Hydrologic and Water Quality Integration Tool: HydroWAMIT

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Abstract: A spatially distributed and continuous hydrologic model focusing on total maximum daily load (TMDL) projects was developed. Hydrologic models frequently used for TMDLs such as the hydrologic simulation program—FORTRAN (HSPF), soil and water assessment tool (SWAT), and generalized watershed loading function (GWLF) differ considerably in terms of spatial resolution, simulated processes, and linkage flexibility to external water quality models. The requirement of using an external water quality model for simulating specific processes is not uncommon. In addition, the scale of the watershed and water quality modeling, and the need for a robust and cost-effective modeling framework justify the development of alternative watershed modeling tools for TMDLs. The hydrologic and water quality integration tool (HydroWAMIT) is a spatially distributed and continuous time model that incorporates some of the features of GWLF and HSPF to provide a robust modeling structure for TMDL projects. HydroWAMIT operates within the WAMIT structure, developed by Omni Environmental LLC for the Passaic River TMDL in N. J. HydroWAMIT is divided into some basic components: the hydrologic component, responsible for the simulation of surface flow and baseflow from subwatersheds; the nonpoint-source (NPS) component, responsible for the calculation of the subwatershed NPS loads; and the linkage component, responsible for linking the flows and loads from HydroWAMIT to the water quality analysis simulation program (WASP). HydroWAMIT operates with the diffusion analogy flow model for flow routing. HydroWAMIT provides surface runoff, baseflow and associated loads as outputs for a daily timestep, and is relatively easy to calibrate compared to hydrologic models like HSPF. HydroWAMIT assumes that the soil profile is divided into saturated and unsaturated layers. The water available in the unsaturated layer directly affects the surface runoff from pervious areas. Surface runoff from impervious areas is calculated separately according to precipitation and the impervious fractions of the watershed. Baseflow is given by a linear function of the available water in the saturated zone. The utility of HydroWAMIT is illustrated for the North Branch and South Branch Raritan River Watershed (NSBRW) in New Jersey. The model was calibrated, validated, and linked to the WASP. The NPS component was tested for total dissolved solids. Available weather data and point-source discharges were used to prepare the meteorological and flow inputs for the model. Digital land use, soil type datasets, and digital elevation models were used for determining input data parameters and model segmentation. HydroWAMIT was successfully calibrated and validated for monthly and daily flows for the NSBRW outlet. The model statistics obtained using HydroWAMIT are comparable with statistics of HSPF and SWAT applications for medium and large drainage areas. The results show that HydroWAMIT is a feasible alternative to HSPF and SWAT, especially for large-scale TMDLs that require particular processes for water quality simulation and minor hydrologic model calibration effort.

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Introduction

The simulation of hydrology and nonpoint-source pollutant loads are important components of computer applications designed to model water quality. The better assessment science integrating point and nonpoint-sources (BASINS 3.0) (USEPA 2001) is one of the computer applications designed to provide hydrologic and water quality modeling tools for total maximum daily load (TMDL) purposes. The BASINS framework integrates modeling and digital data. The hydrologic simulation program–FORTRAN (HSPF) (Bicknell et al. 2001) and the soil and water assessment tool (SWAT) (Arnold et al. 1998) are models included within Version 3.0 of BASINS.

The BASINS framework has many advantages. The linkage with the geographic information system (GIS) to easily retrieve data, preformatted weather data available for download, digital water quality databases, and documented modeling applications are among the advantages. The models available within the BASINS framework have been used in a variety of watersheds. However, the effort necessary to calibrate HSPF and SWAT, the high level of complexity of the simulation processes used by those models to generate nonpoint-source pollutant loads, the methods and the scale of the transport and fate of pollutants in the stream are factors that limit the application of BASINS for some projects.

Nonpoint-source (NPS) loads are directly associated with the surface runoff and baseflow from the subwatersheds. There is a class of models like SWAT that simulates the yield of nutrients

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and other constituents using physical and empirical relationships that mimic the nutrient cycle and the yield of other constituents (Neitsch et al. 2002). The simulation of nutrient cycling and constituent yields may considerably increase the input and calibration parameters. When multiple watersheds are being simulated, and multiple sites are subject to calibration, the model complexity and consequently the calibration effort increase significantly (White and Chaubey 2005). Another class of models such as HSPF also requires pollutant buildup and washoff rate parameters. Buildup and washoff rates are difficult to measure directly, and only limited guidance and little observed data are available from the literature (Butcher 2003).

In addition to the high effort for calibrating nonpoint-source loading parameters, the simulation methods adopted by HSPF and SWAT may not be adequate to capture the transport and fate of pollutants in the stream. Processes such as the impact of periphyton on diurnal dissolved oxygen and the impact of attached algae on nutrients considering luxury nutrient uptake, which are not present in SWAT or HSPF, may be extremely important for some TMDLs. Besides the simulated processes, the segmentation scheme of the models available with the BASINS framework may not provide the spatial and temporal stream network refinement necessary to simulate diurnal oxygen for large watersheds. In the case of TMDLs, the localized impacts of point-source discharges on dissolved oxygen and special areas of interest with available water quality data could be critical. In order to obtain a finer resolution stream network for the water quality simulation, many watersheds would need to be delineated in HSPF or SWAT. The delineation of several small watersheds to create a denser stream network implies a considerable increase in the number of spatial parameters, and in the calibration effort of these models that require high-resolution spatial input datasets for automatically creating model input files.

Therefore, a spatially distributed modeling framework that could significantly reduce the calibration effort of nonpoint-source parameters by adopting site-specific surface runoff and baseflow concentrations instead of numerous nutrient cycling or buildup/washoff rates, while providing the means for localized water quality variables such as diurnal dissolved oxygen to be captured, is an actual demand for attending the modeling needs of some large TMDL projects.

The hydrologic watershed model integration tool (HydroWAMIT) is a robust hydrologic model with loading functions based on event mean concentrations (EMCs), and tools that makes it easy to link point and nonpoint pollutant loads to the water quality analysis program (WASP) Version 7.1 (Di Toro et al. 1983; Ambrose et al. 1993; Wool et al. 2003). HydroWAMIT is presented in this paper as an alternative approach to the BASINS framework. The objectives of the development of HydroWAMIT are: to provide a robust hydrologic simulation model that provides streamflow simulations comparable with the models available within the BASINS framework; to define simple loading functions based on EMCs for nonpoint source pollution; and to allow the transport and fate of pollutants in the stream to be modeled in a finer scale than HSPF and SWAT.

