FINAL REPORT

WASH MODEL THEORY DOCUMENTATION

Prepared for
South Florida Water Management District

September 12, 2008

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The WaSh model is a coupled watershed water quality model (WaSh) originally developed with funding from the South Florida Water Management District (SFWMD) for simulating conditions in the Saint Lucie Estuary (SLE) basins. WaSh is a time-dependent, coupled hydrologic and hydraulic simulation model. It includes representation of basic processes such as infiltration, runoff, evapotranspiration, percolation, groundwater flow, surface water flow, point sources and losses, and water quality fate and transport. It also includes many special features specifically required to simulate conditions in the SLE basins, such as irrigation demand and supply, high water table conditions, fully coupled groundwater and surface interactions, reservoirs and Stormwater Treatment Areas (STAs), and flow structures.

During the application of the WaSh model over the past few years, numerous enhancements to model algorithms have been made and additional algorithms have been added to increase capabilities. Most recently the ability to use spatially variable rainfall, enhanced structure representations, and the simulation of Dissolved Oxygen and Phytoplankton Dynamics have been added to the WaSh model.

The fundamental time step for the model is one day, and output from the model is provided in daily increments. However, certain model algorithms operate at shorter time steps (30 minutes to one hour), which are required to provide accurate representations of physical processes and provide numerical stability. General model outputs are daily time series of flows, stages, water quality loads and concentrations at points along the surface water flow system. Simulation results at the basin outfall can be provided at one-half hour intervals, for the purpose of viewing diurnal fluctuations in the dissolved oxygen levels due to phytoplankton production and respiration.

The model is supported by a Graphical User Interface (GUI) that is developed as an ArcView extension. The GUI is divided into two modules. The first module provides functions for configuring the model using GIS data. Once a model is configured, the second module provides the user with functions to modify the model, execute simulations and post process model outputs. The WaSh model GUI is not described in this report, which is intended to document the WaSh model theory and structure.

The purpose of this report is to provide documentation of the current WaSh model and provide additional verification and sensitivity analysis. This documentation is divided into three parts. The first part is a description of the WaSh model theory, model equations and numerical solution methods. In the second section, data required to configure and operate the model are described, and in the third section; a series of simulation results are provided for the purpose of model verification and sensitivity.

The WaSh model consists of four basic components: (1) a cell-based representation of surface hydrology, (2) a cell-based representation of subsurface hydrology (groundwater), (3) a reach network that represents streams, rivers, estuaries and canals, and (4) reservoirs and STAs. Each of these components is shown in Figure 2.1. In addition to providing a representation of surface hydrology, each cell can optionally store surface water in a system of tertiary canals. These canals receive direct surface runoff; convey water to the reach network, reservoirs and STAs; and interact with the groundwater (more information is provided in the runoff routing section).

The basin can be considered a bounded system with distinct sources and sinks. The sources and sinks, also identified in Figure 2.1, are:

1) Rainfall
2) Transpiration/Evaporation
3) Point sources or sinks
4) Percolation of a deep aquifer
5) External sources of irrigation water
6) Discharge from the basin

The first three items are user-specified input to the model, whereas the last three items are calculated internally by the WaSh model. External irrigation supplies are irrigation water that is supplied from outside the system, either from another basin or from the deep aquifer. The WaSh model calculates the external supply as the part of the irrigation demand that cannot be met with internally stored water (see Section 3.1.1 on the irrigation module for details).

A functional schematic of the WaSh model components and how they interact is shown in Figure 2.2. This figure also serves as a summary level block diagram of the WaSh model computer program. The computations are divided into four groups:

1) Hydrology calculations
2) Cell discharge routing
3) Component interactions
4) Individual component dynamics

For each time increment, the surface hydrology routine produces a surface and subsurface (percolation) discharge for each cell. The cell's percolated water is routed to the groundwater, and the surface discharge is routed to another cell's surface water, or to one of the receiving water bodies, i.e., either the tertiary canals, reach network, or reservoirs and STAs. The decision as to where each cell's surface discharge is routed depends on the basin geometry and on user-controlled setup of the WaSh model. The surface hydrology simulation is based on the HSPF algorithms (Bicknell et al., 1997; Johanson et al., 1981).

There is some coupling between the cell hydrology routines and the other components, due to possible high groundwater conditions or irrigation demand. The high groundwater module will reduce percolation when the groundwater rises into the surface moisture. When a cell's irrigation module is active, it will sense deficiencies in the moisture zones and calculate an irrigation demand to replenish the deficiency. The demand is allocated by the user to tertiary canals, the reach network and reservoirs, as well as to external sources. The demand is extracted from each component during the component simulation.

After the discharges are routed, the exchange of water between components is calculated. All four components can interact with each other, via groundwater-surface water exchanges, pumping, and gravity flow.

Once the fluxes between components are calculated, the response of each component is determined. The groundwater model consists of an unconfined aquifer, intended to represent the surficial water table. The reach network model is based on the one-dimensional shallow water wave equation, and includes branching and representation of structural control on flow and stages. The tertiary canals are represented in each cell as a storage potential, with flow controlled by user-specified parameters describing weir configurations and pumping operations. The reservoirs and STAs are also represented using a storage potential with six different flow control options for controlling flow into and out of the facilities.

The basic time period for generating model output is one day, with flows, loads and other fluxes provided as daily averages. However, certain processes are simulated using a smaller time step in order to properly resolve the system dynamics. The cell hydrology calculations are simulated with a one-hour time step. Surface water dynamics in the reach network, tertiary canals and reservoirs and STAs are completed on a 5-minute time step, and the cell-to-cell groundwater flows are calculated with a daily time step. However, the groundwater exchanges with surface water (reservoirs, tertiary canals and the reach network) are calculated using a 5-minute time step. Flux rates between components using different time steps are aggregated, as needed, in order to preserve mass balance.

The water quality component of WaSh is based on the time-dependent scalar transport equations and is directly coupled to the flow model. There are two options for simulating water quality, the basic option (BWQ) and the advanced option (AWQ). The basic option consists of simulating the runoff and transport of five water quality constituents, Total Suspended Solids (TSS) and dissolved and particulate nitrogen and phosphorus. The constituent transport is based on mass conservation, but includes first-order decay and settling and re-entrainment of TSS and particulate fractions of nitrogen and phosphorus.

The AWQ option is based on the non-linear dissolved oxygen (DO) balance and eutrophication model as described in the WASP model documentation (Ambrose et al., 1988). There are eight constituents (state-variables): ammonia, nitrate, inorganic phosphorus, phytoplankton carbon, carbonaceous biochemical oxygen demand, dissolved oxygen, organic nitrogen, and organic phosphorus. The run-off and transport portion of the advanced water quality option is identical to that of the basic option. The primary difference occurs in the surface water bodies, for which the transformations between state-variables are also simulated in the AWQ option. Also, each reach in the reach network can be divided into an upper and lower section. Vertical diffusion between the upper and lower section can be simulated also, by specifying a diffusion rate. This capability was added to improve representation of conditions in which there are significant vertical variations in the water quality constituents.

The WaSh model also supports the implementation of numerous Best Managements Practices (BMPs) used to control the flow and water-quality characteristics of the basins. The BMPs are divided into two general categories, explicitly represented, and implicitly represented BMPs. Explicitly represented BMPs include structures that are included directly in the drainage system.

These consist of detention and retention basins and certain irrigation practices. Implicitly represented BMPs include a wide variety of practices, ranging from filter strips to grazing practices, and are represented as modifications to model parameters controlling runoff quantity and quality.

The basin domain is divided into cells using a uniform grid network. Figure 3.1 shows a typical grid network, with 2000-foot-square cells overlaying the C-24 basin. The X-direction is to the east, and the Y-direction is to the north. Those cells intersecting the basin are labeled active. Cells lying outside the basin boundaries are labeled inactive and are not used in the model. Each cell represents a discrete part of the basin and has associated physical characteristics. The primary physical characteristics are:

1) land use
2) soil type
3) ground elevation
4) ground slope
5) cell area
6) tertiary canal length
7) tertiary canal width
8) tertiary canal bottom elevation

The area for cells that intersect the basin boundary includes only the area within the basin boundary, and therefore the cell area may vary for those cells along basin boundaries. Also, when the footprint of a reservoir or STA intersects a cell, the cell's area may be reduced by the area of the footprint of the reservoir or STA in the cell. If tertiary canals are present in the cell, the total length of all canals in the cell are computed, and total canal length, bottom elevation and width are included as a cell attribute.

Hydrology is modeled individually for each cell using the PWATER and IWATER modules of the USGS HSPF Version 12 model. The PWATER routine simulates rainfall, evaporation (and evapotranspiration), infiltration, percolation and surface runoff. Version 12 includes recent model enhancements that simulate irrigation demand (AQUA TERRA, 1998) and high water table conditions (AQUA TERRA, 1996).

The PWATER module code was directly incorporated into the WaSh code, with modifications to provide links to the WaSh code and to revise the algorithms for evaporation, high water table, irrigation and groundwater simulations. The last modification was implemented because the WaSh model uses a distributed groundwater model rather than the storage-discharge relationship in the original HSPF model. The changes to the irrigation module and high water table module were sufficiently significant that new subroutines were developed. Also, the IWATER module was rewritten as a new subroutine, using the original HSPF IWATER code and the HSPF manual as guidance. This approach was adopted because the IWATER routine is relatively simple, and the new code was much easier to link with other modules in the WaSh code.

3.1 SIMULATION OF PERVIOUS CELL FRACTION

A block diagram of the PWATER algorithm, as it is described in the HSPF documentation, is provided in Figure 3.2. There are five storages identified which can be considered the state variables. The fluxes into and out of each storage are functions of the storages and model parameters. The first storage, CEPS, represents interception storage. The surface storage represents water ponded on the soil surface. The lower zone storage, LZS, represents pore water that can only be removed via transpiration. Upper zone storage, UZS, represents pore water that can percolate under the influence of gravity. Interflow storage, IFWS, represents subsurface water that discharges directly to surface water bodies rather than percolating to the water table. The equations used to calculate the fluxes can be found in the HSPF documentation (Bicknell et al., 1997; Johanson et al., 1981). This PWATER algorithm has been modified slightly to accommodate the irrigation module, and these modifications are discussed in Section 3.1.1.

In addition to the standard PWATER runoff algorithm, the WaSh model also includes an option for using a rating curve to simulate surface discharge. The rating curve consists of a depth-discharge relationship which is defined by the user, using five points to describe the curve. The rating curve approach can be selected using the RO_OPT flag, and when selected, it replaces the standard algorithm for calculating SURO during each time interval.

The PAN coefficient method for specifying potential evapo-transpiration (PET) used in HSPF has been replaced with a Penman-Montieth PET. The Penman Montieth calculation has a similar structure to that of the PAN coefficient, except that the coefficients can vary both with land use and season (i.e., monthly).

The model parameters for the PWATER as they are implemented in WaSh are listed in Table 3.1:

Table 3.1 PWATER Module Parameters and Descriptions

HSPF PWATER Parameter (GUI Name)	Description
CEPSC	Interception storage capacity (inches)
DEEPFR	Fraction of infiltration going to deep aquifer
UZSN	Upper zone nominal storage (inches)
NSUR	Manning's n for land surface
IRC	Interflow Recession Constant
INTFW	Interflow coefficient
LZETP	Lower zone evaporation potential (fraction)
LZSN	Lower zone nominal storage (inches)
INFILT	Infiltration rate (inches/hr)
INFEXP	Parameter in infiltration function
INFILD	Parameter in infiltration function
LSUR	Length of element (cell length) (feet)
SLSUR	Slope of land surface (from topography)
BASETP	Base flow (riparian) evaporation (fraction)
AGWETP	Groundwater evaporation potential (fraction)
PET Coefficient	Evaporation scale factor (fraction, varies by month)
RO_OPT	Flag used to select HSPF surface runoff or rating curve approach
Rating curve*	Set of five depth-discharge points defining curve

***optional**

Values for all parameters can vary between cells depending on the cell attributes of land use and soil type.

3.1.1 Irrigation Module

The irrigation module for HSPF that was developed by AQUA TERRA (1998) has been incorporated in WaSh with some modifications. The modifications were applied primarily to simplify the interaction between the groundwater and the moisture zone. The module code as re-written for implementation into WaSh and a description of the revised algorithm are provided below. The irrigation demand monitors the moisture in the soil zones and generates a demand for water based on the existing moisture relative to user-specified desired moisture levels. After the demand is calculated, the algorithm tries to meet the demand by supplying water from a number of sources. Water is extracted from the sources and then applied as irrigation. A number of application methods are represented.

One other enhancement of the WaSh model includes the capability to pump water from the reach network to the tertiary canals to help meet irrigation demand. The WaSh model can be configured such that during the simulation, if the supply from the cell's tertiary canals is limited because the tertiary canals are completely drained, water can be pumped from the reach network to the cell's tertiary canals. This capability is described in more detail in Section 6.0 on the reach network.

The demand is calculated according to the following algorithm, which is a modified version of the method developed by AQUA TERRA. The algorithm requires that the depth of the moisture zone be calculated so that it can be compared to the depth of the user-prescribed root zone depth. This is necessary to determine the moisture deficiency in the root zone. The moisture zone depths are not a defined quantity in the original HSPF PWATER algorithm. However, AQUA TERRA (1998) determined that the lower zone becomes essentially saturated when the moisture content (LZS) is about four times the value for nominal storage (LZSN). For the upper moisture zone, UZS, the ratio is about 2.5. Using the porosity, the depths of each zone can be found as:

$$D_L = \frac{4 * LZSN}{n_{micro}}$$

$$D_U = \frac{2.5 * UZSN}{\rho - n_{micro}} \qquad (1)$$

where D_L and D_U are the depths of the respective zones, and p is the porosity and n_{micro} is the fraction of pore space in which water is prevented from percolating due to surface tension. The user must also specify a root zone depth D_R. The root zone depth must be smaller than the larger of D_L and D_U. Otherwise, the moisture will never saturate the root zone, and an endless demand will be created in the model.

The irrigation demand algorithm is cast in terms of inches of water rather than depths for simplicity. The maximum storage capacity in each of the moisture zone is:

$$CAP_L = 4\ LZSN$$

$$CAP_U = 2.5\ UZSN \qquad (2)$$

And the total soil moisture capacity is:

$$CAP_{TOT} = CAP_U + CAP_L \qquad (3)$$

The capacity within the root zone is:

$$CAP_R = (n_{micro} + n_{macro})\, D_R \tag{4}$$

The actual soil moisture content is:

$$SM_{ACT} = UZS + LZS \tag{5}$$

And the actual storage within the root zone is:

$$\mathrm{SM_R} = \mathrm{SM_{ACT}} \frac{\mathrm{CAP_R}}{\mathrm{CAP_{TOT}}} \tag{6}$$

A irrigation demand is created when the actual moisture content is less than a user specified minimum moisture content MC_{MIN}, expressed as a fraction of the maximum capacity. Thus, when:

$$\frac{SM_R}{CAP_R} < MC_{MIN} \tag{7}$$

A demand is created. The magnitude of the demand, I_{DEM} is:

$$I_{DEM} = AZRI * (CAP_R - SM_R) \tag{8}$$

Where AZRI is a user specified fraction of the total moisture deficiency (CAP_R-SM_R) that will be met. Finally, the duration of the irrigation application, I_{DUR} is specified in terms of a user specified irrigation rate, I_{RATE}, in inches/hour:

$$\mathrm{I_{DUR}} = \frac{\mathrm{I_{DEM}}}{\mathrm{I_{RATE}}} \tag{9}$$

The algorithm for specifying sources to meet the final demand, I_{DEM}, consists of a prioritized order of sources and target percentages for each source. The three sources available, in order of priority, are local tertiary canals, local groundwater sources or external sources.

