FROM THE STANFORD MODEL TO BASINS: 40 YEARS OF WATERSHED MODELING

by

Anthony S. Donigian, Jr.
John C. Imhoff

AQUA TERRA Consultants
Mountain View, CA
650-962-1864; Donigian@aquaterra.com

1.0 Introduction

In the early 1960's the Stanford Watershed Model (SWM) was instrumental in introducing the civil engineering profession to the concept of continuous hydrologic modeling. By the early 1970's the developers of SWM expanded and refined SWM to create the Hydrocomp Simulation Program (HSP), which also included general nonpoint source loadings and water quality simulation capabilities. During the early 1970's EPA sponsored development of the ARM (Agricultural Runoff Management) and the NPS (Nonpoint Source) pollutant loading models to address pollution from agriculture, urban, and other land uses; the SWM approach was selected as the hydrologic foundation for an expanding suite of models of nonpoint pollution impacts.

With wide distribution and application of the SWM in the late 1960's, civil engineers recognized the value of digital continuous simulation for hydrologic applications. By the early 1970's Hydrocomp had demonstrated the utility of quantity/quality simulation by modeling a range of water quality constituents in a large basin in Washington state. In the late 1970's EPA recognized that the continuous process simulation approach contained in all these models would be needed to analyze and solve many complex water resource problems. Grant money from the agency to Hydrocomp resulted in the development of the Hydrological Simulation Program - FORTRAN (HSPF), a non-proprietary system of simulation modules in standard Fortran that handled essentially all the functions performed by HSP, ARM and NPS, and was considerably easier to maintain and modify. HSPF simulates the hydrologic and associated water quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments. Since the first public release (Release No. 5) of HSPF in 1980, the model has undergone a continual series of code and algorithm enhancements producing a succession of new releases, leading up to the most recent Release No.12 in 2001.

Since 1981, the U.S. Geological Survey has been developing software tools to facilitate watershed modeling by providing interactive capabilities for model input development, data storage and data analysis, and model output analysis including hydrologic calibration assistance. The ANNIE, WDM, HSPEXP, and GenScn products developed by the USGS have greatly advanced and facilitated watershed model application, not only for HSPF, but also for many other USGS models.

In 1994 efforts began to develop EPA's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) modeling system. The BASINS system combines environmental databases, models, assessment tools, pre- and post-processing utilities, and report generating software to provide the full range of tools and data, integrated into a single modeling package, needed for performing watershed and water quality analyses. HSPF was incorporated into BASINS as the core watershed model. Since 1998 BASINS has benefited from considerable efforts to integrate and enhance the strongest features of HSPF and the USGS software products (including GenScn) within a common framework. Today HSPF/BASINS serves as a focal point for cooperation and integration of watershed modeling and model support activities between the USGS and the EPA. At the same time HSPF has been integrated into the U.S. Army Corps of Engineer's Watershed Modeling System (WMS), providing a further opportunity for the use of common tools and methodologies by federal agencies, as well as other modeling professionals.

Over the years, development activities and model enhancements, along with lessons learned from model applications, have continued to improve the model's capabilities and preserve its status as a state-of the-art tool for watershed analysis. The primary focus of this paper is to review the evolutionary process that has advanced the Stanford Watershed Model, and its fundamental concepts, from the model's beginnings four decades ago to its embodiment in HSPF/BASINS today. In developing this discussion, we reflect on how and why HSPF has evolved in the direction(s) and form that it has. Forty years of SWM/HSPF/BASINS model development has required the conceptual efforts, ingenuity and programming skills of dozens of individuals from both the academic and professional communities. This paper recognizes many of these contributors, either directly or through its citations.

In concluding, we will share our vision of the directions that we believe HSPF will evolve in the coming years. The current resurgence of government concern for nonpoint source issues and problems and the focus on watershed scale assessment and management, as catalyzed by various sections (e.g., Total Maximum Daily Load (TMDL) assessment) and amendments to the Clean Water Act in the United States, has renewed interest in nonpoint source and comprehensive watershed modeling. The comprehensive nature of HSPF, and its flexibility in allowing consideration of the combined impacts of both point and nonpoint source pollutants at the watershed scale, has led to unprecedented interest in model applications. In addition, the model’s use within a multi-media framework, such as that used in the Chesapeake Bay Program, and linkage with numerous estuarine and multi-dimensional hydrodynamic/water quality models, has further advanced it’s utility for sophisticated environmental analyses. To support this increased interest and usage, there will be a need for HSPF and supporting software to continue to grow. Improvements in process algorithms, enhanced and broadened capabilities to interact with a wide variety of environmental data, and continued refinements in user interaction capabilities will all be required.

2.0 The Model Core: Process Algorithm Development

Hydrologic simulation (sometimes termed rainfall-runoff modeling) began in the 1950s and 1960s with the advent of the digital computer. The purpose was to predict streamflow, given observed precipitation (and other meteorological variables), at time scales short compared to catchment storm response times. Among the various applications of hydrologic simulation models are streamflow forecasting, design and planning (e.g., for flood protection), and extension of streamflow records. The first models were spatially lumped, meaning that the models represented the effective response of an entire catchment, without attempting to characterize spatial variability of the response explicitly. Precipitation forcings were usually represented as mean areal precipitation, and typically were obtained by spatial averaging of gage observations.

2.1 Stanford Watershed Model

The foundation for hydrologic-response simulation, as we know it today, was set in place at Stanford University, under the leadership of the late Professor Ray Linsley, parallel to the advent of high-speed digital computers in the early 1960s. The most well known of the early models developed at Stanford is the “Stanford Watershed Model” (Crawford and Linsley,1962, 1966). Crawford and Linsley (1966) capture the essence of hydrologic-response simulation with the following statement:

> The objective of the research is to develop a general system of quantitative analysis for hydrologic regimes. The most effective way for doing this has been to establish continuous mathematical relationships between elements of the hydrologic cycle. The operation of these mathematical relationships is observed and improved by using digital computers to carry the calculations forward in time... As mathematical relationships are developed, every attempt is made to realistically reproduce physical processes in the model. Experimental results and analytical studies are used wherever possible to assist in defining the necessary relationships.

The first decade of watershed model development is best told directly by Norman Crawford (personal communication, 2002):

> Work on hydrologic modeling started in the summer of 1960 when Ray Linsley asked me to “go over to the electrical engineering department and find out what a 'digital computer' was.” I was working on an MS at the time, and had a research assistantship. Ray had a project underway for several years before I went to Stanford to study flood peaks on small streams, and the project was getting nowhere. So with only a couple of hundred dollars left, Ray was looking for some different way to spend the last of the money. I wrote a daily interval water balance model; we published it, but I felt it did not work well. The next year I proposed working on a Ph.D. to try to write a model that would work. Two years later, and with another computer generation, I had a working model and I clearly remember going into Ray's office hours and showing him simulated/observed plots not that different from what we could do today. His reaction was "people have been trying to do this for a long time". The 1962 model (my thesis) ran on hourly intervals, and included almost all of the hydrologic functions and algorithms that are still in use (snow melt was not included).
>
> We had a lot of graduate students who would later be influential in water resources, and we were clearly onto something, so we obtained a series of NSF grants to expand and extend simulation modeling. One of the first extensions was a thesis to model radio nuclide transport (Huff, 1967). There were at least a dozen Stanford Ph.D.s in the period 1962 to 1970 who expanded, tested, or applied simulation modeling, and contributed to its popularity. Simulation was controversial during this time. Some people felt that ‘calibration’ was improper, and some people at technical meetings actually said the results that we were getting were 'impossible'. Many people did not

> understand what was going on. This changed in the summer of 1966 when Technical Report 39 was published. We gave a two-week workshop that summer at Stanford for 35 university professors. They in turn made modeling popular around the country.

The 1966 Stanford Watershed Model IV was widely distributed; more than 10,000 copies were printed by the university, and many more were distributed by University Microfilms. The refinements from 1962 to 1966, apart from inclusion of snowmelt routines (Anderson and Crawford, 1964), were aimed at reducing the number of parameters that needed to be calibrated and at using more physical processes (e.g., Crawford integrated kinematic wave routing into SWM), rather than empirical processes. Figure 1 shows the flowchart of the SWM, with a few selected refinements developed subsequently, but structurally unchanged from its 1966 origin. Figure 2, developed about a decade later by graduate students of the era, conveys (tongue-in-cheek) the pragmatic approach to modeling developed by Crawford and Linsley.