HydroWAMIT

Overview

HydroWAMIT is a continuous and spatially distributed hydrologic model. It incorporates the features of HSPF and the generalized watershed loading functions (GWLF) (Haith et al. 1992). GWLF is not included in the BASINS framework, but it has been applied successfully for TMDL modeling efforts (USEPA 1998; Shoemaker et al. 1997; Yagow 2004). GWLF is a lumped and robust watershed model that uses the curve number method (USDA-SCS 1986) to predict surface runoff from distinct land use types. By combining features of HSPF and GWLF, HydroWAMIT aims to provide a robust and spatially distributed structure to address TMDL modeling efforts.

HydroWAMIT is an enhancement of the watershed and model integration tool (WAMIT) (Cerucci et al. 2005). WAMIT was initially developed to link the output flows from the diffusion analogy flow model (DAFLOW) (Jobson 1989) to WASP for the nontidal Passaic River TMDL. WAMIT allows flow outputs from DAFLOW to be converted into a fine-scale spatial and temporal hydrodynamic input file for WASP. In addition, nonpoint-source loads can be generated from predefined watershed flows and spatially varying EMCs. WAMIT consists of a series of routines and a GIS graphical user interface (GUI). The GUI serves as a data entry interface and output display for the DAFLOW model. HydroWAMIT is a natural enhancement of WAMIT. It contains all the linkage capabilities between DAFLOW and WASP. Besides the WAMIT features, HydroWAMIT simulates hydrologic inputs for DAFLOW and is designed to capture the spatial and temporal variability of parameters for multiple subwatersheds and to perform continuous hydrologic simulations for a daily timestep.

HydroWAMIT simulates surface runoff, baseflow, interflow, and associated loads for multiple interconnected subwatersheds using weather inputs and two underground compartments for water storage. The conceptual model of HydroWAMIT is similar to the GWLF. However, HydroWAMIT does not adopt the curve number method directly to predict surface runoff. The calculation of surface runoff in HydroWAMIT is similar to that of HSPF. The surface runoff is calculated separately for impervious and pervious surfaces. The flow components, such as surface flow and baseflow, are a function of precipitation, pervious and impervious areas, the water budget in the water storage compartments, and recession coefficients. Although the curve number (CN) method is not used to directly calculate surface runoff, the CN value is used as an input parameter. The CN value is associated with a unique combination of land use and soil type. Thus, it is used in HydroWAMIT to differentiate areas with distinct drainage characteristics, and it affects the infiltration potential of distinct source areas in the model.

Water input to the hydrologic model occurs through precipitation. The precipitation can be in the form of rain or snow, depending on the temperature. When precipitation occurs, it is subject to infiltration into the unsaturated zone and interception. Interception is the fraction of precipitation that does not reach the ground due to the water trapped in structures or vegetation. The fraction of water that is intercepted is lost through evaporation. The water that is not intercepted can either infiltrate into the soil or become surface runoff and interflow. Interflow is the fraction of the surface runoff from pervious areas that occurs in the subsuperficial layer of the soil, and it is subject to recession.

The fraction of precipitation that infiltrates into the unsaturated zone is subject to evapotranspiration and percolation to the saturated zone. The fraction of water that reaches the saturated zone becomes baseflow or can be lost as deep groundwater recharge. The combination of baseflow, surface runoff, and interflow from different land uses form the incremental streamflow for each subwatershed at each time step. HydroWAMIT calculates the total

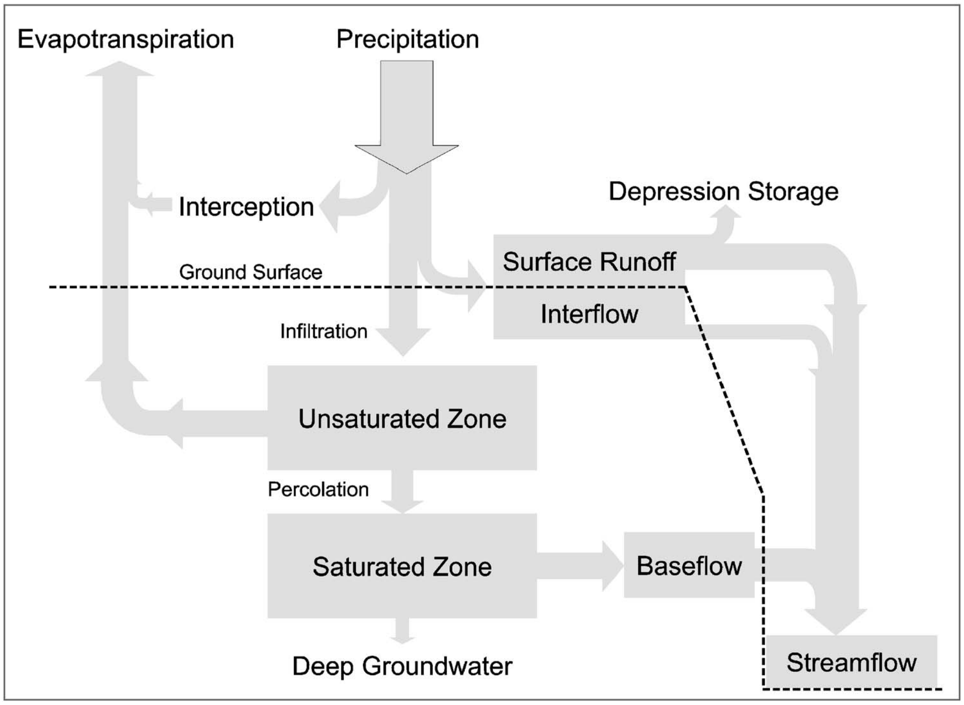

Fig. 1. Land phase of hydrologic cycle adopted by HydroWAMIT

flow contribution of each sub-watershed separately. The flow is then routed downstream using DAFLOW. Fig. 1 shows the land phase of the hydrologic cycle as simulated in HydroWAMIT.

