

## Review of Existing Nutrient, Suspended Solid and Metal Models

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## Section 1: Executive Summary

1. All published models on in stream transport of nutrients, sediment and pollutants were reviewed.
2. Models were categorised into overall conceptual models for nutrients, sediment and pollutants.
3. All models were tabulated and assessed with regards to their data requirements, general modelling approach and key numerical components.
4. The top ten models in each group were selected based on availability of source code, appropriateness of approach, realistic data needs for application in Victorian settings and peer-review status. These top 10 models, in no particular order, were SWAT, WASP, HSPF, EFDC1D, Nutrient Spiralling, INCA, KINEROS, WaterCAST, EPD-RIV1, and STARS.
5. The top ten models were exhaustively reviewed to determine the core quantitative relationships underlying each.
6. Best candidate models for application in EnSym were identified based on the criteria in 4 above.
7. The most suitable in stream nitrogen model is INCA-N. It requires relatively few input data and models both changes in ammonium and nitrate by temperature dependant denitrification/ nitrification rates. INCA-N has been used in most European countries although it has not been validated in Australia. Also, the model does not consider any biological interactions in its model.
8. The best candidate model for phosphorus is WaterCAST. It is the only generic model available and was developed for Australian conditions. It only measures TP and does not account for any biological interactions. The HSPF phosphorus submodel is the best of the more complex models because it accounts for particulate and dissolved phosphorus and measures algal uptake and release.
9. The most suitable suspended solid model was STARS. It was validated in Australia but requires gauging station data for its inputs. The most suitable model for ungauged streams is the HSPF suspended solid sub model. The model divides the particles into clay, silt and sand and measures the deposition and scour based on shear stress curves.
10. Further work is required to determine the accuracy of the generic, low input requirement models over the more complex models. Also, many of the top 10 models were designed in North America or Europe and have not been validated for Australian conditions. As well, there is a shortage of Australian nutrient processing rate data, which is required for the complex models.

## **Acronyms**

BOD- Biochemical oxygen demand

CPOM- Course Particulate Organic Matter

DIP- Dissolved inorganic phosphorus

DNRA- Dissimilatory nitrate reduction to ammonia

DO- Dissolved oxygen

DOM- Dissolved organic matter

DON- Dissolved organic nitrogen

DP- Dissolved phosphorus

M-metal

N- Nitrogen

NOx- Nitrate and nitrite

Org-P- Organic phosphorus

Org-N- Organic nitrogen

P- Phosphorus

POM- Particulate organic matter

PON- Particulate organic nitrogen

SS- Suspended solids

[SS]- Concentration of Suspended solids

STP- Sewage Treatment Plants

TP- Total phosphorus

TN- Total nitrogen

## **Section 2: Literature Review**

### **2.1 Introduction**

The Australian landscape has been drastically altered since European settlement, with land clearing, building of cities and changes to flow regimes in streams as a result of damming, water extraction and diversion. Erosion, eutrophication and subsequent algal blooms, and poor water quality are some of the consequences. Modelling these processes under current and future conditions requires integration of quantitative relationships between key drivers and these processes, and detailed spatial information. EnSym (Environmental Systems Modelling Platform) is a modelling framework developed by the Victorian Government Department of Sustainability and Environment that models the change to the environment derived from a series of actions in the landscape. EnSym allows multiple scientific models to talk to one-another via a single interface, combining the outputs of a series of models assembled into functional 'toolboxes'. The modelling framework is currently being populated with models derived from the peer-reviewed scientific literature across a wide range of toolbox areas. This review addresses the models relevant to nutrient cycling, sediment transport and pollutant contamination in running freshwaters in Victoria. A conceptual review and overview of the known key drivers is provided, then the detailed models available are assessed and evaluated for applicability within EnSym.

### **2.2 Key drivers of nutrient, suspended solid and pollutant movement**

#### **2.2.1 Point and diffuse sources, timing of delivery, rainfall events**

Point sources of nutrients, suspended solids and metals into streams include tributaries, sewage treatment plants (STP), stormwater and industrial drains. Generally, the pollutant loads from point sources are known, as flow and concentrations can be easily measured.

Pollutant loads from diffuse (non-point) sources are much more difficult to determine. Diffuse sources of nutrients include groundwater, runoff, precipitation (although in Australia, N input from precipitation is much less than in Europe and North America), atmospheric deposition, fertilizer, animal waste, erosion (P-bound particles) and septic tanks. Sediments also provide an internal diffuse source of nutrients to the stream. Suspended solids enter the stream through diffuse sources such as gully and bank erosion, runoff, sedimentation from logging and construction and mining. Bushfires and drought in the catchment can also be a source of suspended solids, especially during the first post-event rainfalls where particles are washed into the stream. Diffuse sources of metals into the stream include both natural and contaminated groundwater, atmospheric deposition, runoff, erosion and leaching due to acid rain.

Australia has highly variable rainfall, resulting in most nutrients and suspended solids being transported in short periods of intense rainfall. However, TP and TN loads from these diffuse sources are much less than Europe and North America due to less intensive farming practises and lower population density.

#### **2.2.2 Riparian vegetation**

Riparian vegetation is the vegetation which grows along stream banks. Riparian vegetation acts in three ways to reduce diffuse source of nutrients, suspended solids and

to a lesser extent, metals. 1. Vegetation acts as a filter to trap runoff from the surrounding landscape into the stream. Particulate matter becomes trapped in the undergrowth of the riparian strip, thus preventing it entering the stream. 2. The riparian zone acts as a nutrient sink for subsurface flows (groundwater discharge). Nitrate, which is a common pollutant in groundwater, comes in contact with carbon rich soils, providing an environment for denitrification to occur (nitrate converting to nitrogen gas through microbial processes). Therefore, the concentration of nitrate entering the stream through groundwater discharge is significantly reduced through the riparian zone. 3. Vegetation in the riparian zone drastically reduces erosion along the stream banks as the roots stabilise the soils around the stream bank.

### **2.2.3 Stream geomorphology**

The geomorphology of the stream can impact nutrient, suspended solid and metal processing. Geomorphology reflects the sedimentary and fluvial processes that determine the shape and structure of the stream bed and the nature of the sediment within it. The geology and topography of the catchment impacts the size and type of sediment within the stream. Sediment size can range from consolidated clay to sand to large cobbles and rocks. The stream channel can be confined by bedrock or impermeable clay or unconfined allowing groundwater interactions with the stream water. The stream can have either steep or gentle longitudinal gradients and steep or gentle banks.

In stream geomorphology impacts the type of nutrient transport and processing. Streams with “natural” pool and riffle sequences allow settling of particles and processing of the nutrients in slow moving pools. Connections with the hyporheic zone also have important influences on in stream processing. The hyporheic zone is the sub-surface area immediately adjacent to the flowing channel of a flowing water body, where at least 10% of the subsurface flow is from stream water. Hyporheic zones trap particulate matter, and also have both oxic (oxygen present) and anoxic (no oxygen present) conditions. These oxic and anoxic zones provide ideal conditions for nutrient processing. For nitrogen, ammonium is nitrified in oxic waters to nitrate and subsequently the nitrate denitrified in anoxic waters. Other geomorphologic structures also influence nutrient and sediment dynamics. Floodplains provide large areas of deposition as well as source of nutrients and suspended solids to the stream. Reservoirs and weirs can alter the natural flow of the stream and can trap most of the suspended solids from upstream, thus becoming a sink for particulate bound P. Channelization and other engineering modifications, especially in urban areas, have removed many of the interactions of the water with riparian vegetation, floodplains and groundwater, thus reducing or removing entirely processes that drive nutrients, suspended solids and metal concentrations.

### **2.2.4 Concurrent parameters (DO, CPOM, temperature etc.)**

The processing of many nutrients and metals in the environment are driven by factors such as dissolved oxygen, organic matter, temperature, biological uptake/release, salinity, and pH. Dissolved oxygen concentration (DO) determines the oxic status of the stream, which in turn determines the types of processes. Nitrification, aerobic respiration (breakdown of organic matter) and oxidation of metal species requires oxygen. Denitrification, anaerobic respiration and metal reduction cannot occur with oxygen present. DO increases through photosynthesis of algae and other aquatic plants and by aeration of the stream water. DO decreases with aerobic respiration.

Organic matter plays an important role in DO concentrations as well as many other processes. Organic matter is required for respiration, either with oxygen, or with another

oxidant when oxygen is consumed (i.e. denitrification, fermentation). It is the source of organic nitrogen and phosphorus, which is subsequently broken down into its inorganic components. Organic matter also can bind to metals, thus reducing their toxicity in the water.

Most processes in stream are microbial mediated. Therefore temperature plays an important role. Cooler temperatures slow the microbes' metabolic rates, thus their need for energy reduces too. This in turn slows down processing rates. The opposite is true for warm temperatures. Warmer temperatures promote much higher nutrient processing rates.

Uptake and release of nutrients by algae, bacteria, macrophytes and other photosynthetic groups are two of the main drivers altering nutrient concentrations in the aquatic environment. Both phytoplankton and macrophyte dominated systems depend on nutrients for growth but high concentrations of nutrients often lead to algal blooms. Blue-green algae can fix dissolved nitrogen gas from the atmosphere, therefore their growth is restricted by phosphorus concentrations. However, many rivers in Australia are nitrogen limited, therefore the concentration of nitrogen restricts algal growth. Suspended solids have been found to limit algal growth due to light penetration into the water column being restricted to the upper few centimetres (Boulton and Brock 1999). Finally, terrestrial plants are a source of organic matter (and nutrients) to streams through leaves and limbs falling into the stream.

High salt concentrations can cause flocculation (and settling) of suspended solids. Salt also greatly affects the ecology of the stream, where freshwater organisms that are not salt tolerant are killed and salt tolerant organisms flourish. The subsequent effect on nutrient processing is largely unknown.

pH plays an important role in metal chemistry, where the pH level can determine the metal speciation (dissolved, particulate bound or complexed phase). Lower pH (more acidic conditions) dissociates metals from particles, thus increasing the toxicity risk. pH also drives ammonia chemistry, which is important because ammonia ( $\text{NH}_3$ ) is toxic to aquatic organisms, whereas  $\text{NH}_4^+$  is not. Higher pH increases the ammonia: ammonium ratio in the water, which can lead to fish kills.

## ***2.3 Transport of key nutrients within flowing waters***

The following conceptual models were developed based on a literature review of the transformations each nutrient and metal undergoes in the aquatic environment. These various processes and transport were grouped into five major groups – sources, transient storage, redox, biological and input/output. Figure 1 outlines the physical processes whereas Figure 2 outlines the main biological and chemical processes that occur in the sediments, riparian zones and transient storage zones. All dissolved and particulate species undergo physical process of advection and dispersion in the water column. Advection is the longitudinal movement of the particle downstream, carried by currents. Dispersion is the particles spreading out, due to diffusion or shear stress. Particulate matter also undergoes settling and resuspension.

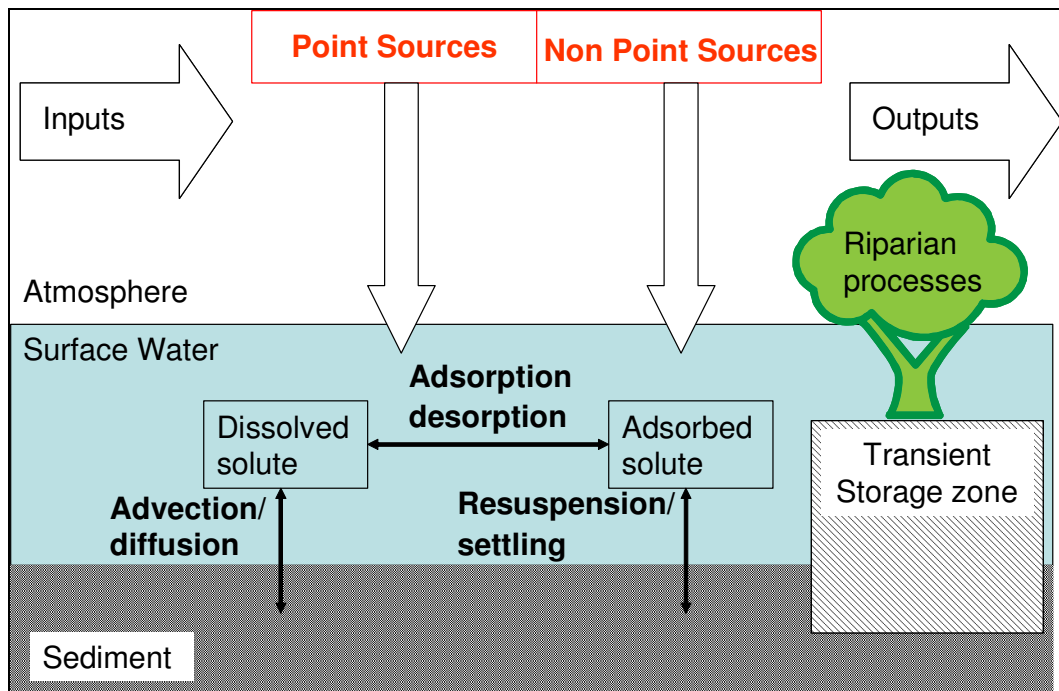


Figure 1: Over-arching conceptual model outlining the physical processes which underlie movement and processing of nutrients, sediment and metals in flowing water ecosystems.

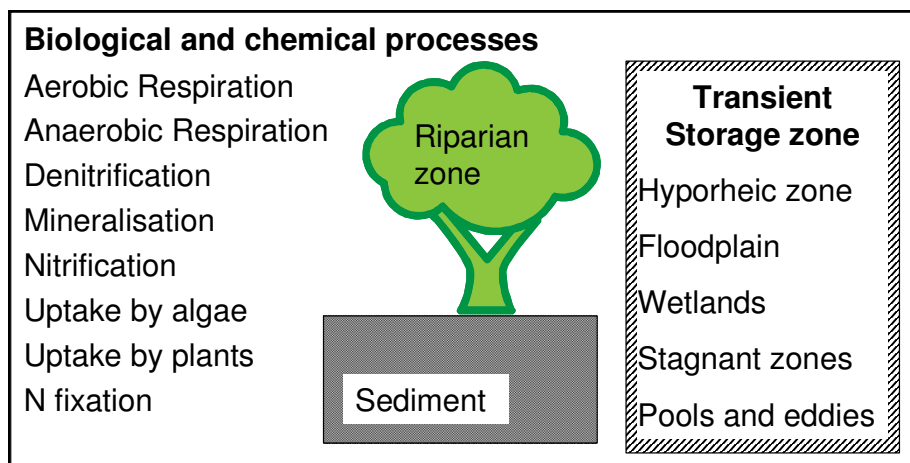


Figure 2: A summary of the main chemical and biological processes that predominately occur in the riparian zone, sediments and transient storage zones.



**Table 1 Summary table outlining what processes represent which number in nitrogen, phosphorus and suspended solid conceptual models.**

<b>Process Number</b>	<b>Process Name</b>	<b>Example of Process</b>
1	Advection/dispersion	Dissolved Phosphorus diffuses from the sediment pore water into water column
2	Settling/resuspension	Suspended solids settle and resuspend.
3	Mineralisation	Algae → Particulate Organic Nitrogen Dissolved Organic Nitrogen
4	Denitrification	$\text{NO}_3^- \rightarrow \text{N}_2$
5	Nitrification	$\text{NH}_4^+ \rightarrow \text{NO}_3^-$
6	Biological Uptake	$\text{NH}_4^+ \rightarrow \text{Algae}$ $\text{NO}_3^- \rightarrow \text{Algae}$
7	Nitrogen fixation	$\text{N}_2 \rightarrow \text{Algae}$
8	Ammonia equilibrium	$\text{NH}_4^+ \leftrightarrow \text{NH}_3(\text{aq})$
9	Volatilization of $\text{NH}_3$	$\text{NH}_3(\text{aq}) \leftrightarrow \text{NH}_3(\text{g})$
10	Factors which affect nutrient processing	Oxygen is required for nitrification but inhibits denitrification. pH regulates equilibrium of $\text{NH}_3$ (8)
11	Storage zones	Storage zones allow settling of particles.
12	Adsorption/desorption	Particulate matter + P $\leftrightarrow$ Particulate matter-P
13	Factors which affect biological uptake	Sunlight is required for algal growth
14	Factors which affect suspended solid processes	Particle size of sediment or particle density.
15	Diffusion	Dissolved Inorganic Phosphorus diffusion from pore water into water column
16	Hydrolysis	Organic-N $\rightarrow \text{NH}_4^+$

### 2.3.1 Nitrogen

Nitrogen exists in streams as dissolved nitrogen gas (usually ignored as it is inert), nitrate, ammonium, dissolved organic nitrogen and particulate organic nitrogen. Ammonium binds to particles or can be in dissolved form. Nitrogen can be removed from the stream through denitrification, uptake by organisms and loss to groundwater. Sinks of nitrogen include wetlands, riparian zones, floodplains and pools.

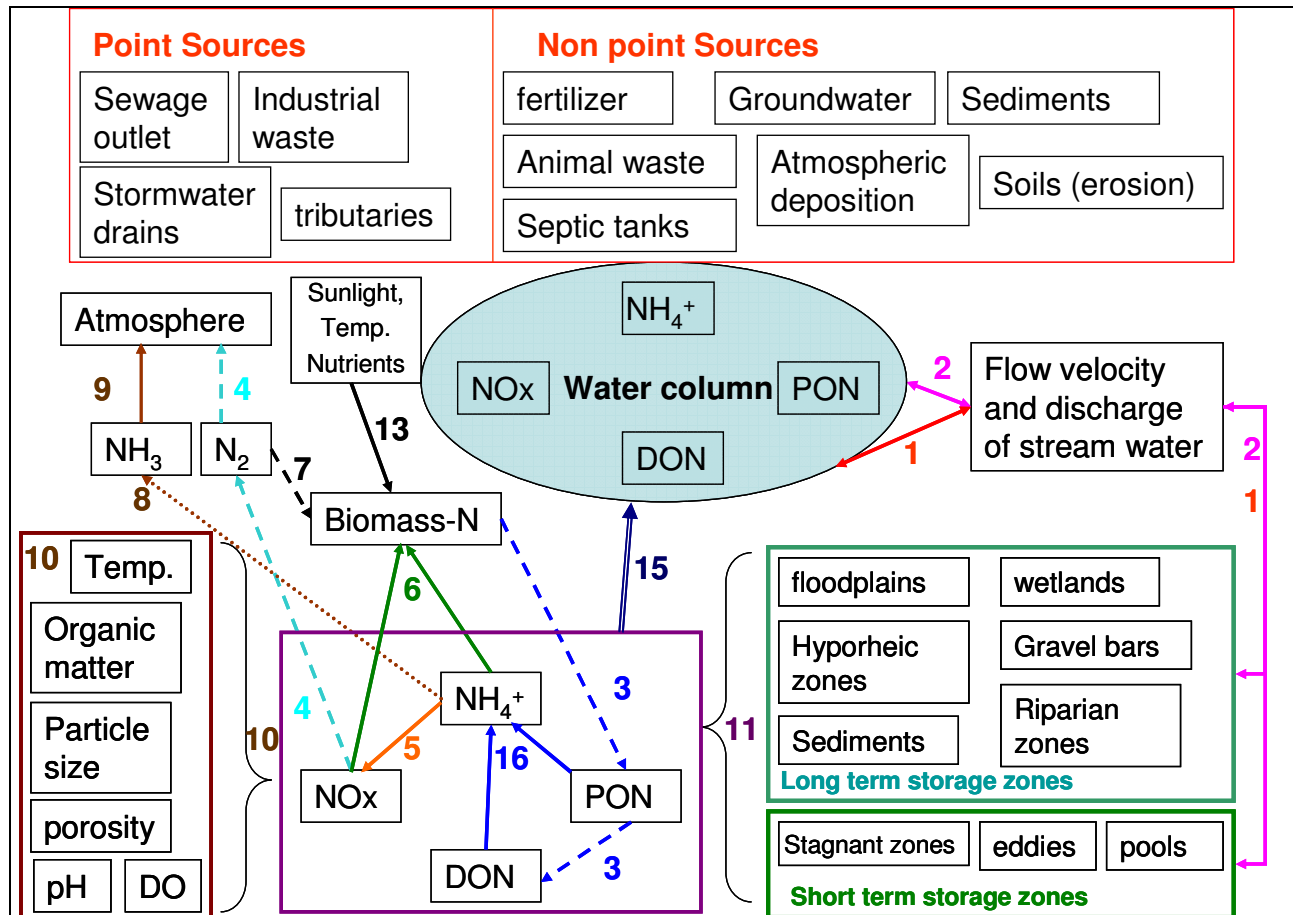


Figure 3: Conceptual model showing the biochemical and physical processes which underlie nitrogen cycling in flowing water ecosystems. Definitions of numbers are outlined in Table 1.

## 2.3.2 Phosphorus

Phosphorus species in streams are dissolved inorganic phosphorus (DIP), organic phosphorus (org-P) and particulate bound phosphorus (part-P). DIP adsorbs onto/desorbs from iron oxyhydroxide (FeOOH) particles depending on redox conditions. Org-P and part-P settle and resuspend in the water column. Pore water DIP diffuses into the water column. Algae and other aquatic plants take up DIP with growth and release org-P with decay. Org-P mineralises to DIP through microbial degradation.

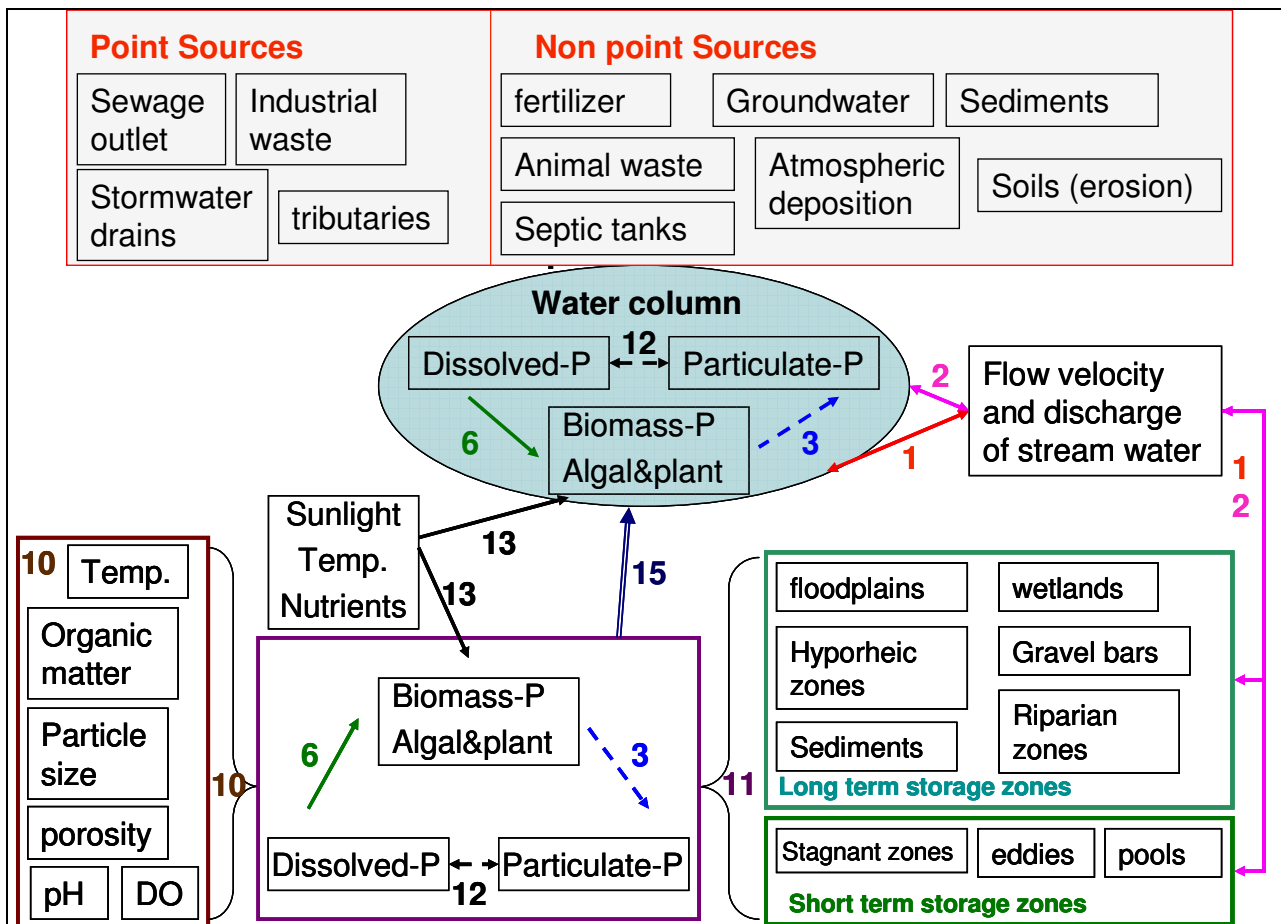


Figure 4: Conceptual model showing the biochemical and physical processes which underlie phosphorus cycling in flowing water ecosystems. Definitions of numbers are outlined in Table 1.

### 2.3.3 Suspended Solids

Suspended solids are a combination of organic and inorganic particles suspended in the water column. Flows are the main driver of suspended solids, where high flows resuspend sediment and low flows allow settling of heavier particles. Smaller particle sizes, e.g. clays and silts, are in suspension longer than larger particles like sands. Particles smaller than ca. 1  $\mu\text{m}$  in diameter will remain suspended indefinitely due to Brownian motion

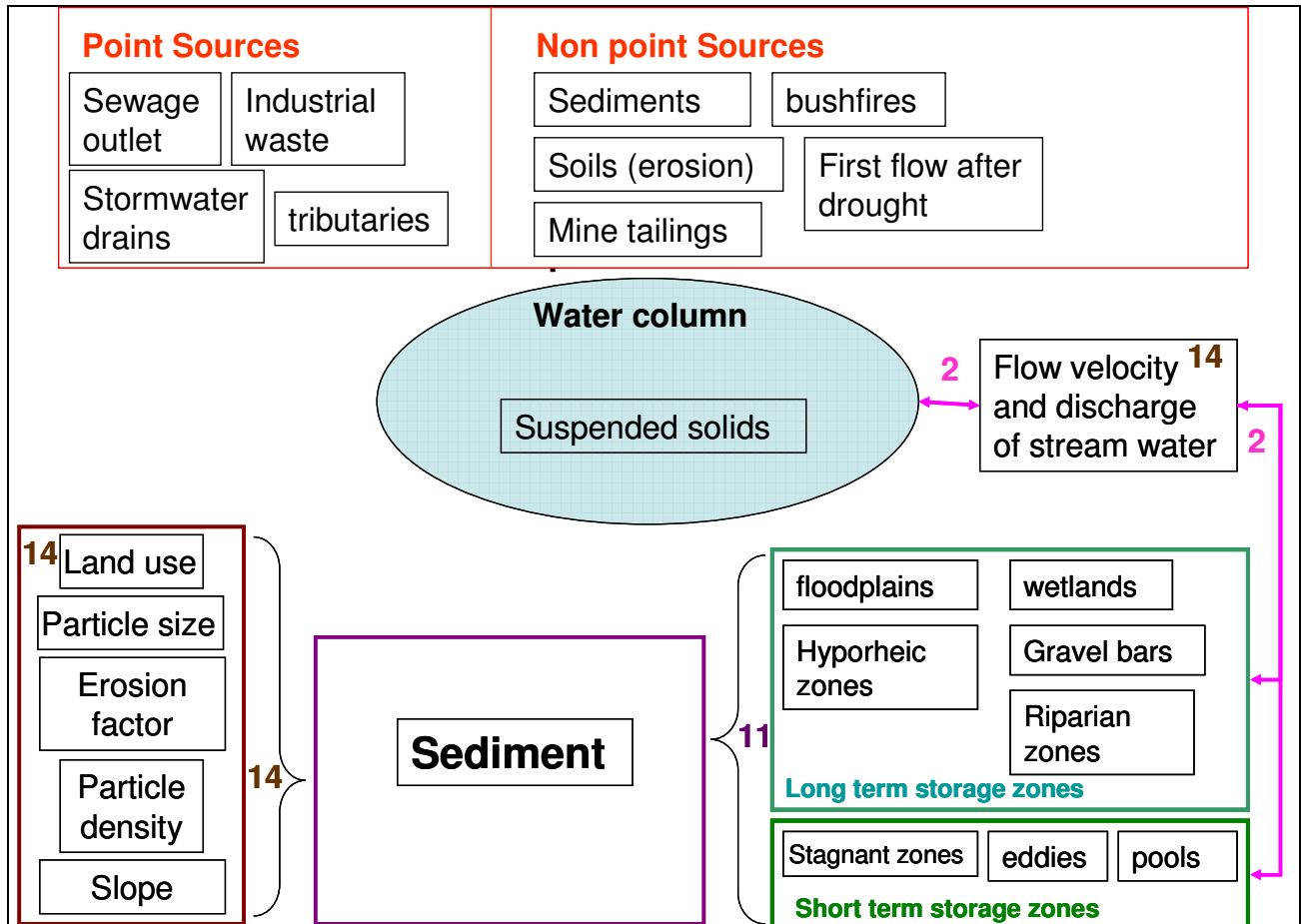


Figure 5: Conceptual model showing the biochemical and physical processes which underlie suspended solid dynamics in flowing water ecosystems. Definitions of numbers are outlined in Table 1.