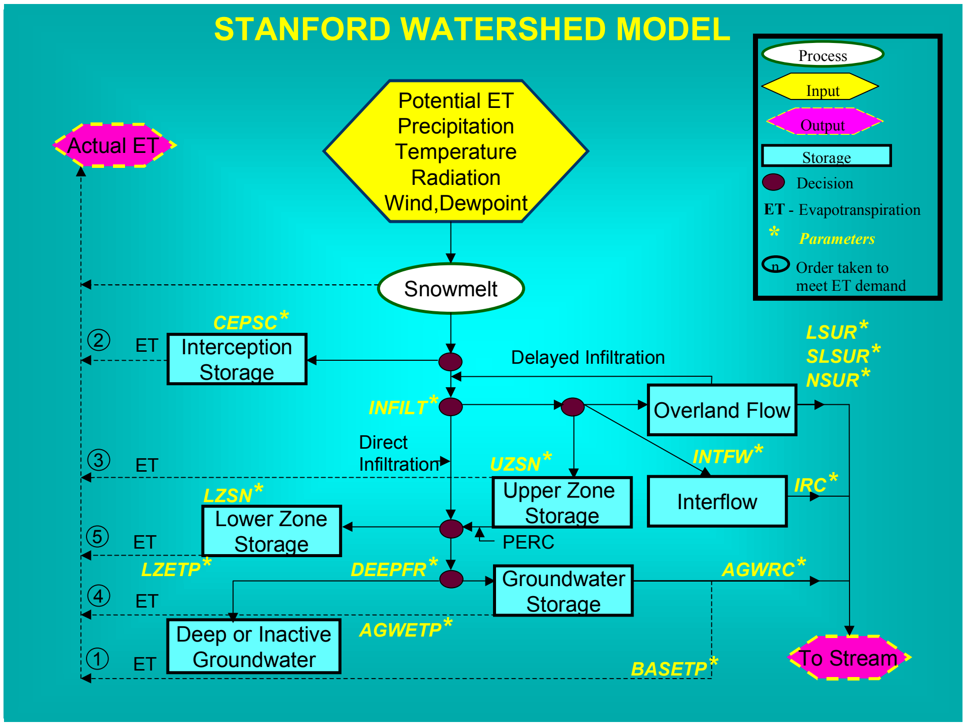


Figure 1. Flowchart for Stanford Waterhed Model IV.

By the early 1970’s Crawford and Linsley had founded Hydrocomp, and SWM was expanded and refined to create the Hydrocomp Simulation Program (HSP), which included nonpoint load and water quality simulation. The water quality code was based on work by Lombardo (1973). Shortly after Hydrocomp started, the firm undertook a project for King County, WA that successfully simulated a range of water quality constituents including plankton in the Lake Washington drainage; this pilot project demonstrated the efficacy of quantity/quality simulation programming running on large basins.

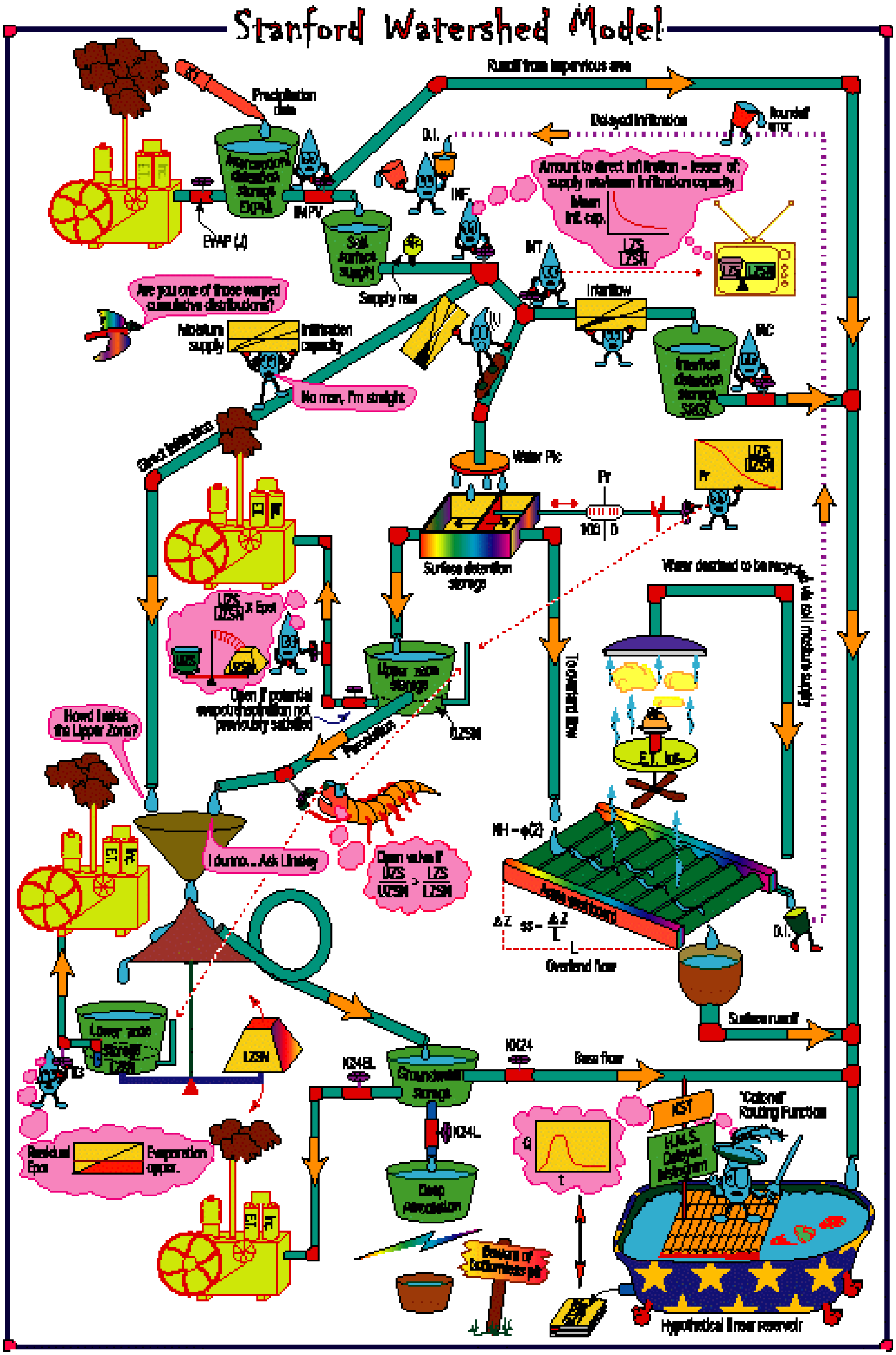


Figure 2. Flow diagram for the Stanford Watershed Model IV (original by Gorelick and Stonestrom in 1977; enhancements by Jones in 1997 and Loague in 2000).

2.2 Contributing EPA Pollutant Models

The 1970's and the early 1980's was a period of increasing recognition of pollution sources and the need for remediation and cleanup efforts. The U.S. EPA was created, the first Earth Day was held (April 1970), and a number of federal agencies began to sponsor the development of mathematical models to both characterize the pollutant loadings and water quality impacts, and evaluate alternative means of control. During this period the EPA, through the Athens-ERL, sponsored a number of model development and testing efforts, primarily for agricultural pollutants, that eventually provided an expanded set of process algorithms for HSPF, as described by Barnwell and Johanson (1981). The early work in this program incorporated two approaches, one using distributed parameter hydrology and the other a lumped parameter model. The distributed parameter model, called SCRAM (Adams and Kurisu, 1976) required two hours of IBM 360/145 CPU time to simulate a 4-month growing season, thus limiting its utility as a management tool.

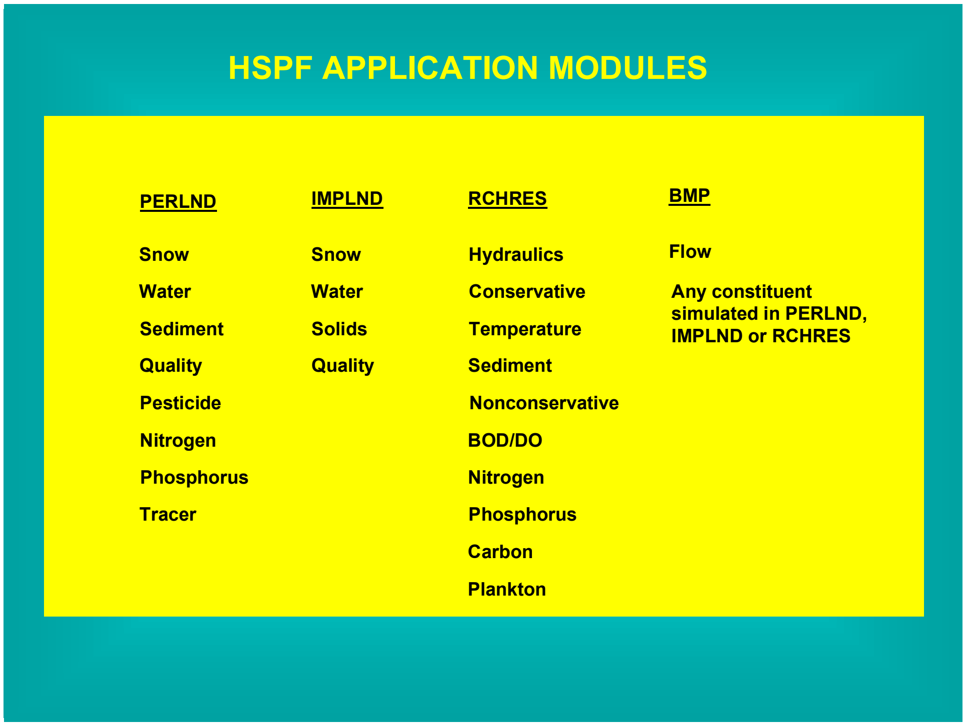
The lumped parameter tool, the Pesticide Transport and Runoff (PTR) model, was developed for EPA by Crawford and Donigian (1973). PTR "piggybacked" sediment erosion and applied pesticide onto the movement of water as predicted by the Hydrocomp Simulation Program. Overland sediment transport in PTR was based on work done by Negev (1967) at Stanford as an extension of the original SWM research. PTR incorporated semi-empirical process descriptions of pesticide transport and fate to simulate adsorption/desorption, volatilization and degradation mechanisms.