The targeted supply from each source is calculated as the prescribed percentage times the total demand. The model automatically looks for canal water first. For instance, if the target percentage for canals were set to 72%, the model would try and satisfy a cell's demand by using canal water until either 72% of the demand was met, or the tertiary canal water was completely drained. If the tertiary canals are drained before the demand is met, the remaining demand is met by the other two sources (surficial and deep aquifers). The supply from these two sources is the sum of their original targeted percentages plus any remaining unsatisfied supply not met by the tertiary canals. If there is an unmet supply from the canals, the supply is proportioned between the surficial and deep aquifers according to the ratio of their target percentages. Since it is possible that the targeted supply from canals may not be completely met during a simulation, the user may need to adjust the targeted value upward to obtain the desired percentage.

The irrigation supply can be applied by a number of options:

(1) added to the rainfall (i.e., spray application)

(2) added to the UZS (drip irrigation)

(3) added to the LZS (subsurface application)

(4) added to the groundwater (crown irrigation)

The user has the option to specify the percentage of irrigation supply that each application option receives.

The model parameters needed to implement the irrigation demand for a cell are shown below in Table 3.2.

Table 3.2 Irrigation Demand Module Parameters and Descriptions

Parameter	Description
IRATE	Irrigation Rate (in/hr)
MC_{min}	Minimum allowable moisture (%)
n_{micro}	Micro-Pore space
D_R	Depth of root zone (ft)
AZRI	Fraction of irrigation demand that will be met
S_CANAL	Percentage of canal water used to meet demand
S_SH_AQ	Percentage of shallow aquifer water used to meet demand
S_EXT	Percentage of external water sources (i.e., deep aquifer)
SPRAY	Percentage of demand applied via spray application
SURF	Percentage of demand applied via surface storage
UPPER_Z	Percentage of demand applied via drip irrigation
LOWER_Z	Percentage of demand applied via subsurface
SHALLOW	Percentage of demand applied via shallow aquifer

3.1.2 High Water Table Algorithm

In some cases, the ground water level may rise to or near the ground surface. This condition is referred to as "high water table". Special handling of this condition is required, since the groundwater will be impinging on the moisture zones (i.e. LZS and UZS). The high water table algorithm originally developed by AQUA TERRA (1996) used the special actions block of the HSPF model to re-route percolated water back to the moisture zones. This approach was adopted because it did not require direct changes to the code, and could be implemented via input commands to HSPF. Although the approach functions as desired, it is cumbersome and makes internal flux tracking difficult because water is constantly re-routed when the groundwater rises into the moisture zones. Because the WaSh model already involved significant changes to various HSPF code, an alternate and simpler approach has been developed. The approach is based on monitoring the groundwater elevation relative to the bottom of the moisture zones (similar to the approach of AQUA TERRA). When the groundwater rises into the moisture zones, the percolation that is calculated in the PWATER module is set to zero, preventing any more discharge to the groundwater. This causes the moisture zones to become saturated, and ultimately infiltration from surface storage is reduced and standing water can develop. This simple approach is shown in Figure 3.3. The bottom elevation of the moisture zones, which is needed to compare to the groundwater elevation, is calculated by subtracting the moisture zone depth D_L from the land surface elevation. When high groundwater conditions exist, the total groundwater elevation is essentially the elevation of the surface storage (SURS). There are no additional parameters needed to implement this algorithm.

3.2 SIMULATION OF IMPERVIOUS CELL FRACTIONS

When a significant portion of a cell has impervious surfaces that drain directly to surface water bodies, the HSPF IWATER module is used to simulate discharges for the impervious fraction. The IWATER module represents interception storage, evaporation and surface runoff and assumes infiltration and percolation are zero. A block diagram of the IWATER algorithm, based on the description in the HSPF documentation (Bicknell et al., 1997) and as coded into the WaSh model, is shown in Figure 3.4.

In the IWATER algorithm, infiltration is zero and the subsurface process is not needed. In order to accommodate impervious surfaces in WaSh, each cell is assigned an impervious fraction IFRAC (which is zero when no significant impervious surfaces exist).

The model coefficients used in the IWATER implementation are listed in Table 3.3 The IWATER algorithm also used the parameters SLSUR, LSUR and PAN, but the values are identical to those used in the PWATER algorithm, and therefore they are only listed in Table 3.2.1.

Table 3.3 IWATER Module Parameters and Descriptions

HSPF PWATER Parameter	Description
IFRAC	Fraction of cell area that is impervious
IRETSC	Impervious interception storage capacity
INSUR	Manning's n for impervious land surface

3.3 CELL-BASED DISCHARGES

Discharges from each cell consist of surface and subsurface discharges. The total surface discharge is comprised of the combination of the surface water and interflow discharges. Thus, at each time interval the fluxes SURO and IFWO (which are the HSPF surface water and interflow discharge flux variable names) that are calculated by the HSPF algorithms are added to form the total surface discharge. If an impervious fraction exists within the cell, then the total surface discharge for the cell is calculated using the weighted sum of the pervious and impervious contributions. Thus the total cell surface discharge is:

$$SURO_{total} = (1 - IFRAC) * (SURO_{pervious} + IFWO_{pervious}) + IFRAC * SURO_{impervious} \quad (10)$$

Most of a cell's subsurface flows are handled directly by the groundwater model. For instance, a cell's calculated infiltration is routed directly to the groundwater, and the groundwater model simulates cell-to-cell groundwater fluxes, as well as exchanges with other surface water bodies, such as the tertiary canals, reaches and reservoirs. However, it may be useful to represent another cell-based subsurface discharge. This discharge may be used to represent sub-grid channels or streams that receive direct groundwater discharges, but are not resolved explicitly in the model configuration. The discharge is calculated using a stage-discharge relationship:

$$GWO = \begin{cases} (H - H_d) * E & \text{if} \quad H > H_d \\ 0 & \text{if} \quad H \le H_d \end{cases} \quad (11)$$

where H is the cell's groundwater elevation, H_d is depth of small drainage features (relative to land surface), and E is the exchange coefficient. The exchange coefficient is calculated as:

$$E = \sqrt{C_{area}} * C_d \qquad (12)$$

where $\sqrt{C_{area}}$ is a length scale based on the cell area, and C_d is a conductance coefficient with units of ft/s. The parameters are described in Table 3.4.

Table 3.4 GW Discharge Parameters for Small Drainage Features

GW Discharge Parameters	Description	GUI Name
H_d	Bottom elevation of small drainage features not explicitly represented by tertiary canals or in reach network	GW_HD
C_d	Conductance controlling discharge from GW to SW for small drainage features.	GW_CD

The groundwater discharge from this algorithm is routed in the same way as $SURO_{total}$ but is retained as a separate quantity within the WaSh model code because its associated water quality will likely be different than that of the surface water. For all subsequent hydrologic or hydraulic discussion in this report, a cell's discharge refers to the combination of $SURO_{total}$ and GWO, and is referred to as Q_{cell}:

$$Q_{cell} = SURO_{total} + GWO \qquad (13)$$

3.4 CELL SURFACE AND SUBSURFACE DISCHARGE ROUTING

A special cell attribute has been developed to identify both cell discharge routing and groundwater exchanges with other objects (i.e., tertiary canals, reservoirs, reaches) in the model. Each cell is labeled as one of six types:

No Feature cell
Canal cell
Reach cell
Canal-Reach cell
Reservoir cell
Canal-Reservoir cell

The designation No feature indicates a cell that does not contain tertiary canals and is not coincident with any other features, such as a reach segment or reservoir. The surface runoff from these cells will be routed to an adjacent cell's surface water based on the local land slope. If a cell's runoff is routed to an adjacent cell that does not have tertiary canals, then the runoff is added to the adjacent cell's surface water storage. In a canal cell, the cell's surface discharge is routed to the cell's tertiary canals, and then from the tertiary canals to a reach or reservoir. In a Reach cell, the cell's groundwater will interact with the surface water in the associated reach, whereas in a No Features cell, the groundwater does not interact with any other objects (except for the cell-to-cell groundwater interactions). A complete list of the surface routing and groundwater interactions is provided in Table 3.5.

Table 3.5 Water Routing Operations for Each Cell Type

Cell Type	Value	Flow Routing Operations
No Feature	F	Cell surface runoff is directed to a nearby cell's surface water
Canal	C	Cell surface runoff is directed to cell's tertiary canals Groundwater and tertiary canal surface water allowed to exchange Tertiary canal water exchanged with a reach or reservoir
Reach	G	Cell surface runoff is directed to the reach segment Groundwater and reach surface water allowed to exchange
Canal-Reach	R	Cell surface runoff is directed to cell's tertiary canals Groundwater can be exchanged with tertiary canal water and with reach Tertiary canal water exchanged with a reach
Reservoir	T	Cell surface runoff is directed to a nearby cell's canals, reach or reservoir Groundwater and reservoir surface water allowed to exchange
Canal-Reservoir	S	Cell surface runoff is directed to cell's tertiary canals Groundwater can be exchanged with tertiary canal water and with reservoir Tertiary canal water exchanged with a reservoir

For each cell in the model, the choice of cell type is guided by the basin characteristics. Large-scale topographic gradients can be used as guidance, but often local knowledge of topographic features and structures must be included in order to properly configure the model. The attribute value is assigned to the cell based on the user's interpretation of the basin characteristics to best reflect the basin's hydrologic and hydraulic properties.

The WaSh has a groundwater module that is based on the numerical solution to the standard groundwater flow equation (Darcy's Law and Continuity) for an unconfined aquifer. The model uses the same grid system as the basin's cell-based hydrology model (i.e. cell-based HSPF) and is applied only to the active cells. The model operates on a daily time step, during which it receives infiltrated water, loses water to evaporation, and exchanges water with adjacent cells and with tertiary canals, reaches and reservoirs/STAs.

4.1 GROUNDWATER MODULE EQUATIONS

The basic governing equation for the groundwater module is:

$$n\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left(K_x(h-h_c)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y(h-h_c)\frac{\partial h}{\partial y}\right)+S_i-S_e+Q_{c-gw}+Q_{r-gw}+Q_{res-gw}$$

(14)

where h is the groundwater elevation relative to the model datum (for instance NGVD), n is the specific yield, K_x and K_y are the hydraulic conductivity in the x-, and y- directions, h_c is the elevation of the aquifer base relative to NGVD, S_i, S_e are source/sink terms representing deep percolation and evapotranspiration, and Q_{c-gw}, Q_{r-gw}, and Q_{res-gw} are exchanges with the canal cells, reaches and reservoirs that are described in Section 8.0.

4.2 HYDROLOGICAL SOURCE TERMS

Two of the source terms on the right-hand side of the equation, S_i and S_e, are outputs from the WaSh hydrology module (specifically, the WaSh implementation of the PWATER algorithm). The deep percolation is set to the HSPF output PERC (see Figure 3.2):

$$S_i = PERC$$

(15)

and the evaporation is set equal to the original HSPF groundwater evaporation rate AGWET:

$$S_e = AGWET$$

(16)

The methods for calculating percolation (PERC) and groundwater ET (AGWET) can be found in the HSPF documentation.

4.3 BOUNDARY CONDITIONS

The only boundary condition is applied automatically and is imposed when an active cell is adjacent to the grid boundary or to an inactive cell. For these conditions, a no-flow condition is imposed along the grid boundary or with an inactive cell.

4.4 NUMERICAL SOLUTION

The governing equation is solved numerically using the basin cell structure. A second-order finite difference approximation is used for the second derivatives, and an explicit backward

$$\frac{1}{n_{i,j}}\frac{h_{i,j}^{m+1}-h_{i,j}^{m}}{\Delta t}=K_x\left[\frac{\left(\frac{h_{i,j}^{m}+h_{i+1,j}^{m}}{2}-h_c\right)}{\Delta x}\left(\frac{h_{i+1,j}^{m}-h_{i,j}^{m}}{\Delta x}\right)-\frac{\left(\frac{h_{i,j}^{m}+h_{i-1,j}^{m}}{2}-h_c\right)}{\Delta x}\left(\frac{h_{i,j}^{m}-h_{i-1,j}^{m}}{\Delta x}\right)\right]+$$

$$Ky\left[\frac{\left(\frac{h_{i,j}^{m}+h_{i,j+1}^{m}}{2}-h_c\right)}{\Delta y}\left(\frac{h_{i,j+1}^{m}-h_{i,j}^{m}}{\Delta y}\right)-\frac{\left(\frac{h_{i,j}^{m}+h_{i,j-1}^{m}}{2}-h_c\right)}{\Delta y}\left(\frac{h_{i,j}^{m}-h_{i,j-1}^{m}}{\Delta y}\right)\right]+S_{i_{i,j}}^{m}-S_{e_{i,j}}^{m}+Q_{c-gw_{i,j}}^{m}+Q_{r-gw_{i,j}}^{m}+Q_{res-gw_{i,j}}^{m} \quad (17)$$

difference approximation is used for the time derivative. By designating the equation parameters and water elevation h for each cell by the indexes i and j, and the time level by the index m, the resulting finite difference equation for each cell is:

where Δt is the time step (one day), and Δx and Δy are the grid cell dimensions in each direction. During each time step, the right-hand side of the equation is evaluated based on current time level conditions, and the new water elevation is found by solving for $h_{i,j}^{m+1}$.

4.5 MODEL PARAMETERS

The model parameters required to configure the groundwater model are listed in Table 4.1.

Table 4.1 Groundwater Model Parameters

Groundwater Model Parameter	Description	GUI Name
n	Specific Yield	Porosity
K_x, K_y	Hydraulic Conductivity (ft/day)	HYDCON
h_c	Aquifer base (ft)	AQFR_BASE
AGWETP	Evaporation parameter	AGWETP

Flow in the cell-based tertiary canal system is represented using a storage-based approach, using the canal water depth D_{tc} as the state variable. The governing equation for each cell's tertiary canals is:

$$\begin{aligned} \frac{dD_{tc}}{dt} &= (F_{in} - F_{out}) / C_{area} \\ H_{tc} &= D_{tc} + C_{be} \\ C_{be} &= \text{'elev'} - C_{dep} \end{aligned} \tag{18}$$

where H_{tc} is the water elevation relative to the model datum, F_{in} and F_{out} are the flows into and out of the canal, C_{area} is the surface area of the canal and C_{be} is the bottom elevation of the canal relative to the model datum. C_{be} is obtained by subtracting the canal depth C_{dep} from the land surface elevation 'elev'. The canal area is defined as:

$$C_{area} = C_w * C_L \tag{19}$$

where C_w and C_L are the canal width and length, and are user-prescribed parameters for each cell. The net flow into or out of the storage is defined as:

$$\begin{aligned} F_{net} &= (F_{in} - F_{out}), \quad \text{where} \\ (F_{in} - F_{out}) &= \sum_{i,j} Q_{cell} + Q_{c-gw} - Q_{c-r} - Q_{c-res} \end{aligned} \tag{20}$$

Here, Q_{cell} is the cell discharge (see section 3.1) for all cells for which the cell discharge has been routed to the cells tertiary canals. $Q_{c\text{-}gw}$, $Q_{c\text{-}r}$ and $Q_{c\text{-}res}$ are flows representing interactions with the cell's groundwater, a reach and/or a reservoir, and are discussed in Section 8.0.