Hydrologic Model Structure

HydroWAMIT was coded within the WAMIT interface, and it operates in conjunction with DAFLOW. DAFLOW is a one-dimensional flow routing model that uses diffusion analogy in conjunction with a Lagrangian solution scheme. Detailed information about DAFLOW and its methods can be found in Jobson (1989). The hydrologic component of HydroWAMIT calculates output flows from subwatersheds for each time step. DAFLOW routes the output flows from the subwatersheds along the stream network elements. The stream network elements are nodes and segments. Nodes are the model boundaries. Input or output flows from the system can be defined at each node. The nodes of the stream network receive the subwatershed flows calculated by the hydrologic component of HydroWAMIT and existing point source flows. A segment is defined as the stream section between two nodes. The smallest simulation unit in the hydrologic component of HydroWAMIT is the land use area of each subwatershed. Surface runoff is calculated for each land use separately and then aggregated for the entire sub-watershed at each time step. A total of six land use types can be defined for each subwatershed.

Three major classes of inputs are defined in HydroWAMIT: stream network, hydrologic input parameters, and weather inputs. Stream network parameters define the nodes of the system and are used as a reference for positioning the subwatersheds and to assign cross-sectional information in the model. Hydrologic input parameters are specific for each subwatershed or land use. Hydrologic input parameters can be fixed in time or vary on a monthly basis. Weather inputs are time series of precipitation, air temperature and daylight hours for each day of simulation. HydroWAMIT can handle weather inputs from different meteorological stations to account for the spatial variability of weather data.

There are three classes of hydrologic input parameters: land use parameters, fixed sub-watershed hydrology parameters, and monthly subwatershed hydrology parameters. Land use parameters are area, curve number, fraction of impervious, land use type, and interception. These parameters need to be specified for the six land use classes of each subwatershed. The land use inputs can be entered through the interface GUI or a land use file.

Fixed subwatershed hydrology parameters are constant for the entire period of simulation, while monthly subwatershed hydrology parameters are setup to assume 12 values over the year. The fixed subwatershed hydrology parameters are the initial water in the saturated zone, initial water in the unsaturated zone, deep groundwater recession, detention storage, impervious recession, interflow recession, interflow fraction, saturated recession, and minimum saturated water for deep groundwater loss. The monthly subwatershed hydrology parameters consist of 12 entries over the simulation year for each parameter and per subwatershed. The monthly parameters are baseflow recession, field capacity, cover factor, and interception season multiplier.

There are two main input files to handle weather inputs: weather sites and weather input data. The weather sites input file assigns a time series of weather inputs to a particular subwatershed. The weather input data file contains precipitation records, average temperature and daylight hours for every simulation day. A list with the necessary model input data and parameters is shown in Table 1.

HydroWAMIT has a total of 25 inputs to account for the hydrologic cycle and pollutant loading. From the list of input data and parameters, 10 are obtained from land use and soil characteristics for each subwatershed or from meteorological records. The remaining 15 parameters can be used for model calibration. The relatively small number of input data and calibration parameters necessary for HydroWAMIT is one of the important distinctions from HSPF and SWAT. HSPF and SWAT need a larger number of parameters in order to simulate flow and pollutant loads. Accord-

Table 1. Model Input Data and Parameters for HydroWAMIT

Model parameter	Class	Description	Units
Area	LU	Area of respective land use type	Acres
CN	LU	Average curve number for land use/soil type	—
FracImpervious	LU	Fraction of impervious area	—
Type	LU	type 1=pervious; type 2=Mixed; type 3=impervious	—
Interception	LU	Percent of precipitation that is subject to interception	%
EMC	LU	constituent event mean concentrations	mg/L
Initial saturated zone	FSH	Initial depth of water in the saturated zone	cm
Initial unsaturated zone	FSH	Initial depth of water in the unsaturated zone	cm
Hydrograph	FSH	Hydrograph adjustment parameter	—
Deepseep	FSH	Deep ground water loss recession coefficient	—
Deep Perc	FSH	Minimum water in the sat zone for deep ground loss	cm
Imperloss Type 2	FSH	percent water lost in depressions	%
Imperloss Type 3	FSH	percent water lost from lakes and wetlands	%
ImperRess	FSH	Impervious recession coefficient	—
InterFlowRess	FSH	Interflow recession coefficient	—
InterFlow%	FSH	percent of pervious runoff that becomes interflow	%
SatRess	FSH	Saturated zone recession coefficient	—
BaseflowRess	MSH	Baseflow recession parameter	—
BFC	FSH	Baseflow concentrations	mg/L
FieldCap	MSH	Available water capacity in the unsaturated zone	cm
CoverFactor	MSH	Cover factor used to calculate evapotranspiration	—
Intercep	MSH	Interception multiplier	—
Precipitation	WTH	Precipitation	cm
Temperature	WTH	Average daily temperature	°C
Daylight	WTH	Total daylight hours	Hours

Note: LU=land use parameters; FSH=fixed subwatershed hydrology; MSH=monthly subwatershed hydrology; and WTH=weather.

ing to Wu et al. (2006), 76 calibration parameters were identified for a HSPF application to simulate flow, phosphorus, and nitrogen loads. The BASINS framework assumes that most of the input parameters necessary for SWAT and HSPF are retrieved automatically from GIS databases. Although this represents significant savings for model setup, it becomes a problem when reliable and compatible digital databases are not available, or custom datasets need to be used.

HydroWAMIT Main Processes

Hydrologic Cycle

The conceptual model of HydroWAMIT and many aspects of the model formulation were derived from GWLF (Haith et al. 1992). The basic components distinguishing HydroWAMIT and GWLF are the surface runoff routine and the spatial structure. GWLF is a lumped watershed model. It calculates surface runoff based on the curve number method for a single watershed divided into multiple land use source areas. GWLF does not have routines to calculate the transport and fate of pollutants in the stream. HydroWAMIT is a spatially distributed model and calculates surface runoff as a direct function of imperviousness, precipitation and available water in the unsaturated zone. The complete set of equations used to simulate the hydrological cycle is available in the HydroWAMIT technical manual (TRC 2006). The equations that depart considerably from GWLF and HSPF formulation are presented in this section.

