Appendix 7. Descriptions of Water Quality Models

Watershed Loading Models

An ArcView GIS Tool for Pollutant Load Application (PLOAD)

Model Objective. The PLOAD model was designed to be a screening tool for end users. This generic model can be used as an analytical tool for many applications, such as National Pollutant Discharge Elimination System (NPDES) stormwater permitting, watershed management, and reservoir protection projects. This simple model based on geographical information system (GIS) calculates pollutant loads for watersheds or sub-watersheds. It estimates nonpoint sources of pollution on an annual average basis for any user-specified pollutant. These nonpoint source loads may be calculated by using either the "export coefficient" method or the U.S. Environmental Protection Agency (USEPA) simple method approach. Optionally, Best Management Practices (BMPs), which serve to reduce nonpoint source loads, may also be included in computing total watershed loads. The model is suitable for both urban and rural study areas (USEPA, 2001b).

Spatial Feature. Watershed boundaries can be defined through the "Delineation extensions" tool in the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) system developed by the USEPA. Delineation of the watershed requires reach, digital elevation model (DEM), and hydrologic unit files (USEPA, 2001a).

Temporal Feature. The PLOAD model enables users to study long-term impacts because it requires only the annual precipitation value and ratio of storms producing runoff (USEPA, 2001b). It is not appropriate for the simulation of rainfall event-driven constituents.

Pre/Post Processor. The PLOAD application requires preprocessed GIS and tabular input data (watershed boundary file, land-use file, and BMP site as point and area data). It does not require any other postprocessor programs except GIS.

Constituents Simulated. The following constituents can be simulated: biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solid (TSS), total dissolved solids, total nitrogen, nitrate and nitrite nitrogen, total Kjeldahl nitrogent (TKN), ammonia nitrogen, organic nitrogen, total phosphorus, dissolved phosphorus, zinc, copper, lead, cadmium, chromium, nickel, and fecal coliform (USEPA, 2001b).

Model Components. The PLOAD model requires GIS input data, such as watershed boundary, land-use, and BMP site files as point and area data. Prior to calculating pollutant loads, the model spatially overlays the watershed and land-use files to determine the area of the various land-use types for each watershed. The land-use file should encompass the entire watershed file. The model also requires the following four tabular input data: pollutant loading rate table, impervious factor table for each land use, efficiency information table indicating pollutant removal rate of each BMP type, and point source facility locations and loads table. In addition, if the simple method is specified, annual precipitation and ratio of storms producing runoff values should be provided (USEPA, 2001b).

Soil and Water Assessment Tool (SWAT)

The SWAT model was developed and maintained by the U.S. Department of Agriculture (USDA) Agricultural Research Service or ARS (Arnold et al., 1998). It incorporates features of several ARS models and is a direct outgrowth of the Simulator for Water Resources in Rural Basins (SWRRB) model (Williams et al., 1985) and Routing Outputs to Outlet (ROTO) model (Arnold et al., 1995). Specific models that contributed significantly to the development of SWAT were the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980), Groundwater Loading Effects on Agricultural Management Systems (GLEAMS) model (Leonard et al., 1987), and Erosion-Productivity Impact Calculator (EPIC) model (Williams et al., 1984). The latest version, SWAT2000, is incorporated into the BASINS3.0 model.

Model Objective. The SWAT model was developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land-use, and management conditions over long periods of time. The SWAT model is ideally suited to rural areas dominated by agricultural applications and requires a great amount of data for vegetative changes and agricultural practices (Neitsch et al., 2002). The SWAT model is appropriate for various watershed and water quality modeling studies. For example, it has been used for national and regional water resource assessment considering both current and projected management conditions; assessment of the impact of global climate on water supply and quality in the United States and Europe; simulation of a single watershed or a system of multiple hydrologically connected watersheds (Neitsch et al., 2002); sediment and phosphorus transport (Kirsch, et al., 2002); total maximum daily load (TMDL) development for watersheds dominated by agricultural operations (Srinivasan et al., 2002); evaluation of sediment, nitrogen, and phosphorus loadings from various sources, including dairy waste application areas, waste treatment plants, urban areas, conventional row crops, and rangeland; and point and nonpoint source pollution analyses (Santhis et al., 2001).

