White Paper (k): HSPF Nutrient TMDL Development Capabilities

Introduction

Section 303(d) of the Clean Water Act and the U.S. Environmental Protection Agency's Water Quality Planning and Management Regulations (40 CFR Part 130) require states to develop total maximum daily loads (TMDLs) for waterbodies that are not meeting applicable water quality standards/guidelines or designated uses under technology-based controls. TMDLs specify the maximum amount of a pollutant which a waterbody can receive and still meet water quality standards. Based upon a calculation of the total allowable load, TMDLs allocate pollutant loads to sources and a margin of safety. Pollutant load reductions are allocated among the significant sources and provide a scientific basis for restoring surface water quality. In this way, the TMDL process links the development and implementation of control actions to the attainment and maintenance of water quality standards and designated uses.

Nutrient impairments rank among the most common problems for which TMDLs are required and for a variety of reasons, TMDLs for nutrients can be some of the most difficult to develop. Nutrients can directly and indirectly impact water quality depending upon multiple environmental variables and there are frequently no numeric water quality objectives available to guide TMDL development. As a result, nutrient TMDLs require that developers have a clear and thorough understanding of the system in question, of the specific problems caused by the nutrient impairment, and the roles that various nutrient related parameters play in the particular impairment. Water quality and watershed models are often used in TMDL development to simulate nutrient loading from watersheds and the impacts of those loads on receiving waters. In selecting an application appropriate for modeling a nutrient impairment, it is critical to consider a variety of factors including water body type, key sources, key nutrient processes and constituents which may contribute to the impairment, and desired targets.

A model that has been used frequently to simulate pollutant loading and impacts to waterbodies is the Hydrologic Simulation Program – Fortran (HSPF) model. First developed in the 1960's as the Stanford Watershed Model, HSPF has been periodically/continually upgraded with enhancements to its process algorithms, software coding, and pre- and post-processing capabilities. Various versions of HSPF are available which use the same algorithms as HSPF but provide alternative interfaces and data storage and manipulation capabilities. Two of these versions include WinHSPF (available with the EPA BASINS System – "BASINS"), and the Loading Simulation Program in C++, or LSPC (available with the EPA TMDL Modeling Toolbox Suite – "Toolbox"). LSPC, in particular, has been applied widely throughout California and in other states to support TMDL development for nutrients and pathogens. This document discusses the applicability of HSPF to address issues associated with modeling nutrient impaired systems. It provides an overview of the model and its capabilities and identifies the key advantages and disadvantages of applying the model to nutrient TMDL development. The document is intended to support the reader in making an informed decision regarding applicability of HSPF to a given situation. It also sheds some light on differences between LSPC and HSPF and advantages of using LSPC for TMDL development.

Model Overview

HSPF is a dynamic watershed model driven by time-variable weather input data that produces time series results for hydrologic and pollutant storages and fluxes. HSPF estimates the behavior of a number of watershed features such as the overland flow plane, the vadose and saturated zones, as well as in-stream components of the system, using an area-weighted or “lumped” methodology. It is capable of simulating loadings from mixed landuse settings for nutrients, toxics, pathogens, metals, and sediment. In addition to predicting loadings from landuses, HSPF simulates in-stream processes that predict the fate and transport of pollutants once they reach a receiving waterbody. The landuse predictive portion of the HSPF model is referred to in this paper as the watershed loading model. The in-stream process model is referred to as the receiving water or water quality model.

Necessary input data for HSPF are substantial, (e.g., continuous precipitation and weather files are required) necessitating a certain level of expertise and training. HSPF requires three main categories of data as input: landscape data (topography, point source locations, streams, etc.), meteorological data (precipitation, air temperature, humidity, etc.), and landuse and pollutant specific data (landuse areas, monitoring data, etc.). The watershed loading model divides all landuses into pervious and impervious segments, which are further grouped by landuse and subbasin. Loads from subbasins are routed to receiving waters (stream segments or reservoirs). Figure 1 provides an illustration of model segmentation in HSPF.

For each pervious land segment, HSPF algorithms provide the foundation for estimating the water budget, snow and ice, sediment, solute transport, general water quality constituents (e.g., bacteria or metals), nitrogen and phosphorus cycles, pesticides, and conservative substances. Fewer processes are simulated for impervious land segments due to the less complex hydrologic nature of paved surfaces. For each impervious land segment, the following can be simulated: snow and ice, water budget, general water quality constituents, and sediment.

