Hydrologic and Watershed Model Integration Tool (HydroWAMIT) and Its Application to North & South Branch Raritan River Basin

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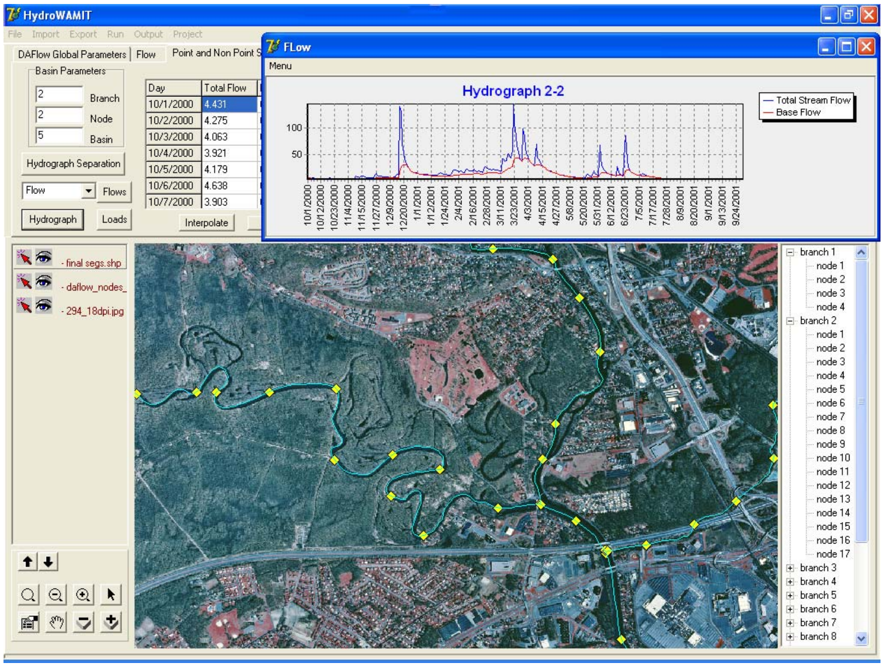


Branch: 2
Node: 2
Basin: 5
Flow

Day	Total Flow
10/1/2000	4.431
10/2/2000	4.275
10/3/2000	4.063
10/4/2000	3.921
10/5/2000	4.179
10/6/2000	4.638
10/7/2000	3.903

INTRODUCTION

Hydrologic models are used to simulate overland flows from the watersheds, and can also be used to calculate the pollutant loads associated with these flows. There are many hydrologic models that are currently available. They are primarily divided into event based models (e.g. HEC-1, TR-55, and HydroCAD) and continuous models (HSPF, SWAT and GWLF). As the definitions suggest, the event based hydrologic models generate flows for specific storm events, while continuous models generate continuous flows for longer periods of time. Continuous hydrologic models are typically used for Total Maximum Daily Load (TMDL) studies.

Continuous hydrologic models differ considerable in terms of spatial resolution and simulated processes. The Better Assessment Science Integrating Point and Non-point Sources (BASINS) (USEPA, 2001) is one of the computer applications designed to provide hydrologic modeling tools for TMDL purposes. BASINS includes the Hydrologic Simulation Program – FORTRAN (HSPF) (Bicknell et al., 2001) and the Soil and Water Assessment Tool (SWAT) (Arnold et. al., 1998) models. The BASINS framework has many advantages, including the linkage with the Geographic Information System (GIS) to easily retrieve data, pre-formatted weather data available for download, digital water quality databases, and incorporation of documented modeling applications. The models available within the BASINS framework have been used in a variety of watersheds. However, the effort necessary to calibrate HSPF or SWAT, the high level of complexity of the simulation processes used by those models to generate nonpoint source (NPS) pollutant loads, and the methods and the scale of the transport and fate of pollutants in the stream are factors that prohibit the application of BASINS for some projects.

NPS loads are directly associated with the surface runoff and baseflow from the sub-watersheds. Models such as SWAT simulate the yield of nutrients and other constituents using physical and empirical relationships that mimic the nutrient cycle and the yield of other constituents. 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, K. L and I. Chaubey, 2005). Models such as HSPF also require 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, J. B., 2003).