### 2.3.4 Metals

Metals exist in the following states: dissolved, particulate bound, organic bound and complexed with hydroxide ligands (and within biota). Metals can absorb/desorb and complex/dissolve from particles depending on pH, surrounding metal concentrations and other competing cation/anions. Particle bound metals settle and resuspend in the same way as suspended solids. Redox conditions determine the charge of the metal, and reduction of Fe and Mn surface coatings on the particles can release trace metals that were bound in the Fe/Mn oxyhydroxide layer. Uptake, sorption and excretion of the metal by organisms in the aquatic food web can have important effects on metal concentrations, but is relatively poorly understood and differs between metal species. Some metals (notably lead, mercury and cadmium) are highly lipid soluble and accumulate up trophic levels. Other metals are not as readily transferred via food chains.

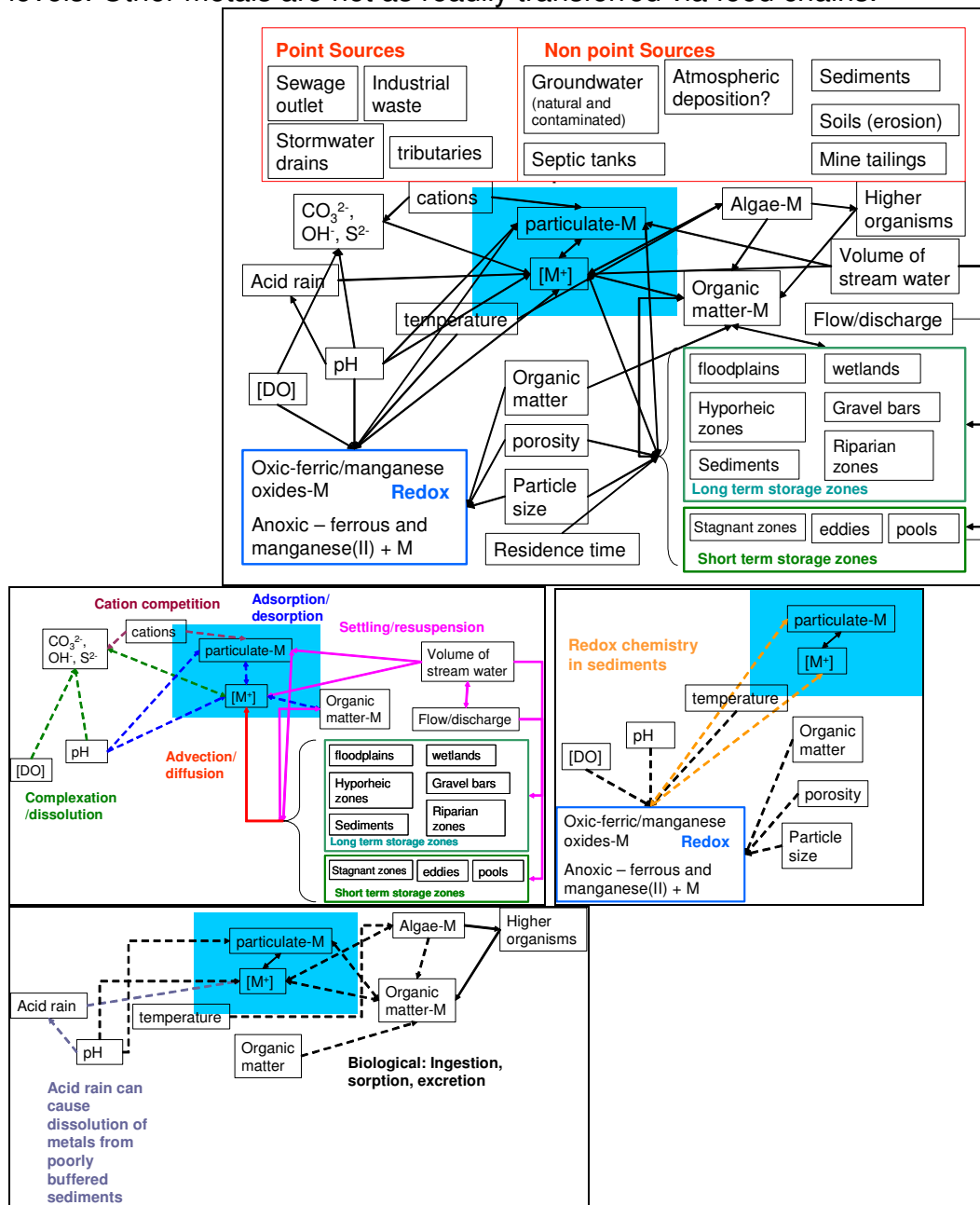


Figure 6: Conceptual model showing the biogeochemical and physical processes which underlie pollutant dynamics for a generic metal in flowing water ecosystems. The three smaller conceptual models outline the transformations in more detail, with dotted lines represent transformations, unbroken lines represent movement of the metal.

## **2.4 Nutrient Modelling**

### **2.4.1 Types of models**

There are three types of model available to describe nutrient flow through rivers (empirical, process, and physical). In some cases a single model may be comprised of more than one module and each module can be a different type of model. This means that the distinction of which type of model is being used overall is not always possible. The three main types of models described in this report are as follows:

#### Empirical Models

Empirical models are often the simplest of models and are developed using relationships between variables as determined by observed data. They are based on statistical analysis of experimental data. The values of the model parameters can be determined via calibration at experimental sites and then extrapolated over other sites. Although empirical models may be site specific they can be useful in identifying sources of nutrient generation.

Empirical models do not take into account spatial variability in the surrounding catchment however this may not necessarily lower their predictive capacity. Additionally, although the output of these models can be accurate, they give no indication as to the relationships or driving factors behind the results. These models are correlative in nature, and may not provide the necessary causative relationships which are required to allow management interventions.

#### Process Models

Process based models are based on knowledge of nutrient generation processes. They generally contain different modules such as storage, and transfer to represent the different processes that affect nutrient concentrations. These types of models can require a large amount of input data to account for all the transport processes and storages. They are able to indicate the impact of changes in land use and point and non point sources on the nutrient outputs.

These models are usually calibrated against observed data and rely on an appropriate and accurate set of data to be available. Process based models are essentially a compromise between empirical and physical models and are most suitable to long term predictions at large spatial scales.

#### Physical Models

Physical based models are highly complex models with high computational requirements and large associated error. The equations of physical based models are often determined under set conditions at a small scale and then scaled up to bigger areas. This approach has significant issues concerning its accuracy and broader suitability in some systems, particularly data-sparse systems such as occur in Australia.

## Section 3: Review of Existing Water Quality Models

### ***3.1 Determination of the top 10 models for river water quality analysis***

There are currently many models that have been developed to assist with the modelling of water quality. These models vary greatly in complexity, and work over various spatial and temporal scales. We conducted a thorough review of published water quality models. This review resulted in the identification of 103 models (see attached materials; Excel spreadsheet and Access database files) that relate to nitrogen, phosphorus, suspended solids or pollutant modelling in catchments, lakes and rivers. These models have been developed for a large range of purposes including lake eutrophication models and entire watershed models. The spreadsheet details all models in alphabetical order specifying:

1. Authors and whether it is peer reviewed.
2. Whether, N, P, SS or Metals are modelled.
3. Summary of inputs.
4. Place of calibration.
5. A descriptive account of what the model does.
6. "drawbacks, disadvantages and negative points"
7. "Positive points, advantages and other good things"
8. References (journal articles, web pages, manual)
9. Cost (if it is not clearly stated it is free or commercial, "?" is used)
10. Summary ranking of suitability for inclusion in EnSym based on an assessment of the above; L (low), M (medium) and H (high), where High represents a model which meets all the requirements for EnSym (i.e. 1D, daily time step, in stream modelling and free to use). Medium ranking represents models that predict in stream processing but are commercial, 2D or 3D or longer time steps. Models that do not model in stream processes were ranked low (e.g. empirical lake models).

The purpose of this study was to decide on the best models for determining nutrient and suspended solids transformations and fate within streams. A series of rules were applied which excluded models from further consideration.

- A. Failure to adequately account for in stream processes. We were able to rule out models that did not model streams specifically. For example LASCAM is designed for modelling nutrient movement over whole catchments but assumes conservative behaviour in stream. These models were considered to be inadequate as it is known that in stream processes are important determinants of nutrient concentrations (Stream Solute Workshop 1990) particularly in slow-flowing systems such as those that predominate in Victoria. Similarly, HBV-NP was ruled out due to the fact that inorganic nitrogen was modelled singly instead of being split into ammonia and nitrate. This was considered inadequate due to the different dynamics of these species (Tank et al. 2000).
- B. 2D and 3D models. We selected models that had one dimensional in stream processes (i.e. on x, y, z coordinate system, 1D models only calculate the x-coordinate, representing the longitudinal change along the river). 1D models assume vertical and lateral homogeneity. We ruled out any 2D and 3D models

such as SED2D, CE-QUAL-W2, SHETRAN and CAWAQS. These more complex models were excluded because data processing requirements are very time consuming, most 2D and 3D models can only work on short time frames (hours/days) due to the large amount of computations and most rivers have sufficient mixing of the water column so that 2D and 3D models would not add much more accuracy to the predictions<sup>1</sup>. CAEDYM was excluded as no literature to date has been found that uses the model for 1D modelling.

- C. Failure to incorporate a daily time step. In order to work well with EnSym the models selected had to work on a daily time step. This eliminated any models that worked on an annual or monthly time step (e.g. SedNet ANNEX, HEC-6, and RivR-N).
- D. Lack of generality of processes. Any models which were highly specific to a certain process but did not appear to model this process in a different manner to that included in more general models, were ruled out. For example, DWSM only models the impact of storm events on nutrient flow and can't be used for simulating normal conditions and QSIM models chlorophyll-a using nutrient data.
- E. Obsolescence. A number of models that were initially found in the list of 103 models fit the criteria but were essentially older versions of newer models. For example, QUASAR has since been replaced by INCA-N. Likewise, EMSS was initially replaced by E2 which has since been replaced by WaterCAST. In these cases the newest model was chosen.
- F. Substantive overlap with other listed superior models. One such model was MRN-MOHID. This model uses very similar equations to SWAT and consequently was not included in the list of final 10 models. QUAL2K is very similar to Epd-Riv1 and its predecessor, QUAL2E is used in SWAT.
- G. Bayesian, Fugacity and Artificial Neural Networks also were disregarded at this stage. Bayesian and Artificial Neural Networks work on steady state models, whereas rivers require dynamic models. Fugacity models are used for metals and pesticides.
- H. Commercial status. We chose models that had freely available software instead of commercial models which in some cases required a staff member of the developing organisation to be paid to run the model on top of the initial cost of the model (MIKE11, BNZ, SWIM).

Based on these criteria, a group of ten models was selected for further detailed analysis.

### ***3.2 Description of the top 10 models for river water quality analysis***

The top 10 models were determined to be SWAT, WASP, HSPF, EFDC1D, Nutrient Spiralling, INCA, KINEROS, WaterCAST, EPD-RIV1, and STARS. For the top 10 models the equations were examined in more detail in order to determine their suitability for the Australian context as well as identifying the input variables and calibration requirements (Appendix A). Details of the top 10 models and their capabilities are explained here in further detail.

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<sup>1</sup> This assumption is only for flowing rivers. Most lake models are more accurate when 2D or 3D modelling is used due to stratification effects and low residence times.



### **3.2.1 SWAT (nitrogen, phosphorus and suspended solids)**

SWAT (Soil and Water Assessment Tool) evaluates the relationship between precipitation regime, water shed flow paths and stream water phosphorus and nitrogen concentrations. The in stream nitrogen and phosphorus equations used in SWAT were adapted from the model QUAL2E. SWAT is designed for large ungauged basins and therefore does not require flow calibration.

In SWAT, in stream nitrogen is modelled as organic nitrogen, nitrate, ammonia, and nitrite. Similarly, phosphorus species modelled include organic and inorganic (soluble) phosphorus. Additionally, algal dynamics play an important role in nutrient dynamics within streams. The growth of algae removes nutrients from a stream and the respiration and death of algae recycles nutrients back into the stream. An assumption made by SWAT is that algal cells use both ammonia and nitrate as a source of inorganic nitrogen for growth. The settling rate of the algae is also included as this represents a loss of algae from the system.

An issue with SWAT is that there are no equations to model denitrification. This means that for in stream processes there is the assumption that the only loss of nitrogen occurs through algal uptake which is not always accurate. Low oxygen levels in streams will result in denitrification and the release of nitrogen back into the atmosphere. Many peer reviewed papers have coupled SWAT with other in stream models to account for this (e.g. SWAT/QUAL2K, SWAT/Ce-QUAL-W2 (Debele et al. 2008)).

In a channel, sediment transport is the result of deposition and erosion working simultaneously. SWAT can simulate both deposition and erosion with constant channel dimensions throughout the simulation, or it is also possible to add in simulations of down cutting and channel widening that alter the dimensions of the channel throughout the simulation. A disadvantage of SWAT is that it only models the median particle size of the sediment, which reduces the accuracy by neglecting the difference in physical processes between sand, silt and clays.

### **3.2.2 WASP (nitrogen, phosphorus and suspended solids)**

WASP (Water quality Analysis Simulation Program) predicts water quality (nutrient, phytoplankton, sediment and micropollutant) responses to natural phenomena and man-made pollution. It is made up of two submodels: TOXIWASP for organic pollutants and metals and EUTROWASP for eutrophication.

In the EUTRO submodel the transport and transformation of four different interacting systems is modelled. These four systems are phytoplankton kinetics, the phosphorus cycle, the nitrogen cycle, and the dissolved oxygen balance. In all four of these systems the effect of algal growth, death, respiration, mineralization and settling is considered. In WASP, phosphorus species modelled are phytoplanktonic, organic and inorganic phosphorus and nitrogen species modelled are phytoplanktonic, organic, ammonia, and nitrate nitrogen.

For suspended solids, WASP is able to model water column transport as well as the sediment bed. Water column transport is modelled in the TOXIWASP sub model. The user can either model the total solids (encompassing all particle sizes) or segment up to three particle fractions. The user needs to enter the applicable settling and erosion rates

based on calibrated data. The program does not require shear stress data curves. The sediment bed is modelled as a constant volume or varying volume, based on deposition/erosion calculations.

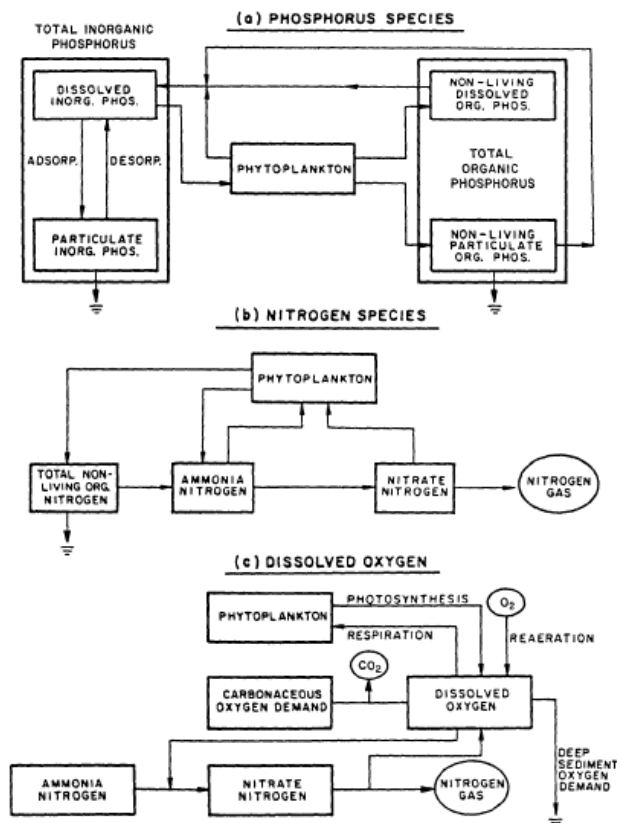


Figure 21. EUTRWASP state variable interactions.

Figure 7: WASP conceptual models for P, N and DO (Wool et al. 2001)

### 3.2.3 HSPF (nitrogen, phosphorus and suspended solids)

HSPF (Hydrological Simulation Program-Fortran) models hydrologic and associated water quality processes on pervious and impervious land surfaces and in streams and well-mixed reservoirs and lakes. It is able to model the effects of land use changes, modifications to point and non point sources as well as flow diversions.

For suspended solids, the model divides particles into clay, silt and sand. Silt and clay models are based on scour and deposition shear stress. When shear stress is less than critical shear stress, deposition occurs. Whenever it is greater, scour occurs.

For the nitrogen cycle both nitrification and denitrification are modelled. Mineralisation is also considered. The phosphorus cycle includes both dissolved and adsorbed phosphorus species, uptake and release of phosphorus by phytoplankton and benthic algae and release of phosphorus by sediments.

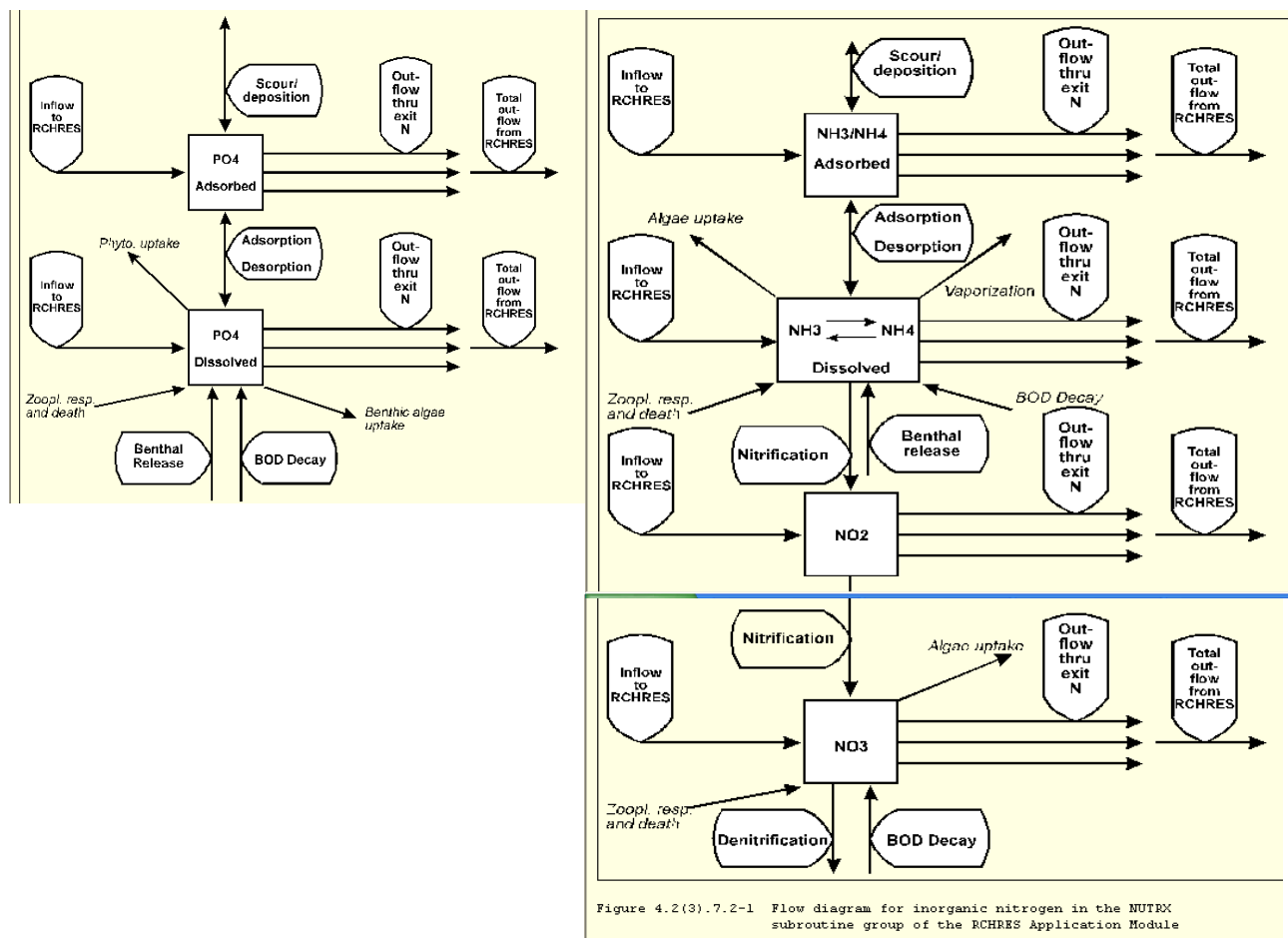


Figure 8: HSPF conceptual models. LHS is the Phosphorus model and RHS is the nitrogen model (Bicknell et al. 1997)

### 3.2.4 EFDC1D (suspended solids)

The EFDC model (Hamrick 2001) models suspended solid movement throughout river systems. The model predicts both cohesive and non-cohesive sediment movement using critical shear stress curves. Multiple size fractions and sediment bed dynamics can also be modelled. This model has been coupled with other models, such as TOXIWASP (Ji et al. 2002). SNL-EFDC is a modified version of the EFDC sediment model which describes cohesive and non-cohesive erosion, transport, and deposition of sediment more accurately than the EFDC model. However, this modified version has mostly been used for 2D and 3D modelling of estuarine systems.

### 3.2.5 Nutrient Spiralling (nitrogen and phosphorus)

Nutrient spiralling models the nutrient uptake and release rates in a stream. The nutrient can undergo biotic or abiotic processes as it is transported downstream. Figure 9 summarises these processes. The total spiral length of a dissolved nutrient,  $S$ , accounts for both uptake length  $S_w$ , and release length  $S_r$ . Uptake length is easily determined experimentally (detailed below), whereas release length has to be calculated using the expensive and time consuming isotope labelling technique. Experiments have found  $S_w$  to account for more than 90% of nutrient spiralling length, therefore  $S_w$  values are mostly commonly measured in the literature.

$S_w$  can be determined by injecting a nutrient and conservative tracer in a stream. The conservative tracer accounts for dilution and dispersion effects (1). Samples are taken at two downstream stations at a set distance apart. Care must be taken that no point source inputs are positioned in between these two stations as this would change the background nutrient concentrations and flow rates. The following equation is used to calculate  $S_w$ :

$$S_w = \frac{x}{\ln\left(\frac{C_{nuts-up}}{C_{nuts-down}}\right) - \ln\left(\frac{C_{tracer-up}}{C_{tracer-down}}\right)}$$

where  $x$ =reach length,  $C_{nuts-up}$ = concentration of nutrient at upstream station,  $C_{nuts-down}$ =concentration of nutrient at downstream station,  $C_{tracer-up}$ =concentration of conservative tracer at upstream station,  $C_{tracer-down}$ =concentration of conservative tracer at downstream station. Note the nutrient and conservative tracer concentrations are background corrected.

Other parameters that can be determined using  $S_w$  include uptake rate coefficient,  $k_c$ , mass transfer coefficient,  $v_f$  (equations in Appendix A). There are dozens of peer reviewed papers on nutrient spiralling for determining  $S_w$  of N and P (as well as C and metals) in streams (e.g. Davis and Minshall, 1999, Marti and Sabater, 1996, Hart *et al.* 1991, Newbold *et al.* 1981). A recent review of these papers by Ensign and Doyle (2006) summarises the variability of  $S_w$ . This variability in  $S_w$  is due to variability in stream morphology, discharge and light, algal community and composition, and canopy density, temperature, primary production, allochthonous organic matter, and substrate type.  $S_w$  only measures the dissolved species of the nutrient. Particulate bound nutrient spiralling is rarely measured.

A nutrient spiralling model differs from a bucket model (e.g. INCA) in two ways. Firstly, a nutrient spiralling model is not capable of incorporating the effects of point and non point source inputs whereas a bucket model can. Secondly, nutrient spiralling models assume that the stream is continuous, unlike bucket models which divide the stream up into a series of segments.

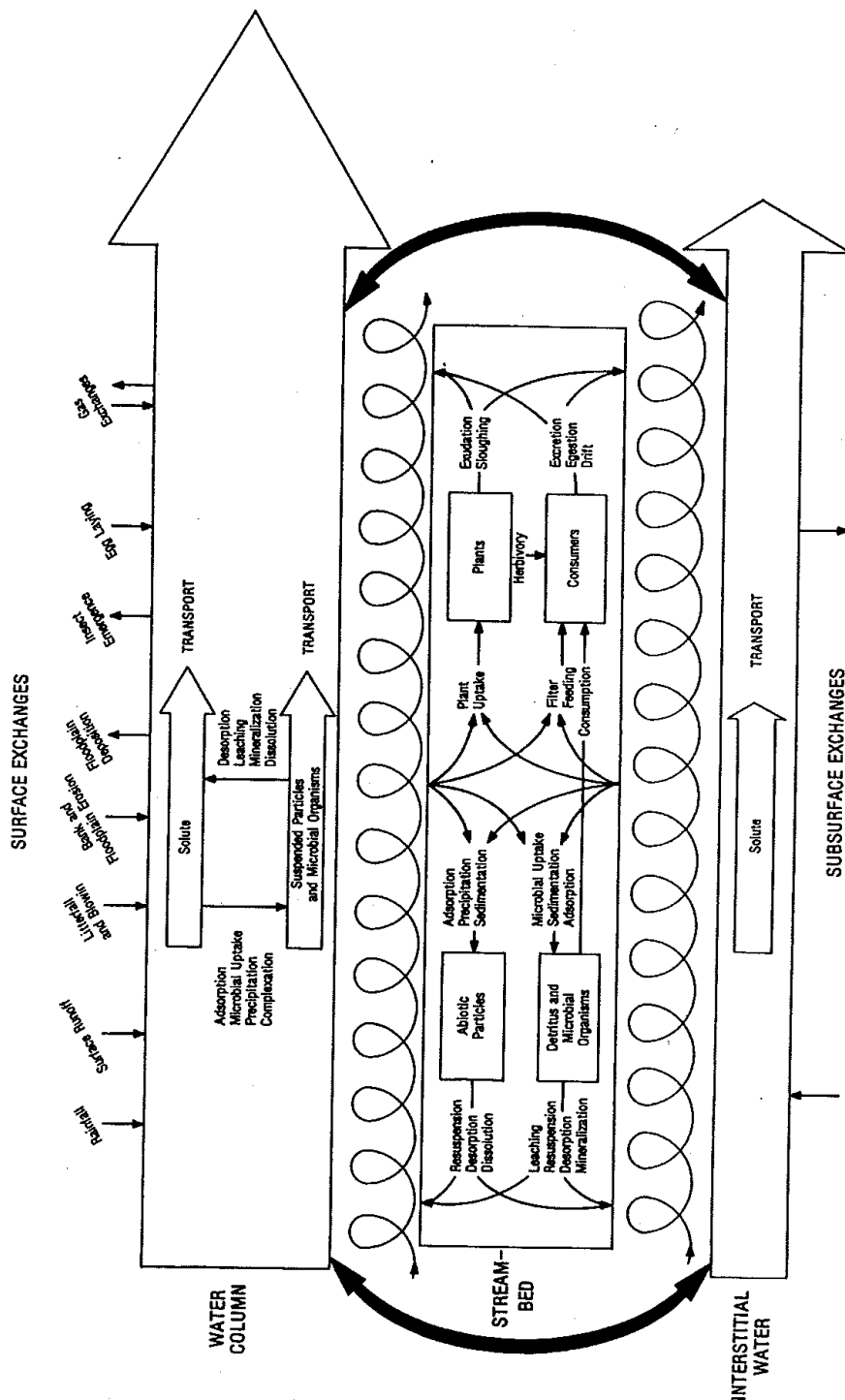


Fig. 1. Conceptual diagram of solute processes in streams, many of which are discussed in this paper. The two spirals represent the continuous exchange of solutes and particle-bound chemicals between the streambed and water column and between the streambed and interstitial water. Materials in the water column and interstitial water are moving downstream, while the streambed materials are stationary.