The model parameters for specifying the tertiary canal operation are listed in Table 5.1.

Table 5.1 Tertiary Canal Model Parameters

Tertiary Canal Parameter	Description	GUI Name
C_w	Canal width	CAN_WIDTH
C_L	Canal length	CAN_LENGTH
C_{dep}	Canal depth	CAN_DEPTH

The reach network is intended to provide explicit representation of the major flow conduits in the basin. It is based on the one-dimensional shallow-water wave equation, and includes branching and representation of structural control on flow and stages, interactions with groundwater and with reservoirs and STAs. Figure 6.1 shows a typical reach network, including branches. At each juncture between branches, the two branches are identified as the "upstream" or "downstream" branch for that juncture.

6.1 GOVERNING EQUATIONS

The governing equations for the reach network are:

$$\frac{\partial w_r h_r}{\partial t} + \frac{\partial q_r}{\partial s} = Q_{io}$$
$$\text{where} \quad Q_{io} = \sum_{i,j} Q_{cell} + Q_{re} + Q_e + Q_{c-r} + Q_{r-res} + Q_{r-gw} \tag{21}$$
$$\frac{\partial q_r}{\partial t} + \frac{\partial u q_r}{\partial s} + g w_r h_r \frac{\partial h_r}{\partial s} = -w_r \tau_b - g w_r h_r \frac{\partial \eta_r}{\partial s}$$

where q_r is the flow, u is the width- and depth-averaged flow velocity, g is the acceleration due to gravity, w_r is the channel width, h_r is the water depth (referenced to the channel bed), η_r is the bed elevation (referenced to model datum), t is time and s is distance along the channel. The equation is for a channel with a rectangular cross-section. Here, Q_{cell} is the cell discharge (see Section 3.1) for all cells for which the cell discharge has been routed to the reach. The flux Q_{re} is the net flux due to rainfall and evaporation. The source term Q_e represents external flow sources to the reach, and are provided as a time series in an input file. The source terms Q_{c-r}, Q_{r-res} and Q_{r-gw} represent exchanges between model objects and are described in Section 8.0.

The bottom stress τ_b is based on a Manning's n formulation:

$$\tau_b = \frac{u|u|}{h_r\ n} \tag{22}$$

where n is Manning's n.

6.2 BOUNDARY CONDITIONS

Boundary conditions can be one of two types; a specified flow or specified water elevation. Specified flow conditions are typically used when a flow structure controls the flow out of the system. The water elevation (or head) condition is used when the system drains unobstructed into a receiving water body.

For the specified flow option, the downstream flow q_1' is calculated using an equation for a structure:

$$q_1' = \Im(h_1, \alpha_i,) \tag{23}$$

where α_i are the structure coefficients and h_1 is the water elevation (stage) in the reach.

For tailwater (or specified water elevation) the downstream boundary condition is:

$$h_o = h_s \tag{24}$$

where h_s is the user-specified downstream water elevation.

6.3 NUMERICAL SOLUTION

The governing equations are solved using a semi-implicit finite volume procedure. For this purpose, the reach network is subdivided into a series of interconnected reaches and nodes. The reach and node system, depicted in Figure 6.2 for a single branch of the network, is equivalent to a finite volume staggered grid approach. The index k is used to specify the reach or node. The water depths h_k are defined in each segment, and the flows q_k are defined at each node. Here k refers to the k[th] reach in the reach network. The reach length is designated as Δs_1. Note that the surface water elevation RE_k is equal to the sum of the reach bottom elevation and water depth $h_k+\eta_k$. Using second-order centered finite differences for the spatial derivatives and a first-order forward difference approximation for the time derivatives, the semi-implicit finite difference approximations to the governing equations are:

$$\frac{q_k^{m+1}-q_k^m}{\Delta t}+\frac{F_{k+1/2}^m-F_{k-1/2}^m}{\Delta s_2}+\frac{g\hat{w}_k\hat{h}_h^m\left(h_k^*-h_{k-1}^*\right)}{\Delta s_2}=\hat{w}_k\tau_{bk}-g\hat{h}_k^m\hat{w}_k\left(\frac{\eta_k-\eta_{k-1}}{\Delta s_2}\right) \tag{25}$$

$$\frac{h_k^{m+1}-h_k^m}{\Delta t}-\frac{q_k^{m+1}-q_{k+1}^{m+1}}{\Delta s_k w_k}=Q_{iok} \tag{26}$$

where

$$u_{k+1/2}=\frac{q_k+q_{k+1}}{2h_k w_k},\quad u_{k-1/2}=\frac{q_k+q_{k-1}}{2h_{k-1}w_{k-1}} \tag{27}$$

and

$$F_{k-1/2}^m=\begin{cases}u_{k-1/2}^m q_{k-1}^m, & u_{k-1/2}^m>0\\ u_{k-1/2}^m q_k^m, & u_{k-1/2}^m<0\end{cases} \tag{28}$$

$$F_{k+1/2}^m=\begin{cases}u_{k+1/2}^m q_k^m, & u_{k+1/2}^m>0\\ u_{k+1/2}^m q_{k+1}^m, & u_{k+1/2}^m<0,\end{cases} \tag{29}$$

The bottom stress is:

$$\tau_{bk}=\frac{u_k^m\left|u_k^m\right|}{nh_k^m} \tag{30}$$

The terms $\hat{h}$, $\hat{w}$ and Δs_2 are spatial averages defined as

$$\hat{h}_k = \frac{h_k + h_{k-1}}{2} \quad \hat{w}_k = \frac{w_k + w_{k-1}}{2} \quad \text{and} \quad \Delta_{s_2} = \frac{\Delta s_k + \Delta s_{k-1}}{2} \tag{31}$$

and the index m indicates the time level.

The semi-implicit solution consists of first solving for the flows at the m+1 time level using one momentum equations and two mass conservation equations:

$$\frac{q_k^{m+1} - q_k^m}{\Delta t} + \frac{F_{k+1/2}^m - F_{k-1/2}^m}{\Delta s_2} + \frac{g\hat{w}_k \hat{h}_h^m \left(h_k^* - h_{k-1}^*\right)}{\Delta s_2} = \hat{w}_k \tau_{bk} - g\hat{h}_k^m \hat{w}_k \left(\frac{\eta_k - \eta_{k-1}}{\Delta s_2}\right) \tag{32}$$

$$\frac{h_k^* - h_k^m}{\Delta t} - \frac{q_k^{m+1} - q_{k+1}^m}{\Delta s_k w_k} = Q_{iok} \tag{33}$$

$$\frac{h_{k-1}^* - h_{k-1}^m}{\Delta t} - \frac{q_{k-1}^m - q_{k1}^{m+1}}{\Delta s_k w_k} = Q_{iok} \tag{34}$$

Which represent three algebraic equations for the three unknowns q_k^{m+1}, h_k^* and h_{k-1}^*. When all of the flows are updated, Equation 33 is used to update the stages, h_k^{m+1}.

When the reach network contains branches, the flows and stages for the reaches in each branch are determined at the branch juncture using the same procedure as for nodes and elements along a branch. Thus, q_k^{m+1} and h_k^* are associated with the downstream end of the branch, and h_{k-1}^* is associated with the reach in the main stem to which the branch connects. Figure 6.3 shows an example of a branched system.

6.4 STRUCTURES

Structures can be placed anywhere in the reach network, including branch junctures. When a structure is present, the flow at that node is determined at the beginning of the time step using the structure flow formulas, and its value replaces the momentum equation for that node. The structure options represented in the WaSh model are a sharp-crested weir, a pump, a culvert and a gate. Multiple structures can be applied to one node. The flows are calculated assuming steady flow using standard structure equations. For the weir, the flow is defined in terms of the upstream and downstream segment water elevations:

$$q_k = \begin{cases} C_w * W_w * (h_k - h_w)^{1.5} & h_k > h_w,\ h_{k-1} < h_w \\ -C_w * W_w * (h_{k-1} - h_w)^{1.5} & h_{k-1} > h_w,\ h_k < h_w \\ Cw * (\overline{h_{k-1} + h_k})\sqrt{|h_{k-1} - h_k|} & h_k, h_{k-1} > h_w \\ 0 & h_k, h_{k-1} \le h_w \end{cases} \tag{35}$$

where h_k is the upstream reach stage, h_{k-1} is the downstream reach stage, C_w is the weir coefficient, and W_w is the weir width. The weir crest elevation is h_w and can be set with a single value or with seasonal values.

The pumping options is typically applied to allow for upstream pumping for conditions in water will be pumped upstream across the structure to provide irrigation supply when the water elevations of the upstream reaches are low. The parameters defining the pumping option are the pumping rate $P_{RATE,}$ and the upstream and downstream elevation criteria. Pumping can be specified in the upstream and downstream directions, each with different elevation criteria. For upstream pumping, the pumping is triggered when the water elevation in the upstream segment is below the criteria h^U_{crit} and the water elevation in the downstream segment is above the criteria h^D_{crit}. For upstream pumping:

$$q_k = \begin{cases} -P_{IRR} & h_k < h^U_{crit} \text{ and } h_{k-1} > h^D_{crit} \\ 0 & h_k > h^U_{crit} \text{ or } h_{k-1} < h^D_{crit} \end{cases} \qquad (36)$$

And for downstream pumping:

$$q_k = \begin{cases} P_{IRR} & h_k > h^U_{crit} \text{ and } h_{k-1} < h^D_{crit} \\ 0 & h_k < h^U_{crit} \text{ or } h_{k-1} > h^D_{crit} \end{cases} \qquad (37)$$

The parameters defining a culvert are the bottom invert elevation, B_{CUL}, the culvert length L_{CUL}, Manning's n for the culvert and the cross section type, which is either a box or oval. For the box type, the height 'a' and width 'b' need to be specified, and for the oval type the short and long axis lengths, 'a' and 'b' need to be specified.

The flow equation used to represent a culvert is:

$$q_k = \begin{cases} A_{CUL}\sqrt{\dfrac{|h_k - h_{k-1}|}{\dfrac{0.9}{g} + \dfrac{6.25n^2 L_{CUL}}{R^{4/3}}}} & \hat{h} > B_{CUL} \\ 0 & \hat{h} < B_{CUL} \end{cases} \qquad (38)$$

Where $\hat{h}$ is the average water elevation in the upstream and downstream segments, g is the acceleration due to gravity, R is the hydraulic radius and A_{CUL} is the cross-sectional area of the flow through the culvert. The culvert cross sectional area is dependent on the headwater h_k and tailwater h_{k-1} elevations relative to the culvert bottom invert. For a box culvert, they are:

$$A_{CUL} = \begin{cases} (\hat{h} - B_{CUL}) * b & \hat{h} < (B_{CUL} + a) \\ a * b & \hat{h} > (B_{CUL} + a) \end{cases} \qquad (39)$$

$$R = \begin{cases} \dfrac{A_{CUL}}{2*(a+b)} & \hat{h} > (B_{CUL} + a) \\ \dfrac{A_{CUL}}{b + 2*(\hat{h} - B_{CUL})} & \hat{h} < (B_{CUL} + a) \end{cases} \qquad (40)$$

where $\hat{h} = \dfrac{h_k^m + h_{k-1}^m}{2}$.

For an oval cross-section, the area and hydraulic radius are:

$$A_{CUL} = \begin{cases} \left[-1.15\left(\dfrac{\hat{h}-B_{CUL}}{a}\right)^3 + 1.72\left(\dfrac{\hat{h}-B_{CUL}}{a}\right)^2 + 0.43\left(\dfrac{\hat{h}-B_{CUL}}{a}\right)\right]\pi ab/4 & \hat{h} < B_{CUL} + a \\ \pi ab/4 & \hat{h} \ge B_{CUL} + a \end{cases}$$

(41)

$$R = \begin{cases} \dfrac{A_{CUL}}{P} & \hat{h} \ge B_{CUL} + a \\ \dfrac{A_{CUL}}{\left[2.15\left(\dfrac{\hat{h}-B_{CUL}}{a}\right)^3 - 3.30\left(\dfrac{\hat{h}-B_{CUL}}{a}\right)^2 + 2.15\left(\dfrac{\hat{h}-B_{CUL}}{a}\right)\right]P} & \hat{h} < B_{CUL} + a \end{cases}$$

where $P = \pi\left[3\left(\dfrac{a+b}{2}\right) - \sqrt{\left(\dfrac{3a+b}{2}\right)\left(\dfrac{a+3b}{2}\right)}\right]$. (42)

Implicit in these formulas are a horizontal culvert (no slope) and both the tailwater and headwater elevations are above the culvert bottom invert elevation.

The parameters for the gate are the gate width W_G, the gate bottom elevation B_G, the gate coefficient G_{coeff}, the gate opening rate RO_G, the gate closing rate RC_G, the maximum gate opening GO_{max}, and criteria for triggering the gate opening and closing. A gate can be triggered to open when the upstream water elevation is above a certain criteria, GO_{crit}^U and the downstream water elevation is below a certain criteria, GO_{crit}^D. Either criterion can be omitted by using a constant high or low value for the criteria. The gate closing is triggered when the upstream water elevation is below a specified criteria, GC_{crit}^U.

The gate opening, O, is adjusted each time step according to:

$$O^{m+1} = \begin{cases} O^m + RO_G\,\Delta t & h_k > GO_{crit}^U,\quad h_{k-1} < GO_{crit}^D,\quad O^m < GO_{max} \\ O^m - RC_G\Delta t & h_k < GC_{crit}^U,\quad O^m > 0 \\ O^m & \text{all other conditions} \end{cases} \tag{43}$$

At anytime the gate is open the flow rate is:

$$q_k = G_{coeff}\ O\ W_G\sqrt{2 * g * (h_k - h_{TW})} \tag{44}$$

where the tailwater h_{TW} is:

$$h_{TW} = \max(B_G, h_{k-1}) \tag{45}$$

6.5 MODEL PARAMETERS

The model parameters for the reach network are listed in Table 6.1.