In addition to the high effort for calibrating NPS 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 (attached algae) on diurnal dissolved oxygen and nutrients (considering luxury nutrient uptake) are not simulated in SWAT or HSPF and may be extremely important for some systems. 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 small watersheds would need to be delineated in HSPF or SWAT. The delineation of several small watersheds to create a denser stream network requires high resolution spatial input datasets for automatically creating model input files, and implies a considerable increase in the number of spatial parameters and associated calibration effort.

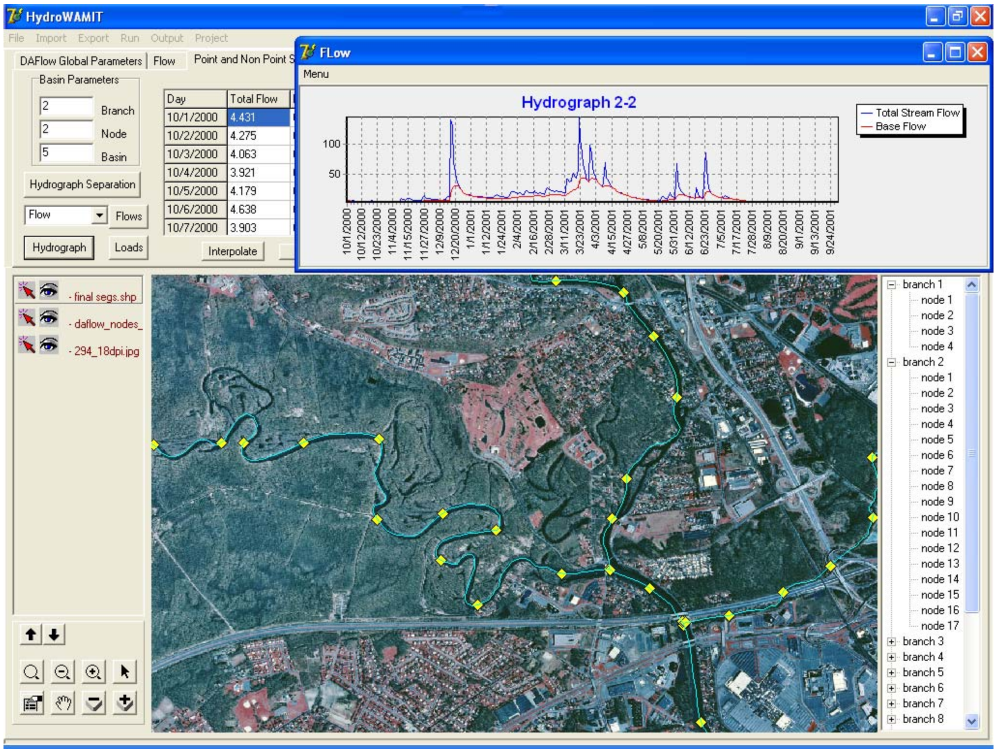
Therefore, many large TMDL projects would benefit greatly from a spatially distributed modeling framework that could significantly reduce the calibration effort of NPS parameters while providing means for capturing localized water quality variables such as diurnal dissolved oxygen. This can be accomplished by adopting site specific surface runoff and baseflow concentrations instead of numerous nutrient cycling or buildup/washoff rates.

MODEL DESCRIPTION

The Hydrologic Watershed Model Integration Tool (HydroWAMIT) is a continuous, spatially distributed, robust hydrologic model with loading functions based on Event Mean Concentrations (EMCs), and tools that makes it easy to link point and non-point pollutant loads to the Water Quality Analysis Program Version 7.1 (WASP) (Di Toro et al., 1983; Ambrose, R.B. et al., 1993; Wool et al., 2003). HydroWAMIT is presented 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 non-point 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 provides surface runoff, baseflow and their associated loads as outputs for a daily timestep, and is relatively simple to calibrate compared to other hydrologic and pollutant loading models like HSPF. HydroWAMIT operates with the Diffusion Analogy Flow Model (DAFLOW) for flow routing and hydraulics. HydroWAMIT has a GIS Graphical User Interface (GUI) which serves as a data entry interface and display for the input parameters and output. The post-processor of the HydroWAMIT GUI helps not only to display the flow at any give node on the stream network, but also to compare with the measured flows from an existing gage (e.g. USGS flow gages) and to display the goodness-of-fit statistics. The post-processor also has an option to compare the flow at any give node to the precipitation gage. This option assists in choosing the precipitation gage or combination of precipitation gages for a given subwatershed. The post-processor is a powerful too that greatly facilitates calibration of the model. Figure 1 and 2 show HydroWAMIT GUI and HydroWAMIT post-processor.