Figure 9 Conceptual model outlining the chemical, biological and physical processes of solutes in a stream. Diagram taken from Stream Solute Workshop (1990).

### 3.2.6 INCA (nitrogen and phosphorus)

The INCA-N model (Integrated Nitrogen in Catchments model) simulates nitrogen exports from different land use types within river systems. It has been used over a wide variety of climates and topography in Europe, including the Mediterranean region. The model is process based but very basic. It doesn't include mineralization. The original model used concentrations, but the modified model uses mass loads.

Within INCA a model is designed by reach scale processes, and each reach output flows into the next reach, where denitrification, nitrification and inputs from diffuse and point sources are used to calculate nitrate and ammonia loads. Organic nitrogen and therefore mineralisation is not considered by the model.

The INCA-P model-previously known as the Kennet Model is designed on a similar process based model to INCA-N. It has not been widely validated and has been designed on macrophyte dominated chalky streams in England. INCA-N and INCA-P are free for bona-fide researchers to use. INCA-P program will be available in early 2010.

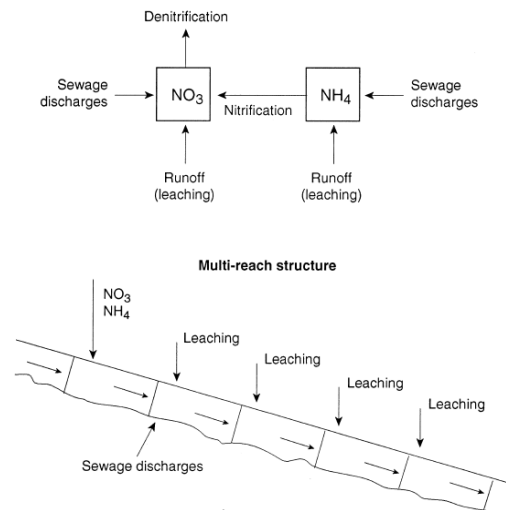
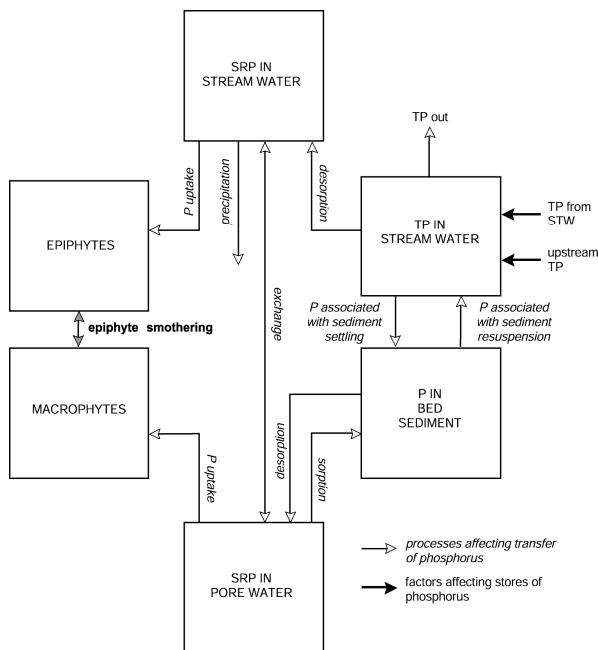


Fig. 3. The structure of the in-stream component of the new version of INCA. (After Whitehead et al., 1998a: published with permission of STOTEN, Elsevier).

Figure 10: INCA-P and INCA-N conceptual models (Wade et al. 2002a; Wade et al. 2002b)

### 3.2.7 KINEROS (suspended solids)

KINEROS is an event oriented, physically based model describing the processes of interception, infiltration, surface runoff and erosion from small agricultural and urban watersheds. Sediment dynamics, channel erosion, and sediment transport are all able to be modelled by KINEROS.

Channel cross sections may be either trapezoidal or circular. The model requires the user to make a choice between Manning's  $n$  or Chezy's  $c$  coefficients for stream characteristics. Appropriate values for Manning's  $n$  or Chezy's  $c$  depend on the following factors:

- the channel material (i.e.-grassed water way vs. gravel bed)
- the degree to which the channel conforms to the trapezoidal shape
- how straight the channel reach is

Due to these factors the choice between the two coefficients is highly subjective. However, the values of these coefficients have been calculated from a number of streams, including Victorian streams<sup>2</sup> and can be obtained from literature.

KINEROS is designed for catchments up to 760ha in size and is best suited to catchments with lots of rain gauges. Up to five particle size fractions can be modelled. The main difference with this model compared to other models is that it uses one-dimensional

<sup>2</sup> <http://lwa.gov.au/files/products/river-landscapes/pn30109/case-studies-victoria.pdf>

kinematic equations to simulate flow over rectangular planes and through trapezoidal open channels, circular conduits and small detention ponds. The parameters required for this model are rainfall and soil data to estimate flow and sediment transport. The catchment is divided up into overland flow and open channel elements, based on soils, slope, vegetation, land use or something else. Each of these overland elements is given parameters for the model, based on soil characteristics. The channel elements are assigned to the overland elements and to connection channels upstream. Rainfall data is then used to estimate flow and suspended solid concentrations at the end of the catchment.

### 3.2.8 WaterCAST (nitrogen, phosphorus)

WaterCAST (Water and Contaminant Analysis Simulation Tool) evaluates flows, loads and concentrations of constituents, under scenarios that include actual or planned changes in land use, land management, climate variability and climate change. It is a flexible, whole catchment model that can be built around a problem. In stream nutrient processing is modelled by simple decay rate equations or by event or dry weather flows. An optional riparian N model can be used to account for denitrification in riparian zones. The model is derived from the original EMSS model, which was subsequently replaced by the E2 model which provided enhancements enabling it to be better integrated with other models. The E2 model has since been replaced by WaterCAST, which is expected to be released in mid 2010.

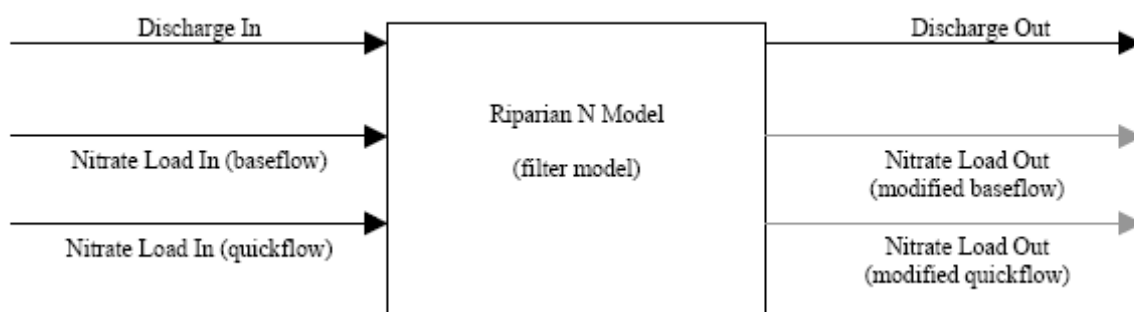


Figure 11: WaterCAST conceptual model for nitrate (Argent et al. 2008)

### 3.2.9 EPD-RIV1 (nitrogen, phosphorus)

EPD-RIV1 analyses existing conditions and performs waste load allocations. It uses kinetic values for the processes, accounting for temperature, solar radiation, and local weather data. It is designed for regulatory decisions. It doesn't contain a sediment processes component of scour or deposition (which is important for particulate-P dynamics). For the nitrogen cycle, nitrogen is split into organic nitrogen, ammonia, and nitrate. Similarly, for the phosphorus cycle phosphorus is split into organic and inorganic phosphorus. The effect of death, respiration, and growth of both algae and macrophytes on the nitrogen and phosphorus cycle is considered. Benthic release rates of inorganic-P and ammonium are modelled however the sediment processes controlling these rates are not.

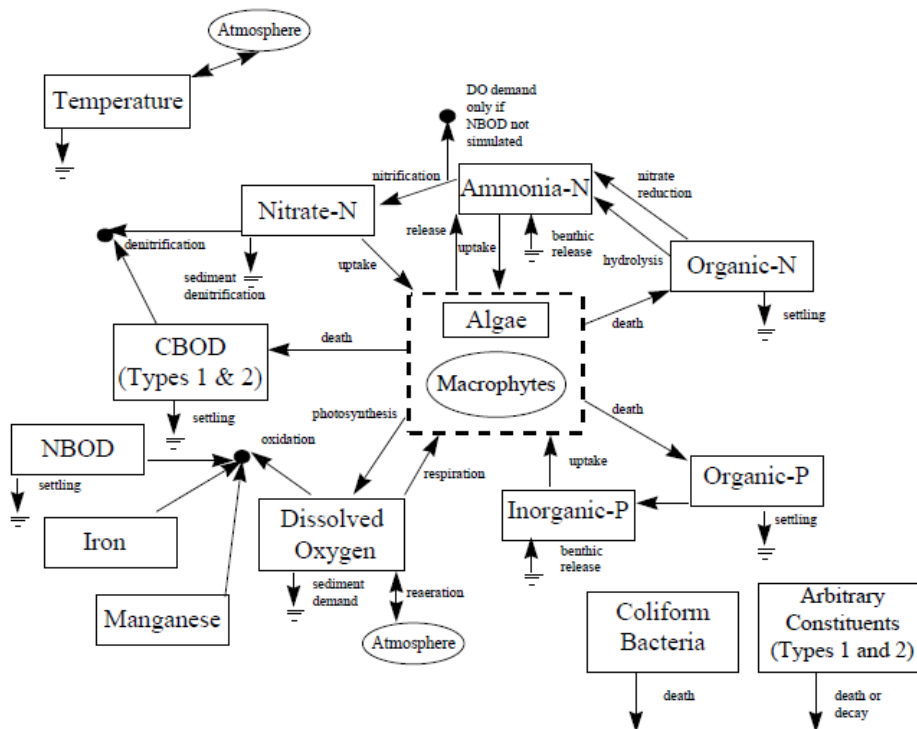


Figure 12: Conceptual model for Epd-Riv1 (Olsen 2002)

### 3.2.10 STARS (suspended solids)

STARS models sediment transport in a single stream reach. It has been calibrated in Australia (Murrumbidgee and Murray Rivers, (Dietrich et al. 1999; Green et al. 1999)). The model can work from reach size to 100km length, however long rivers need data every 10's of km for good accuracy. The model overestimated turbidity during low flow periods (Dietrich et al. 1999). It is able to incorporate rainfall/runoff and bank erosion submodels if these values are known. It is a gauged model relying on data from gauging stations. The model assumes sediment settling velocity is constant and stream length is generally less than 100km to allow for slow changes in sediment sources and flow over the stream reach.

There is some concern that the model may be obsolete. The authors of STARS were contacted about using the model and stated that they had not maintained the software 'for years' but that source code, IMSL libraries (requiring an IMSL license) and executable files are available.



	Point sources	Non-point sources	1	2	3	4	5	6A	6M	6E	6B	7	8	9	10 OM	10T	10 pH	10 DO
SWAT	✓	✓	✓	✓	✓	X	✓	✓	X	X	X	X	X	X	X	✓	X	✓
WASP	✓	✓	✓	✓	✓	✓	✓	✓	X	X	X	X	X	X	X	✓	X	✓
HSPF	✓	✓	✓	✓	✓	✓	✓	✓	X	X	✓	X	✓	✓	✓	✓	✓	✓
EFDC1D	✓	✓	✓	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Nutrient spiralling	X	X	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
INCA-N	✓	✓	✓	X	X	✓	✓	X	X	X	X	X	X	X	X	✓	X	X
INCA-P	✓	✓	✓	✓	✓	X	X	✓	✓	✓	X	X	X	X	X	✓	X	X
KINEROS	✓	✓	✓	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X
WaterCAST	?	?	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
EPD-RIV1	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	X	X	X	X	✓	✓	X	✓
STARS	✓	✓	✓	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Table 2a Summary of the processes that each model uses in its equations. 1: Advection/dispersion. 2: Settling/resuspension. 3. Mineralisation. 4: Denitrification. 5: Nitrification. 6A: Algal uptake of nutrient. 6M: Macrophyte uptake of nutrient. 6E: Epiphyte uptake of nutrient. 6B: Benthic algal uptake of nutrient. 7: Nitrogen fixation. 8: Ammonia speciation 9: Volatilization of Ammonia. 10: Factors that affect nutrient processing – OM: Organic matter, T=temperature, DO=dissolved oxygen

	10 por	11	12	13 sun	13T	13 nuts	14 PS	14E	14S	14 PD	14F	15	16
SWAT	X	✓	X	✓	X	✓	X	✓	X	X	✓	✓	✓
WASP	X	X	X	✓	✓	✓	✓	X	X	✓	✓	X	✓
HSPF	X	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EFDC1D	X	X	X	X	X	X	✓	X	X	✓	✓	X	X
Nutrient spiralling	X	X	X	X	X	X	X	X	X	X	X	X	X
INCA-N	X	X	X	X	X	X	X	X	X	X	X	X	X
INCA-P	✓	✓	✓	✓	✓	✓	✓	X	X	X	✓	✓	X
KINEROS	X		X	X	X	X	✓	X	✓	✓	✓	X	X
WaterCAST	X	X	X	X	X	X	X	X	X	X	X	X	X
EPD-RIV1	X	✓	✓	✓	X	✓	X	X	X	X	X	✓	X
STARS	X	X	X	X	X	X	X	X	X	✓	✓	X	X

**Table 2b. Summary of the processes that each model uses in their equations. 10: Factors that affect nutrient processing – por: Porosity. 11: Storage zones (e.g. sediment). 12: Adsorption/desorption. 13: Factors that affect biological uptake – Sun=sunlight, T=temperature, Nuts=nutrients. 14: Factors that affect suspended solid concentrations – PS=particle size, E=erosion factor, S=slope, PD=particle density, F=flow velocity. 15: Diffusion. 16: Hydrolysis**

### **3.3 Determination of the best model**

The choice of which model would be best suited for EnSym to model Victorian waterways depends on data availability, the complexity of the model and the output information the model provides. The top 10 models chosen from the list of 100 models were divided into two broad categories: high or low input data requirements for nutrient models (Tables 3 and 4) and gauged or ungauged calibration requirements for suspended solids models (Table 5). Table 6 outlines the hydrological models that accompany the top 10 models to aid with the selection of suitable models and Table 7 summaries the geomorphological processes each model includes in their calculations.

The nutrient models with the high data requirements were quite complex in nature. Compared to the simple models with low data requirements, they consider many more important interactions within streams that could affect water quality and nutrient concentrations. In some cases the data required for these models may be unrealistic to collect for any more than a very small number of sites (for example the parasitisation rate of algae is required by WASP, and has not been measured for any stream in Australia).

More generic, low data requirement models have far fewer input variables, many of which may already be collected in standard water quality monitoring surveys across the state (e.g. nitrate concentration, water temperature). These variables are simpler to collect compared to most of the variables required by complex models.

More specifically, each model has their advantages and disadvantages, regardless of their input requirements. In relation to Nitrogen modelling, HSPF, WASP, SWAT and EPD-RIV1 are complex models. They all include at least one biological component (predominantly algae). These models require mineralisation and uptake rates of the Nitrogen species, as well as other factors that impact algal growth, death and movement in the water column. This added complexity of the biological parameters can possibly propagate errors due to assumptions and lack of local Victorian data. As well, the biological transformations of nitrogen in streams are affected by whether it is an algal or macrophyte dominated stream. Therefore, some of the more complex models with large data requirements that do take these biological transformations into consideration may not be accurate for all types of streams, especially if they only consider algae. SWAT also has the drawback that it does not model denitrification, which is an important process in nitrogen dynamics in-stream. The simpler models, INCA-N, WaterCAST and nutrient spiralling, do not require as much calibration data as the more complex models. However, WaterCAST only uses decay loss in its equations, and does not account for different species of nitrogen. Nutrient spiralling can be used for modelling both nitrate and ammonia but does not account for point and non-point sources in its equations. INCA-N models both nitrate and ammonia but does not model total nitrogen, because it does not measure the organic nitrogen component. INCA-N uses simple kinetic rates for nitrification and denitrification (adjusted to local water temperature), which is an advantage over WaterCAST, since INCA accounts for increase and loss of nitrate whereas WaterCAST only measures decay. Another advantage of INCA-N is that it specifically accounts for groundwater input in its equations. This is important in many catchments in Victoria because groundwater can be a source of nitrate to streams.

The complex phosphorus models include INCA-P, HSPF, WASP, EPD-Riv1 and SWAT. These phosphorus models have at least one biological component, which as mentioned above, adds complexity to the models. INCA-P is the most complex model in our list of

models, since it has three biological components as well as sediment/stream water exchange. It has the advantage that it accounts for both TP and DIP and uses the same hydrological model as INCA-N. However, it has not been validated outside England. WASP and SWAT have both an organic-P and inorganic-P component but do not account for adsorption/desorption of inorganic phosphorus to particles. EPD-Riv1 accounts for adsorption/desorption in the benthic release equations only. HSPF uses simple algal parameters but does not have an organic-P component. HSPF only models adsorbed and dissolved phosphate, and accounts for scour, deposition and diffusion from sediments. The two simple phosphorus models, nutrient spiralling and WaterCAST have the similar issue that they only model one phosphorus species. WaterCAST has no equations to predict the species of phosphorus apart from its simple decay rate. Nutrient spiralling has been mostly used for dissolved inorganic phosphorus but requires expensive, labour intensive field experiments to obtain organic or particulate bound phosphorus.

While the more data intensive models are likely to be more accurate at predicting point values for nutrients, there is a lack of the needed data to parameterise them for most Victorian waterways. For modelling at large scales to determine relative changes in nutrient concentrations, it is likely that generic models will perform adequately. These will allow approximations of mass budgets for a range of catchments.

Based on these considerations and the practicality of obtaining the data needed to parameterise the nutrient models we selected two of the low-data generic models; INCA-N for nitrogen, and WaterCAST for phosphorus. INCA-N was chosen because it is a simple kinetic model for both nitrate and ammonia and does not require the biological component. WaterCAST was chosen for phosphorus models because it can model total phosphorus in a river adequately. It has low input data requirements, no algal parameters, it is the most recently developed model and has been developed for Australian conditions. It has the additional advantage that it is likely to be maintained and updated into the future as validation data becomes available. However, if phosphorus speciation is required for EnSym, then we recommend the HSPF model. This is for two reasons: it includes the main sources and sinks of both particulate and dissolved phosphorus and it can be used in conjunction with the suspended solids model (as discussed below).

For suspended solids, the models were divided into two categories. These were models that require gauging stations to run and models that can be run without gauging stations using stream characteristic data. STARS was the only model that required gauging river stations for its calibration. It would be useful for large rivers, where it has been tested in NSW and Victoria. However, it does not appear to have been used for smaller streams so it is difficult to determine its ability to predict suspended solids in the smaller catchments. Also, STARS does not account for bed sediments, but can account for erosion sources if the calibration data is available. The other models, KINEROS, EFDC1D, HSPF, INCA-P, WASP and SWAT all vary in types of input data required and what particle size classifications they model. KINEROS and HSPF uses bed shear stress and critical shear stress to calculate scour and particle settling velocity to determine deposition. HSPF models clay, silt and sand fractions separately and adds them together. KINEROS can model up to five particle sizes. SWAT calculates suspended solids by comparing the concentration in the reach at the start of time step to the maximum concentration of sediment that can be transported by the water. If the concentration at the beginning is more than what is the maximum, then deposition is calculated. Otherwise, scour is calculated using the channel erodibility factor calibrated for US rivers. SWAT does not use particle size or density in any calculations, therefore does not need to model different particle sizes separately. INCA-P uses the cumulative frequency curve (change of grain

size with flow) to determine the threshold of resuspension/settling. INCA-P also accounts for mass of bed sediment. WASP uses scour velocity and deposition rates based on particle size and density to calculate a net sediment flux. The user can model up to three particle size fractions. EDFC1D calculates net sediment flux based on multiple cohesive and non-cohesive sediment fractions. The model uses critical shear stress, bed shear stress and settling velocity over a range of particle sizes to predict sediment flux depending on flow velocity.

The suspended solid models recommended for use in EnSym are STARS for gauged rivers and HSPF for ungauged rivers. The reason why STARS was chosen was that it has been developed and used for Australian rivers, including some Victorian rivers. The only drawback is the necessity for good turbidity and flow data. Another benefit of STARS is that it doesn't require the shear stress curve as do most other models. This shear stress relationship is fairly specific to individual rivers and must be calibrated. This calibration has only been completed for some rivers and not for Victorian rivers. The model is quite a simple model but still covers the main processes. The choice of HSPF for ungauged rivers was based on particle size fractions modelled and simplicity of the equations. The net sediment flux calculated by WASP and EDFC1D were similar to HSPF but appeared to have more complex equations. SWAT calibration data requirements for channel erodibility would require labour intensive field work to determine this parameter for each stream. KINEROS was not chosen just because it modelled only suspended solids whereas HSPF can be linked with phosphorus modelling for the particulate-P calculations.

## Nitrogen Models

**Table 3: Summary of the nitrogen models. The data requirements are listed as low, medium or high.**

Model Name	Data Requirements	Input data/Calibration requirements
SWAT	High	Fraction of algal biomass that is nitrogen, algal biomass concentration at the beginning of the day, flow travel time in the reach segment, nitrite concentration at the beginning of the day, rate constant for biological oxidation of nitrite to nitrate, dissolved oxygen concentration in the stream, average water temperature, ammonium concentration in the stream, preference factor for ammonia nitrogen, nitrate concentration in the stream, sediment source rate for ammonium at 20°C, rate constant for the biological oxidation of ammonia nitrogen at 20°C, depth in the water channel, rate coefficient of organic nitrogen settling at 20°C, rate constant for hydrolysis of organic nitrogen to ammonia nitrogen at 20°C, organic nitrogen concentration, local settling rate for algae at 20°C, local respiration or death rate of the algae at 20°C, local specific algal growth rate at 20°C, Michaelis-Menton half-saturation constant for phosphorus, Michaelis-Menton half-saturation constant for nitrogen, non-linear algal self shading coefficient, algal biomass concentration, ratio of chlorophyll a to algal biomass, linear algal self shading coefficient, non-algal portion of the light extinction coefficient, day length, solar radiation reaching the water surface on a given day, fraction of solar radiation that is photosynthetically-active, half saturation coefficient for light, solar radiation reaching the ground during a specific hour on current day of simulation, depth from the water surface, maximum specific algal growth rate, fraction of algal nitrogen uptake from ammonium pool
WASP	High	Net settling velocity of phytoplankton, herbivorous zooplankton population grazing on phytoplankton, grazing rate on phytoplankton per unit zooplankton population, death rate, representing the effect of parasitisation, endogenous respiration rate at 20°C, temperature coefficient, ambient water temperature, Michaelis half saturation constant for Phosphorus, Michaelis half saturation constant for Nitrogen, dissolved inorganic phosphorus and nitrogen (ammonia and nitrate) available for growth, phytoplankton chlorophyll concentration, light extinction coefficient, depth of the water column or model segment, average incident light intensity during daylight hours just below the surface, maximum growth rate, units conversion factor, extinction coefficient per unit of chlorophyll, quantum yield, saturating light intensity of phytoplankton, fraction of day that is daylight, settling rate constant, phytoplankton population size, half saturation constant for phytoplankton limitation of phosphorus recycle, nitrate nitrogen equation, Michaelis constant for denitrification, denitrification rate at 20°C, phytoplankton carbon concentration, nitrogen to carbon ratio, ammonia nitrogen concentration, half saturation constant for oxygen, dissolved oxygen concentration, water temperature, temperature coefficient, nitrification rate, organic nitrogen concentration, organic nitrogen mineralization rate at 20°C, fraction of dead and respired phytoplankton recycled to the organic nitrogen pool, organic matter settling velocity, fraction of dissolved organic nitrogen
EPDRIV1	High	Monod half velocity constant for oxygen limitation of macrophyte decay, cross sectional area, average dissolved oxygen concentration, width, macrophyte specific decay rate, macrophyte density, specific macrophyte growth rate, hydraulic depth, light extinction coefficient for the particular reach, light intensity (net short-wave radiation) at the water surface, maximum specific algal decay rate, algal concentration, half velocity constant relating phosphate concentration to algal growth rate, phosphate concentration, half velocity constant relating inorganic nitrogen to algal growth, nitrate + ammonia concentration, light growth adjustment factor, maximum specific growth rate, sediment denitrification rate, conversion factor coefficient for oxygen to nitrogen equivalents, temperature, temperature coefficient for ammonia release, benthic release rate, nitrogen to biomass ratio in macrophytes, nitrogen to biomass ratio in algae, concentration of nitrate nitrogen, concentration of ammonium nitrogen, Monod half velocity constant for oxygen limitation of nitrification, temperature coefficient for ammonium oxidation, uncorrected rate coefficient for nitrification, temperature coefficient for organic nitrogen decay, rate coefficient for organic nitrogen decay to NH <sub>3</sub> , concentration of organic nitrogen, settling rate for organic nitrogen
INCA-N	low	Initial ammonia concentration and nitrate concentration, denitrification rate, nitrification rate, volume in reach, total nitrate input in reach, total ammonia input in reach, total flow input in reach, water residence time, water temperature, flow velocity measured from either a tracer experiment or from gauge station data.
WaterCAST	low	Decay constant, discharge, event mean concentration, dry weather concentration (base flow)
Nutrient Spiralling	medium	Tracer experiments (short term solute injections) to develop profile to fit equation, channel depth, channel width, reach length, ambient nitrate/ammonium concentration, flow (discharge and velocity)
HSPF	high	Volume, sorption, equilibrium constant, mass of suspended solids in reach, mass of N in sediment, scour and deposition rates, Org-N, NO <sub>3</sub> <sup>-</sup> and NH <sub>4</sub> <sup>+</sup> concentrations from upstream and diffuse sources, atmospheric deposition, velocity, BOD decay, BOD concentration, ammonia ionization constant, ammonia volatilization constant, water temperature, reaeration rate, wind speed, nitrification rate, denitrification rate, growth rate of phytoplankton, depth of water, light available, light extinction coefficient, Michaelis-Menton coefficients for nitrogen, phosphorus and light limited growth, death rate of phytoplankton, benthic algae growth rate, amount of benthic algae, benthic algae death rate