Spatial Feature. Watershed boundaries can be defined through the “Delineation extensions” tool in the system. Delineation of the watershed requires reach, DEM, and hydrologic unit files (USEPA, 2001a). The hydrologic response units (HRU) distribution can be defined exclusively using the “Land use and Soil overlay and HRU distribution extension” in BASINS. Each watershed is divided into sub-basins and then into HRUs based on land use and soil distributions (Neitsch et al., 2002).

Temporal Feature. The SWAT model uses a daily time step for simulations running from one to 100 years allowing long-term impact analyses (Neitsch et al., 2002). However, it is not appropriate for the simulation of rainfall event-driven constituents, such as pathogens and bacteria. This model uses a daily interval precipitation, temperature, solar radiation, wind speed, potential evapotranspiration, and relative humidity data (Neitsch et al., 2002).

Pre/Post Processor. The Generation and Analysis of Model Simulation Scenarios (GenScn) serves as a postprocessor for the SWAT model, as well as a tool for visualizing observed water quality data and other time series data. It allows users to select locations and time periods within the subject watershed area and to create tables and graphs based on these selections. It can process a variety of data formats, including SWAT output data. It also performs statistical functions and data comparisons (USEPA, 2001a).

Constituents Simulated. The following constituents can be simulated: water flow, sediment loading, organic nitrogen, organic phosphorus, nitrate, mineral (soluble) phosphorous, ammonium, nitrite, algae as chlorophyll *a*, conservative metals (aluminum, antimony, arsenic, cadmium, etc.), persistent bacteria, less persistent bacteria (fecal coliform), carbonaceous BOD, DO, and pesticides (Neitsch et al., 2002).

Model Components. Major model components describe processes associated with water movement, sediment movement, soils, temperature, weather, plant growth, nutrients, pesticides and land management (Neitsch et al., 2002). The SWAT model uses seven input files and databases to store required information about plant growth and urban land uses, tillage, fertilizer components, and pesticide properties (Neitsch et al., 2002).

Hydrological Simulation Program-Fortran Version 12 (HSPF) Pervious Land (PERLND) and Impervious Land (IMPLND) Modules

The first version of the HSPF module was released in 1976 by the USEPA and was created by combining three pre-existing models: the Hydrocomp Simulation Program (HSP), the Agricultural Runoff Management Model (ARM), and the Nonpoint Source Pollutant Loading Model (NPS). Pre- and postprocessing components were added by the USEPA and U.S. Geological Survey (USGS) in 1980s. Version 12 comes with BASINS (Bicknell et al., 2001) and is accessed through a user-friendly Windows-based graphical user interface called WinHSPF.

Model Objective. As an analytical tool, the HSPF model has been used for flood control planning and operation; river basin and watershed planning; storm drainage analysis; fate, transport, exposure assessment, and control of pesticides, nutrients, and toxic substances (Donigian et al, 1997); water quality planning and management (Bicknell et al., 1985); point and nonpoint source pollution analyses (Donigian et al., 1991); soil erosion and sediment transport studies; and evaluation of urban and agricultural BMPs (Moore et al., 1992), and for evaluating the impacts of land-use changes (Brun and Band, 2000). This model is suitable for both urban and rural areas (Donigian et al., 1991).