In each water body segment, simulations can be performed for hydraulic behavior, constituent transport, behavior of conservative constituents, heat exchange and water temperature, inorganic sediment, general water quality constituents, and biochemical transformations of chemicals, (e.g., DO and BOD reactions, inorganic nitrogen and phosphorus, phytoplankton, pH, and inorganic carbon).

Input data requirements for HSPF are substantial. Continuous precipitation and weather data are necessary as well as elevation, landuse, soils, and stream geometry.

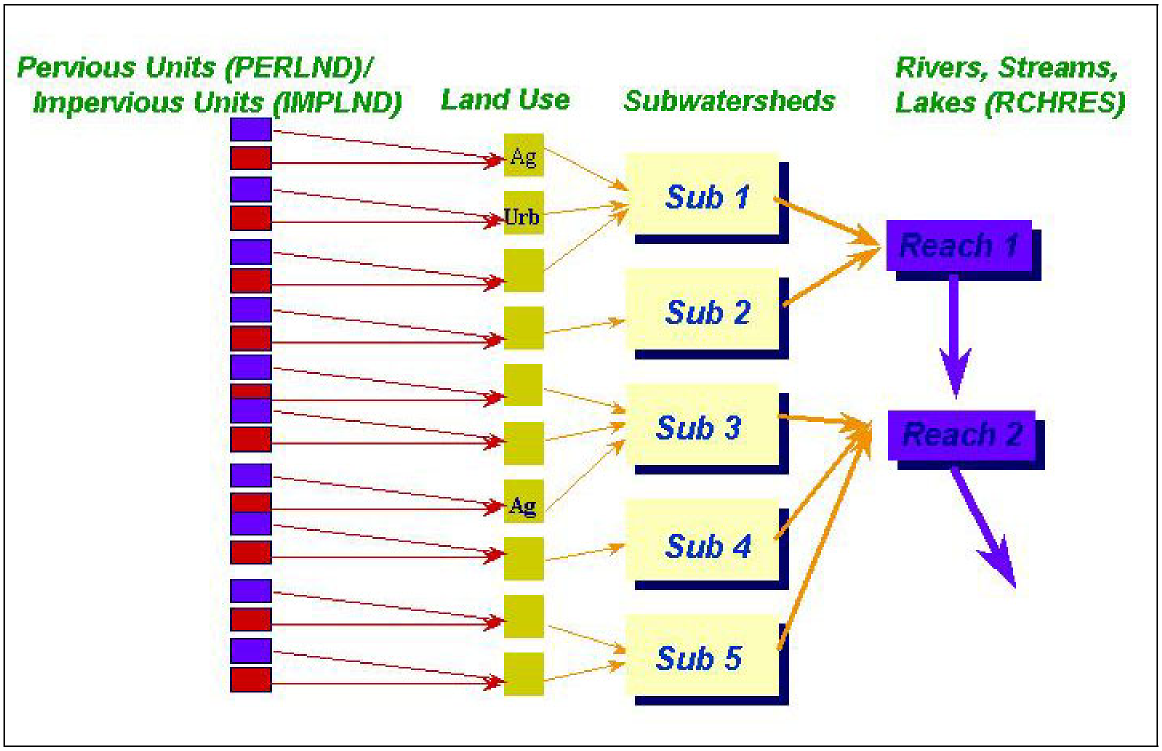

Figure 1. Model Segmentation in HSPF

Surface Water Modeling Capabilities

In the nutrient TMDL development process, one of the critical issues driving model selection is the type of waterbody affected. Streams and rivers, lakes, and estuaries may all be impacted by nutrients. Since HSPF functions as both a watershed and receiving water model, one should first examine the capabilities of the receiving water model to determine its suitability to address the impairment in question.

Note on LSPC: As a component of EPA's TMDL Modeling Toolbox, LSPC can readily be linked to advanced receiving water hydrodynamic and water quality models like EPA's Environmental Fluid Dynamics Code (EFDC) and Water Quality Analysis Simulation Program (WASP).