Table 6.1 Reach Network Model Parameters

Item	Parameter	Description	GUI Name
Reaches	w_r	width	WIDTH
	Δs	length	
	η_r	bottom elevation	ELEVATION
	n	Manning's n	MANNING'S_N
Weir	C_w	weir coefficient	Accessed by menus with descriptive names
	W_w	width	
	h_w	crest elevation	
Pump	h^U_{crit}	Elevation criteria in upstream reach (feet)	
	h^D_{crit}	Elevation criteria in downstream reach (feet)	
	P_{IRR}	Pumping rate (inches/hour)	
Culvert	B_{cul}	Bottom invert of culvert (feet)	
	n	Manning's n	
	L_{CUL}	Length of Culvert	
	a	Height of Culvert Opening	
	b	Width of Culvert Opening	
Gate	W_G	Gate width	
	B_G	Gate bottom invert	
	G_{coeff}	Gate coefficient	
	RO_G	Opening rate	
	RC_G	Closing rate	
	GO_{max}	Maximum opening	
	GO^U_{crit}	Upstream critical elevation for opening	
	GO^D_{crit}	Downstream critical elevation for opening	
	GC^U_{crit}	Upstream critical elevation for closing	

Reservoirs and STAs are represented as a flow in the cell-based tertiary canal system, which is represented using a storage-based approach with the reservoir volume V_R as the state variable. Reservoirs and STAs are modeled identically, and are differentiated by the user only by the water quality parameter values assigned to represent the reservoir or STA. For simplicity, the term "reservoir" is used to refer to both reservoirs and STAs. The reservoirs are characterized in WaSh by their geometric footprint, total footprint area A_R, and bottom elevation η_R. The geometry and location of the reservoir are included in the WaSh model because the reservoirs will often be sufficiently large that they may cover numerous cells in the cell-based hydrology model. When this occurs, the cells that are completely covered by the reservoir are excluded from the model. Furthermore, the area for any cells that intersect the reservoir/STA boundary will be reduced to reflect the area subsumed by the reservoir. Figure 7.1 shows a typical configuration identifying inactivated cells and those cells for which the cell area has been reduced.

7.1 GOVERNING EQUATIONS

The governing equation for the reservoir or STA is based on mass balance, and is:

$$\frac{\partial V_R}{\partial t} = \sum Q_{cell} - Q_{ext} + Q_{io} + R\ A_R - E\ A_R \tag{46}$$

The flux Q_{io}, representing exchanges with other objects in the WaSh model, is defined as:

$$Q_{io} = Q_{c-res} + Q_{res-gw} + Q_{res-res} + Q_{r-res} \tag{47}$$

the components of which are described in Section 8.0.

The water elevation relative to the model datum, h_{res}, in the reservoir is defined as

$$h_{res} = \eta_R + \frac{V_R}{A_R} \tag{48}$$

where η_R is the bottom elevation of the reservoir.

Each reservoir in the WaSh model is divided into five compartments that are arranged serially. This is done to accommodate the effects of retention time on the water quality in the reservoirs. All of the inflows are directed to the first segment, and all flows out of the reservoir leave from the fifth segment. Figure 7.2 shows the basic configuration. The basic flow equation is solved for each time step to obtain the new reservoir volume, and then the flows between segments are obtained using the level-pool assumption (water surface is the same for all segments). Referring to the basic reservoir flow equation above, the inflows are defined as:

$$Q_{in} = \sum Q_{cell} + \max(Q_{io}, 0) + R\ A_R \tag{49}$$

$$Q_{out} = -Q_{ext} - \left|\min(Q_{io}, 0)\right| - E\ A_R \tag{50}$$

In this formulation, the component flows comprising Q_{io} are defined as positive when they flow into the reservoir, and negative when they flow out of the reservoir.

The flux Q_{ext} represents potential discharges from the reservoir out of the model domain. In the WaSh model, these flows are represented as flow over a weir. The equation for the external flow is:

$$Q_{ext} = \begin{cases} C_w^e * W_w^e * (h_r - h_w^e)^{1.5} & h_r > h_w^e \\ 0 & h_r \le h_w^e \end{cases} \tag{51}$$

where h_w^e is the elevation of the weir crest, C_w^e is the weir coefficient and W_w^e is the weir width.

7.2 NUMERICAL SOLUTION

The change in reservoir volume for a time step is:

$$\Delta V_R = (Q_{in} - Q_{out})\Delta t \tag{52}$$

The reservoir volume and the five segment volumes V_{Ri} are updated according to:

$$\begin{aligned} V_R^{n+1} &= V_R^n + \Delta V_R \\ V_{Ri}^{n+1} &= V_{Ri}^n + \frac{\Delta V_R}{5} \end{aligned} \tag{53}$$

The flows between segments for a time step are obtained as follows:

$$\begin{aligned} q_1 &= \Delta V_{R1} - Q_{in} \\ q_2 &= \Delta V_{R2} - q_1 \\ q_3 &= \Delta V_{R3} - q_2 \\ q_4 &= \Delta V_{R4} - q_3 \\ q_5 &= Q_{out} \end{aligned} \tag{54}$$

Note that the internal segment volumes and flows are only needed for the water quality simulation.

7.3 MODEL PARAMETERS

The model parameters for the reservoir or STA are listed in Table 7.1.

Table 7.1 Reservoir/STA Model Parameters

Reservoir Parameter	Description
A_R	Bottom area
η_R	Bottom elevation
Geo-referenced footprint	Used to deactivate cells and/or adjust cell areas

The routing schemes for each individual component described in Sections 4.0 through 7.0 for groundwater, tertiary canals, reaches and reservoirs contained numerous interactions between components. The terms are:

$$Q_{c-gw},\quad Q_{r-gw},\quad Q_{res-gw},\quad Q_{c-r},\quad Q_{c-res},\quad Q_{r-res},\quad Q_{res-res} \tag{55}$$

When a cell has tertiary canals, the canals will exchange water with the cell's groundwater according to a conductance-based formulation:

$$Q_{c-gw} = \left(h_{gw} - h_{tc}\right)C \tag{56}$$

where h is the groundwater elevation in the cell containing the tertiary canals and C is the conductance. The discharge can be positive or negative depending on the relative elevations of the groundwater and canal surface water. The conductance is defined as:

$$C = \frac{C_L\ P\ K_{c-gw}}{d}, \tag{57}$$

where

$K_{c\text{-}gw}$ = hydraulic conductivity of stream bed material

P = wetted perimeter of stream cross section (C_w+2*D_{tc}),

d = thickness of stream bed material (set to 1 foot)

C_L = canal length

When a cell intersects a reach in the reach network, the reach will exchange water with the cell's groundwater according to a conductance-based formulation:

$$Q_{r-gw} = \left(h_{gw} - hr\right)C \tag{58}$$

where h is the groundwater elevation in the cell containing the tertiary canals, C is the conductance, and A is the cell area. The conductance is defined as:

$$C = \frac{\Delta S\ P\ K_{r-gw}}{d}, \tag{59}$$

where

$K_{r\text{-}gw}$ = hydraulic conductivity of stream bed material

P = wetted perimeter of stream cross section (W_r+2*h_r),

d = thickness of stream bed material (set to 1 foot)

ΔS = reach length

The cells intersecting the reservoir are those that have had their cell area reduced due to the reservoir footprint overlying the cell. Cells that are completely covered by the reservoir are removed from the model and are not considered for groundwater exchanges.

When a cell intersects a reservoir, the reservoir will exchange water with the cell's groundwater according to:

$$Q_{res-gw} = \frac{K_{res-gw}(h_{res} - h_{gw})(h_{res} + h_{gw})\sqrt{A_1}}{2\sqrt{A_2}} \tag{60}$$

where

$K_{res\text{-}gw}$ =hydraulic conductivity of stream bed material

A_1 = the area of the cell covered by the reservoir or STA

A_2 = the area of the cell not covered by the reservoir or STA

For each cell with tertiary canals, there are two options for controlling the discharge from the tertiary canal to the designated reach, either weir-controlled flow or pumped flow. For weir-controlled flow the equation is:

$$Q_{c-r} = \begin{cases} C_{c-r} * W_{c-r} * (h_{tc} - h_{rw})^{1.5} & h_{tc} > h_{rw} \\ 0 & h_{tc} \le h_{rw} \end{cases} \tag{61}$$

Where $C_{c\text{-}r}$ is the weir coefficient, $W_{c\text{-}r}$ is the weir width and h_{rw} is the weir crest elevation. For the pumping option, the tertiary canals are pumped at the pumping rate P_{tc} when the water elevation rises above a prescribed level $H_{tc\text{-}max}$, and then pumping continues until the water level in the tertiary canals drops below another prescribed level, $H_{tc\text{-}cutoff}$. This approach allows for simulation of “pumping down” the tertiary canals, a practice used in many agricultural areas during the wet season. The pump discharge is sent to the designated reach.

Also, the tertiary canal pumps can be used to pump from the reach to the tertiary canals. This option is used when an irrigation demand exists for a cell, and the supply from the tertiary canal is exhausted because the tertiary canals become dry. When these conditions occur, the WaSh model will pump water from the reach at a rate P_{tc} until the canals reach the $H_{tc\text{-}cutoff}$ level

For each cell with tertiary canals, there are two options for controlling the discharge from the tertiary canal to the designated reservoir, either weir-controlled flow or pumped flow. These options and the option for pumping from the reservoir to the tertiary canal to replenish irrigation water supply are essentially identical to those for the tertiary canal-reach exchange. For weir-controlled flow the equation is:

$$Q_{c-res} = \begin{cases} C_{c-res} * W_{c-res} * (h_{tc} - h_{resw})^{1.5} & h_{tc} > h_{resw} \\ 0 & h_{tc} \le h_{resw} \end{cases} \tag{62}$$

where $C_{c\text{-}res}$ is the weir coefficient, $W_{c\text{-}res}$ is the weir width and h_{resw} is the weir crest elevation. For the pumping option, the tertiary canals are pumped at the pumping rate P_{tc} when the water elevation rises above a prescribed level $H_{tc\text{-}max}$, and then pumping continues until the water level in the tertiary canals drops below another prescribed level, $H_{tc\text{-}cutoff.}$ The pump discharge is sent to the designated reservoir.

Also, the tertiary canal pumps can be used to pump from the reservoir to the tertiary canals. This option is used when an irrigation demand exists for a cell, and the supply from the tertiary canal is exhausted because the tertiary canals become dry. When these conditions occur, the WaSh model will pump water from the reach at a rate P_{tc} until the canals reach the $H_{tc\text{-}cutoff}$ level.

The model parameters for all groundwater and tertiary canal exchanges are listed in Table 8.1.

Table 8.1 Model Parameters

Flow	Parameter	Description	GUI Name	GUI Table
Q_{c-gw}	$K_{c\text{-}gw}$	Hydraulic conductivity of stream bed material	CAN_CONDUCTANCE	Tertiary Canals Hydraulics and Hydrology
Q_{r-gw}	$K_{r\text{-}gw}$	Hydraulic conductivity of stream bed material	CONDUCTANCE	Reach: Hydrography and Hydrology
Q_{res-gw}	$K_{res\text{-}gw}$	Hydraulic conductivity of material near base of reservoir	CONDUCTANCE	Reservoir menus
Q_{c-r}	$C_{c\text{-}r}$	Weir coefficient	WEIR-COEFF	Tertiary Canal Hydraulics and Hydrology
	$W_{c\text{-}r}$	Weir width	WEIR_WIDTH	
	H_{rw}	Weir crest elevation	WEIR_ELEV	
	P_{tc}	Canal pumping rate	CANPMPPARM	
	$H_{tc\text{-}max}$	Critical elevation to start pumping	PMP_UC	
	$H_{tc\text{-}cutoff}$	Critical elevation to stop pumping	PMP_LC	
Q_{c-res}	$C_{c\text{-}res}$	Weir coefficient	WEIR-COEFF	Tertiary Canal Hydraulics and Hydrology
	$W_{c\text{-}res}$	Weir width	WEIR_WIDTH	
	H_{resw}	Weir crest elevation	WEIR_ELEV	
	P_{tc}	Canal pumping rate	CANPMPPARM	
	$H_{tc\text{-}max}$	Critical elevation to start pumping	PMP_UC	
	$H_{tc\text{-}cutoff}$	Critical elevation to stop pumping	PMP_LC	

There are four possible exchanges between reaches and reservoirs supported in the WaSh model. The exchanges are defined in Table 8.2 below:

Table 8.2 Specific Reach-Reservoir Exchanges

Flow	Description	Equation	Parameter Definition
Q^{1}_{r-res}	Base Reservoir inflow	$= f_1 * \max(Qb - Qc, 0)$	$\mathbf{f_1}$ is fraction of basin outfall flow Q_b that is diverted to reservoir or STA, Q_b must exceed $\mathbf{Q_c}$ before flow is diverted, Q_c is user-specified critical flow, Q_b is reach flow.

Flow	Description	Equation	Parameter Definition
Q^2_{r-res}	Release to Reach	$= C_w * W * (h_R - H_W)^n$	**C_w** and **n** are weir coefficients, **H_w** is the elevation of the weir, and **W** is the weir width
Q^3_{r-res}	Irrigation Releases	$= \begin{cases} 0 \text{ if } H_p > H_c \\ Q_{irr} \text{ if } H_p < H_c \end{cases}$	If canal water (reach network) level H_p is lower than critical level **H_c**, the water is supplied from reservoir at rate **Q_{irr}**
Q^4_{r-res}	Emergency Release to Reach	$= C_w * W * (h_R - H_W)^n$	**C_w** and **n** are weir coefficients, **H_w** is the elevation of the weir, and **W** is the weir width
Q^5_{r-res}	Seepage Flow to Reach	$= C_s * (h_R - H_s)$	H_s is the surface water elevation in the designated canal or reach, **Cs** scales the seepage flow

*Bold characters in parameter definition column indicate model parameter.

There is one possible exchange between two reservoirs. This exchange was originally designed to simulate a reservoir discharging to an STA. The exchange is depicted in Figure 8.1 and described in Table 8.3.

Table 8.3 Reservoir-Reservoir Exchange

Flow	Description	Equation	Parameter Definition
$Q_{res-res}$	Reservoir-to-STA	$Q_2 = f_2 * V_R$	**f_2** is fraction of reservoir volume released each day

*Bold characters in parameter definition column indicate model parameter.

The water quality component of WaSh supports two options: (1) basic water quality and (2) advanced water quality. The basic water quality option consists of production and transport of five constituents: total suspended sediments (TSS), particulate nitrogen and phosphorus (PN and PP) and soluble nitrogen and phosphorus (SN and SP). Production is modeled using event mean. Transport through canals, reaches and in reservoirs is modeled using conservation of mass and either first-order decay or settling. When settling is included, the transport model also includes a stream bed simulation.

The advanced water quality option consists of simulating the production, transport and in-stream processes for dissolved oxygen, carbonaceous oxygen demand, ammonia, nitrate, organic nitrogen, organic phosphorus and soluble phosphorus. The event mean concentration approach is used for all constituents except for dissolved oxygen. Transport is modeled using conservation of mass, including settling; and in-stream processes are modeled using non-linear kinetic routines adopted from the WASP model (Ambrose, et al., 1988).

In all water quality simulations, the state-variables are the constituent concentrations in mass/unit volume.

9.1 BASIC WATER QUALITY SIMULATION

9.1.1 Production Terms

The source terms for the five basic water quality constituents PN, PP, SN, SP and TSS are modeled using an EMC approach. The EMC approach consists of assigning each cell runoff concentrations based on measured data for the cell's land use attribute. For each land use, the surface discharge and groundwater discharges are assigned concentrations for each water quality constituent based on a compilation of site-specific or regional data. The EMC values can vary monthly and be specified separately for each land use and soil type. In addition, the surface water concentrations can vary with runoff intensity according to the following function:

$$C^{surface} = C^{surface}_{emc}(m)*(1+(SURO_{total}/C_1)\hat{}C_2) \quad (63a)$$

where C_1 and C_2 are user-specified parameters, and $SURO_{total}$ is the surface runoff. $C^{surface}_{emc}$ is the value for the constituent for each month m. The EMC concentrations for pervious and impervious contributions are assumed to be the same. The individual EMC coefficients used to set each surface discharge value are listed in Table 9-1a. The dissolved and particulate fraction EMC values are derived from the total and fraction input parameters. For example, for dissolved nitrogen,

$$C^{surface}_{emc} = BWQ\_SW\_N\_Diss\_frac * BWQ\_SW\_TN\_EMC\_Mon_i \quad (63b)$$

And for the particulate nitrogen,

$$C^{surface}_{emc} = (1 - BWQ\_SW\_N\_Diss\_frac) * BWQ\_SW\_TN\_EMC\_Mon_i \quad (63c)$$

A separate set of EMC values can be set for groundwater discharges:

$$C^{gw} = C^{gw}_{emc} \quad (64)$$

The individual EMC coefficients used to set each groundwater discharge concentration are listed in Table 9-1b.