## Phosphorus Models

**Table 4: Summary of the phosphorus models. Data requirements are listed as low, medium or high.**

Model Name	Data Requirements	Input data/Calibration requirements
<b>SWAT</b>	High	Algal biomass concentration at the beginning of the day, local settling rate for algae at 20 °C, local respiration or death rate of the algae at 20 °C, local specific algal growth rate at 20 °C, Michaelis-Menton half-saturation constant for phosphorus, Michaelis-Menton half-saturation constant for nitrogen, non-linear algal self shading coefficient, algal biomass concentration, ratio of chlorophyll a to algal biomass, linear algal self shading coefficient, non-algal portion of the light extinction coefficient, day length, solar radiation reaching the water surface on a given day, fraction of solar radiation that is photosynthetically-active, half saturation coefficient for light, solar radiation reaching the ground during a specific hour on current day of simulation, depth from the water surface, maximum specific algal growth rate, fraction of algal nitrogen uptake from ammonium pool, flow travel time in the reach segment, fraction of algal biomass that is phosphorus, organic phosphorus concentration at the beginning of the day, rate constant for mineralization of organic phosphorus at 20 °C, average water temperature for the day or hour, rate coefficient for organic phosphorus settling at 20 °C, sediment source rate for soluble phosphorus at 20 °C
<b>WASP</b>	High	Net settling velocity of phytoplankton, herbivorous zooplankton population grazing on phytoplankton, grazing rate on phytoplankton per unit zooplankton population, death rate, representing the effect of parasitisation, endogenous respiration rate at 20 °C, temperature coefficient, ambient water temperature, Michaelis half saturation constant for Phosphorus, Michaelis half saturation constant for Nitrogen, dissolved inorganic phosphorus (orthophosphate) available for growth, dissolved inorganic nitrogen (ammonia plus nitrate) available for growth, phytoplankton chlorophyll concentration, light extinction coefficient, depth of the water column or model segment, average incident light intensity during daylight hours just below the surface, maximum growth rate, units conversion factor (0.083, assuming 43% incident light is visible and 1 mole of photons is equivalent to 52,000 cal), extinction coefficient per unit of chlorophyll, quantum yield, saturating light intensity of phytoplankton, fraction of day that is daylight, settling rate constant, phytoplankton population size, phosphorus to carbon ratio, concentration of phytoplankton carbon, fraction of dead and respired phytoplankton recycled to the organic phosphorus pool, dissolved organic phosphorus mineralization at 20 °C, temperature coefficient, water temperature, half saturation constant for phytoplankton limitation of phosphorus recycle, concentration of organic phosphorus, organic matter settling velocity
<b>EPDRIV1</b>	High	Monod half velocity constant for oxygen limitation of macrophyte decay, cross sectional area, average dissolved oxygen concentration, depth, width, macrophyte specific decay rate, macrophyte density, specific macrophyte growth rate, hydraulic depth, light extinction coefficient for the particular reach, light intensity (net short-wave radiation) at the water surface, maximum specific algal decay rate, algal concentration, half velocity constant relating phosphate concentration to algal growth rate, phosphate concentration, half velocity constant relating inorganic nitrogen to algal growth, nitrate + ammonia concentration, light growth adjustment factor, maximum specific growth rate, phosphorus to biomass ratio in algae, phosphorus to biomass ratio in macrophytes, organic P concentration, organic P hydrolysis rate, organic P settling rate, depth, benthic release rate, temperature coefficient for phosphate release, phosphate loss rate, temperature coefficient for phosphate sorption or loss, phosphate concentration
<b>WaterCAST</b>	Low	Decay constant , discharge, event mean concentration, dry weather concentration (base flow)
<b>Nutrient Spiralling</b>	Medium	Tracer experiments (short term solute injections) to develop profile to fit equation, channel depth, channel width, reach length, ambient nitrate/ammonium concentration, flow (discharge and velocity)
<b>INCA-P</b>	High	Macrophyte temperature dependency, macrophyte growth rate, constant associated with macrophyte self-shading, half saturation constant associated with the macrophyte growth, macrophyte death rate, solar radiation, water temperature, pore water and surface water SRP concentration, macrophyte biomass, epiphyte biomass, epiphyte temperature dependency, epiphyte growth rate, half saturation constant associated with the epiphyte growth, epiphyte death rate, total mass of P entering the reach, reach length, reach width, SRP constant for exchange between pore water and water column, constant associated with the co-precipitation of P with calcite in the water column, bulk sediment depth, surface water TP concentration, TP mass associated with the bed sediment, sorption coefficient for P and suspended sediment and bed sediment, porosity, bed sediment bulk density, sediment depth, reach length, masses of live and dead algae input to reach from the upstream flow, algal temperature dependency, algal death rate, algal growth rate, the P half-saturation for algal growth, self-shading factor, settling rate for dead algae
<b>HSPF</b>	High	Volume, sorption, equilibrium constant, mass of suspended solids in reach, mass of P in sediment, scour and deposition rates, Org-P, particulate-P and DIP concentrations from upstream and diffuse sources, atmospheric deposition, velocity, BOD decay, BOD concentration, growth rate of phytoplankton, depth of water, light available, light extinction coefficient, Michaelis-Menton coefficients for nitrogen, phosphorus and light limited growth, death rate of phytoplankton, benthic algae growth rate, amount of benthic algae, benthic algae death rate

## Suspended Solids Models

**Table 5: Summary of the suspended solids models. The data requirements are listed.**

Model Name	Gauged/ Ungauged	Input data/Calibration requirements
SWAT	Gauged	Volume of water in the reach segment, volume of outflow during the time step, amount of suspended sediment in the reach at the beginning of the time period, channel cover factor, channel erodibility factor, concentration of sediment in the reach at the beginning of the time step, average rate of flow, peak rate adjustment factor, cross sectional area of flow in the channel
WASP	Ungauged	Absolute viscosity of the water, density of the solid, density of the water, particle diameter, benthic surface area, scour velocity, sediment concentration of the benthic segment, sediment concentration of the water segment, probability of deposition upon contact with the bed, depth of the upper bed, sedimentation velocity of the upper bed, sediment velocity of the lower bed, depth of the lower bed
KINEROS	Ungauged	Bottom width of the channel, rate of lateral sediment inflow for channels, concentration at equilibrium transport capacity, hydraulic depth, particle diameter, kinematic viscosity of water, particle specific gravity, critical shear stress, bed shear stress, channel discharge, cross sectional area of flow, sediment concentration, rate of lateral sediment inflow for channels, rate of erosion of the soil bed, hydraulic radius
STARS	Gauged	Stream reach with upstream and downstream gauging stations with turbidity and flow data, reach length
INCA-P	Gauged or ungauged	Mean grain size diameter, reach length, reach width, total bed mass, potential moveable bed mass, reach volume, cumulative frequency curve of grain size vs. flow (default is river in England), mass SS from upstream
HSPF	Gauged or ungauged	Fraction of sand, silt and clay in sediment, volume of sediment in reach, porosity, reach length, reach width, depth of water column, sheer stress, critical sheer stress for each particle fraction, settling velocity, of each particle fraction, volume of water, erodibility coefficient, amount of sediment stored in reach
EFDC1D	Gauged or ungauged	Concentration of suspended solids from upstream, tributaries, lateral flows, channel dimensions, flow velocity, sediment particle diameter, sediment particle density, kinematic molecular viscosity of water, critical shear stress, bed shear stress, critical depositional stress, near bed depositing sediment concentration



**Table 6. Summary of the in-stream hydrological models. Note this does not include the catchment hydrological processes.**

<b>Model</b>	<b>Summary</b>	<b>Assumptions</b>	<b>Calibration req.</b>
SWAT	Uses Mannings equations for flow rate and velocity. Throughout the channel network, SWAT uses the “variable storage routing method” (volume of inflow, outflow and storage are used to calculate a storage coefficient) or the Muskingum routing method (storage volume in channel length is a series of wedges and prisms). SWAT calculates transmission losses, evaporation losses and bank storage.	Channel is trapezoidal shape. Channel sides have 2:1 run to rise ratio. Floodplains have 4:1 run to rise ratio and slope is 0.25	Width and depth when filled to top of bank, length of channel, slope of channel, Mannings ‘n’, coefficients for storage times for the Muskingum method, hydraulic conductivity of channel length, reach evaporation coefficient, fraction of transmission losses, bank flow recession constant.
WASP	WASP does not have its own hydrodynamic model but uses compatible models (most commonly EFDC or DYNHYD5)		
HSPF	HSPF uses basic continuity to model water flow through the channel (otherwise known as “storage routing” or “kinematic wave.”) The channel is divided into reaches. Each reach is modelled using inputs from upstream (tributaries, point sources, non-point sources, including groundwater). Direct precipitation (input in reach) and evaporation (loss in reach) can also be modelled. Outputs include flows downstream, extraction and diversions.	There is a fixed relation between depth (at the deepest point in the reach), surface area, and volume. No set shape for the channel.	For each reach: depth, surface area, volume, and volume dependent functions
EFDC1D	Uses 1D continuity and momentum equations based on reach segments. Includes lateral runoff, withdrawals, groundwater interactions, evaporation and direct rainfall into reach. Can include overbank. Calculates the centroid depth of the channel.	Assumes a rectangular shaped cross-section.	Channel cross-section area, surface width, bottom width, wetted perimeter, water surface elevation of each reach. Time series of upstream inflows, and lateral inflows and withdrawals. Time series of rainfall and evaporation parameters.
Nutrient spiralling	Nutrient spiralling does not have a hydrology component however hydrological parameters, such as flow velocity and discharge can be calculated from tracer experiments.		
INCA	Simple input/output mass balance equations along reach lengths of a channel. Flows were calculated from upstream flow input plus any point (sewage) and non-point (leaching from groundwater and soil water) inputs. Equations are solved by using the fourth-order Runge-Kutta technique.	When calculating the initial flows, it is assumed that the reach volumes on day, $t = 0$ are the same on day $t = 1$ .	Sewage effluent flow rates, initial conditions of flow, daily time series of flow discharge, flow velocity measurements (or estimates)

INCA-P	Simple linear input/output mass balance equations along reach lengths of a channel. Flows were calculated from upstream flow input plus any point (sewage) and non-point (direct runoff, groundwater and soil water) inputs. Equations are solved by using the fourth-order Runge-Kutta technique.	When calculating the initial flows, it is assumed that the reach volumes on day, $t = 0$ are the same on day $t = 1$ .	Daily time series of flow discharge, flow velocity measurements (or estimates), base flow index derived from flow gauges, reach length, reach width, sewage flow rates.
KINEROS	KINEROS uses kinematic and continuity equations, solved using a four point implicit technique. Channel dimensions can be either trapezoidal or circular. KINEROS models overbank flows with the trapezoidal channels. Includes lateral flows (overflow and infiltration)	Direct rainfall in channel is not considered by default. Circular channels do not have any lateral flow. No energy transfer between channel and overbank.	Length and type of channel reach, baseflow discharge, bottom width, bottom slope, Mannings or Chezy's coefficient, bank side slopes. Infiltration: soil saturation constant, soil thickness, hydraulic conductivity, capillary drive, porosity, rock fraction, pore size. Overbank: overbank slopes, threshold depth for overflow.
WaterCAST	WaterCAST uses routing mass balance to calculate the flow out of a reach by using inflow, storage and lateral flow data. Storage is calculated using a number of methods including Muskingum (prism and wedge method) or Laurenson (an empirical parameter is used to calculate storage).	No explicit assumptions were given in the in-stream hydrological section.	Using RAP (River Analysis Package): cross sectional area slope and Mannings coefficient for each reach. Laurenson requires a dimension and dimensionless empirical parameter for storage equation. Muskingum requires slope and length and width of reach, flow discharge and velocity.
EPD-RIV1	EPD-RIV1H predicts flows, depths, velocities, water surface elevations and other hydraulic characteristics using gravity, friction of river bottom and sides and pressure from river slope. The hydrodynamic model solves the St. Venant equations (continuity and momentum) as the governing flow equations. Also includes both point (tributaries) and non-point (lateral) inflows and withdrawals. Includes equation for constriction of channel (i.e. bridge), which causes flow to lose momentum.	Lateral and vertical gradients are small and can be neglected; thus the equations are cross-sectionally averaged for flow and constituent variables. All lateral point and non-point source flows and input concentrations are known. All cross sections and bottom configurations are known. If data are only provided for an upstream cross-section, the model assumes that the cross-section of the downstream node is identical in shape.	Between each node: length, cross-sectional shape, roughness (Mannings "n"), bottom elevation, constant lateral inflows, the momentum correction coefficient, and initial conditions (the starting point for the first iteration) for flow and depth.
STARS	STARS hydrological model is incorporated within the SS model. IHACRES can be used to convert rainfall into runoff and flow data if no flow gauges are available.	STARS model assumes negligible sources and sinks of water along the reach. The stream length $L$ is small enough (typically no more than 100 km) to ensure discharge change only slowly over the stream reach $[0, L]$ within each travel time period.	Flow data at upstream and downstream gauges. Otherwise, IHACRES rainfall/runoff model data requirements are: rainfall, streamflow and temperature time series (for evaporation calculations).

**Table 7. The three types of geomorphological processes, Mannings roughness coefficient, gradient/slope and land/sediment characteristics of both the catchment/land and streams component for each model. Although the catchment/land models are not discussed in this report, their geomorphology parameters are included in the table.**

	<b>Mannings roughness coefficient</b>		<b>Gradient/slope</b>		<b>Land/sediment characteristics</b>	
	<b>Catchment</b>	<b>Stream</b>	<b>Catchment</b>	<b>Stream</b>	<b>Catchment</b>	<b>Stream</b>
<b>SWAT</b>	yes	yes	yes	yes	yes	yes
<b>WASP</b>	no	optional	yes	no	yes	yes
<b>HSPF</b>	yes	yes	yes	yes	yes	yes
<b>EFDC1D</b>	N/A	no	N/A	no	N/A	yes
<b>Nutrient spiralling</b>	N/A	no	N/A	no	N/A	no
<b>INCA-N</b>	no	can be used to estimate water residence time	no	no	yes	no
<b>INCA-P</b>	no	can be used to estimate water residence time	no	no	yes	yes
<b>KINEROS</b>	yes	yes	yes	yes	yes	yes
<b>WaterCAST</b>	no	yes	yes	yes	yes	no
<b>EPD-RIV1</b>	N/A	yes	N/A	yes	N/A	no
<b>STARS</b>	N/A	no	N/A	no	N/A	yes

## Section 4: Knowledge gaps and future needs

### 4.1 Identification of key knowledge gaps

There are many areas in which knowledge could be extended to assist with the modelling of in stream nutrient and sediment dynamics. The large majority of the top 10 models have never been validated in Australian systems. Most of the models currently available have been designed for North America and Europe. It has not yet been determined whether these models then relate to Australian systems and produce reliable information. Future research could focus on validating some of the more well known or used European or North American models to determine whether they are relevant.

In addition to the lack of validation, each model is usually designed and tested on a specific area and is built around the data currently available to the developers. This then means that often the required input data is not available in other areas restricting the ability of other groups to apply the model. In addition, for more complex models, the data requirements are often so large that it makes it extremely difficult to collect all of the required data, especially when the model is intended to be applied across a large area. Strong effort should be made to attempt to collect these baseline datasets so that input data is available to run the models. Likewise, for Australian rivers there is a shortage of data reporting on the common processing rates (e.g. denitrification, nitrification). These rates are required for the majority of models to determine the rate of denitrification and other important reactions.

Another decision that has to be considered is the choice between generic or complex models. Due to the smaller amount of input data required, generic models have been recommended in this study, however, it is not known what the difference is in the level of error between generic and more complex models. No model is ever going to be 100% accurate but what matters is the degree to which the model is predicting large uncertainties. It may be that the more complex models produce far more accurate results and the investment of time and money into collecting the input data is justified by the output result. However, it is also equally likely that the generic models produce results that do not vary greatly from complex models. In this case, utilising a simpler, easier model may do the job adequately. The difference between generic and complex models has not been tested to any great degree and would provide an interesting comparison.

**Recommended data project:** *Comparison of data-intensive and generic nitrogen, phosphorus and sediment models for Victorian streams. While we have chosen the approach of using low-data generic models here, it is unclear what loss of accuracy results from this decision. A study comparing highly parameterised models with generic models across at least three Victorian catchments would provide a core validation element to the use of generic models within EnSym.*

## Section 5: References

- Argent, R. M., et al. (2008). WaterCAST User Guide. eWater CRC, Canberra.
- Bicknell, B. R., et al. (1997). Hydrological Simulation Program-Fortran, User's manual for version 11. U.S. Environmental Protection Agency, National Exposure Research Laboratory, Athens, Ga, pp 755.
- Boulton, A. J. and M. A. Brock (1999). Australian Freshwater Ecology. Processes and Management. Glen Osmond, Australia, Gleneagles Publishing.
- Davis, J. C. and G. W. Minshall (1999). "Nitrogen and phosphorus uptake in two Idaho (USA) headwater wilderness streams." Oecologia **119**(2): 247-255.
- Debele, B., et al. (2008). "Coupling upland watershed and downstream waterbody hydrodynamic and water quality models (SWAT and CE-QUAL-W2) for better water resources management in complex river basins." Environ. Model. Assess. **13**(1): 135-153.
- Dietrich, C. R., et al. (1999). "An analytical model for stream sediment transport: application to Murray and Murrumbidgee river reaches, Australia." Hydrol. Process. (5): 763-776.
- Ensign, S. H. and M. W. Doyle (2006). "Nutrient spiraling in streams and river networks." J. Geophys. Res. **111**.
- Green, T. R., et al. (1999). "Relating stream-bank erosion to in-stream transport of suspended sediment." Hydrol. Process. **13**(5): 777-787.
- Hamrick, J. M. (2001). EFDC1D - A One Dimensional Hydrodynamic and Sediment Transport Model for River and Stream Networks: Model Theory and Users Guide EPA/600/R-01/073 U.S Environmental Protection Agency, Washington, DC.
- Hart, B. T., et al. (1991). "Phosphorus spiralling in Myrtle Creek, Victoria, Australia." Verh. Internat. Verein. Limnol. **24**(3): 2065-2070.
- Hart, B. T., et al. (1992). "Whole-stream phosphorus release studies: variation in uptake length with initial phosphorus concentration." Hydrobiol. **235/236**: 573-584.
- Ji, Z.-G., et al. (2002). "Sediment and Metals Modeling in Shallow River." J. Environ. Eng. **128**(2): 105-119.
- Marti, E. and F. Sabater (1996). "High variability in temporal and spatial nutrient retention in Mediterranean streams." Ecology **77**(3): 854-869.
- Newbold, J. D., et al. (1981). "Measuring nutrient spiralling in streams." Can. J. Fish. Aquat. Sci. **38**: 860-863.
- Olsen, R. (2002). A Dynamic One-Dimensional Model of Hydrodynamics and Water Quality EPD-RIV1 Version 1.0 User Manual. U.S. Environmental Protection Agency, Washington, DC.
- Stream Solute Workshop (1990). "Concepts and methods for assessing solute dynamics in stream ecosystems." J. N. Am. Benthol. Soc. **9**(2): 95-119.
- Tank, J. L., et al. (2000). "Analysis of nitrogen cycling in a forest stream during autumn using a <sup>15</sup>N-tracer addition." Limnol. Oceanogr. **45**(5): 1013-1029.
- Wade, A. J., et al. (2002a). "A nitrogen model for European catchments: INCA, new model structure and equations." Hydrol. Earth Syst. Sci. **6**(3): 559-582.
- Wade, A. J., et al. (2002b). "The Integrated Catchments model of Phosphorus dynamics (INCA-P), a new approach for multiple source assessment in heterogeneous river systems: model structure and equations." Hydrol. Earth Syst. Sci. **6**(3): 583-606.
- Wool, T. A., et al. (2001). Water Quality Analysis Simulation Program, WASP. User Documentation for Version 6.0. US Environmental Protection Agency, Atlanta, GA.

## APPENDIX A

STARS	Parameters	Purpose of equation	Calibration requirements	Issues	Reference number from Table 1
<b>Suspended solids</b>					
$C_L(t) = C_0(t - \tau)e^{\frac{-\alpha}{Q_t}} + \left[ \frac{\eta\beta(Q_t - Q^*)^\mu + \gamma}{\alpha} \right] (1 - e^{\frac{-\alpha}{Q_t}})$ $\tau(t) = a\overline{Q}_t^{-b}$	$C_L(t)$ =downstream [SS] as function of time (kg m <sup>-3</sup> ) $C_0$ =[SS] upstream (kg m <sup>-3</sup> ) $Q_t$ = stream discharge (m <sup>3</sup> day <sup>-1</sup> ) $\overline{Q}_t$ = average discharge over the reach (m <sup>3</sup> day <sup>-1</sup> ) $\tau$ =effective water parcel travel time between gauging stations a and b= parameters $\alpha$ = particle setting velocity (m <sup>2</sup> day <sup>-1</sup> ) $\gamma$ =lateral source term (bank erosion and sediment washout) (kg day <sup>-1</sup> ) $Q^*$ =resuspension threshold flow rate (m <sup>3</sup> day <sup>-1</sup> ) $\beta$ = resuspension function based on $\mu$ $\mu$ = resuspension power (dimensionless) $q_0$ =flow rate at gauge station (m <sup>3</sup> day <sup>-1</sup> ) $\eta$ =part of resuspension function where $\eta=1$ when $Q_t > Q^*$ otherwise $\eta=0$  note: [SS] is concentration of Suspended solids	Calculates [SS] downstream  Calculates [SS] in high flow event. Assumptions: $e^{\frac{-\alpha}{Q_t}} \cong 1 - \frac{\alpha}{Q_t}$ $Q_t \gg Q^* \Rightarrow \beta Q_t^\mu$ $\beta Q_t^\mu \gg \gamma$ and $\alpha/Q_t \rightarrow 0$ since resuspension and advection are the dominant processes	Stream reach with upstream and downstream gauging stations with turbidity and flow data.  a and b are calculated using the time between the upstream and downstream discharge peaks and troughs from gauging stations. a and b can be calculated from linear regression of the subsequent log transformed data (Dietrich et al 1989).  $\alpha$ , $\beta$ , $\mu$ , $\gamma$ and $Q^*$ are calibrated using linear and non-linear output least squares minimization technique using suspended solids concentrations at discrete times.	Stream reach with upstream and downstream gauging stations with turbidity and flow data, reach length.	1,2,14PD,14F, non-point sources  1,2,14F
high flow event $C_L(t) = C_0(t - \tau) + \beta Q_t^{\mu-1}$		Calculates [SS] during periods of low flow. Assumptions: reverse the high flow assumptions			1,2,14PD,14F
low flow event $C_L(t) = C_0(t - \tau)e^{\frac{-\alpha}{Q_t}} + \frac{\gamma}{\alpha}$					
weighted conc. when there are two tributaries upstream $C_0 = \frac{c_{0_1}q_{0_1} + c_{0_2}q_{0_2}}{q_{0_1} + q_{0_2}}$					point sources

Model Name	Language	Output
STARS	Unknown	SS concentration as function of time

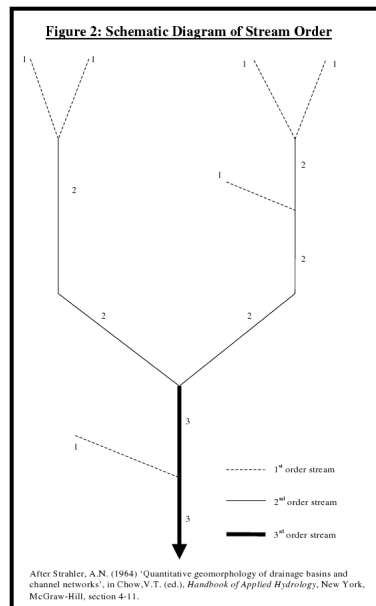
### References

- Dietrich, C. R., T. R. Green, *et al.* (1999). "An analytical model for stream sediment transport: application to Murray and Murrumbidgee river reaches, Australia." *Hydrological Processes*(5): 763-776.
- Green, T. R., S. G. Beavis, *et al.* (1999). "Relating stream-bank erosion to in stream transport of suspended sediment." *Hydrological Processes* **13**(5): 777-787.
- Jakeman, A. J., T. R. Green, *et al.* (1999). "Modelling upland and in stream erosion, sediment and phosphorus transport in a large catchment." *Hydrological Processes*(5): 745-752.
- Dietrich, C. R., A. J. Jakeman and G. A. Thomas (1989). "Solute Transport in a Stream-Aquifer System 1. Derivation of a Dynamic Model." *Water Resour. Res.* **25**(10): 2171-2176.

Nutrient Spiraling	Parameters	Purpose of equation	Calibration requirements	Issues	Reference number from Table 1
$S = S_w + S_r$ $S_w \gg S_r$	S=spiral length $S_w$ =uptake length $S_r$ =release length	Measure dissolved nutrient spiraling length as uptake and release length.	Nutrient and conservative tracer injection upstream and subsequent concentrations collected at two downstream stations, channel depth, channel width, reach length, flow (discharge and velocity)	Tracer experiments are required to assess the dilution and dispersion effects and nutrient uptake length. Assumes a single limiting nutrient, the channel geometry is constant and flow is uniform and steady. Doesn't account for temporal variability. Most experiments have been conducted at base flow thus doesn't account for high flow periods (Brookshire 2009)	1
$S_w = \frac{x}{\ln\left(\frac{C_{nuts-up}}{C_{nuts-down}}\right) - \ln\left(\frac{C_{tracer-up}}{C_{tracer-down}}\right)}$	x=reach length (length) $C_{nuts-up}$ = concentration of nutrient at upstream station, background corrected $C_{nuts-down}$ = concentration of nutrient at downstream station, background corrected $C_{tracer-up}$ =concentration of conservative tracer at upstream station, background corrected $C_{tracer-down}$ =concentration of conservative tracer at downstream station, background corrected	Uptake length (average distance travelled of nutrient in dissolved phase before uptake) (length)			1
$k_c = \frac{u}{S_w}$		Uptake rate coefficient (first order) (time <sup>-1</sup> )			1
$v_f = \frac{Q}{wS_w}$		Mass transfer coefficient (vertical velocity of nutrient towards sediment/benthic) (length time <sup>-1</sup> )			1
$U = v_f \times C$	u= stream velocity (Length time <sup>-1</sup> ) h=water depth (Length) w=channel width (length) C=background solute concentration (mass volume <sup>-1</sup> ) $v_f$ = mass transfer coefficient from water to benthic compartment. (Length time <sup>-1</sup> ) $k_c$ =first order uptake rate coefficient (time <sup>-1</sup> ) $S_w$ =uptake length (Length) U=solute uptake rate per unit area of stream bottom (mass length <sup>-2</sup> time <sup>-1</sup> ) Q=stream discharge (volume time <sup>-1</sup> )	Uptake rate (gross nutrient uptake) (mass length <sup>-2</sup> time <sup>-1</sup> )			1
$S_w \approx \sqrt{Q}$	Q=stream discharge (Volume time <sup>-1</sup> ) u=stream velocity (Length time <sup>-1</sup> ) h=stream depth (length) w=channel width (length)	Approximate relationship between discharge and spiral length. Assumption that discharge increase due to increase depth, not increase velocity		These equations have been sourced from the paper: Ensign and Doyle (2006). The authors collated all published $S_w$ values and estimated relationships between stream discharge and $S_w$ .	1
$S_w = \frac{Q}{w}$	Q=stream discharge (Volume time <sup>-1</sup> ) w=channel width (length)	Approximate relationship with spiral length and channel width to compare two streams with similar flow but different channel			1

		characteristics.		
$G_i = L_i \times W_{b(i)} \times N_i \times U_i$	$G_i$ =Cumulative nutrient uptake within all streams of stream order* i $L$ =channel length for a particular order $W_b$ =channel width $N$ =number of channels of stream order i $U$ =uptake rates	Cumulative nutrient uptake of a catchment using median uptake rates of published data for 1-5 stream orders*.	For each stream: order number*, length, width. Use literature uptake rates	1

\* stream order: the number given to each tributary in a catchment based on its size and position within the riverine network.



Model Name	Language	Output
Nutrient Spiraling	Unknown	Nutrient spiral length, uptake rate coefficient, mass transfer coefficient, uptake rate

#### References

- Ensign, S. H. and M. W. Doyle (2006). "Nutrient spiraling in streams and river networks." *J. Geophys. Res.* **111**.
- Stream Solute Workshop (1990). "Concepts and methods for assessing solute dynamics in stream ecosystems." *J. N. Am. Benthol. Soc.* **9**(2): 95-119.
- Rutherford, K., S. Chapra, *et al.* (2007). Can a Simple Model Quantify Stream Nutrient Dynamics? MODSIM07 International Congress on Modelling and Simulation., Modelling and Simulation Society of Australia and New Zealand.
- Hart, B. T., P. Freeman, *et al.* (1992). "Whole-stream phosphorus release studies: Variations in uptake length with initial phosphorus concentration." *Hydrobiol.* **235/236**: 573-584.
- Brookshire, E. N. J., H. M. Valett, *et al.* (2009). "Maintenance of terrestrial nutrient loss signatures during in stream transport." *Ecology* **90**(2): 293-299.