The surface runoff for impervious areas is calculated separately from surface runoff for pervious areas, according to a structure similar to the one adopted in HSPF. For impervious areas, the surface runoff is a linear function of the net precipitation, depression storage, impervious area, and a recession coefficient. The surface runoff from pervious area n of subwatershed k depends on the maximum infiltration at time t ($\mathrm{MaxInfilt}_{k,n,t}$), which is a function of available water in the saturated zone of subwatershed k ($\mathrm{UZ}_{k,t}$), the field capacity ($\mathrm{FC}_{k,t}$) and the land use/soil type adjustment parameter (FracCN_n)

$$\mathrm{MaxInfilt}_{k,n,t} = \mathrm{FC}_{k,t} * (1 - \mathrm{FracCN}_n) - \mathrm{UZ}_k \tag{1}$$

In order to capture the variability of soil perviousness according to land cover and soil types, FracCN_n is calculated based on average curve number $\mathrm{CN}_{k,n}$ and the representative precipitation. The $\mathrm{CN}_{k,n}$ value varies according to the land use and the hydrologic soil group (USDA-SCS 1986). It is used in the MaxInfilt formulation as a weighting term to differentiate between areas with distinct degrees of perviousness. The FracCN_n is calculated only for pervious areas. Therefore, the high curve number values listed for impervious land uses are not valid for this approach. Because urban areas have pervious and impervious fractions, which are taken into account separately in HydroWAMIT, the curve number value for the pervious portions of urban areas should correspond to the pervious land use of the urban areas. FracCN_n is calculated as function of the representative surface runoff (QT_n) [Eq. (2)], which is obtained from the average curve number for pervious area n of subwatershed k and the representative precipitation applied to the curve number method equations

$$\mathrm{FracCN}_n = QT_n / \sum_T QT_n \tag{2}$$

The surface runoff originated in pervious areas is subdivided into two components: overland flow and interflow. The difference between these two components in HydroWAMIT is the time they will reach the stream. Overland flow is assumed to reach the stream in the same day precipitation occurs, while interflow can be subject to recession. The subdivision of pervious surface runoff intends to provide a better representation of hydrograph raise and recession. The amount of interflow depends on the interflow fraction parameter INTF_k.

Baseflow is calculated as a linear function of the available water in the saturated zone ($\mathrm{SZ}_{k,t}$) and the baseflow recession coefficient ($\mathrm{SatRess}_{k,t}$). The available water in the saturated zone is calculated as a function of the remaining water in the unsaturated zone after evapotranspiration and percolation. Evapotranspiration is calculated according to the Hamon method (Hamon 1961). The Hamon method provides a simple means to estimate daily potential evapotranspiration as a function of daylight hours and temperature. Percolation ($\mathrm{Perc}_{k,t}$) is the water transferred from the unsaturated zone to the saturated zone. $\mathrm{Perc}_{k,t}$ is assumed to occur according to Darcy's law as a linear function of the water level in the unsaturated zone $\mathrm{UZ}_{k,t}$ and a saturated recession rate ($\mathrm{SatRess}_k$) for each subwatershed k

$$\mathrm{Perc}_{k,t} = \mathrm{UZ}_{k,t} * \mathrm{SatRess}_k \tag{3}$$

Nonpoint-Source Loads

HydroWAMIT adopts a simple approach to calculate the watershed yields. HydroWAMIT uses surface flow EMCs and baseflow concentrations (BFCs). An EMC is an estimate of the total mass of pollutant delivered divided by the total storm flow volume. EMC values incorporate the nutrient cycling, buildup, and washoff processes, thus representing the net contribution from a variety of land uses (Butcher 2003).

The surface flow EMCs are defined for each constituent, and they are associated with each land use type for each watershed. The BFCs are defined for each constituent and vary by subwatershed. The nutrient cycling and the pollutant buildup and washoff in the subwatersheds are not simulated in HydroWAMIT. The EMCs and BFCs are input parameters and are not meant for calibration. They are obtained from field measurements and should be representative of the areas they are applied to in the model. A methodology for deriving enhanced EMCs and BFCs for a HydroWAMIT application using field data is presented by Cerucci et al. (2007). If watershed-specific field measurements are not available, literature values could also be adopted. Ackerman and Schiff (2003) successfully calculated nonpoint-source pollution emissions for the Southern California Bight based on EMCs and a simple load modeling approach such as HydroWAMIT's.

The surface runoff loads per unit area ($\mathrm{SLoad}_{k,n,t,p}$) from land use n, subwatershed k at time t, and parameter p are calculated by multiplying the surface flows ($\mathrm{Surf}_{k,n,t}$) by their respective $\mathrm{EMC}_{k,n,p}$. The baseflow loads per unit area ($\mathrm{BFLoads}_{k,t,p}$) are calculated by multiplying the subwatershed baseflow ($\mathrm{Base}_{k,t}$) by the respective subwatershed $\mathrm{BFC}_{k,p}$ value. Baseflow concentrations are not assigned by land use, only by subwatershed. Interflow EMCs are not defined in HydroWAMIT. Interflow concentrations are assumed to be the same as the surface flow EMCs for the interflow volume ($\mathrm{Intf}_{k,n,t,p}$) that reaches the stream at the same day of the precipitation event (Tp). During the interflow recession period ($t > Tp$) the concentrations are assumed to be the same as BFCs. The total loads are given by the sum of the surface loads, baseflow loads and interflow loads for each time step

$$\mathrm{SLoad}_{k,n,t,p} = \mathrm{Surf}_{k,n,t} * \mathrm{EMC}_{k,n,p} \tag{4}$$

$$\mathrm{BFLoads}_{k,t,p} = \mathrm{Base}_{k,t} * \mathrm{BFC}_{k,p} \tag{5}$$

$$\mathrm{INTLoads}_{k,n,t,p} = \mathrm{Intf}_{k,n,t,p} * \begin{cases} \mathrm{BFC}_{k,p} & t = Tp \\ \mathrm{EMC}_{K,n,p} & t > Tp \end{cases} \tag{6}$$

Linkage with WASP

HydroWAMIT allows a unique linkage with WASP. The output flows from HydroWAMIT are converted into a hydrodynamic input file for WASP. The models available with the BASINS framework are not designed to capture some processes such as the impact of periphyton on diurnal dissolved oxygen and the impact of attached algae on nutrients considering the nutrient luxury uptake. Caruso (2004) mentions other processes that are simulated by WASP but not simulated by the most commonly used watershed models such as HSPF and SWAT. In addition to the representation of transport and fate of constituents, the stream segmentation of HSPF and SWAT may not be adequate for modeling efforts that require a fine representation of the stream network. The need for refined modeling frameworks to represent diurnal dissolved oxygen for TMDL purposes is also discussed by Zou et al. (2006). Zou describes a system that links the environmental fluid mechanic code (EFDC) with WASP. Although this system provides refined stream network and hydrodynamic inputs to WASP, it does not contain a hydrologic component to provide inputs to WASP's boundaries.