The associated mass flux (or load) for the cell's discharge is for a constituent:

$$L_{cell}=C^{surface}*SURO_{total}+C^{gw}*GWO \quad (65)$$

The parameters for the basic water quality production model are listed in Table 9.1.

Table 9.1a. Basic Water Quality Model Surface Runoff Production Term Parameters

Parameter (GUI Name)	Description
C_1	Coefficient in surface discharge concentration controlling affect of discharge intensity on concentration
C_2	Coefficient in surface discharge concentration controlling affect of discharge intensity on concentration
BWQ_SW_TN_EMC_Mon$_i$	Value of $C_{ems}^{surface}$ EMC for surface runoff concentration of Total Nitrogen
BWQ_SW_N_Diss_frac	Fraction of Total Nitrogen that is Dissolved
BWQ_SW_TP_EMC_Mon$_i$	Value of $C_{ems}^{surface}$ EMC for surface runoff concentration of Total Phosphorus
BWQ_SW_P_Diss_frac	Fraction of Total Phosphorus that is Dissolved
BWQ_SW_TSS_EMC_Mon$_i$	Value of $C_{ems}^{surface}$ EMC for surface runoff concentration of Total Suspended Solids

Table 9.1b. Basic Water Quality Model Groundwater Discharge Production Term Parameters

Parameter (GUI Name)	Description
BWQ_GW_TN_EMC_Mon$_i$	Value of $C_{ems}^{surface}$ EMC for surface runoff concentration of Total Nitrogen
BWQ_GW_N_Diss_frac	Fraction of Total Nitrogen that is Dissolved
BWQ_GW_TP_EMC_Mon$_i$	Value of $C_{ems}^{surface}$ EMC for surface runoff concentration of Total Phosphorus
BWQ_GW_P_Diss_frac	Fraction of Total Phosphorus that is Dissolved

9.1.2 Transport in Reaches

Transport of water quality constituents in each reach network is modeled using the depth- and width-averaged scalar mass transport equation. The WaSh model represents surface water transport for all five constituents. For TSS and particulate nutrients, a simulation of the deposition and erosion from the channel bed is also simulated. The governing equation for transport in the reach network is:

$$\frac{\partial VC_m}{\partial t} + \oint qC_m = S_m \tag{66}$$

where V is the reach volume, C_m is the depth-, and width- averaged concentration for the m_{th} constituent in the surface water, q is the flow in the reaches, S_m represents external sources or sinks, and t is time.

The finite difference equation for a reach is:

$$\frac{C_{k,m}^{n+1} * V_k^{n+1} - C_{k,m}^{n} * V_k^{n}}{\Delta t} + F_{k+1/2}^{n+1} - F_{k-1/2}^{n+1} = (D_{k+1/2}^{n} - D_{k-1/2}^{n}) + S_{k,m} \tag{67}$$

where V_k is the k^{th} reach volume, $S_{k,m}$ is the source for the k^{tn} reach and F is the constituent advective flux defined as:

$$F_{k+1/2} = \begin{cases} C_k^{n+1} q_{k+1}^{n+1}, & q_{k+1}^{n+1} > 0 \\ C_{k+1}^{n+1} q_{k+1}^{n+1}, & q_{k+1}^{n+1} < 0, \end{cases} \tag{68}$$

$$F_{k-1/2} = \begin{cases} C_{k-1}^{n+1} q_k^{n+1}, & q_k^{n+1} > 0 \\ C_k^{n+1} q_k^{n+1}, & q_k^{n+1} < 0 \end{cases} \tag{69}$$

and D are the diffusive fluxes defined as

$$D_{k+1/2}^{n} = w_{k+1/2}\, h_{k+1/2}^{n} \left(\frac{D_{L,k} + D_{L,k+1}}{2} \right) \left(\frac{C_{k+1}^{n} - C_k^{n}}{\Delta s_{k+1/2}} \right) \tag{70}$$

The volumes V_k^{n+1} and the flows q_k^{n+1} are already known from the flow solution, requiring a solution only for the new concentrations C_k^{n+1}. These equations are solved using an explicit upwind difference scheme.

The source term $S_{k,m}^{n}$ represents contributions from the surface runoff, exchanges with other model objects (groundwater, reservoirs, etc.), and first-order decay. For the particulate fractions and TSS, settling is also represented. The individual components of the source term are:

$$S_{k,m}^{n} = \sum_{i,j} L_{cell,m} + Q_e C_{e,m} + Q_{c-r} C_{c-r,m} + Q_{r-res} C_{r-res,m} + Q_{r-gw} C_{r-gw,m} - C_{k,m}\delta_m - F_{b,m} \tag{71}$$

where $L_{cell,m}$ is the cell runoff and the summation is over all cells discharging to the reach, $C_{e,m}$ are the concentrations in the source terms, δ_m is the first-order decay rate and $F_{b,m}$ is the settling flux. The settling flux is also a source in the bed evolution equations. The concentrations for the exchange fluxes, Q_{c-r}, Q_{r-res} and Q_{r-gw} depend on the direction of the flow. When the flow is from the reach, the concentrations are the reach concentrations. When the flow is from the other object (groundwater, reservoir, etc.) to the reach, then the concentrations are those in the other object. This approach is essentially equivalent to an explicit upwind differencing scheme.

For TSS and particulate constituents, exchange with and accumulation in the bed is also simulated. The governing equation for the bed is:

$$\frac{\partial B_{k,m}}{\partial t} = F_{k,m}$$
$$F_{k,m} = -E_{k,m} + D_{k,m} \tag{72}$$

where $B_{k,m}$ is the concentration in the bed (mg/ft^2), and F is the flux between the bed and the water column defined in terms of an erosional flux $E_{k,m}$ and depositional flux $D_{k,m}$. The governing equation for the bed is solved using an explicit backward differenced finite difference scheme.

The erosional and depositional fluxes are defined as:

$$E_{k,m} = \begin{matrix} E_r \tau_{k,m}, & \tau_{k,m} > \tau_c & \text{and } B_{k,m} > 0 \\ 0, & \tau_{k,m} < \tau_c & \text{or } B_{k,m} = 0 \end{matrix}$$

$$D_{k,m} = \frac{C_{k,m} w_s * A_r}{D_r} \tag{73}$$

where E_r and τ_c are the erosion rate parameter and critical stress for erosion. A_r is the area of the bed (i.e., $W_r * L_r$) and D_r is the water depth in the reach. The stress is calculated each time and is based on Manning's Equation, which relates the stress to the instantaneous flow, stage and Manning's n parameter. Erosion is limited to only material that has settled during the simulation. Thus, no erosion of the original canal bed is allowed.

The parameters required to implement the transport and bed simulations are listed in Table 9.2.

Table 9.2 Reach Basic Water Quality Simulation Parameters

Parameter	Description	GUI Name
δ_m	First order decay coefficient	DN_DEC, DP_DEC
w_s	Settling speed, one for each constituent	PN_SETTLING, PP_SETTLING, TSS_SETTLING
τ_c	Critical stress for erosion	T_CRIT
E_r	Erosion Rate coefficient	EROS
D_L	Lateral diffusion coefficient	D_LATERAL

9.1.3 Transport in Reservoirs

Transport in reservoirs is represented using the scalar transport equation with settling and first-order decay. The settling flux is a loss from the system. The governing equation for transport in each of the five cells representing the reservoir is:

$$\frac{\partial V_k C_{k,m}}{\partial t} + \oint q_k C_{k,m} = S_{k,m} \tag{74}$$

where V_k is the reach volume, $C_{k,m}$ is the concentration for the m_{th} constituent in the surface water, q_k is the flow, and $S_{k,m}$ represents external sources or sinks. Here k is the index identifying the cell and t is time.

The finite difference equation for a cell is:

$$\frac{C^{n+1}_{k,m} * V^{n+1}_{k} - C^{n}_{k,m} * V^{n}_{k}}{\Delta t} + C^n_{k,m} q_k - C^n_{k-1,m} q_{k-1} = S_{k,m} \quad (75)$$

where V_k is the k^{th} reservoir cell volume, and $S_{k,m}$ is the source for the k^{th} reservoir cell. The volumes V^{n+1}_k and the flows q^{n+1}_k are already known from the flow solution, requiring a solution only for the new concentrations $C^{n+1}_{k,m}$.

The source term components are cell dependent. For the upstream cell (#1), which receives all inflows, the source term is:

$$S_{1,m} = \sum L_{cell} + Q_{io} C_{io} - \delta_m C_{1,m} - w_s C_{1,m} A_c \quad (76)$$

Where the summation is for all grid cells (not reservoir cells) that drain to the reservoir, δ_m is the first-order decay coefficient, w_s is the settling speed and A_c is the bottom area of the reservoir cell. The term $Q_{io} C_{io,m}$ represents the fluxes due to exchanges with other model objects (e.g., reaches, groundwater) that are into the reservoir. The concentration $C_{io,m}$ is the concentration in the other object.

For the interior cells (#2, #3 and #4) the source term is:

$$S_{k,m} = -\delta_m C_{k,m} - w_s C_{k,m} A_c \quad (77)$$

and for the last cell (#5), the source term is:

$$S_{5,m} = -Q_{io} C_5 - \delta_m C_{5,m} - w_s C_{5,m} A_c \quad (78)$$

The flux Q_{io}, represents the flows from the reservoir to other objects (i.e. reaches, groundwater, etc.).

The parameters used in the reservoir water quality simulation are listed in Table 9.3.

Table 9.3 Reservoir Basic Water Quality Simulation Parameters

Parameter	Description	GUI Name
δ_m	First order decay coefficient	DN_DEC, DP_DEC
w_s	Settling speed, one for each constituent	PN SETTLING, DP_SETTLING, TSS_SETTLING

9.2 ADVANCED WATER QUALITY

The WaSh model Advanced Water Quality module is adopted from the WASP model non-linear DO and EUTRO modules. The constituents modeled are:

Ammonia: C_{NH3}

Nitrate: C_{NO3}

Inorganic Phosphorus: C_{IP}

Phytoplankton Carbon: C_{PhyC}

Carbonaceous Biochemical Oxygen Demand: C_{BOD}

Dissolved Oxygen: C_{DO}

Organic Nitrogen: C_{ON}

Organic Phosphorus: C_{OP}

The model includes production; transport through the tertiary canals, reaches and reservoirs; and the simulation of in-stream processes within the reaches. For the purpose of simulating vertical stratification of water quality variables, the WaSh model provides the option for dividing each reach into an upper and lower layer, with diffusion-type exchanges occurring between layers. The flow in each layer is proportioned by the depth so that the flow speeds through the upper and lower layer are identical.

Additional time series input data requirements are the irradiation time series (hourly) and water temperature time series (hourly).

9.2.1 Production Terms

The EMC approach is applied for all simulated constituents except for dissolved oxygen (DO) in the surface runoff. Thus, for all other constituents, the concentrations in surface and groundwater discharges are controlled using the same parameterization as used in the basic water quality model. The same model parameters listed in Table 9.1 are used in the advanced water quality model. DO in the surface runoff is assigned a value at saturation based on the water temperature. The equation used for DO saturation is:

$$DOsat\ (mg/L) = 0.0032\ T^2 - 0.3254\ T + 14.328, \qquad (79)$$

where T is the water temperature in deg. C. The parameters used to specify the runoff concentrations are listed in Table 9.4.

Table 9.4 Advanced Water Quality Surface Runoff Concentration Terms

Parameter (GUI names)	Description
$AWQ\_SW\_TN\_EMC\_Mon_i$	Monthly Runoff Concentration for Total Nitrogen
AWQ_SW_Amm_frac	Fraction of TN that is ammonia
AWQ_SW_Nitrate_frac	Fraction of TN that is Nitrate
$AWQ\_SW\_TP\_EMC\_Mon_i$	Monthly Runoff Concentration for Total Phosphorus
AWQ_SW_Inorganic_P_frac	Fraction of TP that is inorganic
$AWQ\_SW\_BOD\_EMC\_Mon_i$	Monthly Runoff Concentration for Total BOD
AWQ_SW_Phyt_Seed	Runoff Concentration of Phytoplankton

**the extension _Mon$_i$ indicates that 12 individual values exist, one for each month from January through December*

The runoff concentrations of nitrate and ammonia are specified as a fraction of the total nitrogen TN. The runoff concentration of organic nitrogen is then the remainder:

$$ON\_EMC\_Mon_i = (1\text{-}Amm\_frac\text{-}NO3\_frac)*TN\_EMC\_Mon_i \quad (80)$$

Similarly for organic phosphorus:

$$OP\_EMC\_Mon_i=(1\text{-}IP\_frac)*TP\_EMC\_Mon_i \quad (81)$$

There are two options for setting the groundwater discharge concentrations. The first approach is to set the runoff as a proportion of the surface water concentration. The second approach is to set the groundwater concentrations independently using monthly EMC values. The parameters used in the first approach are listed in Table 9.5a and those for the second approach are listed in Table 9.5b.

Table 9.5a Advanced Water Quality Groundwater Discharge Concentration Terms for First Approach

Parameter (GUI names)	Description
AWQ_GW_ON_Frac	Fraction applied to surface water ON to get groundwater ON discharge concentration
AWQ_GW_Amm_Frac	Fraction applied to surface water Amm to get groundwater Amm discharge concentration
AWQ_GW_Nitrate_Frac	Fraction applied to surface water Nitrate to get groundwater Nitrate discharge concentration
AWQ_GW_OP_Frac	Fraction applied to surface water OP to get groundwater OP discharge concentration
AWQ_GW_OrthoP_Frac	Fraction applied to surface water IP to get groundwater IP discharge concentration
AWQ_GW_DO_Frac	Fraction applied to surface water DO to get groundwater DO discharge concentration
AWQ_GW_BOD_Frac	Fraction applied to surface water BOD to get groundwater BOD discharge concentration
AWQ_GW_Phyt_Frac	Fraction applied to surface water Phytoplankton to get groundwater Phytoplankton discharge concentration

Table 9.5b Advanced Water Quality Groundwater Discharge Concentration Terms for Second Approach

Parameter (GUI names)	Description
AWQ_GW_TN_EMC_Mon$_i$	Monthly Groundwater Discharge Concentration for Total Nitrogen

Parameter (GUI names)	Description
AWQ_GW_Amm_frac	Fraction of TN that is ammonia
AWQ_GW_Nitrate_frac	Fraction of TN that is Nitrate
AWQ_GW_TP_EMC_Mon$_i$	Monthly Groundwater Discharge Concentration for Total Phosphorus
AWQ_GW_Inorganic_frac	Fraction of TP that is inorganic
AWQ_GW_BOD_EMC_Mon$_i$	Monthly Groundwater Discharge Concentration for Total BOD
AWQ_GW_DO_EMC_Mon	Monthly DO Discharge Concentration for Dissolved Oxygen
AWQ_GW_Phyt_EMC_Mon	Monthly Phyt Discharge Concentration for Phytoplankton

*****_the extension _Mon$_i$ indicates that12 individual values exist, one for each month from January through December._

9.2.2 Transport

Transport in reaches, reservoirs and tertiary canals for the advanced water quality option are identical to transport used in the basic water quality model, except for the following additions:

- transport in the reaches includes the simulation of an upper and lower layer
- atmospheric deposition of nitrogen and phosphorus is included
- first order decay is replaced with in-stream process represented in the WASP model non-linear D.O. balance

9.2.2.1 Vertical Mixing in Reaches

Diffusion between the upper and lower layers is simulated with a user-prescribed constant vertical diffusion coefficient. Also, settling from the upper layer is a source to the lower layer, and settling from the lower layer is a loss from the system. During each time step, the flux F_v from the upper to the lower layer is calculated for each constituent as:

$$F_v = E_v \frac{(C_U - C_L)}{0.5 * D} + w_s * C_U \qquad (82)$$

where C_U and C_L are the constituent concentrations in the upper and lower layers, D is the total depth in the reach and E_v is the vertical exchange coefficient.