Spatial Feature. Watershed boundaries can be defined through the "Delineation extensions" tool in the BASINS systems. Watersheds ranging in size from a few square miles to several thousand square miles have been modeled for hydrology, sediment, and water quality simulations using the HSPF module. Delineation of the watershed requires reach (National Hydrography Dataset reach layer, DEM, and watershed boundary (hydrologic cataloging unit layer). The model subdivides large watersheds into smaller, more uniform pervious and impervious land segments based on land use in the watershed. The HSPF model requires users to have a User Control Input (UCI) file to run it. To create a UCI file, three types of data required: spatially distributed data (land use, reach file, soils, DEM, USGS hydrologic unit boundaries, dam sites); environmental monitoring data (locations of water quality monitoring stations, weather station and USGS gaging stations); and point source data (industrial facilities discharge sites, toxic release inventory sites, permit compliance system sites, and loadings) (Bicknell et al., 1985). The HSPF has three sub-modules: Pervious Land (PERLND), Impervious Land (IMPLND), and Reaches (RCHRES). The PERLND sub-module has 12 sub-modules, that require data on air temperature, snow and ice, water budget, sediment, soil temperature, water temperature, water quality constitutions, soil moisture, detailed pesticide, nitrogen, and phosphorous behaviors, and tracer. The IMPLND sub-module also has six sub-modules that require data on air temperature, snow and ice, water budget, solids, water temperature, and wash off of quality constituents. The RCHRES sub-module which simulates in-stream behavior and has 11 sub-modules that simulate hydraulics, inorganic sediment, and generalized quality constituent behaviors, advection, conservative constituents, water temperature, DO, BOD, nitrogen and phosphorus balances, plankton, and pH (Bicknell et al., 1985).

Temporal Feature. The HSPF continuous simulation model also is capable of simulating individual storms. It can be run using a computational time step as small as one minute, but an hourly time step is commonly used. The model can generate outputs on an hourly and a daily basis. It enables users to study both long-term and short-term impacts. It is appropriate for the simulation of rainfall event-driven constituents because it uses hourly interval precipitation data (USEPA, 2001a). It uses both hourly and daily weather data. For example, hourly data used include precipitation, evaporation, temperature, wind speed, solar radiation, potential evapotranspiration, dewpoint temperature, and cloud cover. Precipitation data, the most deterministic input, drive the hydrology of this model. Daily data can be disaggregated into hourly data using the Disaggregation Tool within the Weather Data Management Utility (WDMUtil) program linked to the HSPF model (Hummel et al., 2001).

Pre/Post Processor. As a preprocessor, the HSPF model uses WDMUtil to manage weather data, streamflow data, and other forms of input data series used by the model. Although HSPF model outputs can be viewed and processed in WDMUtil to some extent, a more advanced GenScn post-processor is used in conjunction with the HSPF model. This postprocessor facilitates the display and interpretation of output data derived from model applications, and performs statistical functions and data comparisons (USEPA, 2001a). It allows users to select locations and time periods within the subject watershed area and to create tables and graphs based upon these selections. Due to these qualities, GenScn helps in model calibration and analysis of different environmental systems. In addition, the Expert System for Calibration of HSPF (HSPEXP) can be used to facilitate hydrologic calibration of the model (USGS, 1994).

Constituents Simulated. The HSPF model can simulate the following constituents: streamflow (as a sum of surface runoff, interflow, and baseflow) sediment loading, inorganic suspended sediment, pathogens, BOD, DO, pH, pesticide chemicals, inorganic nitrogen, nitrite, ammonia, nitrate, orthophosphate, phosphorus, phosphate, inorganic phosphorus, tracers (chloride, bromide, dyes, etc.), carbon dioxide, inorganic carbon, zooplankton, phytoplankton, benthic algae, organic carbon, fecal coliform, pH, and alkalinity (Bicknell et al., 2001).

Model Components. The HSPF model contains three application modules and five utility modules. The application modules simulate the hydrologic/hydraulic and water quality components of the watershed. The utility modules are used to manipulate and analyze time-series data (Bicknell et al., 2001).

Application Modules. The HSPF model has three application modules: PERLND, IMPLND, and RCHRES. As PERLND simulates the water quality and quantity processes that occur on pervious land areas, it is the most frequently used part of the HSPF model. To simulate these processes, PERLND models the movement of water along three paths: overland flow, interflow, and groundwater flow. Each of these three paths experiences differences in time delay and differences in interactions between water and its various dissolved constituents. A variety of storage zones are used to represent the processes that occur on the land surface and in the soil horizons. Snow accumulation and melt also are included in the PERLND module so that the complete range of physical processes affecting the generation of water and associated water quality constituents can be represented (Bicknell et al., 2001). Some of the many capabilities available in the PERLND module include the simulation of water budget, snow accumulation and melt, sediment production and removal, nitrogen and phosphorous behavior, pesticide behavior, and movement of a tracer chemical.