The stream network segmentation in HSPF and SWAT is a function of the watershed delineation. The stream reaches defined in these models consist of segments between two consecutive elements receiving the watershed inputs. This type of stream segmentation is not efficient to represent a fine resolution stream network. The complexity of the model and calibration effort increases with the size of the watershed. The BASINS application may not be able to handle fine resolution watershed delineation for large areas due to algorithm and computer memory constraints. In addition, one of the great advantages of the BASINS framework, which is automatically creating model input files from spatial datasets, may be compromised if a great number of small watersheds is needed to create fine resolution stream networks. High-resolution digital elevation models (DEM) for watershed delineation and compatible land use and soil type spatial databases would be necessary to support a fine scale stream network.

The stream network in HydroWAMIT is not a function of the watershed delineation alone. Each subwatershed is associated with a stream network node. However, many other nodes can be added between two consecutive watershed nodes. The additional nodes between watersheds could represent point-source inputs, or dummy nodes that serve solely to increase the spatial resolution of the stream network. The increase in spatial resolution could be important to avoid numerical instability and numerical dispersion of water quality simulations. Because DAFLOW uses a Lagrangian solution method to calculate stream flows at each time step, it allows great flexibility in changing the configuration of the stream network. Nodes can easily be added or deleted through the HydroWAMIT GUI. This flexibility allows that new stream segments to be defined without the need to redefine the sub-watersheds. Stream segments are the water quality simulation compartments

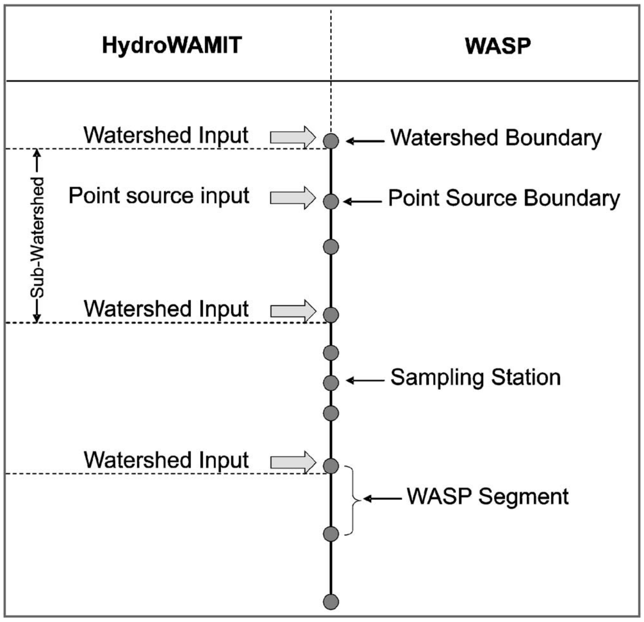

Fig. 2. Stream network and linkage elements from HydroWAMIT and WASP

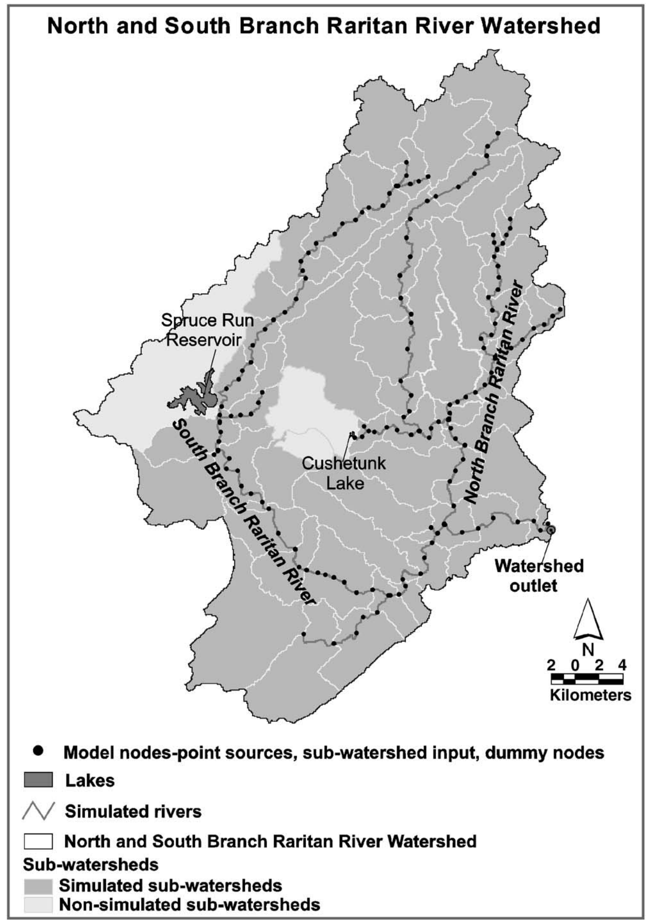

Fig. 3. North and South Branch Raritan River Watershed

in WASP. The possibility of adding multiple input boundaries that are not necessarily associated with subwatershed inputs allows point source dischargers to be positioned more precisely within the stream network. This could provide a better representation of the processes near the dischargers, as well as the variability of cross sections and slopes in the stream.

The stream network used in WASP is given by the hydrodynamic file created by HydroWAMIT. WASP has a built-in function that reads the hydrodynamic file and automatically sets up the stream network and assigns the boundary flows. In a similar mode, the NPS loads from HydroWAMIT are passed to WASP through the NPS input file. The NPS input files contain pollutant loads from the watersheds. The loads are assigned automatically to the respective WASP boundary. A more detailed description of the hydrodynamic and NPS linkage between HydroWAMIT and WASP is provided by Cerucci et al. (2005). Fig. 2 shows the spatial structure of the linkage between HydroWAMIT and WASP.

