of stormwater reduction practices using continuous simulation. In *Proceedings of the 2004 World Water and Environmental Resources Congress: Critical Transitions in Water and Environmental Resources Management*: 841-850

Lukas A B and C M Roe 1993 City of Federal Way Panther Lake surface water study a case study of HSPF modeling in urban detention basins. In *Proceedings of the Twentieth Anniversary Conference on Water Management in the 90's*, Seattle, Washington: 185-188

Meselhe E A, Habib E, Oche O C, and S Gautam 2004 Performance evaluation of physically based distributed hydrologic models and lumped hydrologic models. In *Proceedings of the 2004 World Water and Environmental Resources Congress: Critical Transitions in Water and Environmental Resources* Management: 1578-1587

Nix S J 1994 *Urban Stormwater Modeling and Simulation*. Boca Raton, FL, Lewis Publishers

Oduyemi K 1994 Application of MIKE 11 river modelling package to modelling the middle reaches of an estuary. In *Proceedings of the International Conference on Hydraulic Engineering Software, Volume 2*: 175-183

Ormond T, Ellinger C, Saavedra J, and C Gilligan 1995 Analysis of Houston drainage criteria using XP-SWMM. In *Proceedings of the International Water Resources Engineering Conference Proceedings, Volume 2*: 1066-1070

Ovbiebo T and N She 1995 Urban runoff quality and quantity modeling in a subbasin of the Duwamish River using XP-SWMM. In *Proceedings of the Watershed Management Symposium*: 320-329

Rousseau A N, Mailhot A, and J-P Villeneuve 2002 Development of a risk-based TMDL assessment approach using the integrated modeling system GIBSI. *Water Science and Technology* 45(9): 317-324

Sayre, J M, Devinny J S, and J P Wilson 2006 *Best Management Practices (BMPs) for the Treatment of Stormwater Runoff*. Los Angeles, CA, University of Southern California GIS Research Laboratory and Center for Sustainable Cities, Green Visions Plan Technical Report No. 11

Smith V and West Consultants, Inc. 2004 Petaluma MIKE 11 Studies, California. WWW document, http://www.westconsultants.com

Thompson J R, Refstrup S H, Gavin H, and A Refsgaard 2004 Application of the coupled MIKE SHE/MIKE 11 modeling system to a lowland wet grassland in southeast England. *Journal of Hydrology* 293: 151-179

USACOE (United States Army Corp of Engineers) 2005 Hydrologic Engineering Center. WWW document, http://www.hec.usace.army.mil/software/software.html

USEPA (United States Environmental Protection Agency) 2003 Exposure Assessment Models. WWW document, http://www.epa.gov/ceampubl/swater/hspf

USEPA 2004 Water Science. WWW document, http://www.epa.gov/waterscience/wqm

USEPA 2006 BASINS: Better Assessment Science Integrating Point & Nonpoint Sources. WWW document, http://www.epa.gov/waterscience/basins/basinsv3.htm

USGS (United States Geologic Survey) 2005 Source Loading and Management Model (SLAMM): An Urban Area Nonpoint Source Water Quality Model. WWW document, http://wi.water.usgs.gov/slamm

Ventura S J and K Kim 1993 Modeling urban non-point source pollution with a Geographic Information System. *Water Resources Bulletin* 29: 189-198

Wagener T, Wheater H S, and H V Gupta 2003 Identification and evaluation of watershed models. *Water Science and Application* 6: 29-47

Wilson J P, Mitasova H, and D J Wright 2000 Water resource application of Geographic Information Systems. *URISA Journal* 12(2): 61-79

XP-Software Inc. 2005 XP Software: Model with Confidence. WWW document, http://www.xpsoftware.com

Zacharias I, Dimitriou E, and T Koussouris 2005 Integrated water management scenarios for wetland protection: Application in Trichonis Lake. *Environmental Modeling and Software* 20: 177-185

Zoppou C 2004 Review of urban storm water models. *Environmental Modeling and Software* 16: 195-231