Modifications, testing, and further development of PTR produced the Agricultural Runoff Management (ARM) model (Donigian and Crawford, 1976a). ARM simulated runoff, snow accumulation and melt, sediment loss, pesticide-soil interactions, and soil nutrient transformations. ARM was further improved (Donigian et al., 1977) through refinement of algorithms related to soil moisture and temperature, pesticide degradation, nutrient transformations, and plant nutrient uptake, and tested on small (field-scale) watersheds in Michigan and Georgia. At this point, ARM was considered to be an operational tool and a user's manual (Donigian and Davis, 1978) was developed.

During the development of ARM, it was recognized that a simpler version of the model using algorithms compatible with current urban models such as SWMM (Metcalf and Eddy et al., 1971) and STORM (Hydrologic Engineering Center, 1976) was needed. This need was embodied in Section 208 of the Clean Water Act, which required comprehensive assessments of pollution sources in major metropolitan areas -- essentially a pre-cursor to the current TMDL effort by EPA. To meet this need, EPA sponsored Donigian and Crawford (1976b) to develop the Nonpoint Source (NPS) model. As in ARM, the hydrologic algorithms in NPS were based on the SWM and HSP. The simulation of nonpoint source pollutants was based on sediment as a pollutant indicator; “potency factors” were used to establish the relationship between sediment and associated pollutants, and multiple land use sources within a watershed could be represented.

2.3 HSPF Release 5.0 (1980)

In the late 1970's EPA recognized that the continuous simulation approach contained in the models highlighted in the previous section would be valuable in solving many complex water resource problems. Grant money from the agency to Hydrocomp resulted in the development of a highly flexible, non-proprietary FORTRAN program that contains the capabilities of the HSP, ARM and NPS models, plus many extensions. The late Robert Johanson had the task of pulling together all of these codes to create the Hydrological Simulation Program - FORTRAN, or HSPF. HSPF incorporated the field-scale ARM and NPS models into a watershed-scale analysis framework that included the capabilities needed to model nonpoint loadings from the land, in addition to fate and transport in one-dimensional stream channels. The basic watershed modeling approach embodied in SWM and HSP was chosen, a highly modularized code design and structure was developed, and all the individual models were re-designed and re-coded into FORTRAN to make the resulting package widely useable and available to potential users. As Figure 3 illustrates, the structure of HSPF features four major 'application modules' (PERLND for pervious land segments, IMPLND for impervious land segments, RCHRES for river reaches and well-mixed reservoirs, and BMP for simulating constituent removal efficiencies associated with implementing management practices).



HSPF APPLICATION MODULES

PERLND	IMPLND	RCHRES	BMP
Snow	Snow	Hydraulics	Flow
Water	Water	Conservative	Any constituent simulated in PERLND, IMPLND or RCHRES
Sediment	Solids	Temperature	
Quality	Quality	Sediment	
Pesticide		Nonconservative	
Nitrogen		BOD/DO	
Phosphorus		Nitrogen	
Tracer		Phosphorus	
		Carbon	
		Plankton	

Figure 3. HSPF Application Modules.

By combining these capabilities, HSPF became the only comprehensive model of watershed hydrology and water quality that allowed the integrated simulation of land and soil contaminant runoff processes with instream hydraulic and sediment-chemical interactions. HSPF was first released publicly in 1980 as Release No. 5 (Johanson et al., 1980) by the U.S. EPA Water Quality Modeling Center (now the Center for Exposure Assessment Modeling). Since its initial release, the model has maintained a reputation as perhaps the most useful watershed-scale hydrology/water quality model that is available within the public domain.

Throughout the 1980's, 1990's and into the new millennium, HSPF has undergone a series of code and algorithm enhancements producing a continuous succession of new releases of code, culminating in the recent release of Version No. 12 in 2001 (Bicknell et al., 2001). Throughout this period the continuity of HSPF was assured by careful attention to version control and model maintenance. Software maintenance of HSPF has been supported by the EPA Athens Laboratory in Georgia, and, since the late 1980's, cooperatively by the U.S. Geological Survey in Reston, Virginia. Since the initial release in 1980, almost all of the actual maintenance effort has been performed by two firms: Anderson-Nichols, Inc. and its successor, AQUA TERRA Consultants. These maintenance activities have included maintaining a list of software errors, correcting errors, implementing enhancements, adapting the code to new computer environments (hardware and operating system), testing, and providing new versions to EPA and USGS for distribution to users. At the same time a continual flow of academic contributions have assured that HSPF maintained a strong scientific basis.

The following sections provide a summary of what we believe are the milestones in HSPF enhancement over the period of greater than twenty years between the first release of HSPF and now. These milestones are viewed as a whole in Table 1.

Year	Version	Comments/Enhancements	Document
1980	**5**	**Initial public release**	**Johanson et al. (1980)**
	6	**Performance and portability enhancements**	
1981	**7**	**GQUAL, SEDTRN, MUTSIN, GENER, DURANL enhancements**	**Anderson-Nichols (unpublished, 1981)**
1984	**8**	**Special Actions enhancements**	**Johanson et al. (1984)**
		Initial PC version	**Donigian et al. (1984)**
1988	**9**	**WDM implementation PC version distributed**	**CEAM documentation (unpublished, 1988)**
1993	**10**	**Sediment-nutrient interactions Mass-Link/Schematic Acid-pH Module**	**HSPF Rel. 10 Manual (Bicknell et al., 1993)**
1997	**11**	**Enhanced special actions Water regulation/accounting Atmospheric deposition HSPF/DSS linkage (COE) Increased operations limit Forest Nitrogen Module**	**HSPF Rel. 11 Manual (Bicknell et al., 1997)**
2001	**12**	**Wetland & shallow water tables Land segment links Irrigation modeling capabilities Simplified snow simulation Box model of flow and sediment BMP and Report modules**	**HSPF Rel. 12 Manual (Bicknell et al., 2001)**

Table 1. Historical Progression of HSPF Releases.

2.4 HSPF Release 8.0 (1984)

Concurrent with the early development of HSPF, a second software package named the Chemical Migration and Risk Assessment (CMRA) methodology (Onishi et al., 1979) was developed under the joint sponsorship of Battelle Pacific Northwest Laboratories and EPA Athens-ERL. The CMRA methodology provided more detailed procedures for instream simulation of sediment and chemical (primarily toxics) transport and interactions than those available in HSPF Release 5.0. In addition, CMRA enabled the combined use of chemical frequency-duration data with toxicity data to assess the frequency of acute and chronic toxic conditions to aquatic organisms.

During 1979-1983, HSPF and CMRA were utilized by EPA to support the Iowa Field Evaluation Program (FEP); the purpose of the FEP was to demonstrate the agricultural best management practice (BMP) evaluation, selection and implementation process. Since both HSPF and CMRA included the ARM model functions and identical statistical capabilities, there was some duplication in the models. During the FEP, HSPF was enhanced to include two components (SERATRA and FRANCO) of CMRA. The SERATRA model enabled detailed instream sediment transport, contaminant decay mechanisms, and sediment/contaminant interactions. FRANCO enabled the assessment of acute and chronic toxicity conditions. With the addition of these new capabilities, HSPF provided a single comprehensive system to analyze water quality and toxic conditions for assessing the aquatic impact of candidate BMPs.

In 1984 HSPF Version 8.0 (Johanson et al., 1984) was released. In addition to incorporating the CMRA capabilities described above, the release was notable for being the first PC version of the model, and for significantly expanding the capabilities for what came to be known as "special actions." The special actions enabled in Release 8.0 allowed HSPF modelers to either re-set the value of a variable, or increment the variable by a specified value. This capability can be used to reflect the impact of natural or human interventions that are not represented by process algorithms, such as tillage operations, fertilizer and nutrient applications, frozen ground conditions, etc.

2.5 HSPF Release 10.0 (1993)

HSPF Version 10 (Bicknell et al., 1993) featured two noteworthy enhancements to process algorithms, and a significant improvement to the methods used to specify model configurations. By the late 1980's it became evident that the instream nutrient algorithms of HSPF had deficiencies that, under certain conditions, precluded effective modeling of nutrient loadings to endpoint receiving waters. The process representation limitation of greatest concern was the inability of HSPF to account for instream sediment-nutrient interactions such as adsorption/desorption, and advection and deposition/scour with sediment. To correct these model deficiencies, the EPA Chesapeake Bay program sponsored a model enhancement project in 1990-1991 that resulted in a much more robust representation of sediment-nutrient interactions.

An additional enhancement was sponsored by the USGS in response to the Survey's need to model acid mine drainage from Pennsylvania coal mines. A new generalized module was designed and implemented in HSPF for performing user-defined instream chemical computations. The module enables modeling of acid mine drainage and acid rain affected waters by considering the effects on pH of aluminum and carbonate equilibria; extended alkalinity; and the possible effects of iron complexation and competition with aluminum. The enhancements were based on earlier computer code developed by Gherini (1984).

In HSPF Release 10, two new blocks were added to the input file to facilitate the definition of the watershed network. The SCHEMATIC and MASS-LINK blocks allowed users to specify the basin structure and linkages in a more logical and consistent manner than was possible in previous versions of the model. The SCHEMATIC block contains the global specifications of the watershed structure; i.e., connections of land segments to stream reaches and reach-reach connections. The MASS-LINK block contains the specific time series or material quantities to be transferred from one watershed unit to another.