The time resolution between WASP and HydroWAMIT are not necessarily the same. In general, water quality simulations require considerably smaller timesteps than hydrologic or flow routing modeling. WASP may require time steps in the order of minutes or seconds depending on the size of the segments and the flows. Although HydroWAMIT's simulations are restricted to daily timesteps due to the relative simplicity of the methods used in the model, such as the Hamon method for evapotranspiration, HydroWAMIT can still create hydrodynamic files at any time step down to one second through interpolation. The time frame of the NPS file is also variable in order to provide a compatible time-frame between the boundary flows and the NPS inputs.

Application of HydroWAMIT

The utility of HydroWAMIT is illustrated via application to the North and South Branch Raritan River Watershed (NSBRW) in New Jersey. This 1,270 km^2 (490 $mile^2$) watershed includes the whole extent of the North Branch Raritan River and South Branch Raritan River. It also includes part of the Raritan River upstream of the confluence with the Millstone River (Fig. 3). The land use/land cover distribution of NSBRW consists of 35% forested, 27% agriculture, 21% residential, 8% commercial, 8% wetlands, and 1% water. Multiple point-source dischargers, a major water supply reservoir, and a lake are boundaries for the model. The objective of this application is to demonstrate the result of simulations obtained with the hydrologic and the NPS load components of HydroWAMIT.

The model outputs obtained for the purpose of this paper were evaluated at the outlet of the NSBRW. The most downstream flow gauge and water quality sampling station coincides with the watershed outlet. Besides the existence of a USGS flow gauge and water quality measurements, this location was selected for evaluating the results because the size of the drainage area provides a basis for comparing the results of HydroWAMIT and existing applications of SWAT and HSPF. (The actual calibration performed for the Raritan TMDL was more complex since it included multiple gauges and water quality stations. The calibration of HydroWAMIT for the Raritan TMDL is not within the scope of this paper.)

Model Preparation

The model segmentation and watershed delineation is a prerequisite for modeling with HydroWAMIT. A total of 60 subwatersheds were delineated automatically for the NSBRW using 10-meter

DEM (NJDEP 2002) and GIS methods available in ArcView (Garbrecht and Martz 2000). The branches and junctions of the stream network are defined using the county stream shape files (NJDEP 1998) from New Jersey. The model nodes are defined as a function of the subwatershed outlets, major point-source dischargers, major stream water diversions, and the maximum segment size for the water quality model. The GIS interface of HydroWAMIT does not generate the model input data from digital files. However, it allows the user to visualize the stream network, to edit elements, and to enter input data. The input data necessary for HydroWAMIT can be entered through HydroWAMIT's GUI or by editing the respective tab delimited stream network input files.

Land use parameters such as area, land use fraction, and the impervious fraction of residential and urban land uses were obtained from the most recent land use/land cover digital coverage available for New Jersey (NJDEP 2000). The data were summarized by subwatershed through a series of queries and pivot tables. Curve numbers were assigned based on the land use and the soil drainage classification according to NRCS-STATSGO soil database. Area-weighted curve numbers were calculated for each land use type of the subwatersheds using GIS. Stream network parameters were derived based on cross-section surveys available for many locations in the watershed.

Weather inputs were obtained from two major meteorological stations near the NSBRW. Daily precipitation records from the Bound Brook meteorological station and average daily temperature from the Hightstown meteorological station, both located in the vicinity of NSBRW, were used in the model. Point-source flows and concentrations were obtained for major dischargers in the watershed. A total of 12 point-source dischargers and two diversions were considered. In addition, releases from Spruce Run Reservoir and Cushetunk Lake, which are model boundaries, were also obtained from the United States Geological Survey (USGS) flow gauge for the period of analysis.

EMCs were derived in the Raritan River Watershed considering multiple storm events. Stormwater samples were collected at outlets of drainage areas representing homogeneous land use types. Stream water quality data were collected during low flow periods at the headwaters for estimating base flow concentrations. EMCs and baseflow concentrations are entered in HydroWAMIT through the model GUI or by editing tab delimited input files that can be easily opened in Excel. Point-source water quality data are not an input for HydroWAMIT. Concentrations of point-source flows are entered directly into WASP for their respective segment. Daily average or monthly average input water quality data were obtained directly from point-source dischargers or from the NJPDES discharge monitoring reports (DMR) database provided by NJDEP.

Hydrologic Component Calibration and Validation

The calibration of the hydrologic component of HydroWAMIT was performed for the period from January 2002 to August 2005 for the USGS Raritan at Manville flow gauge (1400500). This time period was selected because it includes years with wet, dry, and average weather conditions. Another reason for selecting this time period for calibration was the availability of measured discharger flows and concentrations. Although the point-source flow contribution at the Manville gauge is not significant from a water quantity perspective, the associated discharger loads is important for calibrating the water quality model and testing the NPS component of HydroWAMIT. The validation of the hydrologic component of HydroWAMIT was performed for the 12-year period, from January 1990 to December 2001. This period includes average, extremely dry, and extremely wet years. Point-source discharger flows were not considered for the validation period. Fig. 4 shows the accumulated precipitation in the NSBRW for the validation and calibration periods.

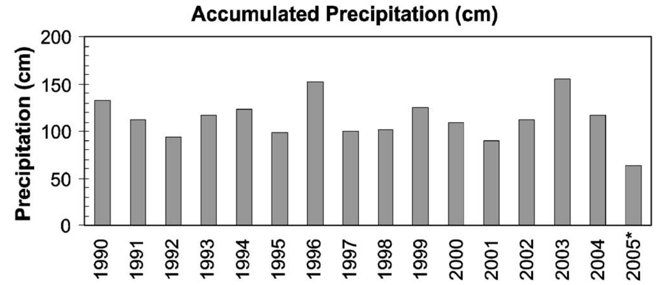

Fig. 4. Accumulated precipitation for calibration (2002–2005) and validation (1990–2001) periods. Year 2005 was from January 1, 2005, to August 31, 2005.

The calibration of hydrology starts by changing the fixed subwatershed parameters and checking the annual water budget. At this stage of calibration, the parameters that affect the global water budget, such as the saturated recession, are adjusted. Values obtained at this stage are not final. They will vary as other parameters that more directly affect the shape of the hydrograph are changed in the monthly and daily calibrations.