INCA-P (in stream equations)	Parameters	Description	Calibration Requirements	Issues	Reference number from Table 1
Flow in Reach					
$\frac{dx_{25}}{dt} = \frac{(S_4 + S_5 + U_7 - x_{25})}{T_4}$ $T_4 = \frac{L}{v} = \frac{L}{ax_{25}^b 86400}$ $S_5 = \sum_{j=1}^n (1 - \alpha - \beta)x_2 + x_1 + x_3$	$x_{25}$ =flow out of reach at time t ( $m^3s^{-1}$ ) $S_4$ =upstream flow into reach at time t ( $m^3s^{-1}$ ) $S_5$ =lateral flow into reach at time t ( $m^3s^{-1}$ ) $U_7$ =STP flow into reach at time t ( $m^3s^{-1}$ ) $v$ =flow velocity (equal to $ax_{25}^b$ ) $L$ =reach length $a/b$ =constants $T_4$ =water residence time (days) 86400=conversion from sec to days $\alpha$ = direct runoff fraction $\beta$ = base flow index $x_1$ =direct runoff ( $m^3day^{-1}km^{-2}$ ) $x_2$ =soil outflow ( $m^3day^{-1}km^{-2}$ ) $x_3$ =groundwater outflow ( $m^3day^{-1}km^{-2}$ )	Flow in reach.	Flow in and out of reach, lateral flow into reach, point source flow into reach, mean grain size diameter, reach length, reach width, total bed mass, potential moveable bed mass, reach volume, cumulative frequency curve of grain size vs. flow (default is river in England), mass SS from upstream		1, point, non point sources
Estimate [SS] by resuspension or deposition					
$\frac{dx_{26}}{dt} = C_{10} \frac{(S_4 + S_5 + U_7 - x_{25})}{T_4}$	$x_{26}$ =mean grain size diameter ( $\mu m$ ) $x_{25}$ =flow out of reach at time t ( $m^3s^{-1}$ ) $C_{10}$ =constant relating flow in reach to mean grain diameter resuspended or deposited ( $\mu m s m^{-3}$ ) $S_4$ =upstream flow into reach at time t ( $m^3s^{-1}$ ) $S_5$ =lateral flow into reach at time t ( $m^3s^{-1}$ ) $U_7$ =STP flow into reach at time t ( $m^3s^{-1}$ ) $T_4$ =flow storage time constant	Change in mean grain diameter of bed material suspended at time t			1,2,11,14PS, point sources, non point sources
$\frac{dx_{27}}{dt} = \frac{dPM}{dx_{26}} \cdot \frac{dx_{26}}{dt}$	$PM$ =potentially moveable bed mass (kg) $x_{26}$ =mean grain size diameter ( $\mu m$ ) $x_{27}$ =SS resuspended or deposited (kg)	Change in grain size held in suspension converted into mass. If negative, then deposition occurs.			2,11,14PS
$\frac{dPM}{dx_{26}} = \Delta CV .x_{28} w L f$	$PM$ =potentially moveable bed mass (kg) $x_{26}$ =mean grain size diameter ( $\mu m$ ) $\Delta CV$ =slope of cumulative curve fraction of bed material ( $\mu m^{-1}$ ) $x_{28}$ =total bed mass ( $kg m^{-2}$ ) $f$ =fraction of total bed material can be resuspended $w$ =reach width $L$ =reach length	Change in potentially available bed material with grain diameter		Default is grain size with flow measured as cumulative frequency curve in River Lambourn England.	2,11,14PS,14F
$\frac{dx_{28}}{dt} = \frac{1}{Lw} \cdot \frac{dx_{27}}{dt}$	$x_{28}$ =total bed mass ( $kg m^{-2}$ ) $x_{27}$ =SS resuspended or deposited (kg) $w$ =reach width $L$ =reach length	Change in moveable bed mass at time. Equation is an expression of the mass of sediment that is gained or lost from the bed following the re-suspension or deposition of sediment.			2,11

$\frac{dx_{29}}{dt} = S_{in} - \frac{x_{29}x_{25}86400}{x_{37}} + \frac{dx_{27}}{dt}$	S <sub>in</sub> =upstream SS at time t (kg day <sup>-1</sup> ) x <sub>37</sub> =reach volume (m <sup>3</sup> ) x <sub>29</sub> =SS stored in reach x <sub>25</sub> =reach outflow	Change in SS stored in reach. If dx <sub>27</sub> /dt is negative, then deposition occurs			1
$a_7 = \frac{x_{29} \cdot 1000}{x_{37}}$	a <sub>7</sub> = concentration of suspended solids in reach (mg L <sup>-1</sup> ) x <sub>29</sub> =mass of SS in reach (kg) x <sub>37</sub> =reach volume (m <sup>3</sup> )	Calculates the concentration of suspended solids in the reach.			
<b>Tracer equation</b>					
$\frac{dx_{30}}{dt} = B_{in} - \frac{x_{30}x_{25}86400}{x_{37}}$	x <sub>25</sub> =reach outflow x <sub>30</sub> =Boron mass in water column x <sub>37</sub> =reach volume B <sub>in</sub> =total Boron input into reach at time t (kg day <sup>-1</sup> )	Change in boron in reach	Tracer measurements were included in the model because it determined the quantity of point source inputs into the stream.	Assumes no boron from lateral flow. Conservative tracer.	1
<b>Macrophyte equations</b>					
$\frac{dx_{31}}{dt} = \frac{C_{11}\theta_M^{(U_4-20)}x_{31}U_{11}C_{12}a_{12}}{(C_{13} + a_{12})(C_{12} + x_{31})} - C_{14}x_{32}x_{31}x_{25}$	θ <sub>M</sub> = macrophyte temp. dependency C <sub>11</sub> = macrophyte growth rate (day <sup>-1</sup> ), C <sub>12</sub> = constant associated with macrophyte self-shading (g C m <sup>-2</sup> ), C <sub>13</sub> = the half saturation constant associated with the macrophyte growth (mg P l <sup>-1</sup> ), C <sub>14</sub> =macrophyte death rate (s m <sup>-1</sup> g C <sup>-1</sup> day <sup>-1</sup> ), U <sub>11</sub> = solar radiation, a <sub>12</sub> = pore water SRP conc. (mg P l <sup>-1</sup> ) U <sub>4</sub> = water temperature (°C) x <sub>25</sub> =in stream reach outflow x <sub>31</sub> =Macrophyte biomass stored in water column in reach gCm <sup>-2</sup> x <sub>32</sub> = Epiphyte biomass stored in water column in reach	Macrophyte growth rate based on Lotka-Volterra model (predator/prey model).	Macrophyte temperature dependency, macrophyte growth rate, constant associated with macrophyte self-shading, half saturation constant associated with the macrophyte growth, macrophyte death rate, solar radiation, water temperature, pore water and surface water SRP concentration, macrophyte biomass, epiphyte biomass, epiphyte temperature dependency, epiphyte growth rate, half saturation constant associated with the epiphyte growth, epiphyte death rate, total mass of P entering the reach, reach length, reach width, SRP constant for exchange between pore water and water column, constant associated with the co-precipitation of P with calcite in the water column, bulk sediment depth, surface water TP conc., TP mass associated with the bed sediment, sorption coefficient for P and suspended sediment and bed sediment, porosity, bed sediment bulk density,	C <sub>11</sub> dependant on SRP in pore water. C <sub>13</sub> dictates the substrate becoming limiting. Seasonal and high flow effects accounted for.	1,3,6E,6M, 13sun,13T, 13nuts
<b>Epiphyte equation</b>					
$\frac{dx_{32}}{dt} = \frac{C_{15}\theta_E^{(U_4-20)}x_{32}x_{31}U_{11}a_{11}}{C_{16} + a_{11}} - C_{17}x_{32}x_{25}$	θ <sub>E</sub> = epiphyte temp dependency C <sub>15</sub> =epiphyte growth rate (m <sup>2</sup> g C <sup>-1</sup> day <sup>-1</sup> ), C <sub>16</sub> = the half saturation constant associated with the epiphyte growth (mg P L <sup>-1</sup> ), C <sub>17</sub> =epiphyte death rate (s m <sup>-3</sup> day <sup>-1</sup> ) a <sub>11</sub> =water column SRP conc (mg P l <sup>-1</sup> ) x <sub>25</sub> =in stream reach outflow x <sub>32</sub> = Epiphyte biomass stored in water column in reach U <sub>11</sub> = solar radiation U <sub>4</sub> = water temperature (°C)	Epiphyte biomass stored in reach at time t.			1,3,6E, 13sun, 13T, 13nuts
<b>TP equations</b>					
$\frac{dx_{33}}{dt} = P_{in} - \frac{x_{33}x_{25}86400}{x_{37}} - \frac{C_{18}C_{15}\theta_E^{(U_4-20)}x_{32}x_{31}U_{11}a_{11}}{(C_{16} + a_{11})1000}$ $\frac{C_{19}(a_{12} - a_{11})}{1000} - \frac{C_{20}a_{11}}{1000} + \left\{ \frac{gain}{loss} \right\}$	P <sub>in</sub> = the total mass of P entering the reach at time, t (kg P), L=length of reach w=width of reach a <sub>11</sub> =water column SRP conc. a <sub>12</sub> =pore water SRP conc.	Change in TP in stream water. Particulate P and dissolved reactive P but not unreactive P.		Calcite sorption not applicable in Australia.  The values of K <sub>D</sub> are taken from literature values based on	1,2,3,6M,6E, 10por, 11, 12, 13nuts, 13sun, 13T, 14PD,15

$gain = \frac{1}{\rho_s(1-n)wLC_{21}} x_{34} \cdot \frac{dx_{27}}{dt}, \text{ if } \frac{dx_{27}}{dt} > 0$ $loss = 10^{-6} a_{11} K_D^{SUS} \frac{dx_{27}}{dt}, \text{ if } \frac{dx_{27}}{dt} < 0$ $K_D^{BED} = C_{28} K_D^{SUS}$ $P_{in} = 86.4(S_4 S_6 + U_7 U_{10} + \sum_{j=1}^n area((1-\alpha-\beta)x_2 a_3 + x_1 a_1 + x_3 a_5) + \sum_{j=1}^n area((1-\alpha-\beta)x_2 a_4 + x_1 a_2 + x_3 a_6))$	<p> <math>\theta_E</math> = epiphyte temp dependency  <math>U_4</math>=air temp  <math>U_{11}</math>=solar radiation  <math>C_{15}</math>=epiphyte growth rate  <math>C_{16}</math>=half saturation of P for epiphyte growth  <math>C_{18}</math> = the ratio of phosphorus to carbon in epiphytes (g P g C<sup>-1</sup>),  <math>C_{19}</math> = the constant associated with the exchange of SRP between the pore water and the overlying water column (m<sup>3</sup> day<sup>-1</sup>),  <math>C_{20}</math> = the constant associated with the co-precipitation of P with calcite in the water column (m<sup>3</sup> day<sup>-1</sup>),  <math>C_{21}</math> = the bulk sediment depth (m)  <math>x_{25}</math>=reach outflow  <math>x_{31}</math>=macrophyte biomass in reach  <math>x_{32}</math>=epiphyte biomass in reach  <math>x_{33}</math>=TP conc. in water column  <math>x_{34}</math> = the TP mass associated with the bed sediment (kg P),  <math>x_{37}</math>=reach volume  <math>K_D^{SUS} = K_D</math> for suspended sediment (dm<sup>3</sup> kg<sup>-1</sup>),  <math>K_D^{BED} = K_D</math> for bed sediment (dm<sup>3</sup> kg<sup>-1</sup>)  <math>K_D</math>=The affinity of the solid phase for sorbing P from the surrounding substrate (dm<sup>3</sup> kg<sup>-1</sup>)  <math>n</math> = the porosity,  <math>\rho_s</math> = the bed sediment bulk density (kg m<sup>-3</sup>).  <math>C_{28}</math>=fraction of sorption  86.4=unit conversion from m<sup>3</sup> to liters and seconds to days  <math>S_4</math>=upstream flow into reach at time t  <math>S_6</math>=upstream TP conc at time t (mg-P/L)  <math>x_1</math>=direct runoff (m<sup>3</sup>day<sup>-1</sup>km<sup>-2</sup>)  <math>x_2</math>=soil outflow (m<sup>3</sup>day<sup>-1</sup>km<sup>-2</sup>)  <math>x_3</math>=groundwater outflow (m<sup>3</sup>day<sup>-1</sup>km<sup>-2</sup>)  <math>a_1</math>= direct runoff organic phosphorus concentration (mg-P/L)  <math>a_2</math>= direct runoff inorganic phosphorus concentration (mg-P/L)  <math>a_3</math>=soil water organic phosphorus concentration (mg-P/L)  <math>a_4</math>=soil water inorganic phosphorus concentration (mg-P/L)  <math>a_5</math>= groundwater organic phosphorus conc. (mg-P/L)  <math>a_6</math>=groundwater inorganic phosphorus conc. (mg-P/L)  <math>U_7</math>=sewage flow into reach at time t  <math>U_{10}</math>=TP conc. in sewage at time t  <math>\alpha</math>= direct runoff fraction  <math>\beta</math>= base flow index </p>		<p> sediment depth, reach length, masses of live and dead algae input to reach from the upstream flow, algal temperature dependency, algal death rate, algal growth rate, the P half-saturation for algal growth, self-shading factor, settling rate for dead algae. </p>	<p> research of a catchment in England. Will need Australian <math>K_D</math> values. </p>	
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$\frac{dx_{34}}{dt} = \frac{C_{22}C_{11}\theta_M^{(U_4-20)}x_{31}U_{11}C_{12}a_{12}Lw}{(C_{13}+a_{12})(C_{12}+x_{31})1000} + \frac{C_{19}(a_{12}-a_{11})}{1000} - \left\{ \frac{gain}{loss} \right\}$ $gain = \frac{1}{\rho_s(1-n)wLC_{21}}x_{34}\frac{dx_{27}}{dt}, \text{ if } \frac{dx_{27}}{dt} > 0$ $loss = 10^{-6}a_{11}K_D^{SUS}\frac{dx_{27}}{dt}, \text{ if } \frac{dx_{27}}{dt} < 0$	<p>C<sub>11</sub>=macrophyte growth rate  C<sub>12</sub>=self shading for macrophytes  C<sub>13</sub>=half saturating of P for macrophyte growth  C<sub>19</sub>=P exchange from water column/sediment  C<sub>21</sub>=sediment depth  C<sub>22</sub> = the ratio of phosphorus to carbon in macrophytes (g P g C<sup>-1</sup>)  x<sub>31</sub>=macrophyte biomass in reach  x<sub>34</sub> = the TP mass associated with the bed sediment (kg P)  L=length of reach  w=width of reach  a<sub>11</sub>=water column SRP conc.  a<sub>12</sub>=pore water SRP conc.  θ<sub>M</sub> = macrophyte temp dependency  U<sub>4</sub>=air temp  U<sub>11</sub>=solar radiation  n = the porosity  ρ<sub>s</sub>=bed sediment bulk density (kg m<sup>-3</sup>).</p>	Change of TP associated with river bed in reach			1, 6M, 10por, 11, 13nuts, 13T, 13sun
<b>Chlorophyll-a</b>					
$\frac{dx_{35}}{dt} = L_{in} - \frac{x_{35}x_{25}86400}{x_{37}} - C_{23}x_{35} + C_{24}x_{35}\theta_A^{(U_4-20)}U_{11}\left(\frac{a_{11}}{a_{11}-C_{25}}\right)\left(\frac{C_{26}}{C_{26}-x_{35}}\right)$ $L_{in} = 86.4 \times 10^6 (S_4 S_8)$	<p>L<sub>in</sub> and D<sub>in</sub> are the masses of live and dead algae input to the reach from the upstream flow  θ<sub>A</sub> = algal temperature dependency  C<sub>23</sub> = the algal death rate (day<sup>-1</sup>),  C<sub>24</sub> = algal growth rate (day<sup>-1</sup>),  C<sub>25</sub> = the P half-saturation for algal growth (mg P l<sup>-1</sup>),  C<sub>26</sub> = the self-shading factor (µg Chl 'a' m<sup>-2</sup>)  C<sub>27</sub> = the settling rate for dead algae (day<sup>-1</sup>)  x<sub>35</sub>= live algae stored in water column in reach µg Chl 'a'</p>	Change in live algal cells in water column			1, 3, 6A, 13nuts, 13T
$\frac{dx_{36}}{dt} = D_{in} - \frac{x_{36}x_{25}86400}{x_{37}} + C_{23}x_{35} - C_{27}x_{36}$ $D_{in} = 86.4 \times 10^6 (S_4 S_9)$	<p>x<sub>36</sub>= dead algae stored in water column in reach  S<sub>4</sub>=upstream flow into reach at time t (m<sup>3</sup> s<sup>-1</sup>)  S<sub>8</sub>= upstream concentration of live algae at time t (µg Chl 'a' L<sup>-1</sup>)  S<sub>9</sub>=upstream concentration of dead algae at time t (µg Chl 'a' L<sup>-1</sup>)</p>	Change in dead algae in water column			1,2,3
<b>SRP concentration</b>					
$TP = PP + SRP + 0.25TP$	<p>TP=total phosphorus  PP=particulate phosphorus  SRP=soluble reactive phosphorus  SUP=soluble unreactive phosphorus</p>			Based on data that 25% of TP is SUP in River Lambourn	
$PP = SRP \cdot 10^{-6} K_D^{SUS} a_7$	<p>PP=particulate phosphorus  SRP=soluble reactive phosphorus  K<sub>D</sub><sup>SUS</sup> = K<sub>D</sub> for suspended sediment (dm<sup>3</sup> kg<sup>-1</sup>)  K<sub>D</sub>=The affinity of the solid phase for sorbing P from the surrounding substrate (dm<sup>3</sup> kg<sup>-1</sup>)  a<sub>7</sub>=SS water column conc.</p>	Water column PP			12

$a_{11} = \frac{0.75a_8}{1 + 10^{-6} K_D^{SUS} a_7}$	a <sub>11</sub> =SRP water column conc. a <sub>8</sub> =TP water column conc. a <sub>7</sub> =SS water column conc. $K_D^{SUS} = K_D$ for suspended sediment (dm <sup>3</sup> kg <sup>-1</sup> ) K <sub>D</sub> =The affinity of the solid phase for sorbing P from the surrounding substrate (dm <sup>3</sup> kg <sup>-1</sup> )	Water column SRP			12
$a_{12} = \frac{0.75a_{10}}{1 + \frac{10^{-3} K_D^{SUS} x_{28}}{nC_{21}}}$	a <sub>12</sub> =SRP pore water conc. a <sub>10</sub> =pore water TP conc. x <sub>28</sub> =reach bed mass n=porosity C <sub>21</sub> =bed sediment depth $K_D^{SUS} = K_D$ for suspended sediment (dm <sup>3</sup> kg <sup>-1</sup> ) K <sub>D</sub> =The affinity of the solid phase for sorbing P from the surrounding substrate (dm <sup>3</sup> kg <sup>-1</sup> )	Pore water SRP			10por, 11, 12
$a_{13} = \frac{x_{35}}{x_{37}1000}$	a <sub>13</sub> =live algae concentration x <sub>35</sub> =live algae in water column reach x <sub>37</sub> =reach volume	Concentration of live algae			
$a_{14} = \frac{x_{36}}{x_{37}1000}$	a <sub>14</sub> =dead algae concentration x <sub>36</sub> =dead algae in water column reach x <sub>37</sub> =reach volume	Concentration of dead algae			
$\frac{\delta x_{37}}{\delta t} = (S_4 + S_5 + U_7 - x_{25})86400$ $\frac{\delta x_{38}}{\delta t} = (S_4 + S_5 + U_7)86400$ $\frac{\delta x_{39}}{\delta t} = x_{25}86400$ $\frac{\delta x_{40}}{\delta t} = P_{in}$ $\frac{\delta x_{41}}{\delta t} = \frac{x_{33}x_{25}86400}{x_{37}}$ $\frac{\delta x_{42}}{\delta t} = \frac{C_{18}C_{15}\theta_E^{(U_4-20)}x_{32}x_{31}U_{11}a_{11}LW}{1000(C_{16} + a_{11})}$	dx <sub>37</sub> /dt=Change reach volume (m <sup>3</sup> day <sup>-1</sup> ) dx <sub>38</sub> /dt= Change in flow volume into reach (m <sup>3</sup> day <sup>-1</sup> ) dx <sub>39</sub> /dt= Change in flow volume out from reach (m <sup>3</sup> day <sup>-1</sup> ) dx <sub>40</sub> /dt= Change in Total Phosphorus input to reach (kg P day <sup>-1</sup> ) dx <sub>41</sub> /dt= Change in Total Phosphorus output from reach (kg P day <sup>-1</sup> ) dx <sub>42</sub> /dt= Change in epiphyte uptake in reach (kg P day <sup>-1</sup> ) dx <sub>43</sub> /dt= Change in Total Phosphorus due to water column/pore water SRP exchange (kg P day <sup>-1</sup> ) dx <sub>44</sub> /dt= Change in Total Phosphorus co-precipitated with calcite (kg P day <sup>-1</sup> ) dx <sub>45</sub> /dt= Change in Total Phosphorus in water column due to PP re-suspension from bed (kg P day <sup>-1</sup> ) dx <sub>46</sub> /dt= Change in Total Phosphorus in water column due to PP deposition on bed (kg P day <sup>-1</sup> ) x <sub>25</sub> =flow out of reach at time t (m <sup>3</sup> s <sup>-1</sup> ) S <sub>4</sub> =upstream flow into reach at time t (m <sup>3</sup> s <sup>-1</sup> ) S <sub>5</sub> =lateral flow into reach at time t (m <sup>3</sup> s <sup>-1</sup> )	Supplementary equations to determine mass balances.		Note: calcite equations are not applicable in Australia.	1, 2, 6M, 6E, 10por, 11, 13nuts, 13sun, 13T, 15

$\frac{\delta x_{43}}{\delta t} = \frac{C_{19}(a_{12} - a_{11})}{1000}$ $\frac{\delta x_{44}}{\delta t} = \frac{C_{20}a_{11}}{1000}$ $\frac{\delta x_{45}}{\delta t} = \frac{1}{\rho_s(1-n)wLC_{20}} x_{34} \frac{\delta x_{27}}{\delta t}$ $\frac{\delta x_{46}}{\delta t} = 10^{-6} a_{11} K_D^{SUS} \frac{\delta x_{27}}{\delta t}$ $input = x_{40,i} + x_{43,i} + x_{45,i}$ $output = x_{41,i} + x_{42,i} + x_{44,i} + x_{46,i}$ $storage = x_{33,i}$ $initial = x_{33,0,i}$ $Pbalance = initial + input - output - storage$	<p>U<sub>7</sub>=STP flow into reach at time t (m<sup>3</sup>s<sup>-1</sup>)  P<sub>in</sub> = the total mass of P entering the reach at time, t (kg P)  x<sub>37</sub>=reach volume  x<sub>33</sub>=TP conc. in water column (mg-P/L)  C<sub>18</sub>= Proportion of P in epiphytes (g P g<sup>-1</sup> C)  θ<sub>E</sub> = epiphyte temp dependency  C<sub>15</sub> =epiphyte growth rate (m<sup>2</sup> g C<sup>-1</sup> day<sup>-1</sup>)  U<sub>4</sub> = water temperature (°C)  x<sub>32</sub>= Epiphyte biomass stored in water column in reach  x<sub>31</sub>=macrophyte biomass in reach  U<sub>11</sub> = solar radiation  a<sub>11</sub> =water column SRP conc (mg P l<sup>-1</sup>)  a<sub>12</sub>=pore water SRP conc.  L=length of reach  w=width of reach  C<sub>16</sub> = the half saturation constant associated with the epiphyte growth (mg P l<sup>-1</sup>)  C<sub>19</sub>=P exchange from water column/sediment  C<sub>20</sub>= Precipitation of P in water column (m<sup>3</sup>day<sup>-1</sup>)  n = the porosity  ρ<sub>s</sub>=bed sediment bulk density (kg m<sup>-3</sup>)  x<sub>34</sub> = the TP mass associated with the bed sediment (kg P)  dx<sub>27</sub>/dt= Change in the suspended sediment deposited or resuspended  K<sub>D</sub><sup>SUS</sup> = K<sub>D</sub> for suspended sediment (dm<sup>3</sup> kg<sup>-1</sup>)  K<sub>D</sub> =The affinity of the solid phase for sorbing P from the surrounding substrate (dm<sup>3</sup> kg<sup>-1</sup>)</p>				
<p>Initial volume conditions:  <math display="block">x_{37,0,1} = T_{4,0}x_{25,0,1}86400</math></p> <p>Calculate T<sub>4</sub> using <math display="block">T_4 = \frac{L}{ax_{25}^b 86400}</math></p> <p>1st time step, integrate  <math display="block">\frac{\delta x_{25}}{\delta t} = \frac{S_4 + S_5 + U_7 - x_{25}}{T_4}</math></p> <p>and add result to x<sub>37,0</sub>. i.e.  <math display="block">x_{37,0,2} = (S_{4,1} + S_{5,1} + U_{7,1} - x_{25,0,2})86400 + x_{37,0,1}</math></p>	<p>T<sub>4,0</sub>= water residence time at time 0 (t=0)  x<sub>25,0</sub>=user defined initial flow at time 0 (t=0)  x<sub>37,0</sub>=reach volume at furthest upstream reach at time 0  x<sub>25</sub>=flow out of reach at time t (m<sup>3</sup>s<sup>-1</sup>)  S<sub>4</sub>=upstream flow into reach at time t (m<sup>3</sup>s<sup>-1</sup>)  S<sub>5</sub>=lateral flow into reach at time t (m<sup>3</sup>s<sup>-1</sup>)  U<sub>7</sub>=STP flow into reach at time t (m<sup>3</sup>s<sup>-1</sup>)  x<sub>37</sub>=reach volume  a and b are calibration parameters  dx<sub>25</sub>/dt= Change in the in-stream flow (m<sup>3</sup>s<sup>-1</sup>day<sup>-1</sup>)</p>	<p>Equations to calculate the initial volume of the furthest upstream reach.</p> <p>Each subsequent reach is initialized in turn by integrating  <math display="block">\frac{\delta x_{25}}{\delta t} = \frac{S_4 + S_5 + U_7 - x_{25}}{T_4}</math> for first time step and adding the result to the upstream volume. Once all reach volumes are initialized, run model for day 1 using calibrated data.</p>			1

$waterbalance = x_{37,0,i} + x_{38,i} - x_{39,i} - x_{37,i}$	$x_{37,0,i}$ =initial reach volume $x_{38,i}$ = Flow volume into reach, i. $x_{39,i}$ = Flow volume out from reach, i. $x_{37,i}$ = Reach volume, i.				
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Model Name	Language	Output
INCA-P	Unknown	Reach flow, concentration of SS resuspended and deposited, final SS concentration at end of reach, bed sediment changes, macrophyte and epiphyte biomass changes in reach, TP concentration in water column, TP conc. in sediment, SRP concentration in water column and pore -waters, chl-a concentration.