There is no bed layer modeled. If settling of a constituent is modeled, then any settling from the lower layer is lost from the system.

Table 9.6 Reach Mixing and Settling Parameters

Parameter	Description	GUI Name
Ev	Vertical Mixing Coefficient	MIX_VERTICAL
w_s	Settling speed (listed individually for each constituent in Section 9.2.3)	VSI

9.2.2.2 Atmospheric Deposition in Reservoirs, Reaches and Tertiary Canals

Both wet and dry Nitrogen and Phosphorus atmospheric deposition are simulated and represent additional sources to the reaches, reservoirs and tertiary canals. Wet deposition is characterized as a concentration associated with rainfall. Dry deposition is characterized as a flux, in mass/year/unit area. The depositions are applied in the model as additional source terms in nitrogen and phosphorus kinetic equations (Section 9.2.3). For wet deposition the fluxes are:

$$Q_{atm}^{wet} = Q_r * C_r \tag{83}$$

and for dry deposition:

$$Q_{atm}^{dry} = F^{dry} \tag{84}$$

Where Q_r is the rainfall rate, C_r is the concentration of each constituent in the rainfall, and F^{dry} is the dry deposition rate. Wet and dry deposition is modeled for nitrate, ammonia and inorganic phosphorus. Dry deposition is assumed to occur at all times except when it is raining. These fluxes are added to the source term $S_{n,m}^{k}$ in Equations 71 and 76 when the advanced water quality simulation is used.

Table 9.7 Atmospheric Deposition Parameters

Parameter	GUI Name	Description
C_r^{NO3}	NO3_WETDEP$_i$	Rainfall concentration of nitrate
C_r^{NH3}	Amm_WETDEP$_i$	Rainfall concentration of ammonia
C_r^{IP}	IP_WETDEP$_i$	Rainfall concentration of inorganic phosphorus
F_{NO3}^{dry}	NO3_DRYDEP$_i$	Dry deposition rate of nitrate
F_{NH3}^{dry}	Amm_DRYDEP$_i$	Dry deposition rate of ammonia
F_{IP}^{dry}	IP_DRYDEP$_i$	Dry deposition rate of inorganic phosphorus

the subscript i indicates that12 individual values exist, one for each month, using 1 through 12 to indicate the months January through December.

9.2.3 In-Stream Process Descriptions

The governing equations for the in-stream DO balance are adopted from the WASP model non-linear DO and EUTRO modules. The governing equations and parameter definitions with ranges for values are given below for each of the eight state-variables. These equations are applied to reservoirs, reaches and the tertiary canals. If an upper and lower layer are represented in the reaches, then the state variables are assigned to both the upper and lower reach layers, and each equation is solved independently in each layer. All of the loads from cell runoff and other inflows are assigned to the upper layer. Thus, sources of concentration in the lower layer are due to diffusion with and settling from the upper layer. Each equation is solved numerically using an explicit upwind first order difference scheme. For each time step, the in-stream calculations are completed prior to the transport calculations.

The reaction term for phytoplankton kinetics are defined as:

$$\frac{\partial C_{PhyC}}{\partial t} = \left(G'_p - D_p - k_s\right) C_{PhyC} \tag{85}$$

where G_p is the growth rate, (day$^{-1)}$), D_p is the death rate, (day^{-1}), and k_s = settling rate in (day^{-1}).

The balance between the magnitude of the growth rate and death rate (together with the transport, settling, and mixing) determines the rate at which phytoplankton mass is created in the volume of water V.

The specific growth rate G'_P in any reach is related to G_p, the maximum growth rate at 20^o C and optimum light and nutrient levels, via the following equation:

$$G'_p = G_p \, X_{RT} \, X_{RI} \, X_{RN} \tag{86}$$

where each X term represents a reduction in growth due to non-optimal conditions.

X_{RN} = the nutrient limitation factor as a function of dissolved inorganic phosphorus and nitrogen.

The temperature correction factor, X_{RT} is:

$X_{RT} = \theta^{T-20}$, where θ = Temperature coefficient and T is the temperature. (86a)

The instantaneous depth-averaged light factor, X_{RI}, is:

$$X_{RI} = \frac{e}{K_e D} f \left[\exp\left\{ \frac{-I_a}{I_S} \exp\left(-K_e D\right) \right\} - \exp\left(\frac{-I_a}{I_S} \right) \right] \tag{87}$$

where f is the fraction of day that is daylight, I_a is the average incident light intensity during daylight hours just below the surface, I_s is the saturating light intensity of phytoplankton and K_e is the light extinction coefficient, and D is the water depth. The average incident light intensity, I_a, is provided as a time-series input.

The extinction coefficient is comprised of a constant and a phytoplankton concentration dependent part, which simulates the effect of phytoplankton growth on limiting light transmission:

$$K_e = K_e^1 + K_e^2 C_{PhyC} \tag{88}$$

Reduction in optimal growth due to limiting nutrient, X_{RN}, is

$$X_{RN} = Min\left(\frac{C_{IN}}{K_{mN} + C_{IN}}, \frac{C_{IP}}{K_{mP} + C_{IP}} \right) \tag{89}$$

The constants, K_mN and K_mP are the half-saturation constants and are the nutrient concentrations at which the growth rate is half the saturated growth rate.

The phytoplankton death rate is:

$$D_p = k_{Dp} C_{PhyC} \quad (90)$$

where k_D (day^{-1}) is the death rate coefficient.

Losses due to settling are described by:

$$k_s = \frac{V_{s4}}{D} \quad (91)$$

where k_s is the effective phytoplankton settling or loss rate, day^{-1}, and v_{s4} is the net settling velocity of phytoplankton. Table 9.8 summarizes the new model parameters and typical values.

Table 9.8 Phytoplankton Reaction Terms

Parameter Description	Notation	Values	Units	GUI Name
Extinction Coeff.	K_e^1	0.1-5	m-1	KE1
Extinction Coeff.	K_e^2	0.1-5	Mg/L-m	KE2
Fraction of day that is daylight	f	0.3-0.7	-	Frac_Daylight
Maximum Growth Rate	G_p	2.0	day^{-1}	GP
Temperature Coefficient	Θ_{Gp}	1.068	None	THETAGP
Carbon-Chlorophyll Ratio*	E_c	20-50	-	EC
Light Intensity at Saturation	Is	200-500	langleys/day	LIS
Half-Saturation Constant for Nitrogen	K_{mN}	25.0	µg N/L	KMN
Half-Saturation Constant for Phosphorus	K_{mP}	1.0	µg P/L	KMP
Endogenous Respiration	k_{1R}	0.125	day^{-1}	K1R
Temperature Coefficient	Θ_{1R}	1.045	None	THETA1R
Phytoplankton Settling Velocity	V_{s4}	0.1	m/day	VS4
Death Rate	k_{Dp}	0.02	day^{-1}	KDP
Incident Radiation	I_a		langleys/day	Input Time Series file

** The Carbon-chlorophyll ratio, E_c, is not used expressly in the model. However it I used to convert phytoplankton carbon mass to Chlorophyll-a in the output files.*

The two phosphorus species models are organic phosphorus and inorganic (orthophosphate) phosphorus. Organic Phosphorus can be divided into particulate and dissolved fractions for the purpose of simulating settling processes using a constant partitioning factor. The governing equations are:

Organic Phosphorus

$$\frac{\partial C_{OP}}{\partial t} = D_p a_{pc} f_{op} C_{PhyC} - k_{83}\, \theta_{83}^{(T-20)} \left(\frac{C_{PhyC}}{K_{mPc} + C_{PhyC}} \right) C_{op} - \frac{V_{s2}}{D} C_{op} \quad (92)$$

Inorganic Phosphorus

$$\frac{\partial C_{IP}}{\partial t} = D_p a_{pc} \left(1 - f_{op}\right) C_{PhyC} + k_{83}\, \theta_{83}^{(T-20)} \left(\frac{C_{PhyC}}{K_{mPc} + C_{PhyC}} \right) C_{op} - G_p a_{pc} C_{PhyC} \quad (93)$$

Table 9.9 summarizes phosphorus reactions terms:

Table 9.9 Phosphorus Reaction Terms

Parameter Description	Notation	Values	Units	GUI Name
Phosphorus to carbon ratio	a_{pc}	0.025	mg P/mg C	APC
Dissolved organic phosphorus mineralization at 20°C	k_{83}	0.22	day^{-1}	K83
Temperature Coefficient	θ_{83}	1.08	None	THETA83
Half saturation constant for phytoplankton limitation of phosphorus recycle	K_{mPc}	1.0	mg C/L	KMPC
Fraction of dead and respired phytoplankton recycled to the organic phosphorus pool	f_{op}	0.5	none	FOP
Organic phosphorus settling velocity	V_{s2}	-	m/day	VS2

Three nitrogen variables are simulated: organic nitrogen, ammonia, and nitrate. Organic nitrogen can be divided into dissolved and particulate fractions for the purpose of simulating settling processes using a constant partitioning factor. The governing equations are:

Organic Nitrogen

$$\frac{\partial C_{ON}}{\partial t} = D_p a_{NC} f_{ON} C_{PhyC} - k_{71} \theta_{71}^{(T-20)} \left(\frac{C_{PhyC}}{K_{mPc} + C_{PhyC}} \right) C_{ON} - \frac{V_{s3}}{D} C_{ON} \quad (94)$$

Ammonia Nitrogen

$$\frac{\partial C_{NH3}}{\partial t} = D_p a_{NC} \left(1 - f_{ON}\right) C_{PhyC} + k_{71} \theta_{71}^{(T-20)} \left(\frac{C_{PhyC}}{K_{mPc} + C_{PhyC}} \right) C_{ON} - G_p a_{NC} P_{NH3} C_p$$

$$- k_{12} \theta_{12}^{(T-20)} \left(\frac{C_{DO}}{K_{NIT} + C_{DO}} \right) C_{NH3} \quad (95)$$

Nitrate Nitrogen

$$\frac{\partial CNO3}{\partial t} = k_{12}\,\theta_{12}^{(T-20)}\left(\frac{C_{DO}}{K_{NIT}+C_{DO}}\right)C_{NH3} - G_p a_{NC}\left(1-P_{NH3}\right)C_p - k_{2D}\,\theta_{2D}^{(T-20)}\left(\frac{k_{NO3}}{k_{NO3}+C_{DO}}\right)C_{NO3} \qquad (96)$$

Where P_{NH3} is the ammonia preference term, approximated by:

$$P_{NH3} = C_{NH3}\left(\left(\frac{C_{NO2}}{(K_{mN}+C_{NO3})(K_{mN}+N_{H3})}\right)+\left(\frac{K_{mN}}{(K_{mN}+C_{NO3})(C_{NO3}+C_{NH3})}\right)\right) \qquad (97)$$

Table 9.10 summarizes the reaction terms for the nitrogen equations.

Table 9.10 Nitrogen Reaction Terms

Parameter Description	Notation	Values	Units	GUI Name
Nitrogen to carbon ratio	a_{NC}	0.025	mg N/gm C	ANC
Organic Nitrogen mineralization at 20°C	k_{71}	0.075	day^{-1}	K71
Temperature Coefficient	θ_{71}	1.08	None	THETA71
Nitrification Rate	k_{12}	0.09-0.12	day^{-1}	K12
Temperature Coefficient	θ_{12}	1.08	-	THETA12
Half Saturation rate for oxygen	K_{NIT}	2.0	mg 0_2/L	KNIT
Denitrification rate at 20°C	K_{2D}	0.09	day^{-1}	K2D
Temperature Coefficient of Denitrification rate	θ_{2D}	1.045	-	THETA2D
Michaelis constant for denitrification	K_{NO3}	0.1	mg O_2/L	KNO3
Fraction of dead and respired phytoplankton recycled to the ammonia nitrogen pool	f_{ON}	0.5	0	FON
Organic nitrogen settling velocity	V_{s3}	-	m/day	VS3

The governing equation for Carbonaceous Biochemical Oxygen Demand is:

$$\frac{\partial C_{BOD}}{\partial t} = a_{OC}k_{12}C_{PhyC} - k_D\theta_D^{T-20}\left(\frac{C_{BOD}}{k_{BOD}+C_{BOD}}\right)C_s - \frac{v_{s5}}{D}C_{BOD} - 2.86\,K_{2D}\theta_D^{T-20}\left(\frac{K_{NO3}}{k_{NO3}+C_{DO}}\right)C_{NO3} \qquad (98)$$

and for dissolved oxygen:

$$\frac{\partial C_{DO}}{\partial t} = k_2(C_s - C_{DO}) - k_D\theta_D^{T-20}\left(\frac{C_{BOD}}{k_{BOD} + C_{BOD}}\right)C_{BOD} - 4.57k_{12}\theta_{12}^{T-20}\left(\frac{C_{NO3}}{k_{NIT} + C_{NO3}}\right)C_{NO3} - \frac{SOD}{D}\theta_2^{T-20} + G_p(2.67 + 4(1 - P_{NH3}))C_{PhyC} - 2.67k_{1R}\theta_{1R}^{T-20}C_{PhyC} \quad (99)$$

where C_s is the DO saturation level. The WaSh model simulates water quality in an upper and lower layer for each reach, and the thickness of each layer is user-specified. In general, all of the above equations are solved for each time step for each layer in each reach. For the DO equation, the re-aeration term (1st term) is only applied to the upper layer, and the SOD term is only applied to the lower layer. Table 9.7 summarizes the reaction parameters.