2.6 HSPF Release 11.0 (1997)

Needs for expanded modeling capabilities to address specific environmental and planning issues resulted in continued development and integration of new process algorithms for HSPF during the mid-1990's. Perhaps the most intensive application of HSPF during this period supported ongoing EPA efforts to establish a nutrient management plan for the Chesapeake Bay watershed. As the agency gained a better understanding of the nitrogen sources that play a significant role in the Chesapeake Bay, it became apparent that improved modeling capabilities were required to represent three critical sources: atmospheric deposition, agricultural fertilizers and forested lands. To accommodate modeling of atmospheric deposition, HSPF was enhanced to accept atmospheric deposition inputs (wet and dry deposition) to all water quality constituent state variables, both on land surfaces and in water bodies. These enhancements were also designed to facilitate linkage of the model with atmospheric transport models, such as EPA's Regional Acid Deposition Model (RADM) (Chang et al., 1987).

In Version 11.0 the plant uptake algorithms in HSPF were expanded to be a function of crop needs and expected yields, in addition to available soil nitrogen. This modification eliminated a hyper-sensitivity of simulation results to fertilizer and manure applications, and enabled more accurate representation of the plant uptake phenomena. The yield-based algorithms were added and tested on selected segments of the Chesapeake Bay Watershed model (Donigian et al., 1998a), and provided the template for extending the approach throughout the Chesapeake bay watershed area.

Because forests are a dominant fraction of watersheds in many parts of the Chesapeake Bay watershed, as well as watersheds throughout the country, EPA and USGS perceived a need to improve the representation of nitrogen cycling in forest systems and estimates of nitrogen loads to receiving waters from forested lands. Consequently, Oak Ridge National Laboratory was asked to review the available literature on forest nitrogen export with a specific focus on the capabilities needed within the Chesapeake Bay Watershed Model (Hunsaker et al., 1994). Upon completion of the review, AQUA TERRA (Bicknell et al, 1996) implemented the recommended algorithmic enhancements. These changes included expanding the single N compartment to allow both particulate and dissolved fractions of both labile and refractory organic N; providing both below- and above-ground plant N compartments; allowing the cycling of above-ground plant N to the soil through a litter compartment; allowing cycling of below-ground plant N to the soil organic N; and providing options to use saturation kinetics for immobilization and plant N uptake. The new algorithms were initially tested on selected small watersheds, and then larger model segments within the Chesapeake Bay drainage to provide the procedures for applying the detailed forest algorithms throughout the region (Donigian et al., 1998b).

In many river basins in the western U.S., the entire flow is allocated to various owners, such as municipal suppliers, farmers, ranchers, and industrial facilities, who can utilize their allocations at specific times of the year. In order to improve the ability to analyze such basins, the HSPF instream module was enhanced to keep track of the ownership of water within the reach network. This capability is implemented as a set of water "categories" that represent ownership. A user can assign the ownership of water inflows and outflows from each stream segment. The ownership of outflowing water can be defined in the form of specified priorities or percentages, or they can be proportional to the current mixture in the stream segment. The initial application of this feature was the Carson-Truckee River system in California and Nevada, where the U.S. Geological Survey has developed allocation and water quality models of the basins.

Increasingly complex modeling requirements for the USGS Carson-Truckee River project and the EPA Chesapeake Bay Watershed Model project led to significant enhancements to HSPF SPECIAL ACTIONS in Version 11.0. The Carson-Truckee project required, and funded, expanded capabilities to represent the operational rules of complex diversions, and an equally complex system of water allocations. In the late 1990's, Chesapeake Bay Watershed Model applications were hindered by the need to individually specify thousands of SPECIAL ACTIONS in order to represent each application of a chemical to a land segment in a very large basin containing large numbers of land segments with different crops, soil types, and meteorologic regions. In Version 11.0 several enhancements were added to the program to significantly reduce the number of SPECIAL ACTIONS instructions (Jobes et al., 1999) required in complex basins. The enhanced capabilities that were developed to support these two projects were

- Repeat - Each SPECIAL ACTION can be "repeated" at regular time intervals. This facilitates application of chemicals several times per year and each year of the simulation.
- Distribution - A SPECIAL ACTION can be "distributed" over time (equal time increments) with a user-defined pattern that is based on fractions of the total amount. This is useful in representing the activities of multiple farmers applying chemicals on different days when all of the farms are represented by a single PERLND.
- User-defined - Several SPECIAL ACTIONS can be combined as a single "user-defined" action which can be invoked multiple times for different PERLNDS and at different times. This reduces the number of actions required to represent incorporation of chemicals in two or more soil layers as a result of plowing, and application of multiple chemical species, e.g. commercial fertilizers and manure.
- Conditional - In addition to the enhancements designed to reduce the user-input requirements of SPECIAL ACTIONS, conditional SPECIAL ACTIONS are possible in which an action can be dependent on the value of some other variable in the model. This can be useful for deferring agricultural operations that are dependent on rainfall or soil moisture, and for reservoir operations that are dependent on river flow or reservoir volume.

2.7 HSPF Release 12.0 (2001)

During the most recent years, a variety of enhancements to the HSPF process algorithms have been made under the sponsorship of numerous agencies. These model development efforts were performed for various clients by AQUA TERRA Consultants in collaboration with various private groups. Most enhancements are available in the 2001 release of HSPF Version 12.0 (Bicknell et al., 2001).

Refinements that allow better representation of wetlands hydrology have been made to the land surface hydrology simulation section of HSPF (i.e., PWATER) under the sponsorship of the South Florida Water Management District (Hydrocomp, Inc. and

AQUA TERRA Consultants, 1996). The wetland module tracks dynamic variation in groundwater level; models interaction between groundwater storage, soil storages, and infiltration/runoff processes; accommodates ponded conditions on the land surface; allows evaporation from ponded surface storage and surface runoff; and allows additional options for surface runoff when it is not gravity driven. The refinements were made with minimal changes to existing routines, and they allow for smooth transition between ‘normal’ hydrologic conditions and ‘water table influence’ effects.

The ability to link water quality outputs from a pervious or impervious land segment as inputs to another pervious or impervious land segment was implemented within HSPF under the sponsorship of the Minnesota Pollution Control Authority. This capability enables effective modeling of buffer strips, riparian zones, grass waterways and other control measures.

Refinements to HSPF included in Version 12 also allow the representation of irrigation waters applied to pervious land segments (AQUA TERRA Consultants, 1998). Applications may be defined by the model user either in terms of a defined schedule, or they can be triggered by crop-specific moisture needs. Irrigation water may be provided by extraction from a lake or channel segment, extraction from the groundwater associated with a land segment, or from a source outside of the modeled system.

Version 12 includes an option for simplified snow simulation (Jobes and Donigian, 1997). The new option allows use of a ‘temperature index/degree approach.’ Snowmelt is computed by applying a user-specified rate per degree to the difference between a reference temperature (often 32 degrees F) and ambient air temperature. As compared to the more detailed energy balance computations used by the alternate snowmelt method contained in HSPF, this method greatly reduces the need for meteorological time series data. (Only precipitation and air temperature data are required.)

A one-dimensional box model of flow and sediment transport has been developed under the sponsorship of the EPA NERL Ecosystem Research Branch (Hayter et al., 2001). As compared to the flow/sediment modeling capabilities contained in the instream module of HSPF, the new model offers a broadened scope of process representation including consideration of downstream boundary conditions, longitudinal dispersion, bi-directional flow, buoyancy effects, multiple bed layers of mixed sediment classes, and variable channel cross-sectional areas. The box model was developed and tested as a stand-alone model, and is undergoing further evaluation for possible integration into HSPF.

Two new modules (BMP module, REPORT module) have been developed for HSPF under the sponsorship of CH2M Hill to support TMDL activities in the state of Georgia. The purpose of the BMP (i.e., ‘best management practice’) module is to allow a broader level of capabilities and support for users to represent the effects of pollution control measures such as detention ponds, swales, filter strips, and stream buffers. The BMP module includes a built-in default database of ‘% reduction’ values, with references, for various BMP alternatives. Users have the option of using or modifying these default values. Input of constant or time-variable removal efficiencies is enabled, and the module keeps track of the amount of pollutant that is being removed by the control measure. Additional BMP characterization methods are under consideration.

A REPORT module for HSPF has been developed that enables users to customize and view model output in the formats that are most useful for their specific modeling analyses. Examples of the types of output that will be enabled include the following:

- Annual and average annual values for the components of the water budget for individual land segments/types
- Annual pollutant information (per acre load, total load, % load) for individual land segments or land uses
- Total annual loads from a sub-watershed for all water quality constituents

The BMP and REPORT modules have been completed, tested and were integrated into HSPF Version 12.

2.8 HSPF Linkage to Other Models

During the last decade, the utility of HSPF had been further enhanced by the development and application of methods for linking the model to other models that have their strengths in environmental media other than the land surface and immediate sub-surface. The major linkage efforts have usually involved using HSPF to provide freshwater and land contributions of flow and pollutants to complex estuarine and riverine systems, and groundwater.