Monthly subwatershed hydrology parameters are calibrated next. Monthly values of the baseflow recession, field capacity, and potential infiltration are calibrated at this stage. Seasonal differences can be captured by adjusting these monthly values. Once a first iteration of seasonal parameters is achieved, the model can be fine tuned using daily flow records. Parameters that determine the magnitude of peaks and the hydrograph recession such as detention storage, impervious recession, interflow recession, and interflow fraction are adjusted at this stage of the calibration.

Statistical tests such as deviation of annual stream flow volume (D_v), Nash–Sutcliff (E_{NS}), and coefficient of determination (R^2) are commonly used to provide a quantitative measure of hydrologic model performance (Van Liew et al. 2003; Santhi et al. 2001). These tests were derived for monthly and daily time series to evaluate HydroWAMIT simulations. Table 2 contains a summary of the statistical tests results for the calibration and validation periods. In addition to statistical tests, the graphical comparison between predicted and simulated time series for the calibration period and the respective frequency distribution plot for flow are show in Fig. 5.

Table 2. Statistical Tests for the Model Calibration and Validation

Test	Model calibration period (2002–2005)[a]	Extended validation period (1990–2001)
Average of accumulated annual precipitation (cm)	112	113
R^2_{monthly}	0.72	0.80
$E_{\text{NS monthly}}$	0.72	0.78
R^2_{daily}	0.68	0.66
$E_{\text{NS daily}}$	0.68	0.63
D_v	1.2%	7%

[a]Year 2005 is from January 1, 2005 to August 31, 2005.

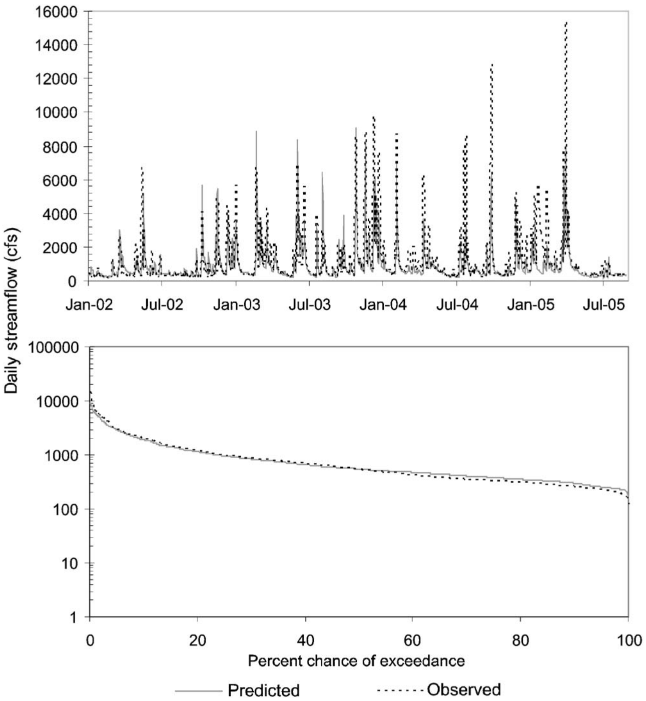

Fig. 5. (a) Observed and predicted streamflow at the USGS Manville gauge for the calibration period (2002–2005); (b) observed and predicted daily streamflow duration curves for the calibration period

The results obtained with HydroWAMIT can be compared with studies performed using SWAT and HSPF. Values of E_{NS} and R^2 for the SWAT model obtained from different studies summarized by White and Chaubey (2005) range from 0.58 to 0.98 and 0.63 to 0.97, respectively. Statistical tests for HSPF and SWAT applications for medium watersheds with drainage areas between 500 and 700 km^2, which are comparable to NSBRW (1,270 km^2) in size, are reported by Van Liew et al. (2003). The reported E_{NS} values for SWAT range from 0.43 to 0.89 for monthly records and −0.07 to 0.6 for daily records. The reported E_{NS} values for HSPF range from 0.37 to 0.92 for monthly records and 0.14 to 0.87 for daily records. The reported absolute D_v for medium size watersheds varied from 5.3 to 38.7% for SWAT and from 0 to 35.3% for HSPF.

Singh et al. (2005), compares the hydrologic simulations of HSPF and SWAT for a 5,000 km^2 watershed. The reported E_{NS} values for SWAT range from 0.80 to 0.93 for monthly records and 0.70 to 0.83 for daily records. The reported E_{NS} values for HSPF range from 0.80 to 0.88 for monthly records and 0.69 to 0.81 for daily records. The reported absolute D_v for large size watersheds varied from 0.8 to 13.7% for SWAT and from 0.3 to 16.4% for HSPF.

The values of E_{NS} and R^2 obtained with HydroWAMIT are within the range of simulations shown in studies using HSPF and SWAT. Monthly values of E_{NS} are 0.72 and 0.78, respectively, for the calibration and validation periods. Daily values of E_{NS} obtained with HydroWAMIT are 0.68 and 0.63, respectively, for the calibration and validation periods. According to Motovilov et al. (1999), the simulation results are considered to be good for values of $E_{NS} > 0.75$, and satisfactory for E_{NS} values between 0.75 and 0.36. According to Donigian et al. (1983), the simulated streamflow is considered "very good" if the percent difference in annual streamflow volume for the calibration period is less than 10%, "good" when it is between 10 and 15%, and fair when it is between 15 and 25%. The percent difference between simulated and observed mean annual streamflow is 1.2% for the period of calibration and 7% for the validation period. In addition to the statistical tests, the daily timeseries plots and the daily stream flow duration curves obtained with HydroWAMIT are comparable to the results presented by Singh et al. (2005), and Van Liew et al. (2003), for SWAT and HSPF.