Basin Parameters
Branch: 2
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10/1/2000	4.431
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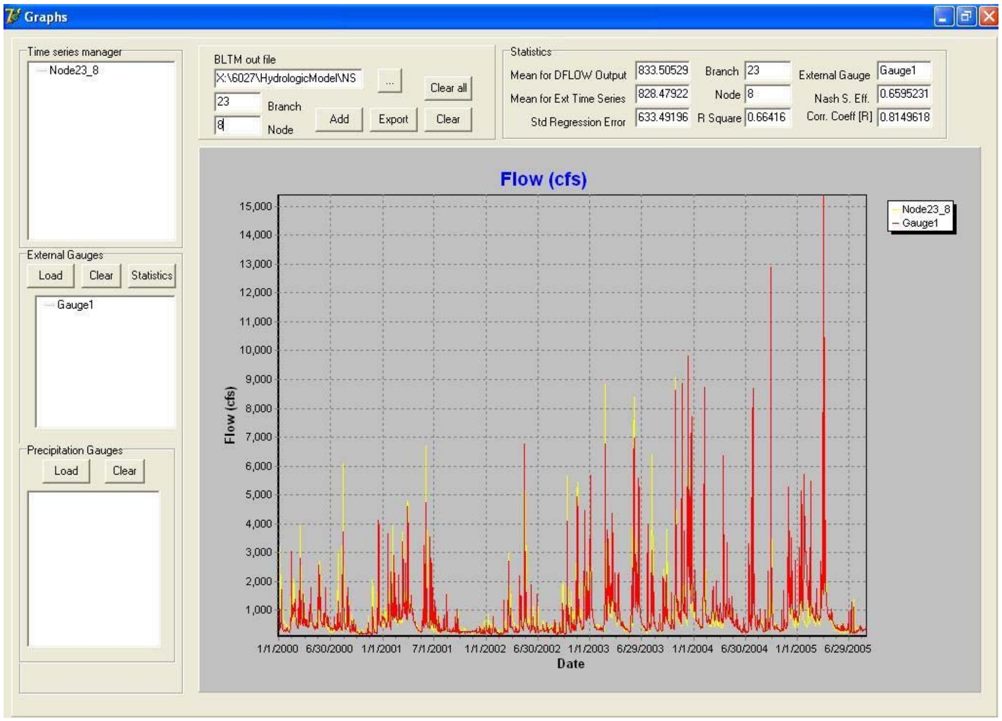
Figure 1: HydroWAMIT GUI



BLTM out file: X:\6027\HydrologicModel\NS
Branch: 23
Node: 8

Statistics
Mean for DFLOW Output: 833.50529
Mean for Ext Time Series: 828.47922
Std Regression Error: 633.49196
Branch: 23
Node: 8
R Square: 0.66416
External Gauge: Gauge1
Nash S. Eff.: 0.6595231
Corr. Coeff [R]: 0.8149618

Figure 2: HydroWAMIT Post Processor showing the comparison between predicted and observed flow as well as goodness-of-fit statistics.

Precipitation provides the water input to the hydrologic model. Surface runoff from impervious areas is calculated separately from pervious areas, based on the impervious fraction of the each subwatershed. Precipitation occurring over pervious areas is subject to infiltration to unsaturated zone and interception. Interception is the fraction of precipitation that does not reach the ground because it is trapped in structures or vegetation. The fraction of water that is intercepted is assumed to be lost by evaporation. The water that is not intercepted can infiltrate into the soil or become surface runoff and interflow. Interflow is a fraction of the surface runoff from pervious areas that occurs in the superficial layer of the soil, which 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 sub-watershed at each time step. HydroWAMIT calculates the total flow contribution of each sub-watershed separately. The flow is then routed downstream in the modeled stream using DAFLOW. Figure 3 shows the land phase of the hydrologic cycle as simulated in HydroWAMIT.