Numerous watershed assessments have included the need to determine both the land and river loads to an estuary, large waterbody, or complex riverine system that can not be accurately represented by HSPF. The Chesapeake Bay effort is a prime example of HSPF providing watershed loads to the tidal tributaries and Chesapeake Bay proper, that are then modeled with a 3-D hydrodynamic and water quality model (Linker and Thomann, 1996). Similar linkages have been developed for other models and other sites, including ongoing studies in the Pacific Northwest and PCB studies on a highly meandering river with contaminated bed sediments in western Massachusetts (Beach et al., 2000). Linkage procedures have been refined to account for spatial and temporal connections between models, unit conversions, and correspondence of differing water quality state variables between models.

In regions with shallow water tables, interactions between surface water and groundwater are often critical in accurately representing the watershed behavior and response to both natural events (i.e. storms) and intervention by man (e.g., well pumping). These interactions can be extremely complex, dynamic, and difficult to accurately model, especially when water tables are rising and falling above and below the land surface. In Florida, where these conditions are common, HSPF has been linked to the USGS groundwater model MODFLOW (McDonald and Harbaugh, 1984), to assess the impacts of pumping (SDI, 1997 and 1999) and mining procedures (Ross et al., 1997) on groundwater levels and wetlands. Although further refinements are ongoing, the linked modeling systems are being used for both operational and planning purposes with recognition of the continuing need for improvements in linkage and process understanding.

3.0 Other Modeling System Components

From the beginnings of watershed model development, the core model(s) of scientific and engineering process algorithms have been only one of the components needed to allow practical use of digital computer simulation. The complexity of the systems that are modeled and the requirement to use and interpret a vast amount of data, particularly time series data, have kept the needs for data management and user interaction with both models and data at the forefront. Early recognition of the need for data management and analysis tools to complement hydrologic models is evidenced in Franz and Linsley's (1971) technical report describing the development of time series data plotting software. Concurrent with the enhancement of the Stanford Watershed Model, as it grew to become the Hydrocomp Simulation Program, was the development at Hydrocomp of HSP Library, a data management tool, and HSP Utility, an early collection of pre- and post-processing routines. Unfortunately, in the early years of hydrologic modeling, methods and technology had not yet been developed that would allow expedient user interaction. Early modelers first bore the burden of wrestling with computer card decks, and later of developing batch input sequences on a line-by-line basis. Many years would pass before model set-up and use became "interactive," beginning as character-based packages and evolving to today's graphical user interfaces (GUIs).

At the conclusion of the 1970's, Dr. Alan Lumb (recently retired) left Hydrocomp, became an employee of the United States Geological Survey, and continued to pursue hydrologic modeling and support services within the USGS. Since 1981, under Dr. Lumb's influence, the U.S. Geological Survey has been supporting the development of software tools to facilitate watershed modeling by providing interactive capabilities for model input development, data storage and data analysis, and model output analysis including hydrologic calibration assistance. Most noteworthy of these tools, which have been developed by collaboration between Alan Lumb and Jack Kittle of AQUA TERRA, are the ANNIE/WDM, HSPEXP, and GenScn products; each has greatly advanced and facilitated watershed model application, not only for HSPF, but also for many other USGS and EPA models.

3.1 ANNIE/WDM

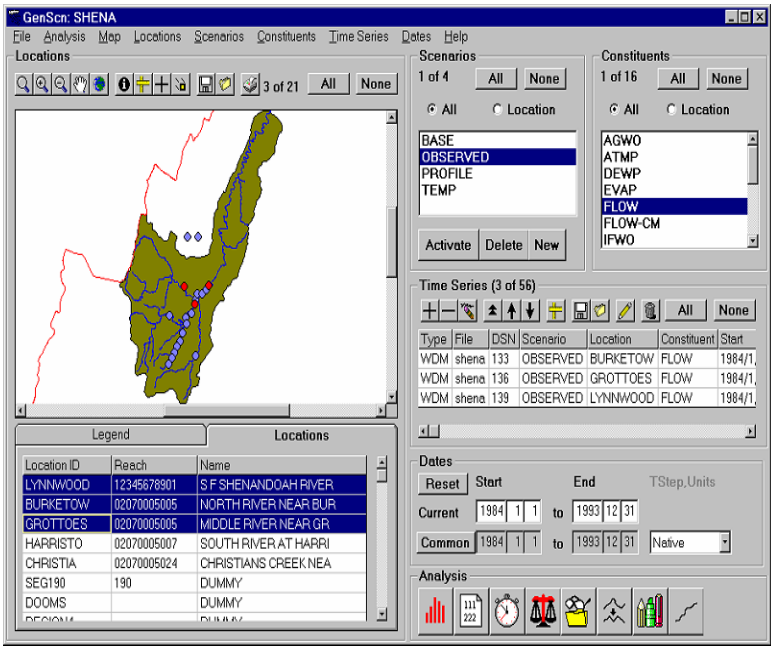
ANNIE (Lumb and Kittle, 1984) is noteworthy both as one of the earliest interactive computer programs written to support a hydrologic model, and as one of the few successful attempts by a software developer to name an enduring software product after his wife. ANNIE was created to help users interactively store, retrieve, list, plot, check, and update spatial, parametric, and time-series data for hydrologic models and model analyses. A binary, direct-access file was, and is, used to store data in a logical, well-defined structure and is called the Watershed Data Management (WDM) file. HSPF and a number of other hydrologic and water quality models and analysis tools developed by the USGS currently use either ANNIE or the WDM file, or both. The WDM file provides the user with a common data base for many applications, thus eliminating the need to reformat data from one application to another.

3.2 HSPEXP

In the early 1990's a stand-alone version of the HSPF land surface hydrologic computations was developed as an expert system for calibrating watershed models for drainage basins. The resulting product, called HSPEXP (Lumb and Kittle, 1993), represents an effort to make the knowledge of experienced surface hydrology modelers available to general model users. The 'knowledge' component of HSPEXP consists of a set of hierarchical rules designed to guide the calibration of the model through a systematic evaluation of the model parameters. The estimation procedure consists of the statistical representation of the observed hydrograph in terms of the system parameters that drive the precipitation-runoff process. The system has been applied successfully to numerous watersheds throughout the United States.

3.3 GenScn

GenScn (Kittle et al., 1998) came as a response to the need to make HSPF input sequences easier to build and HSPF output easier to analyze. The requirements for the software were refined based on experiences with ANNIE and the HSPEXP. The scenario generator provides advanced, GUI-based interaction with the HSPF input sequence and integrated analysis capabilities. The program provides an interactive framework for analyses performed using HSPF. The results of different scenarios can be easily compared and analyzed because the model and analysis tools are linked in one package and use a common data base. A map (Figure 4) is available to specify locations where results are to be analyzed. Analysis tools included in the software consist of graphs, tables, statistical measures of comparison, analysis of the duration of events exceeding critical levels, and analysis of frequency of events. An animation option provides a means of viewing time-series data on a map over a specified time span, allowing the user to see where, when, and how long critical conditions exist.



Type	File	DSN	Scenario	Location	Constituent	Start
WDM	shena	133	OBSERVED	BURKETOW	FLOW	1984/1,
WDM	shena	136	OBSERVED	GROTTOES	FLOW	1984/1,
WDM	shena	139	OBSERVED	LYNNWOOD	FLOW	1984/1,

Location ID	Reach	Name
LYNNWOOD	12345678901	S F SHENANDOAH RIVER
BURKETOW	02070005005	NORTH RIVER NEAR BUR
GROTTOES	02070005005	MIDDLE RIVER NEAR GR
HARRISTO	02070005007	SOUTH RIVER AT HARRI
CHRISTIA	02070005024	CHRISTIANS CREEK NEA
SEG190	190	DUMMY
DOOMS		DUMMY

	Start		End	TStep,Units
Current	1984 1 1	to	1993 12 31	
Common	1984 1 1	to	1993 12 31	Native

Figure 4. Opening GenScn Screen Showing Interface to an HSPF Application.

3.4 BASINS

In 1994 Tetra Tech began efforts on the development of EPA's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) modeling system (Lahlou et al., 1998). The BASINS system combines environmental databases, models, assessment tools, pre- and post-processing utilities, and report generating software to provide the range of tools needed for performing watershed and water quality analyses. HSPF was incorporated into BASINS as the core watershed model. A graphical representation of the current BASINS components (Version 3.0) and their operating platform is provided in Figure 5.

The BASINS physiographic data, monitoring data, and associated assessment tools are integrated in a customized geographic information system (GIS) environment. The GIS used is ArcView 3.2 developed by Environmental Systems Research Institute, Inc. The simulation models are integrated into this GIS environment through a dynamic link in which the data required to build the input files are generated in the ArcView environment and then passed directly to the models. The models themselves run in either a Windows or a DOS environment. The results of the simulation models can also be displayed visually and can be used to perform further analysis and interpretation.

Since 1998 BASINS has benefited from considerable efforts to integrate and enhance the strongest features of HSPF and the USGS software products (including GenScn) within a common framework. Today HSPF/BASINS serves as a focal point for cooperation and integration of watershed modeling and model support activities between EPA and the USGS. At the same time HSPF has been integrated into the U.S. Army Corps of Engineer's Watershed Modeling System (WMS), providing a further opportunity for the use of common tools and methodologies by federal agencies, as well as other modeling professionals.

The BASINS development effort has resulted in additional stand-alone products that facilitate the use of HSPF. Three such products (HSPFParm, WDMUtil, WinHSPF) are described below.