#### References

- Wade, A. J., D. Butterfield, *et al.* (2007). "Eutrophication control in river-systems: an application of INCA-P to the River Lugg." *Hydrol. Earth Syst. Sci.* **11**(1): 584-600.
- Wade, A. J., P. G. Whitehead, *et al.* (2002). "The Integrated Catchments model of Phosphorus dynamics (INCA-P), a new approach for multiple source assessment in heterogeneous river systems: model structure and equations." *Hydrology and Earth System Sciences* **6**(3): 583-606.
- Wade, A. J. et. al. (2001). On modelling the mechanisms that control in stream phosphorus, macrophyte and epiphyte dynamics: An assessment of a new model using general sensitivity analysis. *Water resources research* **37**(11): 2777-2792



INCA-N	Parameters	Description	Calibration	Issues	Reference number from Table 1
$\frac{dx_{22}}{dt} = \frac{S_4 - x_{22}}{T_3}$ $T_3 = \frac{L}{ax_{22}^b 86400}$	t-1= changes to nitrate and ammonia due to nitrification and denitrification at previous time step. Increases stability of model (Wade <i>et al.</i> 2002) L=reach length (m) x <sub>22</sub> =reach outflow (m <sup>3</sup> s <sup>-1</sup> ) x <sub>23</sub> =nitrate stored in reach (kg N) x <sub>24</sub> =ammonia stored in reach (kg N) a <sub>5</sub> =in-stream nitrate concentration (mg-N/L) a <sub>6</sub> =in-stream ammonia concentration (mg-N/L) C <sub>10</sub> = nitrification rate (day <sup>-1</sup> ) C <sub>11</sub> = denitrification rate (day <sup>-1</sup> ) x <sub>29</sub> =volume in reach (m <sup>3</sup> ) S <sub>5</sub> =total nitrate input in reach (kg N day <sup>-1</sup> ) S <sub>6</sub> = total ammonia input in reach (kg N day <sup>-1</sup> ) S <sub>4</sub> =total flow input in reach (m <sup>3</sup> s <sup>-1</sup> ) T <sub>3</sub> =water residence time U <sub>4</sub> =water temperature a and b = discharge-velocity parameter 86400=conversion from sec to days 1000=conversion from liters to m <sup>3</sup> 1.047=temperature correction coefficient	Flow equations	Initial ammonia concentration and nitrate concentration, denitrification rate, nitrification rate, volume in reach, total nitrate input in reach, total ammonia input in reach, total flow input in reach, water residence time, water temperature, flow velocity measured from either a tracer experiment or from gauge station data.	Designed for Europe. Doesn't include mineralisation. The original model used concentrations, but the modified model uses mass loads.	1
$\frac{dx_{24}}{dt} = S_6 - \frac{x_{22}x_{24}86400}{x_{29}} - \frac{C_{10}a_6x_{24}x_{29}}{1000}$		Change in ammonia in reach			1,5
$\frac{dx_{23}}{dt} = S_5 - \frac{x_{22}x_{23}86400}{x_{29}} - \frac{C_{11}a_5x_{23}x_{29}}{1000} + \frac{C_{10}a_6x_{24}x_{29}}{1000}$		Change in nitrate in reach			1,4,5
$C_n = C1.047^{(U_4-20)}$		Adjusting rates of denitrification and nitrification due to temperature			10T
$a_5 = \frac{1000x_{23}}{x_{29}}$					
$a_6 = \frac{1000x_{24}}{x_{29}}$					
Initial volume conditions: $x_{29,0,1} = T_{3,0}x_{22,0}86400$ Calculate T <sub>3</sub> using $T_3 = \frac{L}{ax_{22}^b 86400}$	T <sub>3,0</sub> = water residence time at time 0 (t=0) x <sub>22,0</sub> =user defined initial flow at time 0 (t=0)	Equations to calculate the initial volume of the furthest upstream reach.			1

<p>1st time step, integrate <math>\frac{\delta x_{22}}{\delta t} = \frac{S_4 - x_{22}}{T_3}</math></p> <p>and add result to <math>x_{29,0}</math>. i.e.</p> $x_{29,0,2} = (S_{4,1} - x_{22,0,2})86400 + x_{29,0,1}$		<p>Each subsequent reach is initialized in turn by integrating</p> $\frac{\delta x_{22}}{\delta t} = \frac{S_4 - x_{22}}{T_3}$ <p>for first time step</p> <p>and adding the result to the upstream volume. Once all reach volumes are initialized, run model for day 1 using calibrated data.</p>			
$S_{4,j} = U_{7,j} + \sum_{i=1}^n area_{i,j}((1 - \beta)x_1 + x_2)$	$\sum_{i=1}^n area_{i,j}((1 - \beta)x_1 + x_2)$ =flow input from land use type, i, into reach, j. $S_{4,j}$ =total flow input in reach, j. ( $m^3 s^{-1}$ ) $U_{7,j}$ =sewage flow into reach, j ( $m^3 s^{-1}$ ) $x_1$ =soil outflow ( $m^3 s^{-1} km^{-2}$ ) $x_2$ =groundwater outflow ( $m^3 s^{-1} km^{-2}$ ) $\beta$ = base flow index	Input flow to reach, j, from total n land use types, i			1, non point and point sources
$S_{5,j} = 86.4(U_{7,j}U_{8,j} + \sum_{i=1}^n area_{i,j}((1 - \beta)x_1 a_1 + x_2 a_3))$	$\sum_{i=1}^n area_{i,j}((1 - \beta)x_1 + x_2)$ =flow input from land use type, i, into reach, j. $S_{5,j}$ =total nitrate input in reach, j. ( $kg-N day^{-1}$ ) $U_{7,j}$ =sewage flow into reach, j ( $m^3 s^{-1}$ ) $U_{8,j}$ =sewage nitrate concentration (mg-N/L) $x_1$ =soil outflow ( $m^3 s^{-1} km^{-2}$ ) $x_2$ =groundwater outflow ( $m^3 s^{-1} km^{-2}$ ) $\beta$ = base flow index $a_1$ =Soil water nitrate concentration (mg/L) $a_3$ =groundwater nitrate concentration (mg/L) 86.4=units conversion to $m^3$ to litres and seconds to days	Input $NO_3$ load into reach j			1, non point and point sources
$S_{6,j} = 86.4(U_{7,j}U_{9,j} + \sum_{i=1}^n area_{i,j}((1 - \beta)x_1 a_2 + x_2 a_4))$	$\sum_{i=1}^n area_{i,j}((1 - \beta)x_1 + x_2)$ =flow input from land use type, i, into reach, j. $S_{6,j}$ =total ammonium input in reach, j. ( $kg-N day^{-1}$ ) $U_{7,j}$ =sewage flow into reach, j ( $m^3 s^{-1}$ ) $U_{9,j}$ =sewage ammonium concentration (mg-N/L) $x_1$ =soil outflow ( $m^3 s^{-1} km^{-2}$ ) $x_2$ =groundwater outflow ( $m^3 s^{-1} km^{-2}$ ) $\beta$ = base flow index $a_2$ =Soil water ammonium concentration (mg/L) $a_4$ =groundwater ammonium concentration (mg/L) 86.4=units conversion to $m^3$ to litres and seconds to days	Input $NH_3$ load into reach j.			1, non point and point sources

$\frac{\delta x_{25}}{\delta t} = S_5$ $\frac{\delta x_{26}}{\delta t} = S_6$ $\frac{\delta x_{27}}{\delta t} = \frac{x_{22}x_{23}86400}{x_{29}}$ $\frac{\delta x_{28}}{\delta t} = \frac{x_{22}x_{24}86400}{x_{29}}$ $\frac{\delta x_{29}}{\delta t} = (S_4 - x_{22})86400$ $\frac{\delta x_{30}}{\delta t} = S_4.86400$ $\frac{\delta x_{31}}{\delta t} = x_{22}.86400$ $\frac{\delta x_{32}}{\delta t} = \frac{C_{11}a_{5,t-1}x_{29}}{1000}$ $\frac{\delta x_{33}}{\delta t} = \frac{C_{10}a_{6,t-1}x_{29}}{1000}$ <p>The above equations are integrated and the input, output and storage within each reach are calculated.</p> $input = x_{25} + x_{26}$ $output = x_{27} + x_{28} + x_{29}$ $storage = x_{29}$ $Nbalance = initial + input - output - storage$ $waterbalance = x_{29,0,i} + x_{30} - x_{31} - x_{29}$	<p> <math>x_{22}</math>= Reach outflow (<math>m^3 s^{-1}</math>)  <math>x_{23}</math>= Nitrate mass stored in reach (kg N)  <math>x_{24}</math>= Ammonium mass stored in reach (kg N)  <math>dx_{25}/dt</math>= Gross input rate of Nitrate mass into the system (kg-N/day)  <math>dx_{26}/dt</math>= Gross input rate of Ammonium mass into the system (kg-N/day)  <math>dx_{27}/dt</math>= Gross output rate of Nitrate mass from the system (kg-N/day)  <math>dx_{28}/dt</math>= Gross output rate of Ammonium mass output from the system (kg-N/day)  <math>x_{29}</math>= Volume stored in reach(<math>m^3</math>)  <math>dx_{29}/dt</math>= Change reach volume (<math>m^3 d^{-1}</math>)  <math>dx_{30}/dt</math>=Change in flow volume into reach (<math>m^3 day^{-1}</math>)  <math>dx_{31}/dt</math>= Change in flow volume out from reach (<math>m^3 day^{-1}</math>)  <math>dx_{32}/dt</math>=Change in denitrification mass (kg N <math>day^{-1}</math>)  <math>dx_{33}/dt</math>=Change in nitrification mass (kg N <math>day^{-1}</math>)  <math>C_{10}</math>= in-stream denitrification rate (<math>d^{-1}</math>)  <math>C_{11}</math>=in-stream nitrification rate (<math>day^{-1}</math>)  <math>a_5</math>=in-stream nitrate conc. (mg-N/L)  <math>a_6</math>=in-stream ammonium conc. (mg-N/L)  <math>S_4</math>=total flow input into reach (<math>m^3 s^{-1}</math>)  <math>S_5</math>=total nitrate input into reach (kg N <math>day^{-1}</math>)  <math>S_6</math>=total ammonium input into reach (kg N <math>day^{-1}</math>) </p>	<p>Supplementary equations to determine mass balances. Initial values are calculated from what was initially in soil water and groundwater.</p>			1, 4, 5
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Model Name	Language	Output
INCA-N	Unknown	Ammonia and nitrate concentrations at end of reach and stored in the reach.

#### References

- Wade, A. J. et. al. ( 2002). A nitrogen model for European catchments: INCA, new model structure and equations. Hydrology and Earth System Science 6(3): 559-582
- Whitehead, P. G., E. J. Wilson, *et al.* (1998). "A semi-distributed integrated nitrogen model for multiple source assessment in catchments (INCA): Part I -- model structure and process equations." Science of The Total Environment 210-211: 547-558.
- Wade, A. J., P. Durand, *et al.* (2002). "A nitrogen model for European catchments: INCA, new model structure and equations." Hydrol. Earth Syst. Sci. 6(3): 559-582.

WaterCAST	Parameters	Description	Calibration requirements	Issues	Reference to Table 1
<b>Nutrient loss in stream</b>					
Constant removal coefficient for 2 flow types. No equation available		Percentage of constituent passing with base flow and surface flow	Decay constant, discharge, event mean concentration, dry weather concentration (base flow)	We found that WaterCAST was also very difficult to understand. There were very few equations in the WaterCAST manual and what was reported was all that was given in the manual. Although the manual states there is a range of options available for representing simple in-stream processing, unfortunately it was lacking in detail.	1
If flow Q<base flow, $C_{out}=C_{in}*DWC$ If flow Q>=base flow, $C_{out}=C_{in}*EMC$	Q is discharge EMC = event mean concentration DWC = dry weather concentration				1
$Newload = oldload \times 2^{-\left(\frac{time.step}{half.life}\right)}$	half life= the load of the selected constituent decays by 50% in the specified half-life (seconds) time step= seconds	Simple decay equation between nodes			1
$C_{out} = C^* + (C_{in} - C^*)e^{-\frac{k}{q}}$ $q = \frac{Q}{A}$	C*=background concentration C <sub>in</sub> =input concentration C <sub>out</sub> =output concentration k=rate constant q=hydraulic loading Q=incoming flow A=area of treatment	Calculates the amount of constituent lost using treatment facilities (wetlands, swales, sedimentation basins and pools)			1
Riparian N submodel This submodel estimates the nitrate loss as denitrification in the riparian zone. No in-stream modeling of nitrogen is included in this submodel.					

Model Name	Language	Output
WaterCAST	TIME (The Invisible Modeling Environment)	Concentration of solute

References:

Kandel, D. D. and R. M. Argent (2005). Estimating Sediment and Nutrient Loads in Gippsland Lakes Catchments Using E2 Modelling Framework. MODSIM 2005 International Congress on Modelling and Simulation., Melbourne, Modelling and Simulation Society of Australia and New Zealand.  
 Argent, R.M, Brown, A, Cetin, L. T, Davis, G, Farthing, B, Fowler, K, Freebairn, A, Grayson, R, Jordan, P. W, Moodie, K, Murray, N, Perraud, J-M, Podger, G. M, Rahman, J, Waters, D. (2008) WaterCAST User Guide, eWater CRC, Canberra.

HSPF	Parameters	Description	Calibration requirements	Issues	Reference to Table 1
<b>Suspended solid</b>					
$VOLSED(J) = RSED(J+3)/RHO(J)*1.0E06$	VOLSED(J) = volume occupied by bed sediment of fraction J(m <sup>3</sup> ) RSED(J+3) = bed storage of sediment fraction J (mg.m <sup>3</sup> /l) RHO(J) = particle density of fraction J (gm/cm <sup>3</sup> )	Volume occupied by each fraction of bed sediment.	Fraction of sand, silt and clay in sediment, volume of sediment in reach, porosity, reach length, reach width, depth of water column, sheer stress, critical sheer stress for each particle fraction, settling velocity of each particle fraction, volume of water, erodibility coefficient, amount of sediment stored in reach		14PS, 14PD
$VOLSEDA = VOLSED/(1.0 - POR)$	VOLSEDA = volume of bed adjusted to account for volume occupied by materials other than sediment VOLSED = volume of sediment contained in bed (sand + silt + clay) POR = porosity of bed sediment (ratio of pore volume to total volume)	The volumes of the three fractions of bed sediment are summed, and the total bed volume is adjusted to account for the fraction of the volume which is void of sediment (i.e., the porosity)			14PS
$BEDDEP = VOLSEDA/(LEN*BEDWID)$	BEDDEP = depth of bed (m) VOLSEDA = volume of bed (m <sup>3</sup> ) LEN = length of RCHRES (m) BEDWID = effective width of bed for calculation of bed thickness	Depth of bed sediment is calculated for use as an indicator of excessive deposition		If the calculated value for BEDDEP exceeds a specified value, a warning message is printed to alert the user to potential modeling problems.	
$DEPCONC = CONC*(1.0 - EXP((-W/AVDEPM)*(1.0 - TAU/TAUCD)))$	DEPCONC= The conc. of suspended sediment lost to deposition during a simulation interval CONC= conc. of suspended sediment at start of interval (mg/l) W= settling velocity for sediment fraction (m/ivl) AVDEPM = average water depth RCHRES in meters (HYDR) TAU= shear stress (kg/m <sup>2</sup> ) TAUCD= critical shear stress for deposition (kg/m <sup>2</sup> )	The concentration of suspended sediment lost to deposition during a simulation interval		The user must supply values for settling velocity (W) and critical shear stress for deposition (TAUCD) for each fraction of cohesive sediment (silt and clay).	1,2,14flow,14PS
$SUSP = SUSP-(DEPCONC*VOL)$ $BED = BED + (DEPCONC*VOL)$	SUSP = suspended storage of sediment fraction (mg.m <sup>3</sup> /l) BED = storage of sediment fraction in bed (mg.m <sup>3</sup> /l) VOL =volume of water in RCHRES (m <sup>3</sup> )	The storage of sediment in suspension and in the bed is updated			1,2
$SCRCONC = M/AVDEPM*1000*(TAU/TAUCS - 1.0)$	SCRCONC=concentration of suspended sediment added to suspension by scour during a simulation interval M=erodibility coefficient (kg/m <sup>2</sup> ) AVDEPM = average water depth TAU= shear stress (kg/m <sup>2</sup> ) TAUCD= critical shear stress for deposition (kg/m <sup>2</sup> )	The concentration of suspended sediment added to suspension by scour during a simulation interval		The user is required to supply values for the erodibility coefficient (M) and critical shear stress for scour (TAUCS) for each fraction of cohesive sediment (silt and clay) which is	1,2,14E,14F,14PS

				modeled.	
$BED = BED - (SCRCONC * VOL)$ $SUSP = SUSP + (SCRCONC * VOL)$	SCRCONC=concentration of suspended sediment added to suspension by scour during a simulation interval SUSP = suspended storage of sediment fraction (mg.m <sup>3</sup> /l) BED = storage of sediment fraction in bed (mg.m <sup>3</sup> /l) VOL = volume of water in RCHRES (m <sup>3</sup> )	Following the calculation of SCRCONC, the storage of sediment in suspension and in the bed is updated			1
USTAR = $\sqrt{GRAV * SLOPE * HRAD}$  and  TAU = $SLOPE * GAM * HRAD$	USTAR = shear velocity (m/s) GRAV=acceleration due to gravity (9.81 m/sec <sup>2</sup> ) SLOPE = slope of RCHRES (-) HRAD = hydraulic radius (m) TAU= stream bed shear stress (kg/m <sup>2</sup> )	If the RCHRES being simulated is a stream or river, both shear velocity and shear stress are determined as functions of the slope and hydraulic radius of the reach.			1,2,14S, 14F,
USTAR = $AVVEL / (17.66 + (ALOG10(AVDEP / (96.5 * DB50))) * 2.3 / AKAPPA)$  and  TAU = $GAM * (USTAR ** 2) / GRAV$	USTAR= shear velocity (m/s) AVVEL=average flow velocity (m/s) AVDEP=average water depth (m) DB50= median diameter of bed material (m) AKAPPA = Karman constant (AKAPPA = 0.4) TAU = bed shear stress (kg/m <sup>2</sup> ) GAM = density of water (1000 kg/m <sup>3</sup> ) GRAV = acceleration due to gravity (9.81 m/sec <sup>2</sup> )	If the RCHRES is a lake, shear velocity is computed using Equation 8.49 from "Hydraulics of Sediment Transport", by W. H. Graf.			1,2,14F,14PS
There are 3 different type of equations to simulate the deposition, scour, and transport processes of the sand fraction. Toffaleti equation, the Colby method, or an input power function of velocity. Note the equation numbers given are from HSPF manual.				User needs to chose between the 3 sand transport equations.	
$PSAND = (GSI * TWIDE * 10.5) / ROM$	PSAND=potential sandload(mg/l) GSI= sand transport capacity (tons/day/ft of width) (calculated in COLBY or TOFFAL) TWIDE= width of RCHRES (ft) 10.5 = conversion factor ROM= total rate of outflow of water from RCHRES (m3/sec)	If sand transport capacity is calculated using the Toffaleti (TOFFAL) or Colby (COLBY) methods, the potential sandload concentration is determined by this conversion.			
$PSAND = KSAND * AVVELE ** EXPSND$	KSAND = coefficient in the sandload suspension equation (input parameter) EXPSND = exponent in sandload suspension equation (input parameter) AVVELE=average velocity (ft/s)	Power function of velocity equation.			1,2,14F
$U = (1 + CNV) * V * (Y / FHRAD) ** CNV$	The velocity profile is represented by the power relation: U = flow velocity at distance Y above the bed (ft/sec) V = mean stream velocity (ft/sec) CNV = exponent derived empirically as a function of water temperature (0.1198 + 0.00048*TMPR)	Toffaleti (TOFFAL) equations. Refer to Figure HSPF1 below. In Toffaleti's methodology, the actual stream for which the sand discharge is to be calculated is assumed to be equivalent to a two-dimensional stream of width equal to that of		The Toffaleti equations use imperial units.  The Toffaleti equations equate depth of flow to hydraulic radius. This	1,2,14F

	TMPR = water temperature (degrees F)	the real stream and of depth equal to the hydraulic radius of the real stream (FHRAD). For the purposes of calculation, the depth, FHRAD, of the hypothetical stream is divided into four zones shown in Figure HSPF1 below These are: (1) the bed zone of relative thickness $Y/FHRAD = 2*FDIAM/FHRAD$ ; (2) the lower zone extending from $Y/FHRAD = 2*FDIAM/FHRAD$ to $Y/FHRAD = 1/11.24$ ; (3) the middle zone extending from $Y/FHRAD = 1/11.24$ to $Y/FHRAD = 1/2.5$ ; and (4) the upper zone extending from $Y/FHRAD = 1/2.5$ to the surface.		approximation is best for wide rivers. The authors of HSPF do not know the accuracy of this method for narrow streams.	
$ZI = (VSET*V)/(CZ*FHRAD*SLOPE)$	ZI= the exponent, ZI, in Equations 23-25 VSET = settling velocity for sand (ft/s) SLOPE = slope of RCHRES (ft/ft) CZ = empirical factor derived as a function of water temperature ( $260.67 - 0.667*TMPR$ ) FHRAD= hypothetical radius of stream	Toffaletti's equations: equation to calculate the exponent, ZI, in Equations 23-25(written in Figure HSPF1)			1,2,14F,14S
Equation 28 denoted in Figure HSPF1 $GSL = CMI*(((HRAD/11.24)**(1.0 + CNV - 0.758*ZI) - (2*FDIAM)**(1.0 + CNV - 0.756*ZI)))/(1.0 + CNV - 0.756*ZI))$  Equation 29 denoted in Figure HSPF1 GSM = $CMI*(((HRAD/11.24)**(0.244*ZI)*((HRAD/2.5)**(1.0 + CNV - ZI) - (HRAD/11.24)**(1.0 + CNV - ZI)))/(1.0 + CNV - ZI))$  Equation (30) denoted in Figure HSPF1 GSU = $CMI*(((HRAD/11.24)**(0.244*ZI)*((HRAD/2.5)**(0.5*ZI)*(HRAD)**(1.0 + CNV - 1.5*ZI) - (HRAD/2.5)**(1.0 + CNV - 1.5*ZI)))/(1.0 + CNV - 1.5*ZI))$	GSL= sand transport capacity of lower zone GSM= sand transport capacity of middle zone GSU= sand transport capacity of upper zone CMI=the concentration of sand in the middle zone (calculated in equation 31) HRAD=hydraulic radius of stream CNV= exponent derived empirically as a function of water temperature ( $0.1198 + 0.00048*TMPR$ ) TMPR = water temperature (degrees F) FDIAM= median bed sediment diameter (ft) ZI = the exponent (calculated above)	Toffaletti's equations: The resulting equations for sand transport capacity in the three zones			1,2,14PS
Equation (31) denoted in Figure HSPF1 $CMI = 43.2*CLI*(1.0 +$	CMI=the concentration of sand in the middle zone CLI=the concentration of sand in the lower	Toffaletti's equations A value for CLI, the concentration of sand in the lower zone, can be			1,2,14F

$CNV) \cdot V \cdot HRAD^{(0.758 \cdot ZI - CNV)}$	<p>zone</p> <p>V= mean stream velocity (ft/sec)</p> <p>HRAD = hypothetical radius of stream</p> <p>ZI= the exponent (calculated above)</p> <p>CNV= exponent derived empirically as a function of water temperature (<math>0.1198 + 0.00048 \cdot TMPR</math>)</p> <p>TMPR = water temperature (degrees F)</p>	obtained by setting the expression for GSL in Equation 28 equal to equation 32 and solving for CLI.			
<p>Equation (32) denoted in Figure HSPF1</p> <p><math>GSL = 0.6 / ((TT \cdot AC \cdot K4 / V^{**2})^{**}(1.67) \cdot DIAM / 0.00058)^{**}(1.67))</math></p>	<p>GSL= sand transport capacity of lower zone</p> <p>TT= empirical factor derived as a function of water temp (<math>1.10 \cdot (0.051 + 0.00009 \cdot TMPR)</math>)</p> <p>AC= empirical factor derived as a function of the kinematic viscosity of water (VIS) and shear velocity based on shear stress due to sand grain roughness (USTAR)</p> <p>K4= empirical factor derived as a function of AC, slope of the RCHRES (SLOPE), and particle diameter for which 65% by weight of sediment is finer (D65).</p> <p>V= mean stream velocity (ft/sec)</p> <p>FDIAM= median bed sediment diameter (ft)</p>	<p>Values for factors AC and K4 are given in Figure HSPF2. The dimensions of AC are such that GSL is expressed in tons per day per foot of width. Consequently, when CLI is evaluated and substituted back into Equations 28-30 the resulting units of sand transport capacity for all three zones are tons per day per foot of width.</p>			1,2,14F,14S,14PS
<p>Equation (33) denoted in Figure HSPF1</p> <p><math>GSB = CMI \cdot (2 \cdot FDIAM)^{**}(1.0 + CNV - 0.758 \cdot ZI)</math></p>	<p>GSB=sand transport capacity of bed zone</p> <p>CMI = the concentration of sand in the middle zone</p> <p>FDIAM= median bed sediment diameter (ft)</p> <p>CNV=exponent derived empirically as a function of water temperature (<math>0.1198 + 0.00048 \cdot TMPR</math>)</p> <p>TMPR = water temperature (degrees F)</p> <p>ZI=exponent (calculated above)</p>	<p>Toffaletti's equations: Prior to calculation of sand transport capacity for the zones, Equation 25 is solved to be sure that the value for concentration at <math>Y=2 \cdot FDIAM</math> does not exceed 100 lbs/ft<sup>3</sup>. If it does, the concentration at this depth is set equal to 100 lbs/ft<sup>3</sup> and an adjusted value of CLI is calculated and used in Equations 28-30. The transport capacity of the final zone, the bed zone is also determined using the adjusted value of CLI.</p>			1,2,14PS
$GSI = GSB + GSL + GSM + GSU$	<p>GSI= total sand transport capacity</p> <p>GSB= sand transport capacity of bed zone</p> <p>GSL= sand transport capacity of lower zone</p> <p>GSM= sand transport capacity of middle zone</p> <p>GSU= sand transport capacity of upper zone</p>	<p>Toffaletti's equations: The total sand transport capacity (GSI) for the RCHRES is the sum of the transport capacities for the four zones</p>			1



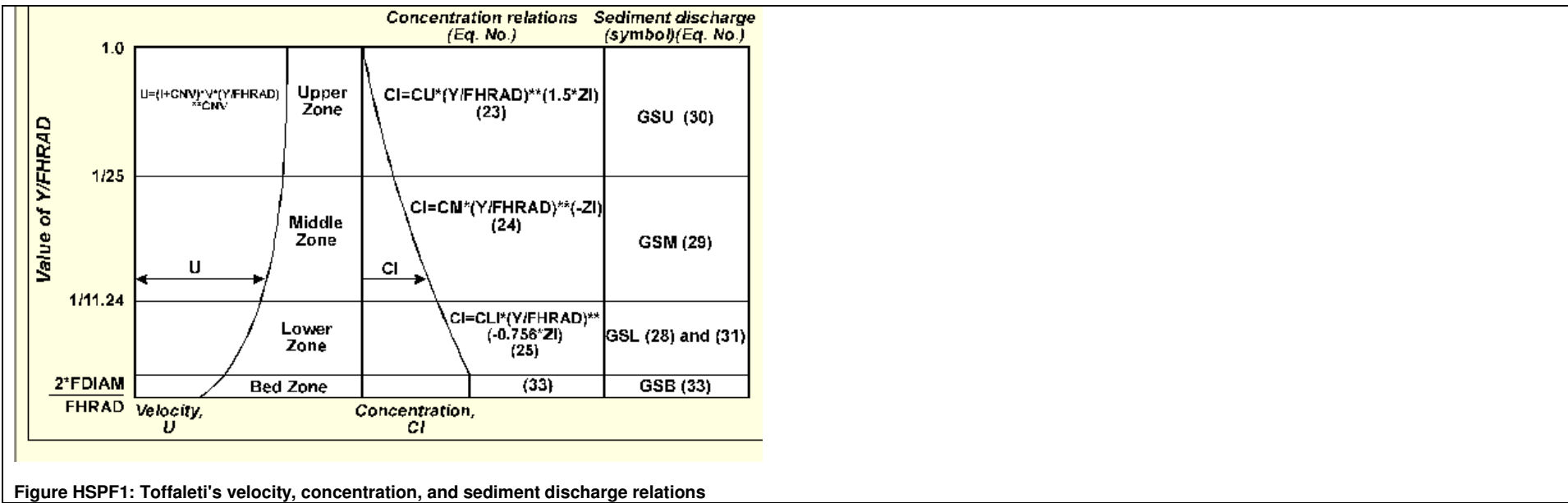
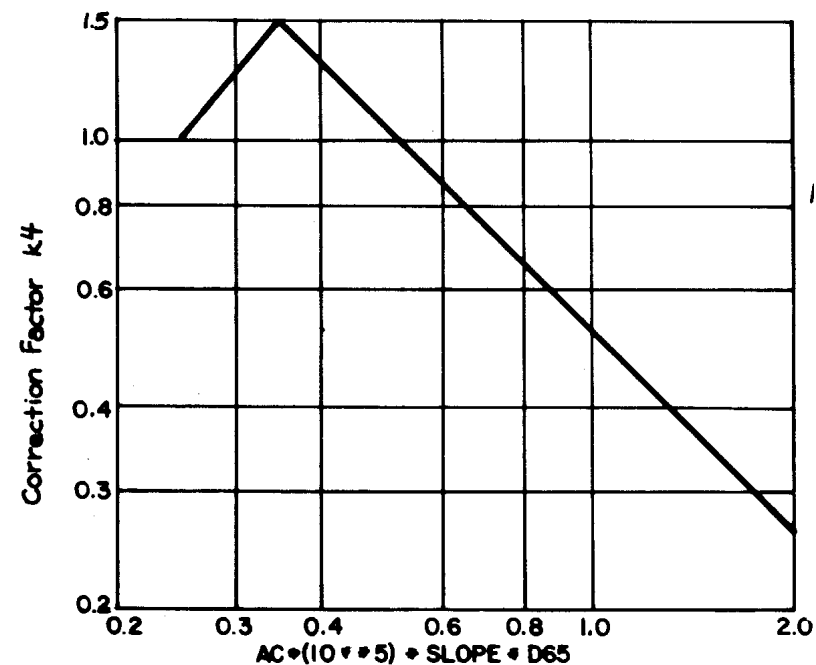
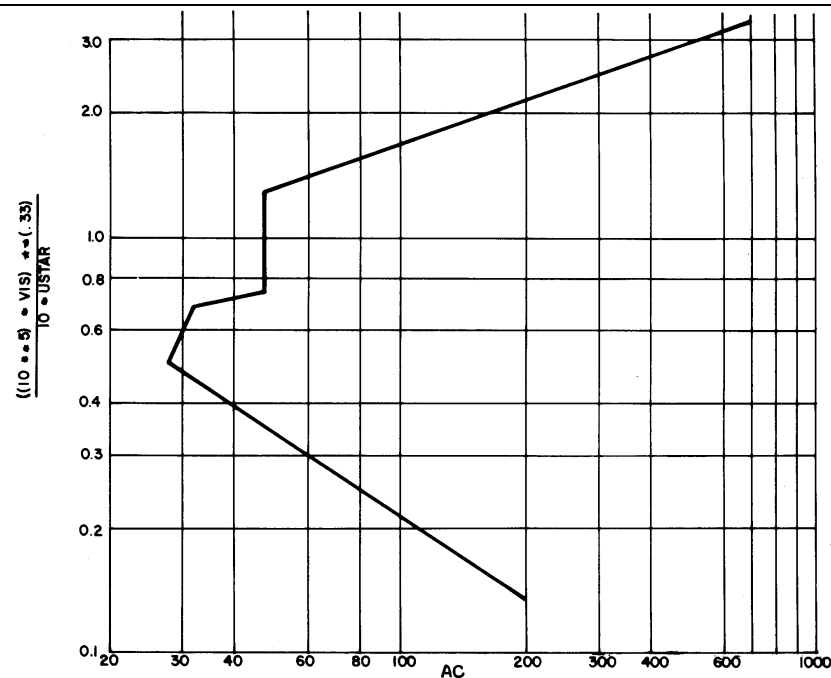


Figure HSPF1: Toffaleti's velocity, concentration, and sediment discharge relations



**Figure HSPF2: Factors in Toffaleti relations**

COLBY calculates the capacity of the RCHRES to transport sand based on the median bed sediment diameter (DB50), average stream velocity (V), hydraulic radius (HRAD), fine sediment load concentration (FSL), and water temperature (TEMPR).