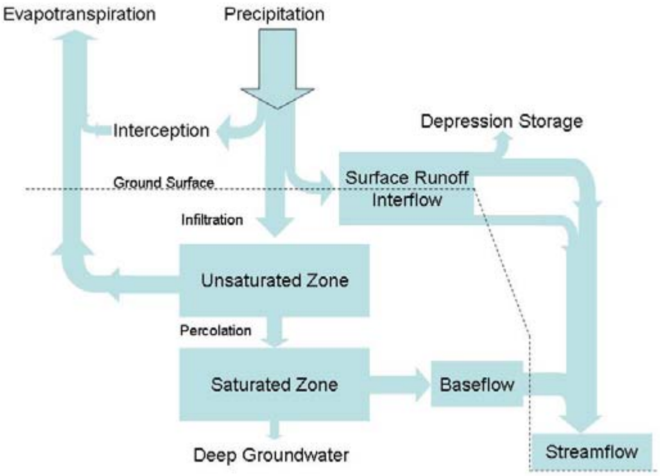


Figure 3: Land phase of hydrologic cycle adopted by HydroWAMIT

HydroWAMIT has a total of twenty five inputs to account for the hydrologic cycle and pollutant loading. A list with all the necessary input data and parameters is shown in Table 1. A detailed description of all the parameters and the equations involved to simulate the hydrologic cycle are available in the HydroWAMIT Technical Manual (Omni 2006) and also provided by Cerucci & Jaligama (2008). From the list of input data and parameters, ten are obtained from land use and soil characteristics for each sub-watershed or from meteorological records. The remaining fifteen 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.

Model Parameter	Class	Description	Units
Area	LU	Area of respective land use type	acres
CN	LU	Average curve number for land use	
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 paramenter	
Deepseepage	FSH	Deep ground water loss recession coefficient	
Deep Perc	FSH	Minimun water in the sat zone for deep groud 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	FSH	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	oC
Daylight	WTH	Total daylight hours	hours

Table 1: HydroWAMIT input parameters - land use parameters (LU), fixed subwatershed hydrology (FSH), monthly subwatershed hydrology (MSH), weather (WTH).

MODEL APPLICATION IN NORTH & SOUTH BRANCH RARITAN RIVER BASIN

The utility of HydroWAMIT is illustrated via application to the North and South Branch Raritan River Watershed (NSBRW). This 1270 km^2 (490 mi^2) watershed includes the Raritan River basin upstream of its confluence with the Millstone River (Figure 4), including the extents of the North Branch Raritan River and South Branch Raritan River. The land use/land cover distribution of NSBRW consists of 35 percent forested, 27 percent agriculture, 21 percent residential, 8 percent commercial, 8 percent wetlands and 1 percent 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 component of HydroWAMIT.

The model outputs obtained for the purpose of this paper were evaluated at the outlet of the NSBRW. As an illustration, the calibration at two continuous flow gages, one in the mid-region of the watershed and the other at the watershed outlet, is shown in this paper. In addition to the two flow gages, calibration at two flow sampling locations is also shown.