Table 9.11 CBOD and DO Reaction Terms

Description	Notation	Range	Units	GUI Name
Oxygen to carbon ratio	a_{OC}	32/12	mg O_2/mg C	AOC
Deoxygenation rate @ 20˚C	k_D	0.21-0.16	day^{-1} --	KD
Temperature Coefficient	θ_D	1.047		THETAD
Half saturation constant for oxygen limitation	K_{BOD}	0.5	mg O_2/L	KBOD
Sediment Oxygen Demand	SOD	0.2-4.0	g/m^2-day	SOD
SOD Temperature coefficient	Θ_2	1.08	--	THETA2
BOD settling velocity	v_{s5}	--	m/day	VS5
Reaeration Rate	k_2	--	day^{-1}	K2
Endogenous Respiration Temperature coefficient	θ_{1R}		--	THETA1R
Endogenous Respiration	k_{1R}		day^{-1}	K1R

Best Management Practices (BMPs) are represented in the WaSh model either explicitly or implicitly. The explicit method consists of small or "local" detention or retention basins. These basins are represented as storage capacities and are assigned to each cell designated with the BMP. These structures intercept runoff generated in each cell and release it at a prescribed rate. Implicit BMPs represent the effect of numerous management practices, such as the application of filter strips, or critical area planting, and are represented in the model by adjusting the value of model input parameters.

10.1 EXPLICIT BMPS: LOCAL STORAGE STRUCTURES

Relatively small local detention or retention ponds are represented in the model as an additional storage component in each cell. Surface runoff generated in the cell is first routed to the storage, and if capacity is available, the runoff is captured. The storage then drains at a prescribed rate (zero for retention). If appropriate, a first-order decay rate can be supplied, which causes the water quality constituents to decrease over time while in storage. The storage is defined in terms of rainfall capacity (e.g., ¼ inch) and is multiplied by the cell area to determine the storage capacity V_{max} for the cell. During each time step the volume of water stored and the runoff are updated. If the actual storage V_{det} is less than capacity V_{max}, the storage is increased and the cell runoff is updated according to:

$$\begin{aligned} &\text{if } \left(V_{det}^{n} < V_{max}\right), \text{then} \\ &V_{det}^{n+1} = V_{det}^{n}\left(1 - \Delta t\ \gamma_{det}\right) + SURO_{total} \\ &SURO_{total} = V_{det}^{n} \Delta t \gamma_{i} \end{aligned} \qquad (100)$$

where γ_{det} is the drainage rate coefficient.

If the storage is at or above capacity, then:

$$\begin{aligned} &\text{if } \left(V_{det}^{n} \geq V_{max}\right), \text{then} \\ &V_{det}^{n+1} = V_{det}^{n}\left(1 - \Delta t \gamma_{det}\right) \\ &SURO_{total} = SURO_{total} + V_{det}^{n} \Delta t \gamma_{det} \end{aligned} \qquad (101)$$

After the detention pond storage is updated to account for inflow and discharge, it is adjusted to account for direct rainfall and evaporation:

$$V_{det}^{n+1} = V_{det}^{n+1} + A_{det} * (R - E) \qquad (102)$$

where A_{det} is the surface area of the detention basin and R and E are the rainfall and evaporation.

Note that a retention pond can be simulated by setting γ_{det} =0.

Water quality is also adjusted based on conservation of mass and first-order decay in the basins. The concentration of each constituent modeled is first updated using conservation of mass to determine the new detention pond concentration C_{det}^{k}, where k refers to the constituent (soluble nitrogen, particulate phosphorus, etc.). At the end of the time step, the concentration is adjusted to account for losses using a first-order decay coefficient:

$$C_{det}^{k} = C_{det}^{k} * \left(1 - \Delta t * \delta_{k} - \Delta t v_{k} \frac{V_{det}}{A_{det}}\right) \qquad (103)$$

where δ_k is the prescribed decay rate for the k_{th} constituent.

The parameters required to apply an explicit BMP are listed in Table 10.1.

Table 10.1 Detention/Retention Pond Parameters

Parameter	Description	GUI Name
V_{max}	Maximum storage	Pnd_Vol
γ_{det}	Volume-based discharge rate	Pnd_Rec
δ_k	Decay rate of kth constituent in	DEC_DN, DEC_PN
A_{det}	surface area	AREA
v_k	Settling speeds	V_PP, V_PN, V_TSS

10.2 IMPLICIT BMPS

The effect of numerous BMPs can be simulated in the model by adjusting the model input parameters. The general intent is to reflect the effect of the BMP on runoff and water quality. Typically, the effect of a BMP on a particular quantity can be determined via field study or from a review of the literature. For instance, if a particular BMP has been found to reduce total nitrogen concentrations in agricultural runoff, the EMC for dissolved and particulate nitrogen could be reduced by an appropriate amount for the model cells with that land use. Specific HSPF parameters have been identified which control the simulated results in a study by Donigian, et al. (1983), and the results of the study can be used for guidance on which parameters to adjust to reflect each BMP implementation.

11.1 SPATIAL DATA

1) Basin (primary watershed): Polygon feature with basin name attribute.
2) Sub-basin (secondary watersheds): Polygon feature with subbasin name and numeric ID attributes. If subbasin is not available, then primary basin will be recognized as secondary basin.
3) Hydrography (streams, canals, etc.): Line or Polyline feature. The stream or canal width and bottom elevation are not typically available in the GIS data. Therefore, default values, which vary by land use, are used as initial values.
4) Land use: Polygon feature with six attributes (three integer and three descriptive) that follow FLUCS standards.
5) Soil: Polygon feature with USGS soil hydrogroup attribute.
6) Land Surface Elevation: ARC/INFO or ArcView - Spatial Analyst Digital Elevation Map (DEM) of land surface elevation.

11.2 TEMPORAL DATA

1) Rainfall: hourly time-series in an ASCII delimited text file.
2) Evaporation: daily time-series in an ASCII delimited text file.
3) Point Sources and Sinks: daily time-series in an ASCII delimited text file.
4) Water Temperature (advanced water quality option only) : daily time-series in an ASCII delimited text file.
5) Daily Average Irradiation (advanced water quality option only) : daily time-series in an ASCII delimited text file.

A series of WaSh model simulations have been made to verify the WaSh model code. Each simulation is designed to provide a direct comparison with existing models. The simulations and intended comparison are listed in Table 12.1. Two WaSh model grids were constructed to make the comparisons and are shown in Figures 12.1 and 12.2. The first grid configuration consists of a 17-by-14 grid, with cells dimensions of 2,000 x 2,000 ft. Ground elevation is constant at 20 feet. A channel 50 feet wide, and with a bottom elevation of -5 feet, was represented. The channel has a branch that connects to the main stem at the mid-way point in the main stem, as shown in Figure 12.1. At the basin outfall, a 50-foot-wide weir with a crest elevation of 4 feet was used. This grid was used for comparisons with HEC-RAS and WASP simulations.

Table 12.1 WaSh Model Verification Simulations

Run Number	Purpose	Component / Algorithm	Description
1	Verification	Surface Water	Compare WaSh surface water simulation to equivalent HEC-RAS simulation (using weir as downstream structure)
2	Verification	Water Quality	Compare WaSh implementation of non-linear DO balance to equivalent simulation in WASP
3	Verification	Hydrology	Compare WaSh hydrology output to equivalent HSPF (periodic rainfall)
4	Verification	Groundwater	Compare WaSh model groundwater to equivalent MODFLOW simulation (steady recharge and discharge to stream)

The second grid consists of a 5-by-5 grid with constant land use and a single channel. The ground elevation was set to 20 feet, and the channel width and bottom elevation are 50 feet and -10 feet, respectively. This grid was used for comparisons with HSPF and MODFLOW.

For the comparison with HEC-RAS, a flow source was assigned to the upstream ends of the main stem and the branch with peak flow rates of 2500 cfs each. WaSh model conductivities that represent exchanges with the groundwater were set to zero. Also, rainfall and evaporation time series were set to zero so that the channel flow was isolated from the hydrology. Manning's n for HEC and for WaSh was set to 0.035. This setup allowed a direct comparison with the HEC-RAS hydraulics. The gradually varying flow over a one-year period was used. The flow rate is shown in Figure 12.3. For different times during the flow rate curve, the computed upstream head in WaSh and HEC-RAS were compared. The comparison is shown in Figure 12.4 for the main stem and branch.

For a comparison with the WASP model, the 17-by-14 grid was reconfigured to isolate the main stem from the branch. This configuration simplifies the flow scenario and allows for a direct assessment of the WaSh model simulation of water quality kinetics. The branch was isolated from the main stem by eliminating the input flow and inserting a weir structure with a crest elevation of 15 feet. For the upstream flow into the main stem, the flow rate was set to 200 cfs, and the CBOD load was 5.26 milligrams per liter (mg/L). The model parameters for the simulation of DO are listed in Table 12.2.

Table 12.2 Model Parameters for WaSh Comparison with WASP

Parameter	Value	Units
BOD decay rate (K_d)	4	day^{-1}
Oxygen Carbon Ratio (a_{oc})	2.67	mg O_2/mg C
Re-aeration Rate (K_2)	1	day^{-1}
Temperature (T)	25	^oC
Sediment Oxygen Demand (SOD)	0	g/m^2-day

The model configuration produces a steady state CBOD and DO profile that varies in the downstream direction. The simulated CBOD and DO profiles for WaSh and WASP are shown in Figure 12.5. The comparison indicates that the WaSh model is reproducing the results of the WASP model.

For the comparison with HSPF, the 5-by-5-grid was used. The HSPF model was configured to simulate a single cell of the 5-by-5-grid, and the comparison was made with the direct surface runoff and percolation. The HSPF parameters used in the simulation are listed in Table 12.3.

Table 12.3 HSPF Model Parameters

Parameter	Value	Units
CEPSC	0.1	Inches
UZSN	1.128	Inches
LZSN	0.1128	Inches
INFILT	0.16	Inches/hour
NSUR	0.2	-
LSUR	250	Ft
SLSUR	0.0882	-
AGWRC	0.98	day^{-1}

Each simulation consisted of a one-year period using measured rainfall and ET data from stations in the C24 basin. The rainfall and ET data were obtained from SFWMD DBHYRO database from the LOXAHATCHEE area and used to force the simulations. A comparison of the WaSh and HSPF simulated surface runoff and percolation is shown in Figure 12.6. The comparison indicates that the implementation of the HSPF PWATER algorithm WaSh is performing properly.

The 5-by-5 grid was also used for the comparison with MODFLOW. The MODFLOW model was configured with the same 5-by-5 grid and channel dimensions as for the WaSh model. The unconfined aquifer option was used, with an aquifer base elevation of -30 feet, a hydraulic conductivity of 25 ft/day and conductivity of 1ft^2/day. A constant recharge rate of 5 inches/year was applied in the MODFLOW simulation. The WaSh model does not provide for direct specification of a recharge rate (i.e. percolation). In order to develop a scenario with a constant rate, the constant rainfall and evaporation were used. After some experimentation, a rainfall rate of 0.1 inches per day and an ET rate of 0.06 inches per day were found to yield 5 inches per year percolation. Each model was run for a one-year period to create a steady groundwater elevation and discharge. For the two cross sections shown in Figure 12.7, the groundwater elevations were compared. The comparison is shown in Figure 12.8, and indicates that the WaSh model simulation of groundwater is consistent with that of MODFLOW.

The WaSh model algorithms and numerical solutions have been implemented in a Fortran program called WaShModel. The model is supported by a Graphical User Interface that is accessible as an Arcview extension. The Fortran code variable names are listed and defined in Table 13.1. A block diagram of the Fortran code is provided in Figure 13.1.

Table 13.1 WaSh Model Fortran Code Implementation Variables

ARRAY SIZES	
imx	Array dimension for rows
imy	Array dimension for columns
nstruct	Array dimension for structures
nbranch	Array dimension for branches
nreach	Array dimension for reaches
numWQvarsT	Array dimension for WQ variables (5 for basic, 8 for advanced)

TYPE wqvar_type	
real c(numWqvarsT)	Water quality concentration
real f(numWQvarsT)	Water quality flux
TYPE TideBC_type	
Real sal1	
Real sal2	
Real elev1	Salinity at time less than sim time
Real elev2	Salinity at time greater than sim time
Real t1	Tide height at time less than sim time
Real t2	Tide height at time greater than sim time
Real sal	Time associated with h1,sal1 and elev1
real elev	Time associated with h1, sal1 and elev1
real h1	These values represent year, month, day and hour read from input file representing time before sim time (1) and time greater than sim time (2)
Real h2	
Integer y1	
Integer y2	
Integer m1	
Integer m2	
Integer d1	
Integer d2	
Integer unit	Unit number of file with tide and salinity data
TYPE hydper_type	
real cepsc	HSPF: Interception storage capacity
real uzsn	HSPF: Upper zone nominal storage
real nsur	HSPF: Mannings n for land surface
real intfw	HSPF: Inter flow fraction
real irc	HSPF: Interflow recession constant
real lzetp	HSPF: Lower zone evapotranspiration coefficient
real lzsn	HSPF: Lower zone nominal storage
real infilt	HSPF: Infiltration rate
real infild	HSPF: Parameter describing uniformity of infiltration rate
real lsur	HSPF: Length representing distance between drainage features
real slsur	HSPF: Land surface slope
real infexp	HSPF: Coefficient controlling lower zone infiltration
real deepfr	HSPF: Fraction of percolation going to deep aquifer (out of system)
real agwetp	HSPF: Coefficient controlling evaporation from groundwater

real suro	Discharge from surface storage
real ifwo	HSPF: Discharge from interflow storage
real taet	HSPF: Actual evapo-transpiration
real supy	HSPF: Combination of rainfall, surface storage and irrigation – what is available for infiltration
real ceps	HSPF: Interceptions storage
real surs	HSPF: Surface storage
real ifws	HSPF: Interflow storage
real uzs	HSPF: Surface storage (at end of day)
real lzs	HSPF: Interflow storage (at end of day)
real agws	HSPF: Upper zone storage (at end of day)
real gwvs	HSPF: Lower zone storage (at end of day)
real rlzrat	HSPF: ratio of lower zone to upper zone
real lzfrac	HSPF:
real uzil	Depth of upper zone
real lzil	Depth of lower zone
integer rtopfg	Surface discharge option
TYPE hydimp_type	
real retsc	HSPF: Impervious: retention storage capacity
real nsur	HSPF: Impervious: mannings n
real rets	HSPF: Impervious: retention storage
real surs	HSPF: Impervious: surface storage
real suro	HSPF: Impervious: discharge from surface storage
real taet	HSPF: Impervious: Surface storage (at end of day)
TYPE irr_type	
real irate	Applied Irrigation rate
real min_cap	Minimum moisture that triggers irrigation
real root_dp	Root depth
real canal	% of irrigation demand from canals
real sh_aqfrom	% of irrigation demand from aquifer
real external	% of irrigation demand from external sources
real spray	% of irrigation application added to rainfall
real surface	% of irrigation application added to surface storage
real upper_z	% of irrigation application added to upper zone
real lower_z	% of irrigation application added to lower zone
real sh_aqto	% of irrigation application to Upper Soil Zone
real eff	% of irrigation application to Lower Soil Zone
real vol_rem_c	Total actual volume removed form canals
real vol_rem_aq	Total actual volume removed from shallow aquifer
real vol_rem_c_interval	Actual volume removed from canals for single time step
real vol_rem_aq_interval	Actual volume removed from s. aq. for single time step
real azri	Fraction of demand that is applied
real extsrc	
real extsrc2	Fraction of Irrigation Demand that is met
real cansrc	
real cansrc2	
real gwsrc	
real gwsrc2	
real irrdem	The irrigation that is ultimately applied
real irrwater	
TYPE wqparP_type	
real sqolim(3,12)	TN,TP and TSS EMC values for basic wq and TN, TP and CBOD EMC values for advanced WQ. (monthly values)
real wetdep(3,12)	Wet deposition rate of ammonia, nitrate and IOP (monthly