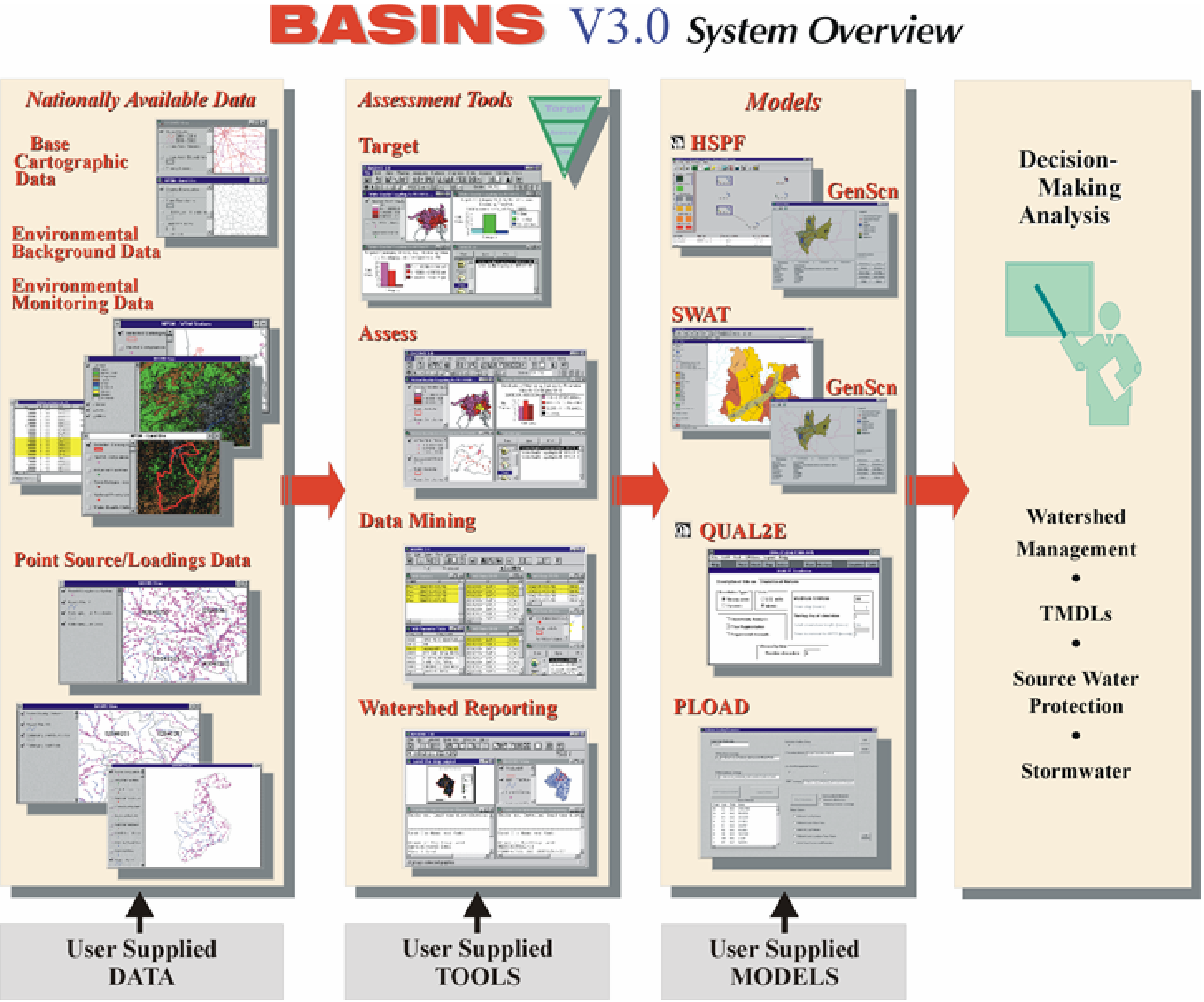


Figure 5. BASINS 3.0 Modeling System.

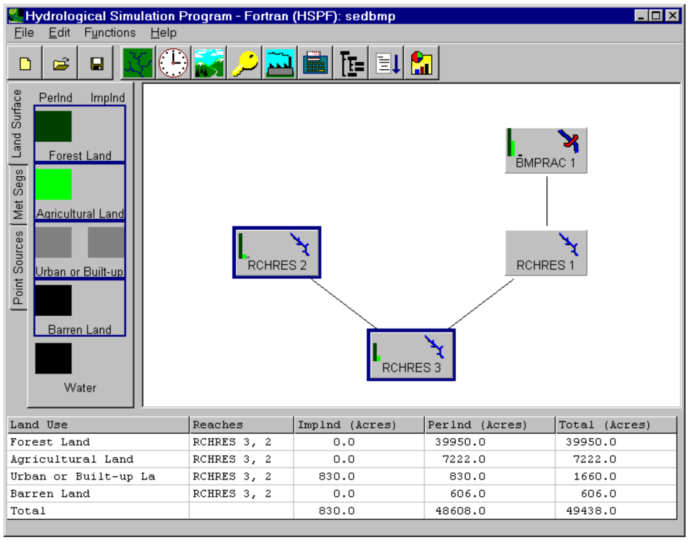
3.5 HSPFParm

A stand-alone, interactive database of HSPF model parameters, named HSPFParm (Donigian et al., 1999), has been developed under the sponsorship of the EPA Office of Science and Technology. The database includes sites at all scales, throughout North America, where HSPF water quality simulation has been performed and calibrated parameters are available as of September 1998. In addition to the actual model parameter values, HSPFParm includes seventeen types of coarse characterization data (e.g., drainage area, HUC code, land use types, channel types, chemical sources) for each site and modeling scenario. The purpose of HSPFParm is to provide modelers with the best starting point for developing appropriate parameter values for new applications. HSPFParm is currently linked to BASINS 3.0 so that model users can access calibrated parameter values, extract them form the database, and directly insert the values into their own model input as starting values for calibration.

3.6 WinHSPF

AQUA TERRA recently developed WinHSPF (Duda et al., 2001), a graphical user interface to the full capabilities of HSPF and the data provided with BASINS. WinHSPF enhances the usability of HSPF by providing assistance with initial HSPF input sequence setup, simulation management, and parameter modification for calibration and evaluation of watershed management strategies. It includes tools for interacting with the HSPF input sequence at various levels of sophistication.

The main window of WinHSPF (Figure 6) contains a schematic diagram of the watershed. Displayed within this watershed schematic are graphical representations of the amount of each land use contributing to each reach. Point sources and meteorological segments are also visible through this schematic. A direct manipulation capability allows the user to select any HSPF operation and edit the tables associated with that operation. HSPF operating logic is included in the interface, so that when a user turns on a new operating module, graphic displays indicate prerequisite tables and time series.



Land Use	Reaches	Implnd (Acres)	Perlnd (Acres)	Total (Acres)
Forest Land	RCHRES 3, 2	0.0	39950.0	39950.0
Agricultural Land	RCHRES 3, 2	0.0	7222.0	7222.0
Urban or Built-up La	RCHRES 3, 2	830.0	830.0	1660.0
Barren Land	RCHRES 3, 2	0.0	606.0	606.0
Total		830.0	48608.0	49438.0

Figure 6. WinHSPF Main Screen.

Other interface tools include a reach editor, a simulation time and meteorological data specifier, a land user editor, a HSPF option editor, a pollutant selector, a point source editor, an input data editor, and an output manager. The WinHSPF output manager and a direct linkage to GenScn facilitates the creation of output time series for multiple simulation scenarios, which can then be analyzed for developing watershed management strategies.

3.7 WDMUtil

Another recent software product developed to support the BASINS effort is the WDM Utility (WDMUtil) program (Hummel et al., 2001). WDMUtil was created to provide a graphical user interface to WDM files. The goal of WDMUtil was to provide an interface to build new meteorological data sets and store them on a WDM file. To facilitate data manipulation activities, WDMUtil is directly accessible from BASINS 3.0.

An essential feature of WDMUtil is the capability to import timeseries data from files external to WDM. Once the data have been imported, they may be stored on the WDM file and/or further analyzed and manipulated. WDMUtil contains several tools for analyzing timeseries data. One such tool provides the ability to locate and summarize missing, accumulated, or faulty data values. The list tool allows listing of timeseries values at any constant time step. The graph tool contains a suite of timeseries plots useful in visualizing data. WDMUtil also contains several tools for manipulating timeseries data. A suite of meteorological algorithms allows for computation of new constituents based on existing related constituents (e.g. computing solar radiation based on cloud cover). Similarly, a suite of meteorological algorithms allows for disaggregating a daily time series to an hourly (e.g. generating hourly temperature values based on daily min/max values). Another suite of mathematical computation and transformations is also available to create new time series.

4.0 The Future

The current resurgence of government concern for nonpoint source issues and problems and the focus on watershed scale assessment and management, as catalyzed by various sections and amendments to the Clean Water Act in the United States, has renewed interest in nonpoint source and comprehensive watershed modeling. The comprehensive nature of HSPF, and its flexibility in allowing consideration of the combined impacts of both point and nonpoint source pollutants at the watershed scale, has led to unprecedented interest in model applications. In addition, the model's use within a multi-media framework, such as that used in the Chesapeake Bay Program, and linkage with numerous estuarine and multi-dimensional hydrodynamic/water quality models, has further advanced it's utility for sophisticated environmental analyses. To support this increased interest and usage, there will be a need for HSPF and supporting software to continue to grow. Improvements in process algorithms, enhanced and broadened capabilities to interact with a wide variety of environmental data, and more powerful user interaction will all be required. In this section, possible enhancements to process algorithms and computational techniques are noted, first in general terms. Then specific capabilities of particular interest to the authors are elaborated.