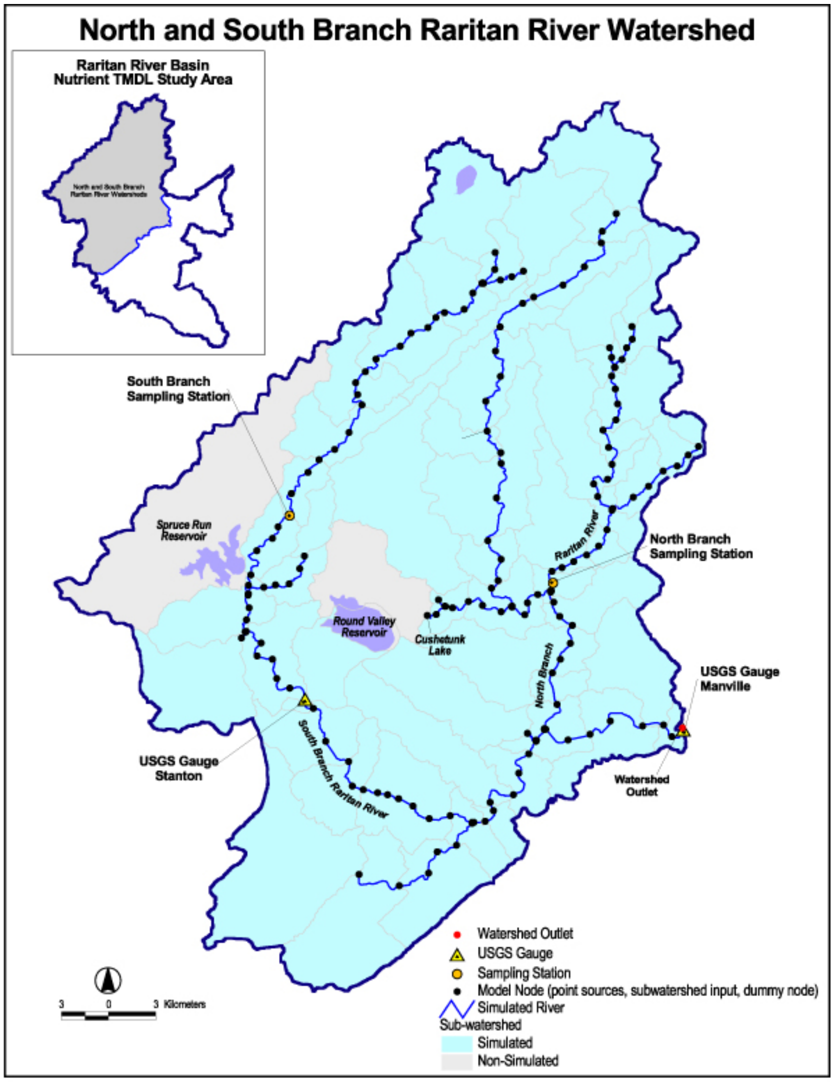


Figure 4: North and South Branch Raritan River Watershed.

A total of 60 sub-watersheds were delineated automatically for the NSBRW using ten meter Digital Elevation Models (DEM) (NJDEP, 2002) and GIS methods available in ArcView (Maidment and Djokic, 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 sub-watershed 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). 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 sub-watersheds 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 were obtained for major dischargers in the watershed. A total of twelve point source dischargers and two diversions were considered. In addition, releases from Spruce Run Reservoir, Cushetunk Lake, and Round Valley Reservoir, which are model boundaries, were also obtained from the United States Geological Survey (USGS) flow gage for the period of analysis.

The calibration of the hydrologic component of HydroWAMIT was performed from January 2002 through August 2005. Results are provided for the South Branch Raritan River at Stanton (1397000) and Raritan River at Manville (1400500) USGS flow gages. This time period was selected because it includes years with wet, dry and average weather conditions, and it includes the time periods during which intensive water quality sampling was performed for water quality model calibration and validation. The validation of the hydrologic component of HydroWAMIT was performed for a twelve year period, from January 1990 through December 2001. This period includes average, extremely dry, and extremely wet years.

Statistical tests such as deviation of annual streamflow 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 and Santhi et al., 2001). These tests were derived for monthly and daily time series to evaluate HydroWAMIT simulations. Table 2 shows 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 Figures 5 and 6. Graphical comparison between predicted flows and measured flows at two sampling stations, one in South Branch and other in North Branch Watershed are shown in Figure 7. (The locations of these two sampling stations are shown in Figure 3).

Parameter	SB Raritan at Stanton	Raritan River at Manville
R^2 daily	0.75	0.68
R^2 monthly	0.86	0.73
E_{NS} daily	0.75	0.68
E_{NS} monthly	0.86	0.73
D_v	2.55%	-2.85%

Table 2: Statistical tests for the model calibration.