The IMPLND model is used in urban areas where little or no infiltration occurs. However, some land processes do occur, and water, solids, and various pollutants are removed from the land surface by moving laterally downslope to a pervious area, stream channel, or reservoir. The IMPLND model includes all pollutant washoff capabilities of the commonly used urban runoff models, such as the storage, treatment, overflow, runoff model (STORM), and storm water management model (SWMM) (Bicknell et al., 2001).

Receiving Water Models

Hydrological Simulation Program-Fortran Version 12 (HSPF) Reaches (RCHRES) Module

Model Objective. This analytical tool, has applications in planning, design, and operation of water resources systems. The model enables the use of probabilistic analysis in the fields of water quality management. The HSPF model uses such information as the time history of rainfall, temperature, evaporation, and parameters related to land-use patterns, soil characteristics, and agricultural practices to simulate processes that occur in a watershed (Bicknell et al., 2001). Model applications and uses are water quality planning and management, point and nonpoint source pollution analyses and fate, transport, exposure assessment, and control of pesticides, nutrients, and toxic substances (Bicknell et al., 1985; Donigian et al., 1984).

Hydraulics. The HSPF dynamic model is appropriate for simulation of rainfall event-driven constituent transport and transformation (USEPA, 2001a). The HSPF model can simulate the continuous, dynamic event or steady-state behavior of both hydrologic/hydraulic and water quality processes in a watershed. It can be used to simulate time-varying flow conditions.

Spatial Feature. The HSPF is a one-dimensional model (Duda et al., 2001). It requires input data for river geometry and boundary conditions, inflows, withdrawals, and meteorology of each sub-basin (USEPA, 1997).

Temporal Feature. The HSPF model allows users to study both long-term and short-term impacts. Any time period from a few minutes to hundreds of years may be simulated (USGS, 2003d). In order to run the HPSF model, hourly precipitation metrological data are required (Hummel et al., 2001).

Constituents Simulated. The HSPF model can simulate sediment loading, inorganic suspended sediment, pathogens, BOD, DO, pH, pesticide chemicals, inorganic nitrogen, nitrogen, nitrite, nitrate, ammonia, orthophosphate, organic phosphorous, inorganic phosphorus, tracers (chloride, bromide, dyes, etc.), carbon dioxide, inorganic carbon, organic carbon, zooplankton, phytoplankton, benthic algae, fecal coliform, and alkalinity (Bicknell et al., 2001).

The RCHRES module is used to route runoff and water quality constituents simulated by the PERLND and IMPLND models through stream channel networks and reservoirs. A number of processes can be modeled, including hydraulic behavior; water temperature, inorganic sediment depositions, scour, and transport by particle size; chemical partitioning, hydrolysis, volatilization, oxidation, biodegradation, and radionuclide decay: DO, and BOD balances; inorganic nitrogen and phosphorous balances; plankton populations; and pH, carbon dioxide, total inorganic carbon, and alkalinity (Bicknell et al., 2001).

Enhanced Stream Water Quality (QUAL2E) Model

Model Objective. The Enhanced Stream Water Quality (QUAL2E) model is intended for use as a water quality-planning tool for developing TMDLs. This model has been used to study the impact of wasteloads on in streamwater quality and to identify the magnitude and quality characteristics of nonpoint waste loads as part of a field-sampling program (USEPA, 2003d). This model is applicable to well-mixed, dendritic streams, and it allows users to simulate the fate and transport of water quality constituents in streams under a given flow condition such as steady flow (USEPA, 2001a).

Hydraulics. In general, the QUAL2E model is classified as a steady-state water quality model. However, it also can be operated as a quasi-dynamic model, making it a very helpful water quality-planning tool. When operated as a steady-state model, this model can be used to study the impact of wasteloads (magnitude, quality, and location) on in-stream water quality. Otherwise, by operating the model dynamically, the user can study the effects of diurnal variations in meteorological data on water quality (primarily DO and temperature) and also can study diurnal variations due to algal growth and respiration. However, this model cannot model the effects of dynamic forcing functions, such as time-varying headwater flows or point loads (USEPA, 1995).