4.1 Important Environmental State Variables and Processes

In order to provide the basis for multi-stressor analysis of whole-ecosystem effects, many chemical and biological state variables and processes must be represented. While the majority of these state variables are already considered in the model, HSPF might be enhanced to include the following additional state variables:

- Selected additional biological variables (herbivorous fish, predatory fish))
- Selected habitat variables (% pools and riffles, streambank vegetation and shading, substrate character, turbidity)

- Selected ecosystem variables (elemental dynamics, energy dynamics, trophic dynamics, biodiversity, critical species (presence/abundance), genetic diversity, dispersal and migration, natural disturbance, ecosystem development)

4.2 Man-made Effects on Environmental State Variables and Processes

In addition to representing natural processes, modeling systems such as HSPF must provide process algorithms that represent the effects of man-induced sources or processes on environmental state variables. Models must include algorithms that can be used to represent any environmental disturbance that could influence the behavior of the natural watershed system. Examples of such phenomena include nutrient and pesticide application, tillage practices, crop harvest and residue practices, tile drainage, livestock grazing, feedlot runoff, highway drainage, urban development, stormwater detention structures, stream channelization, combined sewers, construction practices, mine drainage, silvicultural practices, municipal and industrial discharges, etc.

Many of these effects can be represented by adjusting values for parameters contained in existing HSPF algorithms; others may require development of enhanced algorithms. We envision that considerable work will be done to develop additional sets of HSPF parameter value changes (i.e., model scenarios) that reflect our best understanding of the physical/chemical changes resulting from a particular modification or activity. This may be the most critical area of model development activity as it directly affects our ability to use models like HSPF for environmental management and decision-making.

4.3 Process Algorithms that Utilize Available Data

HSPF was developed prior to the proliferation of a new generation of data and data generation techniques that offer refined spatial detail for a number of parameters critical to watershed modeling. In some cases these new data are best used to support existing process algorithms that are solved for a higher resolution grid. However, the potential also exists to replace or enhance certain process algorithms to improve the simulation of natural processes by taking advantage of new data. For example, satellite data, GIS and digital elevation models (DEMs) have made it possible to compute the *aspect* (i.e., the direction toward which a slope faces) for watersheds or watershed segments at a high level of detail. The availability of techniques to reliably compute aspect invites the incorporation of improved process algorithms for snowmelt, soil temperature, and water temperature in areas of significant topographical relief.

The two technologies that offer the greatest body of new data that could be used to refine process algorithms are satellite remote sensing data and the transformation of remote sensing data, by use of GIS and related capabilities, to derive other useful data types.

The remote sensing data available from current and future satellites offer an opportunity to develop new process algorithms that could offer improved representation of precipitation, surface runoff, soil moisture, groundwater, and water quality variables including thermal pollution, erosion, sediment load, and trophic state of receiving waters. An immediate need of watershed-scale models are algorithms using radar imaging data to represent thunderstorms.

4.4 Future Modeling Research Areas

Every modeler has his/her own views and opinions as to the most important areas of future modeling research. These are often the result of modeling applications and experiences where obvious deficiencies have been identified, and no satisfying resolution has been developed. Below we discuss a few of the areas we feel deserve attention in future model research and development, borne from our experiences with HSPF and other models.

Wetlands - Modeling of wetlands is an issue that arises in many watershed modeling studies, to varying degrees, and not only in the humid, coastal plain areas of the southeastern U.S. The beneficial effects of wetlands on flood retention, sediment filtration, and nutrient and toxics processing are well known, but not adequately understood. HSPF has been used to approximate the impacts of wetlands, and various code modifications have been proposed; however, these approaches have been primarily 'stop-gap' measures due to lack of resources and alternative models. Coordinated data collection and modeling research efforts (i.e. algorithm development) are needed to improve our ability to represent the complex water quality impacts of wetlands on the watershed system.

Fish - Fish share all zooplankton processes including growth, respiration, death and predation; additional important processes for fish include exposure to environmental stresses such as high temperatures, low dissolved oxygen, toxic chemicals, and sedimentation. Models of various fish species exist, but few are appropriate for inclusion within a comprehensive watershed modeling framework.

Habitat Suitability - As a group, habitat state variables (e.g., velocity, channel gradient, flow, depth, % pools and riffles, streambank vegetation and shading, substrate character, turbidity, salinity, pH, temperature, dissolved oxygen) characterize the physical or chemical setting in which biotic communities live. The physical state variables are tied to considerations of topographical relief, runoff, erosion, sedimentation, channel characteristics and thermal inputs. To a large extent, the habitat state variables that characterize the chemical setting need to be modeled irrespective of whether modeling goals include habitat analysis. A watershed modeling system, like HSPF, is ideally suited to include assessment of habitat variables.

Ecosystem Modeling - The goal of ecological modeling is to determine self-sustainability. To do this, modeling may focus on system elements or components (i.e., species), system structure/organization, system function (based on physical, chemical, and/or biological principles), system dynamics (material and energy transport), or the integration of one or more of these system characteristics, habitat features, and biotic communities. Relative to the other categories described above, habitat and ecological modeling are in their infancies; consequently, it is not possible to identify the important processes in a rigid manner. However, the need exists to integrate these areas into the watershed modeling arena to allow consideration of the full extent of human impacts on the watershed system and its component ecosystems.

5.0 Closure

The 40-year evolution of the SWM to its current embodiment as HSPF Version 12 within the EPA BASINS system is an prime example of government agencies, universities and private organizations pursuing cooperative efforts, both research and application, to meet a public need for advanced tools for water resource systems analysis and management. From the initial funding of the SWM development under NSF grants, to the privatization and commercialization of HSP by Hydrocomp, to the EPA research grants that produced HSPF and the continuing support of both the USGS and EPA, the guiding philosophy has been to provide a public domain, operational tool for comprehensive state-of-the-art watershed planning and assessment. With recent advances in user-interaction, GIS and database technology, as reflected in the HSPF/BASINS system, the HSPF model user population is rapidly expanding to number in the hundreds, and possibly thousands in the coming years, as public agencies wrestle with the mandate and requirements of the TMDL program. This explosion in the user population is a double–edged sword; it will likely bring additional resources to bear for continuing refinement and advancement of the HSPF code and process algorithms, along with the demands to make it easier to use. The challenge that faces us will be to match the level of science in the algorithm refinements, with an equal commitment to user support, user interaction, and training to ensure that appropriate and proper application procedures are followed for comprehensive watershed assessment.

References

Adams, R.T. and F.M. Kurisu. 1976. Simulation of Pesticide Movement on Small Agricultural Watersheds. EPA-600/3-76-066. U.S. EPA Environmental Research Laboratory, Athens, GA

Anderson, E.A. and N.H. Crawford. 1964. The Synthesis of Continuous Snowmelt Runoff Hydrographs on a Digital Computer. Technical Report No. 36, Department of Civil Engineering, Stanford University, Stanford, CA.

AQUA TERRA Consultants. 1998. Addition of Irrigation Module to the HSPF Model. Prepared for the South Florida Water Management District, West Palm Beach, FL.

Barnwell, T.O. and R. Johanson. 1981. HSPF: A Comprehensive Package for Simulation of Watershed Hydrology and Water Quality. In: Nonpoint Pollution Control: Tools and Techniques for the Future. Interstate Commission on the Potomac River Basin, Rockville, MD.

Beach, R.B., P. M. Craig, R. DiNitto, A.S. Donigian, G. Lawrence, R.A. McGrath, R.A. Park, A. Stoddard, W.D. Tate, and C.M. Wallen. 2000. Modeling Framework Design-Modeling Study of PCB Contamination in the Housatonic River. DCN:GE-100500-AADX Prepared by R. F Weston, Inc, for the U.S. Army Corps of Engineers, New England District, Concord MA, (USACE Contract No. DACW33-00-D-0006) and U.S. EPA, Region I, Boston, MA (EPA Contract No. 68-C-98-010 with AQUA TERRA Consultants)

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, Jr., A.S. Donigian, Jr. and R.C. Johanson. 1993. Hydrological Simulation Program - FORTRAN. User's Manual for Release 10. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, GA.

Bicknell, B.R., A.S. Donigian, Jr., T.H. Jobes, and R.V. Chinnaswamy. 1996. Modeling Nitrogen Cycling and Export in Forested Watersheds Using HSPF. Prepared for U.S. EPA Office of Research and Development, Athens, GA and U.S. Geological Survey, Office of Surface Water, Reston, VA.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle Jr., A.S. Donigian, Jr. and R.C. Johanson. 1997. Hydrological Simulation Program -- FORTRAN, User's Manual for Version 11.

EPA/600/R-97/080. U.S. EPA, National Exposure Research Laboratory, Athens, GA.

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 Release 12. U.S. EPA National Exposure Research Laboratory, Athens, GA, in cooperation with U.S. Geological Survey, Water Resources Division, Reston, VA.

Chang, J.S., R.A. Brost, I.S.A Isaken, S. Madronich, P. Middleton, W.R. Stockwell, and C.J. Walek. 1987. A Three-Dimensional Eulerian Acid Deposition Model: Physical Concepts and Formulation. J. Geophysical Research, 92(14):681-700.