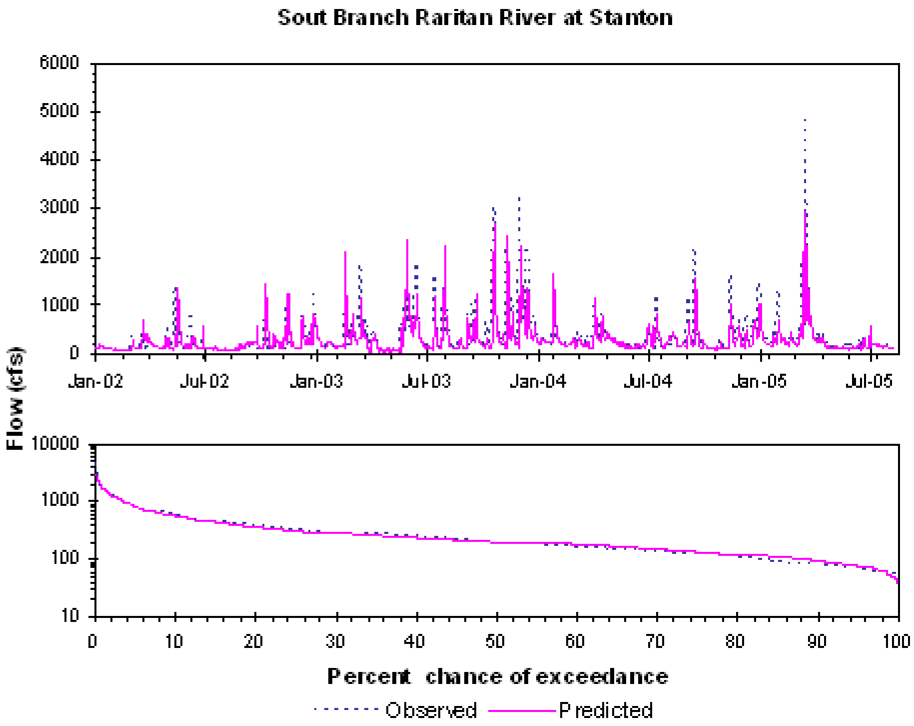


Figure 5: (a) Observed versus predicted streamflow at the USGS Manville gage; (b) Observed and predicted daily streamflow duration curves.

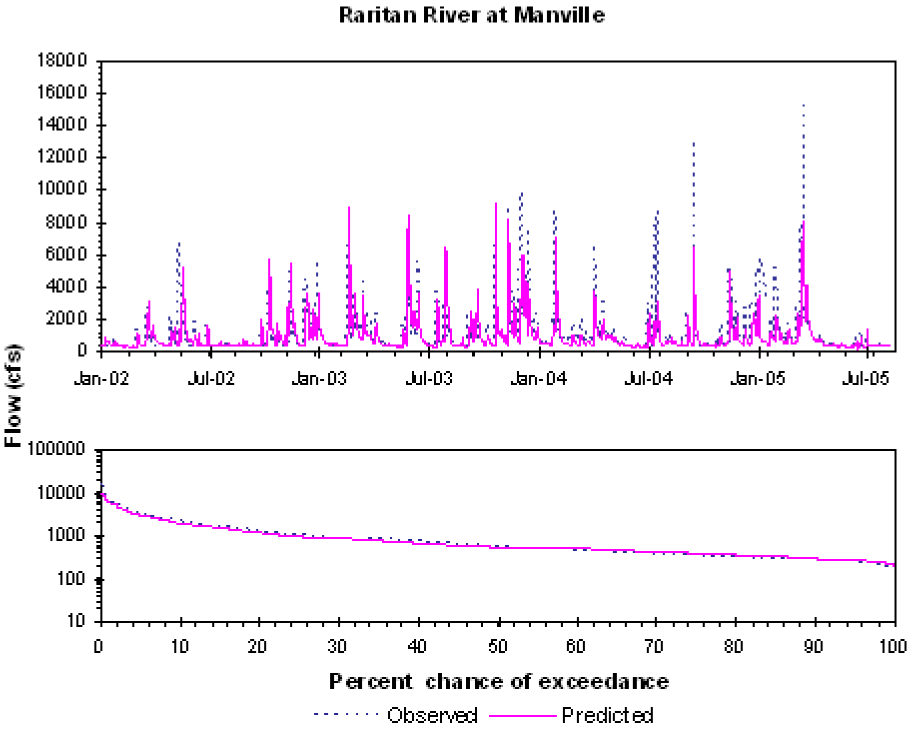


Figure 6: (a) Observed versus predicted streamflow at the USGS Stanton gage
(b) Observed and predicted daily streamflow duration curves