From a hydraulic perspective, HSPF provides a relatively simple receiving water model, representing waterbodies as one dimensional, completely mixed reaches or reservoirs. In general, HSPF is not a suitable model for estuarine and lake/reservoir nutrient modeling efforts, which typically require evaluation of hydrodynamics (including temperature) and chemical and biological processes in multiple dimensions (e.g., longitudinally, vertically, and/or laterally). It is, however, useful in evaluating nutrient conditions in streams that are free-flowing, unidirectional, and well-mixed and/or impoundments that are considered completely mixed. As such, it can be applied in conjunction with a more rigorous hydrodynamic receiving water model to evaluate estuaries and lakes/reservoirs through estimation of appropriate boundary conditions. This has been demonstrated by linking LSPC to EFDC in a number of studies, including Canyon Lake, CA; Clear Lake, CA; Los Angeles

River, CA; Neuse Estuary, NC; Mobile Bay, AL; and Salt River Bay, USVI.

In HSPF, a flow unit (a single reach of open or closed channel or a completely mixed lake) is assumed to be unidirectional. Inflow from other units and local sources enter through a single point while outflows may leave through up to five points. Fluxes such as precipitation and evaporation influence the processes simulated within each unit. Physical processes are simulated first (i.e., longitudinal advection, sinking), followed by simulation of biochemical processes. A rating curve is used to represent outflow demand for routing water between units and requires depth, surface area, volume, and outflow relationships for each exit. Reservoirs can be represented as well because the model allows the user to specify specific times series to be used to represent outflows for a RCHRES.
HSPF also has the ability to simulate "categories" which can be used to model water rights or ownership, whereby each unit keeps track of user-defined categories of all inflows, storages, and outflows.

Note on LSPC: The LSPC model can be set up to impound all upstream flow until water depths exceed specified spillway heights, causing overflow and thus contributing to downstream flow and pollutant loading.

Highlights:

- Well-suited for free-flowing streams
- Not suitable for reservoir/lake or estuaries
- Can provide boundary conditions for more robust receiving water models

Sources of Nutrients

A nutrient model selection process must also consider what are the key sources of nutrients that have led to impairment. This generally requires that the model selected be able to simulate sources that are both nonpoint and point source in nature. Because HSPF is considered a "watershed" model and is capable of simulating both land-based (e.g., rainfall-runoff) impacts as well as in-stream effects, it is inherently capable of evaluating the impacts of both point and nonpoint sources.

Nutrient loading may originate from a wide variety of nonpoint sources, such as agriculture, onsite wastewater treatment systems, urban runoff, forested areas, as well as atmospheric deposition. Models used to simulate nonpoint source nutrient loading should be able to represent these sources. In HSPF, they are incorporated through simulation of landuses, which are each divided into pervious and impervious land units (as shown in Figure 1).

An important aspect of modeling watershed loading involves representing water quality constituents as well as how they are affected by the hydrology of the land units from which they originate. Figure 2 provides a schematic of the hydrologic simulation associated with land units in HSPF. These are important to keep in mind when considering how nutrients travel from the landscape to a receiving water. For example, the ability to simulate impervious landuses is important when developing a nutrient TMDL in an urban watershed due to the high percentage of paved surfaces found in urban areas relative to rural areas.