Table 3. TDS EMCs for the NSBRW

Land use	TDS EMC (mg/L)
Residential	209
Other Urban	119
Forested	114
Agricultural	140
Wetlands	79
Baseflow	127–340

NPS Component Test

The NPS component of HydroWAMIT was tested for total dissolved solids (TDS). The linkage of HydroWAMIT with WASP allows the fate and transport of NPS loads from subwatersheds to be simulated by the water quality model. Because water quality modeling with WASP is not within the scope of this paper, the simulation of a conservative substance was chosen. Conservative substances in a river system such as the Raritan are influenced mostly by loads and dilution, and do not require a formal water quality calibration and validation. The TDS EMCs were assigned according to the land use type in HydroWAMIT. Surface runoff TDS EMCs were assumed to vary by land use. Because a unique baseflow concentration is assigned to a subwatershed, a weighted land use area TDS concentration for baseflow was calculated for each subwatershed. Table 3 shows the EMC per land use type and the TDS concentration range for baseflow.

The loads of TDS are generated by HydroWAMIT based on the EMCs, surface flow, and baseflows calculated by the hydrologic component of HydroWAMIT. The calculated loads are summarized in the NPS file. NPS files are text files that provide NPS input data for WASP. The NPS file created for this example has a 15-min time step in order to avoid instabilities in WASP. In addition, point-source concentrations of TDS were considered for this example. The TDS concentrations for all 12 of the major point-source facilities were entered in WASP. The point-source loads are calculated internally by WASP. The concentrations entered in WASP are automatically multiplied by their respective discharger flows, which are given by the hydrodynamic file.

This example was setup for a one-year period, from January 2004 to December 2004. This period was selected because discrete water quality samples of TDS were available at the Manville USGS gauge. Fig. 6 shows time series of TDS simulated by WASP using NPS inputs from HydroWAMIT.

Statistical tests such as the coefficient of correlation (R) and the R^2 can be used to evaluate the water quality model performance (Reckhow and Chapra 1983; Santhi et al. 2001). A value of 0.65 for R^2 and 0.80 for R were obtained at the Manville USGS gauge for TDS predictions, using a total of 18 water quality sample values. According to Ramanarayanan et al. (1997), the model prediction is satisfactory for R^2 values greater than 0.6. The results obtained for this example demonstrate the effectiveness of the NPS component of HydroWAMIT.

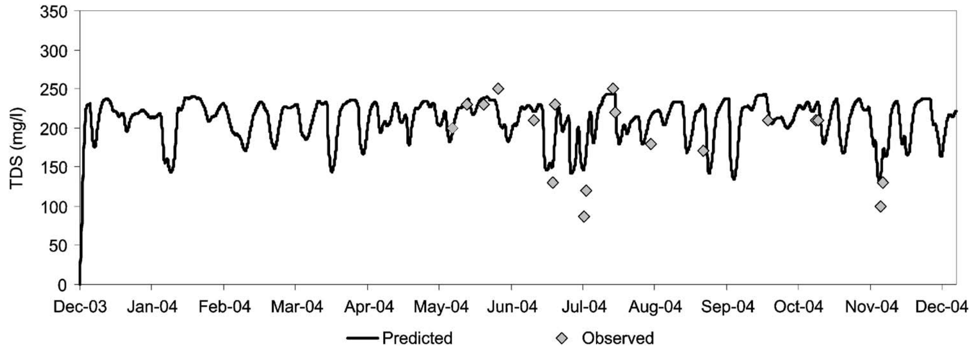

Fig. 6. Simulated and observed TDS at the USGS Manville gauge, main stem Raritan River

Conclusion

HydroWAMIT is a continuous and spatially distributed hydrologic model based on elements of GWLF and HSPF. It operates in conjunction with DAFLOW and WASP for streamflow routing and water quality modeling, respectively. The main components of HydroWAMIT and a practical application of streamflow modeling and TDS modeling were demonstrated in this paper.

The main advantages of HydroWAMIT are the low effort necessary for nonpoint-source load calibration and the easy linkage to WASP. The use of EMCs and BFCs, instead of multiple nutrient cycling or buildup/washoff rates, significantly reduces the calibration effort. The EMCs and BFCs are relatively easy to obtain through field measurements, and they represent site-specific data. The linkage of HydroWAMIT with WASP allows refined stream networks to be modeled. This can be critical for capturing the effects of point-source dischargers in water quality or particular characteristics of the stream network. In addition, simulation processes such as the impact of periphyton and nutrient luxury uptake can be simulated in WASP.

The statistical tests used to measure the model predictability suggest that HydroWAMIT flow simulations are good for the NSBRW. The results of statistical tests obtained with HydroWAMIT for this 1,270 km^2 watershed fall between the range of values obtained with SWAT and HSPF when applied to medium and large size watersheds. Because of the averaging of many watershed processes, the response of flow simulations at gauges of large drainage areas generally results in better statistics. The area of the NSBRW is almost two times the area of the medium size watersheds, and it is four times smaller than the large size watershed used in the HSPF and SWAT studies. Therefore, the results obtained for HydroWAMIT are comparable with results obtained with SWAT and HSPF.

The results obtained for the TDS simulation indicate that the NPS component of HydroWAMIT also provides good results. The NPS component uses EMCs and the flows derived by the hydrologic component to calculate loads. This is a very simple and efficient approach for deriving the NPS contributions. The models available within the BASINS framework present a more complete, but also more complex, approach, which can significantly increase the number of input parameters for the models. Models that simulate nutrient cycling explicitly provide a more direct assessment of best-management practices. This class of models adopts parameters that can be translated into a change in management practice, such as fertilizer application rate. The use of EMCs to simulate NPS loads also allows for best management practices to be evaluated. However, the input EMCs would need to be translated in order to reflect the respective change in management practices.

Presently, HydroWAMIT does not have a GIS interface to derive model parameters automatically. However, the relatively small number of parameters could be easily derived using any kind of GIS software. This could be seen as an advantage for users that do not have access to the GIS software necessary to process the BASINS input datasets. Also, the need for fewer input parameters can be an important advantage for projects that require custom datasets that are not compatible with the BASINS framework.

The scale of the TMDL projects and the issues involved vary considerably. HydroWAMIT provides a flexible structure that allows a robust, spatially distributed hydrological model to be combined with a fine scale in stream water quality model. This framework also allows point-source loads to be easily incorporated in the analysis. The linkage between WASP and HydroWAMIT occurs through two input files, which automatically setup the stream network for the WASP project.

HydroWAMIT can be used as a viable alternative to the BASINS framework for special studies. Projects that require a robust modeling tool for flow and NPS inputs in conjunction with high-resolution water quality simulations are excellent candidates for HydroWAMIT use.

Acknowledgments

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