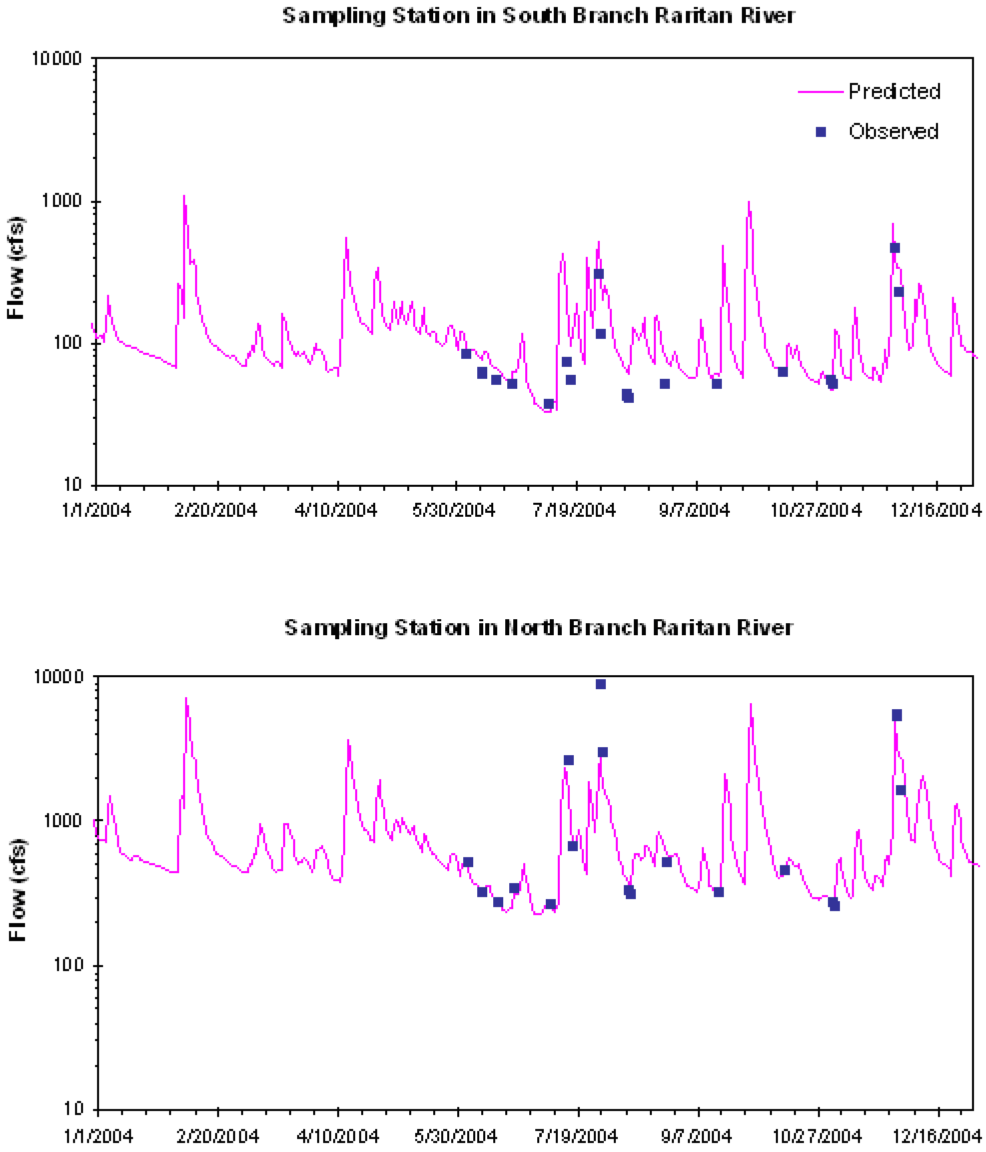


Figure 7: (a) Observed versus predicted stream flow at the South Branch Sampling Station (b) Observed and predicted stream flow at North Branch Sampling Station.