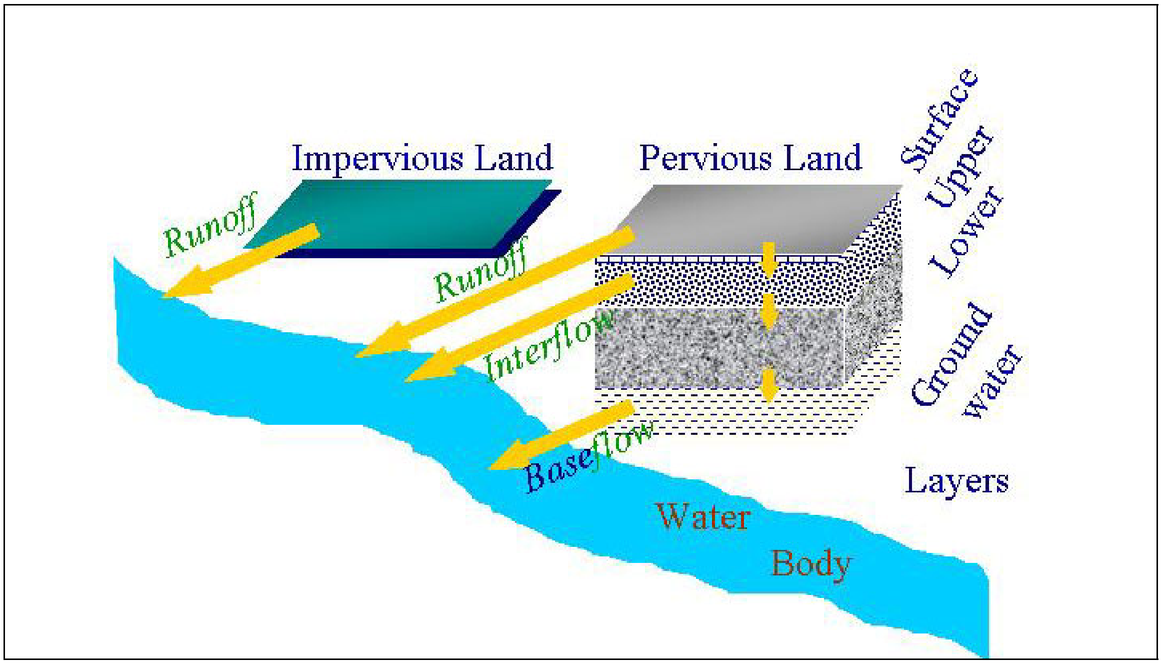

Figure 2. Hydrologic Simulation

Nonpoint Sources

Landuses within an impaired watershed provide much insight into potential nutrient sources. HSPF uses landuse categories as the basis for simulating nonpoint source contributions to surface water. Therefore, specific nonpoint sources are not explicitly included. Rather, they must be considered in how the landuses are characterized in the model setup. For example, one landuse may have multiple sources contributing nutrients to its surface; runoff from urban or developed land may include inputs from fertilizer, domestic pets, and wildlife. On the other hand, some landuse categories typically represent one general source (e.g., cropland as a source of sorbed nutrients from fertilizer).

Because HSPF represents precipitation driven nonpoint sources as landuse loads, it is necessary to separately evaluate activities (e.g., agriculture) conducted in a watershed that may contribute substantially to nutrient loading. Characterizing the activities can allow for the development of site-specific landuse parameters (e.g., nutrient accumulation) for use in the model. Otherwise, the parameters can be obtained from literature or through model calibration.

Examples of Nutrient Nonpoint Sources Considered in HSPF Applications

A number of agricultural activities affect nutrient loading. Erosion contributes to phosphorus loading as a result of the tendency of phosphorus to adsorb to sediment particles. Application of manure and fertilizer to croplands contributes to nutrient loads, which may also be affected by plant nutrient uptake rates. HSPF allows for supplying monthly potency factors to constituents to represent seasonal fertilizer application rates. Livestock may contribute to nutrient loading through waste production and by exacerbating erosion in and around streams. These sources may be simulated as surface deposition or as aggregated direct instream "point source" inputs.

Poorly functioning or failing onsite wastewater treatment systems may contribute nutrient loads directly to streams and shallow groundwater. Several methods may be used in HSPF or LSPC to simulate these sources. Local census data can be incorporated into the modeling project to provide sewered population estimates and calculate potential loading from the watershed as a whole. Depending on the hydrology, climate, and magnitude of wastewater loading, these sources may be introduced to the simulated stream network as point sources. Another method is to assign pollutant concentrations to discharged interflow and groundwater flows. Both methods can be incorporated relatively easily.

HSPF is also able to simulate net changes in a sediment-associated constituent due to human or wind-induced atmospheric deposition or removal. Atmospheric deposition can be specified as wet (concentration in rainfall) or dry (mass per area per time) deposition.

All landuse categories in rural and urban areas are subdivided into pervious land units (which typically include forested, cropland, pasture, etc.) and/or impervious land units (paved surfaces) depending on their physical nature. Hydrologic and water quality algorithms are then used to quantitatively describe processes for each of these lands.