Crawford, N.H. 1962. The Synthesis of Continuous Streamflow on a Digital Computer. Ph. D. Dissertation, Stanford University.

Crawford, N.H. and R.K. Linsley. 1966. Digital Simulation on Hydrology: Stanford Watershed Model IV. Stanford University Technical Report No. 39, Stanford University, Palo Alto, CA.

Crawford, N.H. and A.S. Donigian, Jr. 1973. Pesticide Transport and Runoff Model for Agricultural Lands, Office of Research and Development, U.S. Environmental Protection Agency, EPA-660/2-74-013.

Donigian, A.S. Jr. and N.H. Crawford. 1976a. Modeling Pesticides and Nutrients on Agricultural Lands, Office of Research and Development, U.S. Environmental Protection Agency, EPA-600/3-76-043.

Donigian, A.S. Jr. and N.H. Crawford. 1976b. Modeling Nonpoint Pollution from the Land Surface, Office of Research and Development, U.S. Environmental Protection Agency, EPA-600/3-76-083.

Donigian, A.S. Jr., D.C. Beyerlein, H.H. Davis, Jr. and N.H. Crawford. 1977. Agricultural Runoff Management (ARM) Model - Version II: Testing and Refinement, U.S. Environmental Protection Agency, EPA-600/3-77-098.

Donigian, A.S. Jr. and H.H. Davis, Jr. 1978. User's Manual for Agricultural Runoff Management (ARM) Model, U.S. Environmental Protection Agency, EPA- 600/3-78-080.

Donigian, A.S. Jr., J.C. Imhoff, B.R. Bicknell and J.L. Kittle. 1984. Application Guide for Hydrological Simulation Program - Fortran (HSPF), prepared for U.S. EPA, EPA-600/3-84-065, Environmental Research Laboratory, Athens, GA.

Donigian, A.S. Jr., B.R. Bicknell, R.V. Chinnaswamy and P.N. Deliman. 1998a. Refinement of a Comprehensive Watershed Water Quality Model with Application to the Chesapeake Bay Watershed. Technical Report EL-98-6. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS. 244p.

Donigian, A.S. Jr., R.V. Chinnaswamy and P.N. Deliman. 1998b. Use of Nutrient Balances in Comprehensive Watershed Water Quality Modeling of Chesapeake Bay. Technical Report EL-98-5. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS. 118p.

Donigian, A.S. Jr., J.C. Imhoff and J.L. Kittle Jr. 1999. HSPFParm: An Interactive Database of HSPF Model Parameters. EPA-823-R-99-004. U.S. EPA Office of Water, Washington DC.

Duda, P.B., J.L. Kittle, Jr., M.H. Gray, P.R. Hummel and R.A. Dusenbury. 2001. WinHSPF - An Interactive Windows Interface to HSPF: User's Manual. U.S. EPA Office of Water, Washington DC.

Franz, D.D. and R.K. Linsley. 1971. An Interactive Time Series Plotting System for Classroom Instruction in Hydrology. Technical Report 143, Department of Civil Engineering, Stanford University, Stanford, CA.

Gherini, S.A., C.W. Chen, L. Mok, R.A. Goldstein, R.J.M. Hudson and G.F. Davis. 1984. "The ILWAS Model: Formulation and Application. In: The Integrated Lake-Watershed Acidification Study. Chapter 4: Summary of Major Results. Prepared by Tetra Tech, Inc. for the Electric Power Research Institute, Palo Alto, CA.

Hayter, E.J., J.M. Hamrick, B.R. Bicknell, M.H. Gray, and C.N. Smith. 2001. One-Dimensional Hydrodynamic/Sediment Transport Model for Stream Networks. Technical Report in Support of APM 125, Complete Total Maximum Daily Load (TMDL) Modeling Application and Sampling Procedures for Sediments in Streams, U.S. EPA Office of Research and Development, Athens, GA

Huff, D.D. 1967. Simulation of Hydrologic Transport of Radioactive Aerosols. Ph.D. Thesis. Department of Civil Engineering, Stanford University, Stanford, CA.

Hummel, P.R., J.L. Kittle, Jr. and M.H. Gray. 2001. WDMUtil - A Tool for Managing Watershed Modeling Time-Series Data: User's Manual. U.S. EPA Office of Water, Washington DC.

Hunsaker, C.T., C.T. Garten and P.J. Mulholland. 1994. Nitrogen Outputs from Forested Watersheds in the Chesapeake Bay Drainage Basin. Draft. ESD Publication No. 4275. Environmental Sciences Division, Oak Ridge National Laboratories, Oak Ridge, TN.

Hydrocomp, Inc. and AQUA TERRA Consultants. 1996. Modifications to HSPF for High Water Table and Wetlands Conditions in South Florida. Prepared for the South Florida Water Management District, West Palm Beach, FL.

Hydrologic Engineering Center. 1976. Storage, Treatment, Overflow, Runoff Model (STORM), Computer Program 723-58-L7520. Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, CA.

Jobes, T.H. and A.S. Donigian Jr. 1997. Temperature Index Method for Modeling Snow Accumulation and Melt in the U.S. EPA HSPF Model. U.S. EPA Office of Water, Office of Science and Technology, Washington, DC.

Jobes, T.H., J.L. Kittle, Jr., and B.R. Bicknell. 1999. A Guide to Using Special Actions in The Hydrological Simulation Program – Fortran (HSPF). U.S. Geological Survey, Office of Surface Water, Reston, VA.

Johanson, R.C., J.C. Imhoff and H.H. Davis, Jr. 1980. User's Manual for Hydrological Simulation Program - FORTRAN (HSPF). Research Grant No. R804971- 01. Office of Research and Development, U.S. Environmental Protection Agency, Athens, GA.

Johanson, R.C., J.C. Imhoff, J.L. Kittle, Jr. and A.S. Donigian, Jr. 1984. Hydrological Simulation Program - FORTRAN (HSPF): User's Manual for Release 8.0, U.S. EPA, EPA-600/3-84-066, Environmental Research Laboratory, Athens, GA.

Kittle, J.L., A.M. Lumb, P.R. Hummel, P.B. Duda and M.H. Gray. 1998. A Tool for the Generation and Analysis of Model Simulation Scenarios for Watersheds (GenScn). WRI Report 98-4134. U.S. Geological Survey, Reston VA.

Lahlou, M., L. Shoemaker, S. Choudhury, R. Elmer, A. Hu, H. Manguerra, A. Parker, 1998, Better Assessment Science Integrating Point and Nonpoint Sources – BASINS 2.0 User's Manual, EPA-823-B98-006, U.S. E.P.A., Office of Water, Washington, DC.

Linker, L.C. and R.V. Thomann, 1996. The Cross-Media Models of the Chesapeake Bay: Defining the Boundaries of the Problem. Watershed '96: A National Conference on Watershed Management, Baltimore, MD.

Lombardo, P. 1973. A Critical Review of Available Water Quality Simulation Models. Hydrocomp, Inc., Palo Alto, CA.

Lumb, A.M. and J.L. Kittle. 1984. ANNIE, an Interactive Processor for Hydrological Models, in: Emerging Computer Techniques in Stormwater and Flood Management, pp. 352-365. American Society of Civil Engineers. New York, NY.

Lumb, A.M. and J.L. Kittle, Jr. 1993. Expert System for Calibration and Application of Watershed Models, in: Proceeding of the Federal Interagency Workshop on Hydrologic Modeling Demands for the 90's, U.S. Geological Survey WRI Report 93-4018, pp. 4:1-7, Reston, VA.

McDonald, M.G. and A.W. Harbaugh. 1984. A Modular Three-Dimensional Finite-Difference Groundwater Flow Model. Open-File Report 83-875, U.S. Geological Survey, Reston, VA. 528p.

Metcalf and Eddy, Inc., University of Florida and Water Resources Engineers, Inc. 1971. Storm Water Management Model, vols I-IV. Report No. 11024DOC04/71. EPA Water Quality Office, Washington, DC.

Negev, M. 1967. A Sediment Model on a Digital Computer. Department of Civil Engineering, Stanford University, Stanford, CA. Technical Report No. 76. 109 p.

Onishi, Y., S.M. Brown, A.R. Olsen, M.A. Parkhurst, S.E. Wise and W.H. Walters. 1979. Methodology for Overland and Instream Migration and Risk Assessment of Pesticides. Prepared for U.S. EPA Environmental Research Laboratory, Athens, GA by Battelle Pacific Northwest Laboratories, Richland WA. 20 p.

Ross, M.A., P.D. Tara, J.S. Geurink and M.T. Stewart. 1997. FIPR Hydrologic Model: User's Manual and Technical Documentation. Prepared for Florida Institute of Phosphate Research and Southwest Florida Water Management District. Depts. of Environmental Engineering and Geology, University of South Florida, Tampa, FL.

SDI Environmental Services, Inc. 1997. Water Resource Evaluation and Integrated Hydrologic Model of the Central Northern Tampa Bay Region. Final Report. ISGW/CNTB Model SDE Project No. WCF-690, Prepared for West Coast Regional Water Supply Authority, Clearwater, FL.

SDI Environmental Services, Inc. 1999. Update to Integrated Hydrologic Model of the Central Northern Tampa Bay Area: ISGW/CNTB Model Run No. 121. Prepared for Tampa Bay Water Authority, Clearwater, FL. 87p.