	values)
real drydep(3,12)	Dry deposition rate of ammonia, nitrate and IOP (monthly values)
real DNfrac, DPfrac	Basic wq – fraction of TN and TP EMC that is dissolved
Real C1,C2	Coefficients in EMC formulation
AmmFrac	Adv. Wq : fraction of TN EMC that is ammonia
NitrateFrac	Adv. Wq : fraction of TN EMC that is nitrate
IOPfrac	Adv. WQ: fraction of TP that is inorganic
PhytoSeed	EMC value for phytoplankton
TYPE wb_type	
double precision rain	Daily rainfall
double precision irrdem	Daily irrigation demand
double precision et	Daily actual evapo-transpiration
double precision et_gw	Daily evapo-transpiration from groundwater
double precision surf_ro	Daily surface runoff
double precision infw_ro	Daily interflow discharge
double precision infilt	Daily percolation
real surs_1	Initial surface storage
real surs_2	Final surface storage
real lzs_1	Initial lower zone storage
real lzs_2	Final lower zone storage
real uzs_1	Initial upper zone storage
real uzs_2	Final upper zone storage
real ceps_1	Initial interception storage
real ceps_2	Final interception storage
real gwh_1	Initial groundwater elevation
real gwh_2	Final groundwater elevation
real ifs_1	Initial interflow storage
real ifs_2	Fainl interflow storage
TYPE gen_type	
integer Id	Cell id
character*1 activity	Flag identifying weather cell is active
real elevation	Cell Land elevation
real slope	Cell Land slope
character*1 type	Cell type (C,R,G,F,S,T)
integer to_row	Row id of ell where surface runoff is routed
integer to_col	Column id of cell where surface
integer to_reach	Reached where cell surface and groundwater is routed
integer to_res	Reservoir id where cell surface and groundwater is routed
real res_area	Are of reservoir footprint on cell
real area	Cell area
real length	Representative length of cell = sqrt(area)
integer lucode	Land use of cell
integer subbasin_id	Cell subasin id
real macropore	Cell macropore value
real micropore	Cell micropore value
real pan(12)	Monthly pan coefficients (evaporation) for cell
integer icolrf	Column in rainfall input file that applies to the cell
real impfrac	Cell’s Impervious fraction
logical irr_on	Flag indicating whether irrigation is applied
TYPE wqparL_type	
real dec(numWQvarsT)	Decay rates for detention pond water quality
TYPE pond_type	
real storage	Cell pond storage

real holdtime	Cell pond recession coefficient
real storagecap	Cell pond storage capacity
TYPE(wqparL_type) :: wqparL	Cell pond decay coefficients (see wqparL_type definition)
TYPE(wqvar_type) :: wqvar	Cell pond water quality values (see wqvar_type definition)
TYPE wqparC_type	
real dec(numWQvarsT)	Decay coefficients for canal basic water quality
real tssprod	Production rate of TSS in canal basic water quality
TYPE wqparG_type	
real WQ_opt	Option for GW EMC calculations
Real DNfrac, DPfrac	Basic water quality – fraction TN, TP that is dissolved
Frac(8)	Adv. WQ: fraction of surface EMC applied as GW EMC
TN(12)	Adv. WQ: monthly values of GW EMC for TN
TP(12)	Adc. WQ: monthly values of GW EMC for TP
AmmFrac,NitrateFrac,IOPFrac	Fraction of TN or TP to get GW EMC for ammonia, nitrate and IOP
TYPE gw_type	
double precision GWhgt	Groundwater height
real HydCon	Hydraulic conductivity
double precision Rchrg	Percolation rate from moisture zones
double precision RchrgT	Inflow to groundwater from reaches, canals and reservoirs
real Base	Bottom of shallow aquifer
real porosity	Porosity
logical high	Flag identifying if high water table conditions exist
real drain	Small drainage feature bottom elevation
real conductance	Conductance applied to discharge to small drainage features
double precision discharge	GW discharge from cell
real ave	Average gw height over simulation
TYPE(wqvar_type) :: wqvar	GW water quality values (see wqvar_type definition)
TYPE(wqparG_type) :: wqparG	Cells gw wq parameters (see wqparG_type definition)
TYPE wqparR_type	
real dec(numWQvarsT)	Reach Basic WQ: decay rates for SN,SP,PN,PP
real tssprod	Reach Basic WQ: instream production rate of TSS
real TSS_Settling	Reach: Basic WQ: settling speed of TSS
real PN_Settling,PP_Settling	Settling speed of par. P and part. N
real wetdep(2,12)	Reach: Wet deposition rate of ammonia, nitrate and IOP (monthly values)
real drydep(2,12)	Reach: Dry deposition rate of ammonia, nitrate and IOP (monthly values)
TYPE Phyto_type	
real Ke1	Extinction coefficient
real Ke2	Extinction coefficient
real Ia	Maximum growth rate
real f	Fraction of daylight
real Theta	Temp. coefficient for maximum growth rate
real Ec	Carbon-to-chlorophyll ratio
real Is	Saturation light intensity
real Kmn	Half-saturation constant for nitrogen
real Kmp	Half-saturation constant for phosphorus
real Kr	Endogenous respiration
real Er	Temp. coefficient for endogenous respiration
real Vs4	Phytoplankton setline speed
real Kd	Death rate
TYPE Nit_type	
real An	Nitrogen-to-carbon ratio

real K71	Nitrogen mineralization rate
real Theta71	Temp. coefficient for nitrogen mineralization rate
real K12	Nitrification rate
Real theta12	Temp. coefficient for nitrification rate
real Knit	Half-saturation constant of oxygen
real K2d	Denitrification rate
real Theta2d	Temp. coefficient for denitrification rate
real Kno3	Michaelis constant
real Fon	Fraction of N released from dead phytoplankton appearing as ammonia
real Vs3	Organic Nitrogen settling speed
TYPE Phos_type	
real Ap	Phosphorus-to-carbon ratio
real K83	Phosphorus mineralization rate
real E83	Temp. coefficient for mineralization rate
real KMpc	Half saturation constant for phosphorus
real Fop	Fraction of P released from dead phytoplankton appearing as inorganic P
real Vs3	Organic phosphorus settling speed
TYPE Oxy_type	
real Aoc	Oxygen –to-carbon ratio
real Kd	De-oxygenation rate
real Thetad	Temp. coefficient for de-oxygenation rate
real Kbod	Half saturation constant for oxygen
real Theta12	Temp coefficient for sediment oxygen demand
real Sod	Sediment oxygen demand
real K2	Re-aeration rate
real Vs5	CBOD settling speed
TYPE wqparA_type	
type(Nit_type) :: Nit	Adv. WQ: Nitrogen Eq. Parameters (see Nit_type definition)
type(Oxy_type) :: Oxy	Adv. WQ: Oxy/CBOD Eq. Parameters (see Oxy_type definition)
type(Phyto_type) :: Phyto	Adv. WQ: Phytoplankton Eq. Parameters (see Phyt_type definition)
type(Phos_type) :: Phos	Adv. WQ: Phosphorus Eq. Parameters (see Phos_type definition)
real Vdiff	Adv. WQ: vertical mixing in reach segment
TYPE canals_type	
real canlength	Total length of canals
double precision swhgt	Canal water depth
logical pumpnow	.true. = pumping is active
real botelev	Canal bottom elevation
real width	Canal width
real weir	Weir elevation
real pmprate	Pumping rate
real conductance	Canal conductance
real inflow	Flow into canal
real weir_flag	Option for pumping or weir discharge
real drain_den	Upland area discharging to canal
real weir_coeff	Weir coefficient
real area	Canal surface area
real PMP_UC, PMP_LC	Upper and lower critical elevation to initiate pumping

TYPE(wqparC_type) :: wqparC	Canal basic WQ parameters (see wqparC_type definition)
TYPE(wqvar_type) :: wqvar	Canal water quality values (see wqpar_type definition)
TYPE(wqparA_type) :: wqparA	Canal adv. WQ parameters (see wqparA_type definition)
TYPE LL_type	
type(wqvar_type) :: wqvar	Reach lower layer WQ values (see wqvar_type definition)
real dailywql(numWqvarsT)	Reach lower layer daily WQ loads
real daconc(numwqvarsT)	Reach lower layer daily average concentrations
TYPE reach_type	
double precision swhgt	Reach segment surface water elevation
real botelevation	Reach segment bottom elevation
real inflow	Flow rate into reach segment
real length	Reach segment length
real width	Reach segment width
double precision q	Reach segment flow rate
double precision dailyq	Single layer or upper layer daily flow rate
real dailyh	Reach segment daily water surface elevation
integer to_reach	Id of downstream reach
real manningsn	Reach segment manning's n
real conductance	Reach segment conductance
integer node	Node id at downstream end of reach
integer Fstruct	Structure id associated with reach segment
double precision dailywql(numWQvarsT)	Daily water quality load at reach
double precision DAconc(numWQvarsT)	Daily water quality concentration at reach
double precision vol	Reach water volume
integer icolrf	Column in rainfall input file for rainfall for reach segment
type(wqparR_type) :: wqparR	Basic WQ parameters (see wqparR_type definition)
type(wqvar_type) :: wqvar	Reach segment WQ values (see wqvar_type definition)
type(wqparA_type) :: wqparA	Adv. WQ parameters (see wqparA_type definition)
type(LL_type) :: LL	Lower layer parameters and WQ values (see LL_type definition)
TYPE branchparameters	
integer numr	Total number of reaches
integer branch_to	Id of downstream branch
integer reach_to	Id of reach in downstream branch that forms connection
integer firstreach	Id of first reach in the branch
integer lastreach	Id of last reach in the branch
type(reach_type) :: reachb(0:nreach)	Reach parameters for reaches in the branch
TYPE Fstruct_type	
integer node	Node for location of structure
character*2 type	Structure type identifier
real width	Weir width
real breadth	W
real elev(12)	Monthly weir elevations
real coeff	Weir coefficient
real irrPrate	Pumping rate
logical pump_on	Flag indicating pump is pumping
real gateopenhgt(3)	Critical height to start gate opening
real gateclosehgt(3)	Critical height to start gate closing
real gaterate	Gate opening rate
integer numgates	Number of gates
real actualopening(3)	Current gate opening
real gateopenmaxhgt(3)	Maximum gate opening

real TWtype	TW conditions downstream of gate (constant, tide input etc.)
TYPE Basin_Irr_type	
double precision demand	Basin wide irrigation demand (tracking only)
double precision external	Basin wide external irrigation supply (tracking only)
double precision internal_total	Basin wide internal irrigation sources (tracking only)
double precision internal_reservoir	Basin wide irrigation taken from reservoirs
double precision internal_canal	Basin wide irrigation taken from tertiary canals
double precision total_ext_and_int	Basin wide total internal and external supply
TYPE con_type	
real hgt(12)	Monthly values for weir elevations for connections
character*80 fname	Filename for output of connection conditions
real parms(4)	Parameters for reservoir connection
integer unit	Unit number for output file
TYPE res_sta_type	
character*80 name	Reservoir name
integer id,unum	Reservoir id and unit number of reservoir output
real area	Reservoir area
real hydcon	Reservoir hydraulic connectivity
character*1 type	Flag indicating reservoir is STA
real elevation	Hydraulic Conductivity
type(con_type) :: con(7)	Type of reservoir connection
real inflow	Current Inflow to reservoir
real inflowS	Inflow to reservoir due to cell runoff
real outflow	Current outflow
real dailyflowo	Daily average outflow
real dailyflowi	Daily average inflow
real depth	Water depth in reservoir
real inwq(numWQvarsT)	Total WQ load to reservoir (including cell runoff)
real inwqS(numWQvarsT)	Water quality load to reservoir due to surface runoff
real outwq(numWQvarsT)	Water quality outflow loads
real wq(5,numWQvarsT)	Reservoir water quality values (one for each of 5 cells in reservoir)
real dailywqout(numWQvarsT)	Daily average inflow to reservoir
real dailywqin(numWQvarsT)	Daily average outflow from reservoir
real gwdis	Exchange of water between GW and reservoir
real gwdiswq(5,numWQvarsT)	
real Edailyflow !emergency outflow(#5)	Daily average emergency outflows
real Edailywq(numWQvarsT) !emergecny wq load	Daily average emergency loads associated with outflows
integer icolrf	Column in rainfall input file that applies to the reservoir
TYPE rpsf_type	
integer node	Reach segment (i.e. node) that point source input is added
character*80 filename	Input filename for point source input
integer unit	Unit number for input file
real flow	Daily flow value from point source input file
TYPE cpsf_type	
integer i	Row for cell canals receiving point source input
integer j	Column for cell receiving point source input
character*80 filename	Input filename for point source input
integer unit	Unit number for input file
real flow	Daily flow value from point source input file
TYPE rating_type	
integer num	Number of rating curve pairs
real depth(10)	Depth values for each pair

real flow(10)	Flow rates for each pair
TYPE cell_type	
TYPE(hydper_type) :: hydper	Hydrological parameters for cell (see hydper_type definition)
TYPE(hydimp_type) :: hydimp	Impervious land parameters for cell (see hydimp_type definition)
TYPE(wqparP_type) :: wqparP	Pervious water quality parameters (see wqparP_type definition)
TYPE(wqvar_type) :: wqvar	
TYPE(gw_type) :: gw	GW parameters for cell (see gw_type definition)
TYPE(canals_type) :: canals	Canal parameters for cell (see canals_type definition)
TYPE(gen_type) :: gen	General parameters for cell (see gen_type definition)
TYPE(irr_type) :: irr	Irrigation parameters for cell (see irr_type) definition)
TYPE(pond_type) :: pond	Pond parameters for cell (see pond_type) for definition)
type(wb_type) :: wb	Water budget for cell (see wb_type definition)
TYPE Cellio_type	
character*80 filename(7)	Output file name for cell output
integer unum(7),i,j	Unit number for each of 7 output file types
logical written(7)	Flag indicating which of the 7 output types is written
TYPE Rchio_type	
character*80 filename(2)	Output file name for reach output
integer unum(2),id	Unit number for each of 2 output file types
logical written(2)	Flag indicating which of the 2 output types is written

TYPE(cellio_type) :: cellio(50)	These declarations show the dimensions of each object in the FORTAN routines
TYPE(Rchio_type) :: rchio(50)	
TYPE(cell_type) :: cell(imx,imy)	
TYPE(branchparameters) :: branch(0:nbranch)	
TYPE(Fstruct_type) :: Fstruct(nstruct)	
TYPE(canset_type) :: CanSet(200)	
TYPE(rpsf_type) :: rpsf(20)	
TYPE(cpsf_type) :: cpsf(20)	
TYPE(cpsf_type) :: gwpsf(20)	
TYPE(res_sta_type) :: res(40)	
TYPE(rating_type) :: rating(5)	
TYPE(basin_irr_type) :: basin_irr	
TYPE(ludis_type) :: ludis(10)	
TYPE(spec_ops_type) :: spec_ops(5)	
TYPE(sb_type) :: sb(600)	
TYPE(TideBC_type) :: TideBC	
TYPE(pumps_type) :: Rpumps(3)	
type(DECAY_TYPE) :: decay	

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FIGURES

FIGURES