CONCLUSIONS

HydroWAMIT is a continuous and spatially distributed hydrologic model based on elements of GWLF and HSPF models. It operates in conjunction with DAFLOW and WASP for stream flow routing and water quality modeling respectively. The main components of HydroWAMIT and a practical application of streamflow modeling are demonstrated in this paper. The main advantages of HydroWAMIT include robust modeling structure, use of a daily time step, handling of complex stream configuration, handling of more than one point source per sub watershed, simplified input and output data management, the low effort necessary for non-point source load calibration and the easy linkage to WASP. 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.

The scale of 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 stream water quality model. This framework also allows point sources to be easily incorporated in the analysis. The use of HydroWAMIT is demonstrated in this paper with the application to North & South Branch Raritan River Watershed in the context of a large-scale nutrient TMDL study.

REFERENCES

Ambrose, R. B., T. A.Wool, J.L. Martin, 1993. The Water Quality Analysis simulation Program, WASP5 Part A: Model Documentation. Environmental Research Laboratory, Athens Georgia.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams, 1998. Large Area Hydrologic Modeling and Assessment. Part I: Model Development. *Journal of the American Water Resources Association* 34(1):73-89.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, Jr., T.H. Jobes, and A.S. Donigian, Jr., 2001. Hydrological Simulation Program – FORTRAN (HSPF), User's Manual for Version 12.0. USEPA, Athens, Georgia.

Butcher, Jonathan B., 2003. Buildup, Washoff, and Event Mean Concentrations. *Journal of the American Water Resources Association* 39(6):1521-1528.

Cerucci. M, G. Jaligama. 2008 The Hydrologic and Watershed Integration Tool: HydroWAMIT, *Journal of Environmental Engineering*, American Society of Civil Engineers. Vol 134 (8): 600-609.

Di Toro, D.M., J. J. Fitzpatrick, and R.V. Thomann. 1983. Water Quality Analysis Simulation Program (WASP) and model verification program (MVP) – Documentation. Hydroscience, Inc. Westwood, NY, for USEPA.

Maidment, D. and D. Djokic, 2000. Hydrologic and Hydraulic Modeling Support with Geographic Information Systems. ESRI Press.

NJDEP (New Jersey Department of Environmental Protection), 1998. NJDEP Streams County, New Jersey (1:24,000). Available at: http://www.nj.gov/dep/gis/digidownload.htm. Last accessed in May 2006.

NJDEP (New Jersey Department of Environmental Protection), 2002. NJDEP 10-meter Digital Elevation Grid. Available at: http://www.nj.gov/dep/gis/wmalattice.html. Last accessed in May 2006.

NJDEP (New Jersey Department of Environmental Protection), 2000. NJDEP 1995/97 Land use/Land cover Update. Available at: http://www.nj.gov/dep/gis/lulc95shp.html. Last accessed in May 2006.

Omni Environmental LLC 2006. HydroWAMIT technical manual and theory. Princeton, NJ.

Santhi, C., J.G. Arnold, J.R. Williams, L.M. Hauck, and W.A. Dugas, 2001. Application of a Watershed Model to Evaluate Management Effects on Point and Non-point Source Pollution. *Transactions of the American Society of Agricultural Engineers* 44(6):1559-1570.

USEPA (U.S. Environmental Protection Agency), 1998. TMDL Case Study: Tar Pamlico Basin, North Carolina. Office of Water, Washington, D.C.

USEPA (U.S. Environmental Protection Agency), 2001. Better Assessment Science Integrating Point and Nonpoint Sources – BASINS Version 3.0, User's Manual. EPA-823-B-01-001, Washington, D.C.

Van Liew, M.W., J.G. Arnold, and J.D. Garbrecht, 2003. Hydrologic Simulation on Agricultural Watersheds: Choosing Between Two Models. *Trans. ASAE* 46(6):1539-1551.

White, Kati L. and Indrajeet Chaubey, 2005. Sensitivity Analysis, Calibration, and Validations for a Multisite and Multivariable SWAT Model. *Journal of the American Water Resources Association* 41(5):1077-1089.

Wool A. T., Ambrose R. B., Martin J. L., Corner, E. A., 2003. Water Quality Analysis Simulation Program (WASP), Version 6: Draft users manual. Available at: http://www.epa.gov/athens/wwqtsc/html/wasp.html.