For simulating nutrient loading (and water quality constituents in general) from a watershed, HSPF allows for approaches that vary in complexity. One method involves simulating the build-up and washoff of nutrients from the land surface and subsequent introduction to the stream channel. When using this method, nutrients and other constituents can be applied to the land surface over time so that a mass of the pollutant accumulates, and is subsequently removed at a rate correlated to a corresponding quantity of sheet flow on the land surface. This is generally the approach taken to support TMDL development, particularly in the presence of limited land-based calibration data. More detailed modules require comprehensive monitoring to adequately parameterize; and this type of information is typically not available. For most cases, the general water quality module provides adequate representation of nutrient loading, including groundwater and interflow pollutant concentrations and surface build-up washoff and/or sediment associated pollutant generation.

Another option involves simulation of erosion with a potency factor, to mimic the behavior of sorbed pollutants such as phosphorus. This method requires the simulation of sediment in addition to the nutrient constituent, adding to the complexity of model development and calibration, but also providing a sound modeling foundation if sediment data exist for a given watershed.

Note on LSPC: LSPC currently does not provide simulation capabilities for the most detailed nutrient cycle representation. TMDL analyses are often data, time, and resource prohibitive and thus inappropriate for application, calibration, and validation of the advanced modules.

The most complex representation of nutrient processes in HSPF can be obtained through direct simulation of plant uptake, nitrification, denitrification, adsorption, etc. While this is the most deterministic approach, the required level of parameterization typically exceeds available site-specific monitoring information. This approach is generally most applicable to field-scale studies.

Highlights: Simulation of nonpoint nutrient sources is represented as runoff from watershed landuses. Options include varying levels of complexity:

- Build-up/washoff
- Potency factor combined with erosion prediction
- Full nutrient cycle simulation

Point Sources

Point sources may also figure prominently into nutrient loading in a watershed. Wastewater treatment plants for example discharge nitrogen and phosphorus and may account for significant loads, especially if effluents routinely are in violation of permit limits or if permit limits are inadequate. Point sources can be represented in HSPF with constant time series data. This allows for calculating existing loading from point sources based on discharge monitoring report data or permit limit information. Point source loads are spatially associated with the subbasin in which they are located

Highlights: Simulation of point sources is represented using a constant or time-variable discharge directly to the receiving water.

Surface Water Nutrient Processes

Complex interactions between nutrient constituents and multiple environmental factors impact water quality by affecting nutrient transport processes as well as nutrient cycling. As with watershed loading simulations, HSPF can be used to represent these processes with varying levels of complexity. The most basic approach allows for using simple 1st order decay to represent the net loss of a nutrient as it is routed downstream. This approach is often used for studies involving linkage to a more robust receiving water model (such as that developed for Clear Lake, CA). It is also used when a specific instream nutrient concentration or reference watershed nutrient loading

Surface Water Nutrient Processes Simulated in HSPF

Range of options for simulating surface water processes include simple to complex

- 1st order decay simulates net loss upstream to downstream
- Detailed modules simulate cycling and transport, algal response, etc.

rate has been selected as the target for TMDL development.

A more detailed approach can make use of specific modules in HSPF, which have equations representing detailed transport and cycling processes. For example, the NUTRX module simulates algal responses to nutrients. These modules include simulation of nitrogen constituents (organic N, nitrate/nitrite, ammonia, etc.), phosphorus constituents (organic P, orthophosphorus, etc.), dissolved oxygen, algae and sediment interactions. HSPF does not simulate periphyton (attached algae), although some specific modeling applications of HSPF have been developed that address periphyton. Another limitation of HSPF with regard to nutrient modeling is its inability to simulate sediment diagenesis. For free-flowing streams this limitation is not necessarily prohibitive, although it may be necessary for consideration. While these detailed algorithms are contain within HSPF, it is important to note that their utility is limited by the availability of data to characterize the processes and support calibration.

Water Quality Criteria/Targets

In any nutrient TMDL development effort, it is important to consider the affected designated uses, applicable water quality standards, and critical conditions. Nutrient TMDLs often involve the identification of numeric TMDL endpoints to augment existing state water quality criteria, which are often narrative in nature. Typical endpoints used in nutrient TMDLs can vary depending on many factors, including type of waterbody, available monitoring data, and problem conditions. Often, endpoints are established that utilize a surrogate parameter as an indicator of the problem pollutant. For example, a nutrient TMDL for a stream experiencing nuisance periphyton from excess phosphorus loading may designate chlorophyll *a* concentrations or dissolved oxygen (if diurnal swings are observed) as an endpoint. Care must be taken in selecting a model such that the model can actually simulate potential endpoints. Table 1 provides a listing of potential direct and surrogate nutrient endpoints modeled by HSPF. Depending on analysis requirements, TMDL endpoints related to the above parameters may relate to actual constituent concentrations or loading rates (i.e., as with a reference approach).