1. Obtain a value for sediment transport capacity from Figure HSPF3, which covers a range of hydraulic radius, velocity, and mean diameter of bed sediment. Note these values are log log scale, therefore need to transform this value.
2. Correct this value using Figure HSPF4, firstly on water temperature and then fine sediment load (silt+clay). Sand transport capacity increases with increasing fine sediment load and with increasing stream width.

If the value for median bed sediment diameter, hydraulic radius, or average velocity for the given simulation interval falls outside the range of values considered in Colby's graphs, a solution for sand transport capacity cannot be obtained by the Colby method.

Acceptable ranges of parameter values for the Colby method are:

- (a) median bed sediment diameter 0.1-0.8 mm
- (b) hydraulic radius 0.1-100 ft
- (c) average velocity 1.0-10.0 ft/s

The Colby method use imperial units. Instead of using equations, it is based on reading plots.

The Colby formulations equate depth of flow to hydraulic radius. This approximation is best for wide rivers. The authors of HSPF do not know the accuracy of this method for narrow streams.

1,2,14F,14PS

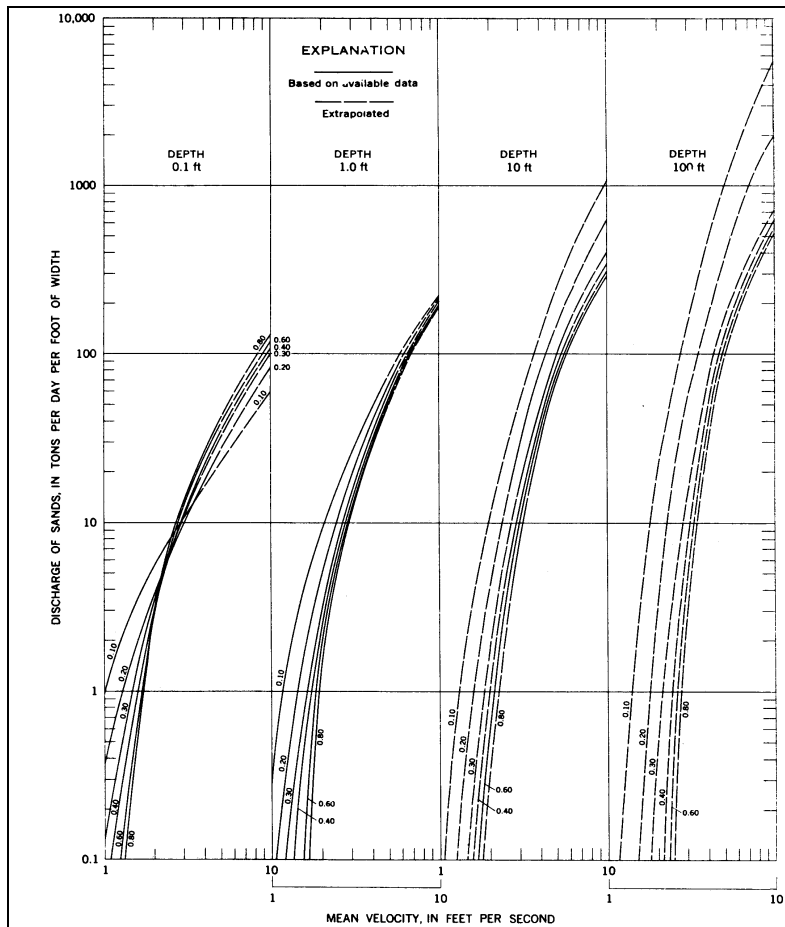
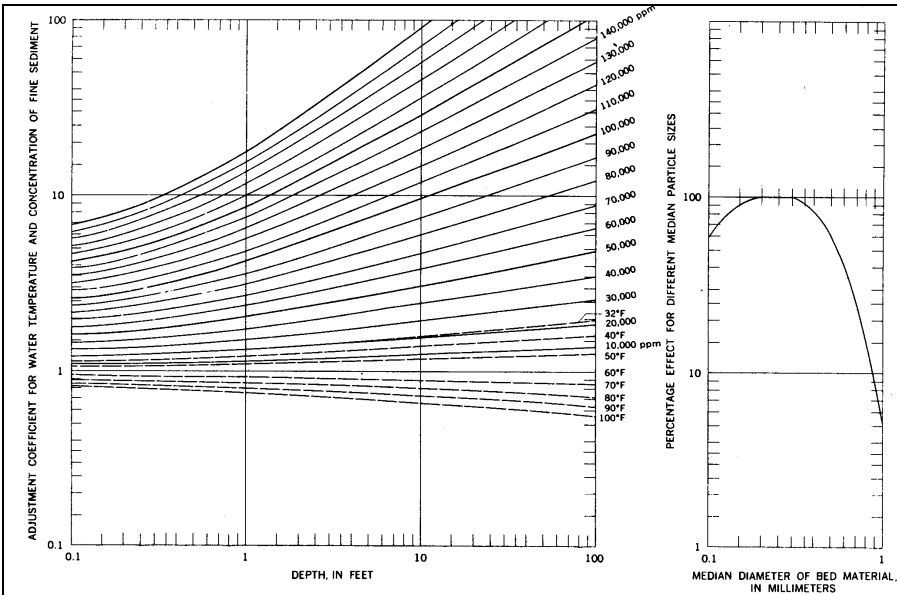


Figure HSPF3: Colby's relationship for discharge of sands in terms of mean velocity for six median sizes of bed sands, four depths of flow, and water temperature of 60 F



**Figure HSPF4: Colby's correction factors for effect of water temperature, concentration of fine sediment, and sediment size; applied to uncorrected discharge of sand given by above graph**

$PROSND = (SANDS * SROVOL) + (PSAND * EROVOL)$  where: $SROVOL = JS * ROS * DELTS$  $EROVOL = COJS * RO * DELTS$	$PROSND$ = potential sand outflow $SANDS$ = concentration of sand at start of interval (mg/L) $SROVOL$ = outflow volume component based on start of interval (m3/interval) $EROVOL$ = outflow volume component based on end of interval (m3/interval) $ROS$ = outflow rate at start of interval (m3/s) $RO$ = outflow rate at end of interval (m3/s) $DELTS$ = number of sec in interval	The potential outflow of sand during the interval			1
$PSCOUR = (VOL * PSAND) - (VOLS * SANDS) + PROSND - ISAND$	$PSCOUR$ = potential scour (+) or deposition (-) $VOL$ = volume of water in RCHRES at the end of the interval (m3) $VOLS$ = volume of water in RCHRES at the start of interval (m3) $ISAND$ = total inflow of sand into RCHRES during interval	The potential scour from, or deposition to, the bed storage is found using the continuity equation.		The potential scour is compared to the amount of sand material on the bottom surface available for resuspension. If scour demand is less than available bottom sands, the demand is satisfied in full, and the bed storage is adjusted accordingly. The new suspended	1,2

				concentration is PSAND. If the potential scour cannot be satisfied by bed storage, all of the available bed sand is suspended, and bed storage is exhausted.	
$SAND = (ISAND + SCOUR + SANDS \cdot (VOLS - SROVOL)) / (VOL + EROVOL)$	<p>SAND = conc. of sand at end of interval</p> <p>ISAND = total inflow of sand into RCHRES during interval</p> <p>SCOUR = sand scoured from, or deposited to, the bottom</p> <p>SANDS = concentration of sand at start of interval</p> <p>VOLS=volume of water in RCHRES at the start of interval (m3)</p> <p>SROVOL = outflow volume component based on start of interval (m3/interval)</p> <p>SROVOL = outflow volume component based on start of interval (m3/interval)</p> <p>EROVOL =outflow volume component based on end of interval (m3/interval)</p>	The concentration of suspended sandload			1,2
$ROSAND = SROVOL \cdot SANDS + EROVOL \cdot SAND$	<p>ROSAND=total amount of sand leaving RCHRES during interval</p> <p>SAND = concentration of sand at end of interval</p> <p>SANDS = concentration of sand at start of interval</p> <p>SROVOL = outflow volume component based on start of interval (m3/interval)</p> <p>EROVOL =outflow volume component based on end of interval (m3/interval)</p>	The total amount of sand leaving the RCHRES during the interval		If a RCHRES goes dry during an interval, or if there is no outflow from the RCHRES, all the sand in suspension at the beginning of the interval is assumed to settle out, and the bed storage is correspondingly increased.	1
<b>P and NH4 adsorption equations</b>					
$NUM = DNUT \cdot VOL + \sum [SNUT(J) \cdot RSED(J)]$	<p>NUM = variable used to represent total nutrient mass in the reach (mg)</p> <p>VOL = volume of reach (l)</p> <p>RSED(J) = mass of sediment fraction J in suspension (kg)</p> <p>SNUT(J) = equilibrium conc. of adsorbed nutrient on sediment fraction J (mg/kg)</p> <p>DNUT = the equilibrium concentration of dissolved nutrient (mg/l)</p> <p>ADPM(J)=adsorption parameter (or <math>K_D</math>) for sediment fraction J (l/kg)</p>	Equation for P adsorption onto SS	Volume, sorption, equilibrium constant, mass of suspended solids in reach, mass of N and P in sediment, scour and deposition rates, Org-N, Org-P, particulate-P, DIP, NO3 and NH4 concentrations from upstream and diffuse sources,		1,12,14PS
$DSNUT = BNUT \cdot DEPSR$	<p>DSNUT = amount of nutrient scoured from bed and added to suspension (mg/l)*(m3/ivl)</p> <p>BNUT = constant concentration of nutrient</p>	SS-P flux	atmospheric deposition, velocity, BOD decay, BOD conc., ammonia ionization constant,		1,2,12

	on bed sediment fraction under consideration (mg/mg sediment) DEPSCR = amount of sediment fraction which is scoured from the bed (mg.m3/l.ivl)		ammonia volatilization constant, water temperature, reaeration rate, wind speed, nitrification rate, denitrification rate, growth rate of phytoplankton, depth of water, light available, light extinction coefficient, Michaelis-Menten coefficients for nitrogen, phosphorus and light limited growth, death rate of phytoplankton, benthic algae growth rate, amount of benthic algae, benthic algae death rate		
SNUT = (ISNUT + RSNUTS - DSNUT)/(RSED + ROSED)	SNUT = concentration of adsorbed nutrient in suspension (mg/mg suspended sediment) ISNUT = inflow of nutrient to the RCHRES as a result of inflowing sediment fraction ((mg/l)*(m³/ivl)) RSNUTS = storage of nutrient on suspended sediment fraction ((mg/l)*m³) RSED= amount of sediment fraction in suspension at end of interval (mg.m³/l) ROSED = amount of sediment fraction contained in outflow from the RCHRES during the interval (mg.m³/l.ivl) DSNUT = amount of nutrient scoured from bed and added to suspension (mg/l)*(m3/ivl)	The concentration of adsorbed nutrient in suspension is updated to account for scour			1,2,12
ROSNUT = ROSED*SNUT	ROSED = amount of sediment fraction contained in outflow from the RCHRES during the interval (mg.m³/l.ivl) SNUT = concentration of adsorbed nutrient in suspension (mg/mg SS) ROSNUT=Amount of nutrient leaving the reach as outflow	Amount of nutrient leaving the reach as outflow is determined			1
The concentration of nutrient on suspended sediment is set equal to zero if the suspended sediment storage is zero. If the sediment simulation in module section SEDTRN indicates that deposition of suspended sediment occurs, ADVNUT performs the following operations:					
SNUT = (ISNUT + RSNUTS)/(RSED + DEPSCR + ROSED)	SNUT = concentration of adsorbed nutrient in suspension (mg/mg SS) ISNUT = inflow of nutrient to the RCHRES as a result of inflowing sediment fraction ((mg/l)*(m³/ivl)) RSNUTS = storage of nutrient on suspended sediment fraction ((mg/l)*m³) RSED(J+3) = bed storage of sediment fraction J (mg.m³/l) DEPSCR = amount of sediment fraction which is scoured from the bed (mg.m3/l.ivl) ROSED = amount of sediment fraction contained in outflow from the RCHRES during the interval (mg.m³/l.ivl)	Concentration of nutrient on total suspended sediment fraction (inflow + suspended storage) for the RCHRES is calculated			1,2,12
ROSNUT = ROSED*SNUT	SNUT = concentration of adsorbed nutrient in suspension (mg/mg SS) ROSNUT=Amount of nutrient leaving the reach as outflow ROSED = amount of sediment fraction contained in outflow from the RCHRES during the interval (mg.m³/l.ivl)	Amount of nutrient leaving the RCHRES due to outflow of sediment fraction is determined:			1
DSNUT = DEPSCR*SNUT	SNUT = concentration of adsorbed nutrient in suspension (mg/mg SS)	Amount of nutrient leaving suspension due to deposition of			1,2,12

	DEPSCR = amount of sediment fraction which is scoured from the bed (mg.m3/l.ivl) DSNUT = amount of nutrient scoured from bed and added to suspension (mg/l)*(m3/ivl)	the sediment to which it is adsorbed is found			
N and P equations 1. longitudinal advection of dissolved NO3, NO2, NH3, and PO4 2. benthic release of inorganic nitrogen (NH3) and PO4 3. ammonia ionization (NH3/NH4+ equilibrium) 4. ammonia vaporization 5. nitrification of NH3 and NO2 6. denitrification of NO3 7. ammonification due to degradation of BOD materials 8. adsorption/desorption of NH3 and PO4 to inorganic sediment in the water column 9. deposition/scour and longitudinal advection of adsorbed NH3 and PO4		Subroutine NUTRX utilizes nine principal routines to simulate inorganic nitrogen and phosphorus. Advection of dissolved NO3, NO2, NH3, and PO4 is performed by ADVECT. BENTH determines the amount of inorganic nitrogen and phosphorus which is released to the overlying waters from the benthos. The nitrification and denitrification processes are simulated by NITRIF and DENIT, respectively. Adsorption/ desorption of NH3 and PO4 is computed by ADDSNU, and the advection and deposition/scour of the adsorbed forms are simulated in ADVNUT. The ammonia ionization and volatilization calculations are performed in AMMION and NH3VOL, respectively. Finally, the production of inorganic nitrogen and phosphorus resulting from decay of BOD materials is simulated by DECBAL.			
INNUT = INUT + SAREA*ADFX + SAREA*PREC*ADCN	INNUT = total input of dissolved nutrient to reach INUT = input of dissolved nutrient from upstream reaches and tributary land SAREA = surface area of reach ADFX = dry or total atmospheric deposition flux in mass/area per interval PREC = precipitation depth ADCN = concentration for wet atmospheric deposition in mass/volume	Before ADVECT is called, NUTRX sums the inputs of dissolved NO3, NH3, and PO4 from upstream reaches, tributary land areas, and atmospheric deposition (deposition of NO2 is not considered)			1, point and non-point sources
RELEAS = BRCON(l)*SCRFAC*DEPCOR	RELEAS = amount of constituent released (mg/l per interval) BRCON(l) = benthic release rate (BRTAM or BRPO4) for constituent (mg/m2 per interval) SCRFAC = scouring factor, dependent on average velocity of the water DEPCOR = conversion factor from mg/m2	Amount of N or P released from benthos	Two release rates are required for each of the constituents: one for aerobic conditions and one for anaerobic conditions. Typically, the aerobic release rate is less than the anaerobic		1,10DO, 15

	to mg/l (computed in RQUAL)		rate, because a layer of oxidized materials forms on the benthic surface during aerobic periods, and this layer retards the release rate of additional benthic materials.		
FRAC=10pH/(10pH+RATIO)	<p>FRAC= fraction of total ammonia that is present as un-ionized ammonia  RATIO = ratio of ionization products for water kw and ammonia (kb)</p> <p>RATIO is computed using an empirical relationship based on pH and temperature as described by Loehr <i>et al.</i> (1973):  RATIO = -3.39753 loge(0.02409 TW) 109</p>	The fraction (FRAC) of total ammonia that is present as un-ionized ammonia	The pH used may be obtained from Section PHCARB (if it is active) or specified by the user in the form of a constant value, 12 monthly values, or an input time series.	RATIO empirical ratio may not apply to Australia	8,10pH, 10T
<p>1/KR=KRINV = 1/ NH3KL + 8.21x10-5 * TWKELV / (HCNH3 * NH3KG)</p> <p>where:  NH3KL = [KOREA * AVDEPM * 100/DELT60] * [1.878**(EXPVNL/2.)]</p> <p>and</p> <p>NH3KG = 700. * WINDSP * 1.057**(EXPNVG/2.)</p> <p>therefore:  KNVOL = KR * DELT60/(AVDEPM * 100)</p> <p>and</p> <p>NH3VLT = KNVOL * TAM</p>	<p>KR = overall mass transfer coefficient (cm/hr)  KRINV= inverse of coefficient (hr/cm)  NH3KL = liquid film mass transfer coefficient (cm/hr)  NH3KG = gas film mass transfer coefficient (cm/hr)  HCNH3 = Henry's Law Constant for ammonia (atm-m3/mole)  8.21E-5 = the ideal gas constant  TWKELV = water temp (K)  KOREA = the oxygen reaeration rate (per interval)  AVDEPM = average depth of reach (m)  DELT60 = conversion from units of per interval to units of per hour  1.878 = ratio of molecular weight of oxygen (32) to ammonia (17)  EXPVNL =user-specified exponential factor  WINDSP = wind speed (m/s)  1.057 = ratio of water molecular weight to that of ammonia  EXPNVG=user-specified exponential factor  KNVOL= first-order rate constant for volatilization (/interval)  NH3VLT = volatilization loss during the interval (mg N/l)  TAM= conc. of total ammonia (mg N/l)</p>	Calculations to account for loss of ammonia through volatilization.			9,10T,10DO
<p>TAMNIT = KTAM20*(TCNIT**(TW - 20.))*TAM</p> <p>NO2NIT = KNO220 * (TCNIT**(TW - 20.)) * NO2</p>	<p>TAMNIT = amount of NH3 oxidation (mg N/l per interval)  KTAM20 = ammonia oxidation rate coefficient at 20 degrees C  TCNIT = temperature correction coefficient, defaulted to 1.07  TW = water temperature (C)</p>	Nitrification equations			5,10T



	<p>TAM= total NH3 conc. (mg N/l)</p> <p>NO2NIT = amount of NO2 oxidation (mg N/l/interval)</p> <p>KNO220 = NO2 oxidation rate coefficient at 20 C (/interval)</p> <p>NO2=nitrite conc. (mg N/l)</p>				
<p>DODEMD = 3.22 * TAMNIT + 1.11 * NO2NIT</p>	<p>DODEMD = loss of dissolved oxygen from the RCHRES due to nitrification (mg O/l per interval)</p>	Oxygen demand due to nitrification		<p>The amount of oxygen used during nitrification is 3.43 mg oxygen per mg NH3 oxidized to NO2, and 1.14 mg oxygen per mg NO2 oxidized to NO3. In the RCHRES module, these figures are adjusted to 3.22 mg and 1.11 mg, respectively, to account for the effects of carbon dioxide fixation by bacteria (Wezerak and Gannon, 1968).</p>	10DO
<p>DENNO3 = KNO320 * (TCDEN**(TW-20)) * NO3</p>	<p>DENNO3 = amount of NO3 denitrified (mg N/l per interval)</p> <p>KNO320 = NO3 denitrification rate coefficient at 20 C (/interval)</p> <p>TCDEN = temp correction coefficient for denitrification</p> <p>NO3= nitrate conc. (mg N/l)</p>	Denitrification equation	Denitrification does not occur in the RCHRES module unless the dissolved oxygen concentration is below a user-specified threshold value (DENOXT)		4,10T
<p>IMAT - ROMAT = (CONC*VOL) - (CONCS*VOLS)</p>	<p>IMAT = inflow of material over the interval</p> <p>ROMAT = total outflow of material over the interval</p> <p>CONCS = conc. at start of interval</p> <p>CONC=conc. at end of interval</p> <p>VOLS = volume of water stored in RCHRES at start of interval</p> <p>VOL = volume of water stored in the RCHRES at end of interval</p>	Advection equation			1
<p>ROMAT = ((JS*ROS*CONCS) + (COJS*RO*CONC))*DELTS</p>	<p>JS = weighting factor</p> <p>COJS = 1.0 - JS</p> <p>ROS = rates of outflow at the start of the interval (m3/s)</p> <p>RO = rates of outflow at the end of the interval (m3/s)</p> <p>DELTS = length of interval (s)</p>	The other basic equation states that the total outflow of material over the time interval is a weighted mean of two estimates; one based on conditions at the start of the interval, the other on ending conditions			1
<p>DECNIT = BODOX*CVON</p> <p>DECPO4 = BODOX*CVOP</p>	<p>BODOX = total BOD decay (mg O/l per interval)</p> <p>CVON = stoichiometric conversion factor from mg oxygen to mg nitrogen</p>	Mineralisation of organic material to inorganic N and P			3, 16

	CVOP = stoichiometric conversion factor from mg oxygen to mg phosphorus				
<b>Phytoplankton equations</b>					
INORG = IORG + SAREA*ADFX + SAREA*PREC*ADCN	INORG = total input of organic to reach IORG = input of organic from upstream reaches and tributary land SAREA = surface area of reach ADFX = dry or total atmospheric deposition flux in mass/area per interval PREC = precipitation depth ADCN = concentration for wet atmospheric deposition in mass/volume	Equation sums the inputs of ORN, ORP, and ORC from upstream reaches, tributary land areas, and atmospheric deposition	PLANK simulates phytoplankton, zooplankton, and/or benthic algae. The HSPF system assumes that biomass of all types (phytoplankton, zooplankton, benthic algae, dead organic materials) has a consistent chemical composition. The user specifies the biomass composition by indicating the carbon: nitrogen: phosphorus ratio and the percent-by-weight carbon.		non-point source inputs
STAY = (MXSTAY - SEED)*(2.0**(-OFLO/OREF)) + SEED  where: PLNKAD = PLANK - STAY  and PLANK = PLNKAD + MSTAY/VOL	STAY= plankton concentration not advected (mg/l) MXSTAY=maximum concentration not subject to advection SEED= concentration of plankton never subject to advection OREF=outflow rate at which STAY has a value midway between SEED and MXSTAY (m3/s) PLANK=concentration of plankton at end of interval PLNKAD = conc. of advected plankton which remain in RCHRES MSTAY = mass of plankton not advected VOL=volume in RCHRES at end of interval	The concentration of plankton which is not subject to advection			1
DOX=DOX+ (CVPB*CVBO*GROPHY)	CVPB = conversion factor from micromoles P to mg biomass CVBO = conversion factor from mg biomass to mg oxygen GROPHY = net growth of phytoplankton (micromoles phosphorus/l per interval)	Dissolved oxygen state variable is adjusted in PHYRX to account for the net effect of phytoplankton photosynthesis and respiration			6A,10DO
PHYLIT = INLIT*Exp(-EXTCO*(.5*Min(EUDEP,AVDEPE))) and BALLIT = INLIT*Exp(-EXTCO*AVDEPE)  where: EUDEP = 4.60517/EXTCO	PHYLIT = light available to phytoplankton (langleys/min) BALLIT = light available to benthic algae INLIT = light available at water surface (langleys/min) EXTCO = light extinction coefficient (/ft) AVDEPE = average depth of water in the RCHRES (ft) Exp=Fortran exponential function	Light correction factor to algal growth and the amount of light available to phytoplankton and benthic algae.			6A,13sun

	Min= Fortran minimum function				
<p>MALGRT = MALGR*TCMALG</p> <p>GROP = MALGRT*PO4*NO3/((PO4 + CMMMP)*(NO3 + CMMNP))</p> <p>GRON = MALGN*MMN/(MMN + CMMN)</p> <p>where: MALGN = MALGRT - 0.757*TAM + 0.051*NO3</p> <p>GROL = MALGRT*LIGHT/(CMMLT + LIGHT)</p>	<p>MALGRT = T corrected maximum algal growth rate (/interval)</p> <p>MALGR = maximum unit growth rate for algae</p> <p>TCMALG = temperature correction to growth (bw 0 and 1)</p> <p>GROP=unit growth rate based on phosphorus limitation (/interval)</p> <p>PO4=orthophosphorus conc.(mg/l)</p> <p>NO3=nitrate conc. (mg N/l)</p> <p>CMMMP= orthophosphorus Michaelis-Menten constant for P limited growth (mg P/l) (CMMMP default 0.015 mg P/l)</p> <p>CMMNP = nitrate Michaelis-Menten constant for P limited growth (mg N/l) (CMMNP is defaulted to 0.0284 mg N/l)</p> <p>MALGN = maximum unit growth rate corrected for ammonia retardation (/interval) (MALGN has the same value as MALGRT if AMRFG is 0)</p> <p>GRON = unit growth rate based on nitrogen limitation (/ interval)</p> <p>MMN= total pool of inorganic N considered available for growth</p> <p>CMMN = Michaelis-Menten constant for nitrogen limited growth (mg N/l)(CMMN is defaulted to 0.045 mg N/l)</p> <p>GROL = unit growth rate based on light limitation (/interval)</p> <p>LIGHT=light intensity available to algae in RCHRES (langleys/min)</p> <p>CMMLT = Michaelis-Menten constant for light limited growth (langleys/min)(CMMLT is defaulted to 0.033 langleys/min)</p>	Equations for algal growth limitation (light, N, P and temp)			6A,13T,13nuts,13sun
DTHPHY = ALD*STC	<p>DTHPHY = amount of phytoplankton death (micromoles P/l per interval)</p> <p>ALD=unit algal death rate determined by environmental conditions (/interval)</p> <p>STC= concentration of phytoplankton (micromoles P/l)</p>	The amount of phytoplankton death which occurs during the interval			3
<p>GROBAL = (GRO*CFBALG - RES*CFBALR)*BAL</p> <p>where: BAL = BENAL*DEPCOR/CVPB</p>	<p>BAL= benthic algae (micromoles P/l)</p> <p>BENAL = benthic algae (mg biomass/m2)</p> <p>CVPB = conversion factor from micromoles phosphorus to mg biomass</p> <p>DEPCOR = conversion from square meters to liters based on average depth of water in RCHRES during the interval (DEPCOR is computed in RQUAL)</p> <p>GROBAL = net growth rate of benthic algae (micromoles P/l per interval)</p> <p>GRO = unit growth rate as calculated in</p>	Benthic algae growth equations			6B,6A,13nuts

	subroutine ALGRO CFBALG = ratio of benthic algae to phytoplankton growth rates under identical growth conditions (default = 1.0) RES= unit respiration rate as calculated in subroutine ALGRO CFBALR = ratio of benthic algae to phytoplankton respiration rates (default = 1.0)				
DOX = DOX + (CVPB*CVBO*GROBAL)  BALORN = REFR*DTHBAL*CVBPN*.014 BALORP = REFR*DTHBAL*.031 BALORC = REFR*DTHBAL*CVBPC*.012 BALBOD = CVNRBO*CVPB*DTHBAL	DOX= concentration of dissolved oxygen (mg/l) CVPB = conversion factor from micromoles phosphorus to mg biomass CVBO = conversion factor from mg biomass to mg oxygen GROBAL = net growth of benthic algae (micromoles phosphorus/l) BALORN = increment to ORN state variable (mg N/l) BALORP = increment to ORP state variable (mg P/l) BALORC = increment to ORC state variable (mg C/l) BALBOD = increment to BOD state variable (mg O/l) REFR = refractory fraction of biomass DTHBAL = benthic algae death (micromoles P/l) CVNRBO = conversion from mg biomass to equivalent mg oxygen demand (allowing for refractory fraction) CVBPN = conversion from micromoles phosphorus to micromoles nitrogen CVBPC = conversion from micromoles phosphorus to micromoles carbon	The DOX state variable is updated to account for the net effect of benthic algae photosynthesis and respiration according to the following equation. The additions to ORN, ORP, ORC, and BOD resulting from benthic algae death.			3,6B,10DO

Model Name	Language	Output
HSPF	FORTRAN	Suspended solids concentrations at end of reach, amount of SS stored in the reach, bed depth, deposition or scour, dissolved and particulate N and P concentrations at end of reach, total N or P stored in reach, amount of atmospheric deposition, process fluxes for N and P, adsorption or desorption of DIP or ammonia

#### References

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jr., Donigian, A.S., Jr., and Johanson, R.C., 1997, Hydrological Simulation Program-Fortran, User's manual for version 11: U.S. Environmental Protection Agency, National Exposure Research Laboratory, Athens, Ga., EPA/600/R-97/080, 755 p.