Spatial Feature. The QUAL2E is a one dimensional (longitudinal) stream water quality model. In riverine systems, lateral and vertical gradients in water quality constituent concentrations are generally insignificant and unimportant relative to longitudinal gradients. Thus, a one-dimensional model can be used for most riverine water quality issues considered (USEPA, 1995). The model is appropriate when flows are relatively constant or change slowly during the simulation with respect to the travel time of the system (USEPA, 1995). The travel time is how long it takes for a “parcel of water” to travel from one point to another. The model cannot simulate the effects of flow variations on constituent concentration and travel time.

This model represents the stream as a system of reaches of variable length, each of which is subdivided into computational elements of the same length in all reaches (USEPA, 1997). It requires input data for river geometry, stream network, flow, boundary conditions, climate, 26 properties for each reach (physical, chemical, and biological), inflows, and withdrawals (USEPA, 1997). The model also incorporates the dam aeration theory to simulate instantaneous change in DO over low-head dams.

Temporal Feature. A steady-state model such as the QUAL2E is limited to the simulation of time periods during which both the streamflow in river basins and input wasteloads are essentially constant (USEPA, 1995). A daily time step is required for QUAL2E reaction coefficients (USEPA, 1995). Modeling steady-state temperature and algae requires average daily local climatologial data. However, dynamic simulations require local climatological data supplied at regular (typically 3-hour) intervals (USEPA, 1987).

Constituents Simulated. The QUAL2E model simulates water quality constituents under either steady-state or quasi-dynamic conditions (USEPA, 1997). It can simulate the major reactions of nutrient cycles, algal production, benthic and carbonaceous demand, atmospheric reaeration, and their effects on the DO balance. It can predict up to 15 water quality constituent concentrations (USEPA, 2003d). The model can simulate the following constituents: DO, BOD, ultimate BOD, 5-day BOD, temperature, algae as chlorophyll *a*, organic nitrogen, ammonia as nitrogen, nitrite as nitrogen, nitrate as nitrogen, organic phosphorus, dissolved phosphorus, coliform, arbitrary nonconservative constituent, and three conservative constituents (USEPA, 1995).

The Water Quality Analysis Simulation Program (WASP 6) Model

Model Objective. The WASP 6 model is a general-purpose modeling system for assessing the fate and transport of conventional and toxic pollutants in surface water bodies (USEPA, 1997). This dynamic compartment model can be used to analyze a variety of water quality problems in such diverse water bodies as ponds, streams, lakes, reservoirs, rivers, estuaries, and coastal waters (Wool et al., 2003).

Hydraulics. The WASP 6 model is a dynamic model. For dynamic simulations, the user must specify initial constituent concentrations (flows and loadings) at the beginning of the simulation (Wool et al., 2003). It can be used to simulate time-varying flow conditions.

Spatial Feature. The WASP 6 model allows users to structure one-, two-, and three-dimensional models (Wool et al., 2003). By using three-dimensional structure, users can simulate estuaries successfully (USEPA, 1997). The water body is divided into a series of segments for simulation purpose. Loads, boundary concentrations, and initial concentrations must be specified for each state variable (USEPA, 1997). It requires input data for water body geometry, climate, water body segmentation, flow (or input from hydrodynamic model), boundary conditions, initial conditions, benthic flux, external loadings, spatially variable and time-variable functions, and rate constants (USEPA, 1997).

Temporal Feature. In general, the WASP 6 model is a short-term water quality analysis model. The water volume and water quality constituent masses being studied in this model are accounted for over time and space using a series of mass balancing equations (Wool et al., 2003). It also allows a more detailed examination of both short-term and long-term receiving water responses as well. (USEPA, 1997). The model represents time-varying processes of advection, dispersion, point and diffuse mass loading, and boundary exchange. For water quality simulation, a time step option (day, hour, and minute as initial time and day as final time) is available (Wool et al., 2003).