Table 1. Nutrient Components simulated by HSPF

TMDL Development Parameter	Component
Nitrogen	Total N
	Dissolved N
	Nitrate
	Nitrite
	Ammonium
Phosphorus	Total Phosphorus
	Orthophosphate
Related Parameters	Dissolved Oxygen
	Phytoplankton
	Periphyton
	pH
	Turbidity

Another important consideration when evaluating TMDL targets with a modeling analysis is the frequency and/or duration of the target. For example, a target may be established as a concentration for a specific time frame (e.g., instantaneous maximum concentration, daily average, 7-day average, monthly average) or as some allowable exceedance frequency in a time period (e.g., not to exceed a maximum concentration more than 10 percent of the time in a 30-day period). Because HSPF can simulate watershed and water quality conditions down to a 15-minute timestep, it provides flexibility in the evaluation of targets and can provide output comparable to a variety of time-scales and targets.

TMDL Analytical and Presentation Capabilities

During development of TMDLs it is often necessary to evaluate multiple loading scenarios, including existing loading conditions, TMDL loading conditions, and baseline loading conditions, which are representative of existing loading with any permits discharging at their allowable limits. HSPF's capabilities allow it to be applied for a variety of management scenarios, including load reductions from different landuses and subwatersheds, under natural or pristine conditions, assuming projected landuse changes or with the addition or modification of point source discharges. HSPF allows for simulating an infinite variety of landuse combinations. Although Best Management Practices (BMPs) are not explicitly simulated in HSPF, implementation scenarios can be simulated as percent removal from individual pollutant sources.

Note on LSPC: The LSPC model was developed using Microsoft Visual C++ programming architecture and allows for seamless integration with modern-day, widely available software such as Microsoft Access and Excel. This greatly simplifies model output analysis and presentation for large, complex watersheds with detailed source allocations.

HSPF's capabilities also support the evaluation of temporal and spatial effects or patterns of loading scenarios as well as the relative impact of different sources, which can be important when considering implementation requirements of a TMDL. Because HSPF can simulate multiple landuses and subwatershed, it supports the evaluation of the spatial variation of source loading and management scenario.   For example, it can evaluate the downstream impacts of reduction loads in upstream subwatersheds and can evaluate the impact of targeted load reductions throughout the watershed and for different landuses. The ability of HSPF to provide output at a variety of time-steps, including daily, facilitates the evaluation of the seasonality of loading and management scenarios. This can help to focus loading controls for times of increased loading and impairment (e.g., summer months). In addition, HSPF's spatial and landuse-specific representation and segmentation of the watershed supports sensitivity analyses of the sources. HSPF can be applied to account for loading from each individual landuse or source rather than the combined effects of all landuses to evaluate the relative magnitude and impact of the sources on instream nutrient levels.

These capabilities also support flexibility in establishing allocations. Allocations can be made to specific areas or at a broader-scale, as well as on a variety of time-scales (e.g., seasonally, monthly, daily).

Summary

The following summarizes the capabilities of HSPF in addressing considerations for developing nutrient TMDLs.

- Suitable for simulating nutrient loads from complex watersheds
- Suitable for simulating free-flowing rivers (well mixed with unidirectional flow)
- Not recommended for lakes/reservoirs (unless well-mixed)
- Appropriate for linkage to more complex hydrodynamic receiving water models
- Able to simulate point and nonpoint sources
- Can include single, continuous, intermittent, multiple, and diffuse sources/inputs
- Simulates the build-up and washoff of accumulated pollutants
- Simulates sediment erosion and sediment-associated pollutant transport
- Does not simulate sediment diagenesis
- Contains algorithms for simulating loads from the watershed and the fate and transport of pollutants once they reach the receiving water body
- Provides continuous simulation and storm-event simulation
- Can represent multiple processes and their interactions.
- Able to support model simulations of varying degrees of complexity depending upon user expertise and available calibration data
- Requires extensive amounts of data for setup and calibration
- Requires experience or training for application

References and Additional Information

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