Constituents Simulated. The WASP 6 model has two kinetic sub-models to simulate two of the major classes of water quality problems: conventional pollution involving DO, BOD, phytoplankton carbon, phytoplankton nitrogen, ammonia nitrogen, nitrate nitrogen, organic nitrogen, ammonium, total Kjeldahl nitrogen (TKN), inorganic phosphorus, organic phosphorous, eutrophication, and toxic pollution involving organic chemicals, metals, and sediment (Wool et al., 2003).

A Dynamic, One-Dimensional (Longitudinal) Water Quality Model for Streams (CE-QUAL-RIV1)

Model Objective. The CE-QUAL-RIV1 model was developed to predict one-dimensional hydraulic and water quality variations in streams and rivers with highly unsteady flows. It has been applied for a wide variety of conditions, such as regulated streams (navigable waterways with multiple locks and dams and stream re-regulation), reservoir tailwaters, and large rivers. It is applicable where lateral and vertical variations are small (USACE, 2002).

Hydraulics. The CE-QUAL-RIV1 model was developed for time-varying and highly unsteady flow conditions, such as a riverine system resulting from the releases from peaking hydropower dams over a limited period of time (USACE, 1995). It can also be used for predictions under steady flow conditions (USACE, 2002).

Spatial Feature. The CE-QUAL-RIV1 model is a one-dimensional (cross-sectional averaged) model, which resolves longitudinal variations in hydraulic and quality characteristics (USACE, 2002). In riverine systems, vertical temperature, density, and chemical stratifications, which can play a dominant role in the water quality of lakes and reservoirs, are nonexistent or negligible for practical purposes. Thus, although this model can be used for run-of-the-river reservoirs, dams, and regulated pools, the user must be sure that vertical stratification does not exist or is so minor that it does not affect water quality conditions (USACE, 1995). This model also has several desirable numerical features, such as a two-point, fourth-order scheme for accurately predicting the advection of water quality concentrations (USACE, 1995).

The CE-QUAL-RIV1 model requires input data for river geometry and upstream boundary conditions, river segmentation, initial conditions, inflows, withdrawals, meteorology, external loadings, benthic flux, spatially variable and time-variable functions, and rate (USEPA, 1997).

Temporal Feature. In general, the CE-QUAL-RIVE1 model is a short-term water quality model. Meteorological data of 1- or 3-hour intervals are needed from National Oceanic and Atmospheric Administration (NOAA). The model allows hourly, daily, monthly, and yearly-based simulation (USACE, 1995).

Constituents Simulated. The CE-QUAL-RIV1 model can predict variations in each of 12 stated variables; temperature, carbonaceous BOD, organic nitrogen, ammonia nitrogen, nitrate plus nitrite nitrogen, DO, organic phosphorus, dissolved phosphates, algae, dissolved iron, dissolved manganese, and fecal coliform bacteria. In addition, it can simulate impacts of macrophytes (USACE, 2002).

Dynamic Toxics Wasteload Allocation (DYNTOX) Model

Model Objective. The DYNTOX model was developed for use in wasteload allocation of toxic substances. This tool assesses the impact of toxic discharges on receiving water quality over the entire range of historical and future conditions (USEPA, 1997). It is a probabilistic model to locate diffuse pollution. It is used mainly for aquatic ecosystems and has a specific interface (Environmental Software and Services, 2003). Additional new model features include partial mix factors and variable water quality criteria for metals and ammonia (Environmental Software and Services, 2003).

Hydraulics. The DYNTOX model is a steady and dynamic wasteload allocation (WLA) model (Limo-Tech, 1985). But, in general, it is classified as a dynamic model (USEPA, 1997).

Spatial Feature. The DYNTOX programs are designed mainly for use in rivers and streams with one dimension (Limo-Tech, 1985). It requires input data for river geometry, flow (continuous records or statistical summaries), external loadings, and boundary conditions (USEPA, 1997).

Temporal Feature. This long-term model is limited when addressing time-variable inputs and short-term violations of acute criteria (USEPA, 1997). As input, daily-based time-series flow data are required for continuous simulations (Limo-Tech, 1985).

Constituents Simulated. The DYNTOX model can simulate toxic discharge and conservative and nonconservative substances (Limo-Tech, 1985).