SWAT	Parameters	Description	Calibration requirements	Issues	Reference to Table 1
<b>Nitrogen Cycle</b>					
$\Delta orgN_{str} = (\alpha_1 \rho_a \cdot algae - \beta_{N,3} \cdot orgN_{str} - \sigma_4 \cdot orgN_{str}) TT$	$\Delta orgN_{str}$ = change in organic N conc.(mg N/L) $\alpha_1$ =fraction of algal biomass that is N(mg N/mg algal biomass) $\rho_a$ = local respiration or death rate of the algae (day <sup>-1</sup> or hour <sup>-1</sup> ) $algae$ = algal biomass conc. at the beginning of the day (mg -algae/L) $\beta_{N,3}$ = rate constant for hydrolysis of organic N to ammonia N (day <sup>-1</sup> or h <sup>-1</sup> ) $orgN_{str}$ = organic nitrogen conc. at the beginning of the day (mg N/L) $\sigma_4$ = rate coefficient of organic N settling (d <sup>-1</sup> or h <sup>-1</sup> ) $TT$ = flow travel time in the reach segment (day or hour)	The change in organic nitrogen concentration	Fraction of algal biomass that is nitrogen, algal biomass concentration at the beginning of the day, flow travel time in the reach segment, ammonia, nitrite and nitrate concentration, rate constant for biological oxidation of nitrite to nitrate, dissolved oxygen concentration in the stream, average water temperature, preference factor for ammonia nitrogen, sediment source rate for ammonium at 20 °C, rate constant for the biological oxidation of ammonia nitrogen at 20 °C, water depth, rate coefficient of organic nitrogen settling at 20 °C, rate constant for hydrolysis of organic nitrogen to ammonia nitrogen at 20 °C, organic nitrogen concentration, local settling rate for algae at 20 °C, local respiration or death rate of the algae at 20 °C, local specific algal growth rate at 20 °C, Michaelis-Menton half-saturation constant for phosphorus, Michaelis-Menton half-saturation constant for nitrogen, non-linear and linear algal self shading coefficient, algal biomass concentration, ratio of chlorophyll a to algal biomass, light extinction coefficient, day length, solar radiation, fraction of solar radiation	In stream N cycling does not include denitrification	2,3, 16
$\beta_{N,3} = \beta_{N,3,20} \cdot 1.047^{(T_{water}-20)}$	$\beta_{N,3}$ = rate constant for hydrolysis of organic N to ammonia N (day <sup>-1</sup> or h <sup>-1</sup> ) $\beta_{N,3,20}$ = rate constant for hydrolysis of organic N to ammonia at 20 °C (d <sup>-1</sup> or h <sup>-1</sup> ) $T_{water}$ = average water temp for the day or hour (°C)	The organic nitrogen hydrolysis rate adjusted to local water temperature			10T, 16
$\sigma_4 = \sigma_{4,20} \cdot 1.024^{(T_{water}-20)}$	$\sigma_4$ = rate coefficient of organic N settling (d <sup>-1</sup> or h <sup>-1</sup> ) $\sigma_{4,20}$ =rate coefficient of org-N settling at 20 °C (d <sup>-1</sup> or h <sup>-1</sup> ) $T_{water}$ = average water temperature (°C)	The organic nitrogen settling rate adjusted to local water temperature			2,10T

$\Delta NH4_{str} = (\beta_{N,3} \cdot orgN - \beta_{N,1} \cdot NH4_{str} + \frac{\sigma_3}{1000 \cdot depth} - fr_{NH4} \cdot \alpha_1 \mu_a \cdot algae) TT$	<p><math>\Delta NH4_{str}</math> = change in ammonium conc. (mg N/L)</p> <p><math>\beta_{N,3}</math> = rate constant for hydrolysis of organic nitrogen to ammonia nitrogen (day<sup>-1</sup> or h<sup>-1</sup>)</p> <p><math>orgN_{str}</math> = organic N conc. at beginning of the day (mg N/L)</p> <p><math>\beta_{N,1}</math> = rate constant for biological oxidation of ammonia</p> <p><math>NH4_{str}</math> = ammonium conc. at beginning of the day (mg L/N)</p> <p><math>\sigma_3</math> = sediment source rate for ammonium (mg N/m<sup>2</sup>-day or mg N/m<sup>2</sup>-hour)</p> <p><math>depth</math> = water depth (m)</p> <p><math>fr_{NH4}</math> = fraction of algal N uptake from ammonium pool</p> <p><math>\alpha_1</math> = fraction of algal biomass that is N (mg N/mg algal biomass)</p> <p><math>\mu_a</math> = local growth rate of algae</p> <p><math>algae</math> = algal biomass conc. at beginning of day (mg algae/L)</p> <p><math>TT</math> = flow travel time in the reach segment (day or hour)</p>	<p>The change in ammonia concentration</p>	<p>that is photosynthetically-active, half saturation coefficient for light, solar radiation reaching the ground during a specific hour on current day of simulation, maximum specific algal growth rate, fraction of algal nitrogen uptake from ammonium pool</p>		1,3,5,6,11,15,16
$\beta_{N,1} = \beta_{N,1,20} \cdot (1 - \exp[-0.6 \cdot Ox_{str}]) \cdot 1.083^{(T_{water} - 20)}$	<p><math>\beta_{N,1}</math> = rate constant for biological oxidation of ammonia</p> <p><math>\beta_{N,1,20}</math> = rate constant for the biological oxidation of ammonia nitrogen at 20 °C (day<sup>-1</sup> or hour<sup>-1</sup>)</p> <p><math>Ox_{str}</math> = dissolved oxygen conc. in the stream (mg O<sub>2</sub>/L)</p> <p><math>T_{water}</math> = average water temp (°C)</p>	<p>The rate constant for biological oxidation of ammonia adjusted to the in stream oxygen concentration and the local water temperature</p>			5,10DO,10T

	$(1 - \exp[-0.6 \cdot Ox_{str}])$ is a nitrification inhibition correction factor- inhibits nitrification at low dissolved oxygen concentrations				
$\sigma_3 = \sigma_{3,20} \cdot 1.074^{(T_{water}-20)}$	$\sigma_3$ = sediment source rate for ammonium (mg N/m <sup>2</sup> -day) $\sigma_{3,20}$ = sediment source rate for ammonium at 20 °C (mg N/m <sup>2</sup> -d) $T_{water}$ = average water temp (°C)	The sediment source rate for ammonia nitrogen adjusted to local water temperature			10T,11,15
$fr_{NH4} = \frac{f_{NH4} \cdot NH4_{str}}{(f_{NH4} \cdot NH4_{str} + (1 - f_{NH4}) \cdot NO3_{str})}$	$fr_{NH4}$ = fraction of algal N uptake from ammonium pool $f_{NH4}$ = preference factor for ammonia $NH4_{str}$ = ammonium conc. in the stream (mg N/L) $NO3_{str}$ = nitrate conc. in the stream (mg N/L)	The fraction of algal nitrogen uptake from the ammonia pool			6A,13Nuts
$\Delta NO2_{str} = (\beta_{N,1} \cdot NH4_{str} - \beta_{N,2} \cdot NO2_{str}) \cdot TT$	$\Delta NO2_{str}$ = change in nitrite conc. (mg N/L) $\beta_{N,1}$ = rate constant for the biological oxidation of ammonia $NH4_{str}$ = ammonium conc. in the stream (mg N/L) $\beta_{N,2}$ = rate constant for biological oxidation of nitrite to nitrate (day <sup>-1</sup> ) $NO2_{str}$ = nitrite conc. at the beginning of the day (mg N/L) $TT$ = flow travel time in the reach segment (day)	The change in nitrite concentration			5
$\beta_{N,2} = \beta_{N,2,20} \cdot (1 - \exp[-0.6 \cdot Ox_{str}]) \cdot 1.047^{(T_{water}-20)}$	$\beta_{N,2}$ = rate constant for biological oxidation of nitrite to nitrate (day <sup>-1</sup> )	The rate constant of biological oxidation of nitrite to nitrate adjusted to dissolved oxygen concentrations and local			5,10T,10DO

	$\beta_{N,2,20}$ = rate constant for biological oxidation of nitrite to nitrate (day <sup>-1</sup> ) $Ox_{str}$ = dissolved oxygen conc. in the stream (mg O <sub>2</sub> /L) $T_{water}$ = average water temp (°C) $(1 - \exp[-0.6 \cdot Ox_{str}])$ is a nitrification inhibition correction factor- inhibits nitrification at low dissolved oxygen concentrations	water temperature			
$\Delta NO3_{str} = (\beta_{N,2} NO2_{str} - (1 - fr_{NH4}) \alpha_1 \mu_a \lg ae) TT$	$\Delta NO3_{str}$ = change in nitrate concentration (mg N/L) $\beta_{N,2}$ = rate constant for biological oxidation of nitrite to nitrate (day <sup>-1</sup> ) $NO2_{str}$ = nitrite conc. at the beginning of the day (mg N/L) $fr_{NH4}$ = fraction of algal N uptake from ammonium pool $\alpha_1$ = fraction of algal biomass that is N(mg N/mg algal biomass) $\mu_a$ = local algal growth rate (d <sup>-1</sup> ) $\lg ae$ = algal biomass concentration at the beginning of the day (mg algae/L) $TT$ = flow travel time in the reach segment (day)	The change in nitrate concentration			1,5,6A
<b>Phosphorus Cycle</b>					
$\Delta orgP_{str} = (\alpha_2 \rho_a \lg ae - \beta_{P,4} \cdot orgP_{str} - \sigma_5 \cdot orgP_{str}) TT$	$\Delta orgP_{str}$ = change in organic P conc. (mg P/L) $\alpha_2$ = fraction of algal biomass that is P(mg P/mg algal biomass) $\rho_a$ = local respiration rate or death rate of the algae (day <sup>-1</sup> )	The change in organic phosphorus concentration	Algal biomass concentration at the beginning of the day, local settling rate for algae at 20 °C, local respiration or death rate of the algae at 20 °C, local specific algal growth rate at 20 °C, Michaelis-Menton half-saturation constant for		1,2,3



	<p><i>algae</i> = algal biomass concentration at the beginning of the day (mg algae/L)</p> <p><math>\beta_{P,4}</math> = rate constant for mineralization of organic P (<math>d^{-1}</math>)</p> <p><math>orgP_{str}</math> = organic P conc. at the beginning of day (mg P/L)</p> <p><math>\sigma_5</math> = rate coefficient for organic P settling (<math>day^{-1}</math>)</p> <p><math>TT</math> = flow travel time in the reach segment (day)</p>		phosphorus, Michaelis-Menton half-saturation constant for nitrogen, linear and non-linear algal self shading coefficient, algal biomass concentration, ratio of chlorophyll a to algal biomass, non-algal portion of the light extinction coefficient, day length, solar radiation, fraction of solar radiation that is photosynthetically-active, half saturation coefficient for light, solar radiation reaching the		
$\beta_{P,4} = \beta_{P,4,20} \cdot 1.047^{(T_{water}-20)}$	<p><math>\beta_{P,4}</math> = rate constant for mineralization of organic phosphorus (<math>day^{-1}</math>)</p> <p><math>\beta_{P,4,20}</math> = rate constant for mineralization of organic phosphorus at 20 °C (<math>day^{-1}</math>)</p> <p><math>T_{water}</math> = average water temperature for the day (°C)</p>	The rate constant for mineralization of organic phosphorus adjusted to local water temperature	ground during a specific hour on current day of simulation, water depth, maximum specific algal growth rate, fraction of algal nitrogen uptake from ammonium pool, flow rate, fraction of algal biomass that is phosphorus, organic phosphorus concentration at the beginning of the day,		3,10T
$\sigma_5 = \sigma_{5,20} \cdot 1.024^{(T_{water}-20)}$	<p><math>\sigma_5</math> = rate coefficient for organic P settling (<math>day^{-1}</math>)</p> <p><math>\sigma_{5,20}</math> = rate coefficient for organic phosphorus settling at 20 °C (<math>day^{-1}</math>)</p> <p><math>T_{water}</math> = average water temperature for the day (°C)</p>	The coefficient for organic phosphorus settling adjusted to local water temperature	rate constant for mineralization of organic phosphorus at 20 °C, average water temperature for the day or hour, rate coefficient for organic phosphorus settling at 20 °C, sediment source rate for soluble phosphorus at 20 °C		2,10T
$\Delta solP_{str} = (\beta_{P,4} \cdot orgP + \frac{\sigma_2}{1000 \cdot depth} - \alpha_2 \mu_a \cdot algae) TT$	<p><math>\Delta solP_{str}</math> = change in soluble P conc. (mg P/L)</p> <p><math>\beta_{P,4}</math> = rate constant for mineralization of organic phosphorus (<math>day^{-1}</math>)</p> <p><math>orgP_{str}</math> = organic P conc. at the beginning of day (mg P/L)</p> <p><math>\sigma_2</math> = sediment source rate for soluble phosphorus (mg P/m<sup>2</sup>-day)</p> <p><math>\alpha_2</math> = fraction of algal biomass that is P (mg P/mg algal</p>	The change in the soluble phosphorus concentration			1,3,6A,11,15

	biomass) $\mu_a$ = local algal growth rate (d <sup>-1</sup> ) $algae$ = algal biomass conc. at beginning of day (mg algae/L) $TT$ = flow travel time in the reach segment (day)				
$\sigma_2 = \sigma_{2,20} \cdot 1.074^{(T_{water}-20)}$	$\sigma_2$ = sediment source rate for soluble phosphorus (mg P/m <sup>2</sup> -day) $\sigma_{2,20}$ = sediment source rate for soluble P at 20°C (mg P/m <sup>2</sup> -day) $T_{water}$ = average water temperature for the day (°C)	The benthos source rate for soluble phosphorus adjusted to local water temperature			10T,11,15
<b>Algae Cycle</b>					
$chla = \alpha_0 \cdot algae$	$chla$ = chlorophyll a concentration (g chl-a/L) $\alpha_0$ = ratio of chlorophyll a to algal biomass (g chl-a/mg algae) $algae$ = algal biomass concentration (mg algae/L)	The relationship between algal biomass and chlorophyll concentration	Algal biomass concentration at the beginning of the day, local settling rate for algae at 20 °C, local respiration or death rate of the algae at 20 °C, local specific algal growth rate at 20 °C, Michaelis-Menton half-saturation constant for phosphorus, Michaelis-Menton half-saturation constant for nitrogen, non-linear algal self shading coefficient, algal biomass concentration, ratio of chlorophyll a to algal biomass, linear algal self shading coefficient, non-algal portion of the light extinction coefficient, day length, solar radiation reaching the water surface on a given day, fraction of solar radiation that is photosynthetically-active, half saturation coefficient for light, solar radiation reaching the ground during a specific hour on current day of simulation, depth from the water surface, maximum specific algal		
$\Delta algae = \left( (\mu_a \cdot algae) - (\rho_a \cdot algae) - \left( \frac{\sigma_1}{depth} \cdot algae \right) \right) \cdot TT$	$\Delta algae$ = change in algal biomass conc. (mg algae/L) $\mu_a$ = local specific growth rate of the algae (day <sup>-1</sup> ) $algae$ = algal biomass conc. at beginning of day (mg algae/L) $\rho_a$ = local respiration or death rate of the algae (day <sup>-1</sup> ) $\sigma_1$ = local settling rate for algae (m/day) $depth$ = water depth (m) $TT$ = flow travel time in the reach segment (day)	The change in algal biomass			1,2,3
$\mu_{a,20} = \mu_{max} \cdot FL \cdot FN \cdot FP$	$\mu_{a,20}$ = local specific algal growth rate at 20 °C (day <sup>-1</sup> ) $\mu_{max}$ = maximum specific	The growth rate of algae- Multiplicative equation			6A,13sun,13nuts

	<p>algal growth rate (day<sup>-1</sup>)</p> <p><math>FL</math> = algal growth attenuation factor for light</p> <p><math>FN</math> = algal growth limitation factor for nitrogen</p> <p><math>FP</math> = algal growth limitation factor for phosphorus</p>		growth rate		
$\mu_{a,20} = \mu_{\max} \cdot FL \cdot \min(FN, FP)$	<p><math>\mu_{a,20}</math> = local specific algal growth rate at 20 °C (day<sup>-1</sup>)</p> <p><math>\mu_{\max}</math> = maximum specific algal growth rate (day<sup>-1</sup>)</p> <p><math>FL</math> = algal growth attenuation factor for light</p> <p><math>FN</math> = algal growth limitation factor for nitrogen</p> <p><math>FP</math> = algal growth limitation factor for phosphorus</p>	The growth rate of algae-Limiting nutrient equation			6A,13sun,13nuts
$\mu_{a,20} = \mu_{\max} \cdot FL \cdot \frac{2}{\left(\frac{1}{FN} + \frac{1}{FP}\right)}$	<p><math>\mu_{a,20}</math> = local specific algal growth rate at 20 °C (day<sup>-1</sup>)</p> <p><math>\mu_{\max}</math> = maximum specific algal growth rate (day<sup>-1</sup>)</p> <p><math>FL</math> = algal growth attenuation factor for light</p> <p><math>FN</math> = algal growth limitation factor for nitrogen</p> <p><math>FP</math> = algal growth limitation factor for phosphorus</p>	The growth rate of algae-Harmonic mean equation		Does this growth rate apply to all algal species?	6A,13sun,13nuts
$FL = \left(\frac{1}{k_{\ell} \cdot depth}\right) \cdot \ln \left[ \frac{K_L + I_{\text{photosyn},hr}}{K_L + I_{\text{photosyn},hr} \cdot \exp(-k_{\ell} \cdot depth)} \right]$	<p><math>FL</math> = algal growth attenuation factor for light</p> <p><math>k_{\ell}</math> = light extinction coefficient (m<sup>-1</sup>)</p> <p><math>depth</math> = water depth (m)</p> <p><math>K_L</math> = half saturation coefficient for light (MJ/m<sup>2</sup>-hour)</p> <p><math>I_{\text{photosyn},hr}</math> = photosynthetically-active solar radiation reaching the ground/water surface during a specific hour on a given day</p>	The algal growth attenuation factor for light			6A,13sun

	(MJ/m <sup>2</sup> -hour)				
$I_{photosyn,hr} = I_{hr} \cdot fr_{photosyn}$	$I_{photosyn,hr}$ = photosynthetically active solar radiation reaching the ground/water surface during a specific hour on a given day (MJ/m <sup>2</sup> -hour) $I_{hr}$ = solar radiation reaching the ground during a specific hour on current day of simulation (MJ m <sup>-2</sup> h <sup>-1</sup> ) $fr_{photosyn}$ = fraction of solar radiation that is photosynthetically-active	Calculation of the photosynthetically-active solar radiation			13sun
$FL = 0.92 \cdot fr_{DL} \cdot \left( \frac{1}{K_L \cdot depth} \right) \cdot \ln \left[ \frac{K_L + \bar{I}_{photosyn,hr}}{K_L + \bar{I}_{photosyn,hr} \cdot \exp(-k)} \right]$	$FL$ = algal growth attenuation factor for light $fr_{DL}$ = fraction of daylight hours $k_L$ = light extinction coefficient (m <sup>-1</sup> ) $depth$ = water depth (m) $K_L$ = half saturation coefficient for light (MJ/m <sup>2</sup> -hour) $\bar{I}_{photosyn,hr}$ = daylight average photosynthetically-active light intensity (MJ/m <sup>2</sup> -hour)	The algal growth attenuation factor for light modified according to the diurnal cycle-for daily simulations			6A,13sun
$fr_{DL} = \frac{T_{DL}}{24}$	$fr_{DL}$ = fraction of daylight hours $T_{DL}$ = day length (hr)	The fraction of daylight hours			13sun
$\bar{I}_{photosyn,hr} = \frac{fr_{photosyn} \cdot H_{day}}{T_{DL}}$	$\bar{I}_{photosyn,hr}$ = daylight average photosynthetically- active light intensity (MJ/m <sup>2</sup> - hour) $fr_{photosyn}$ = fraction of solar radiation that is photosynthetically-active $H_{day}$ = solar radiation reaching the water surface on a given day (MJ/m <sup>2</sup> )	Calculation of the daily average photosynthetically-active light intensity			13sun

	$T_{DL}$ = day length (hr)				
$k_{\ell} = k_{\ell,0} + k_{\ell,1} \cdot \alpha_0 \cdot algae + k_{\ell,2} \cdot (\alpha_0 \cdot algae)^{2/3}$	$k_{\ell}$ = light extinction coefficient (m <sup>-1</sup> ) $k_{\ell,0}$ = non-algal portion of the light extinction coefficient (m <sup>-1</sup> ) $k_{\ell,1}$ = linear algal self shading coefficient (m <sup>-1</sup> (μg-chl-a/L) <sup>-1</sup> ) $\alpha_0$ = ratio of chlorophyll a to algal biomass (μg chl-a/mg algae) $algae$ = algal biomass concentration (mg algae/L) $k_{\ell,2}$ = non-linear algal self shading coefficient (m <sup>-1</sup> (μg-chl-a/L) <sup>-2/3</sup> )	The light extinction coefficient			13sun
$FN = \frac{(C_{NO3} + C_{NH4})}{(C_{NO3} + C_{NH4}) + K_N}$	$FN$ = algal growth limitation factor for nitrogen $C_{NO3}$ =nitrate conc. in reach (mg N/L) $C_{NH4}$ = ammonium conc. in reach (mg N/L) $K_N$ = Michaelis-Menton half-saturation constant for nitrogen (mg N/L)	The algal growth limiting factor for nitrogen			6A,13nuts
$FP = \frac{C_{solP}}{C_{solP} + K_p}$	$FP$ = algal growth limitation factor for phosphorus $C_{solP}$ = conc. of dissolved phosphorus in reach (mg P/L) $K_p$ = Michaelis-Menton half-saturation constant for phosphorus (mg P/L)	The algal growth limiting factor for phosphorus			6A,13nuts
$\mu_a = \mu_{a,20} \cdot 1.047^{(T_{water} - 20)}$	$\mu_a$ = local specific growth rate of the algae (day <sup>-1</sup> ) $\mu_{a,20}$ = local specific algal growth rate at 20 °C (day <sup>-1</sup> ) $T_{water}$ = average water temperature for the day (°C)	Algal growth rate adjusted to local water temperature			6A,10T

$\rho_a = \rho_{a,20} \cdot 1.047^{(T_{water}-20)}$	$\rho_a$ = local respiration or death rate of the algae (d <sup>-1</sup> ) $\rho_{a,20}$ = local respiration or death rate of algae at 20 °C(d <sup>-1</sup> ) $T_{water}$ = average water temperature for the day (°C)	Local respiration or death rate of algae adjusted to local water temperature			3,10T
$\sigma_1 = \sigma_{1,20} \cdot 1.024^{(T_{water}-20)}$	$\sigma_1$ =local settling rate for algae (m/day) $\sigma_{1,20}$ = local settling rate for algae at 20 °C (m/day) $T_{water}$ = average water temperature for the day(°C)	Local settling rate of the algae			2,10T
<b>Suspended sediment</b>					
$v_{ch,pk} = \frac{q_{ch,pk}}{A_{ch}}$	$v_{ch,pk}$ = peak channel velocity (m/s) $q_{ch,pk}$ = peak flow rate (m <sup>3</sup> /s) $A_{ch}$ = cross sectional area of flow in the channel (m <sup>2</sup> )	The peak channel velocity	volume of water in the reach segment, volume of outflow during the time step, amount of suspended sediment in the reach at the beginning of the time period, channel cover factor, channel erodibility factor, concentration of sediment in the reach at the beginning of the time step, average rate of flow, peak rate adjustment factor, cross sectional area of flow in the channel		1
$q_{ch,pk} = prf \cdot q_{ch}$	$q_{ch,pk}$ = peak flow rate (m <sup>3</sup> /s) $prf$ = peak rate adjustment factor $q_{ch}$ = average rate of flow (m <sup>3</sup> /s)	The peak flow rate			1
$conc_{sed,ch,mx} = c_{sp} \cdot v_{ch,pk}^{spexp}$	$conc_{sed,ch,mx}$ = maximum concentration of sediment that can be transported by the water tom/m <sup>3</sup> or kg/L) $c_{sp}$ is a coefficient defined by the user $v_{ch,pk}$ = peak channel velocity (m/s) $sp exp$ is an exponent defined by the user (normally between 1.0 and 2.0)	The maximum amount of sediment that can be transported from the Reach			1,2
If $conc_{sed,ch,i} > conc_{sed,ch,mx}$	$sed_{dep}$ = amount of sediment deposited in the	The net amount of sediment deposited in the reach			2

<p>then</p> $sed_{dep} = (conc_{sed,ch,i} - conc_{sed,ch,mx}) \cdot V_{ch}$	<p>reach segment (metric tons)</p> <p><math>conc_{sed,ch,i}</math> = concentration of sediment in the reach at the beginning of the time step (ton/m<sup>3</sup> or kg/L)</p> <p><math>conc_{sed,ch,mx}</math> = maximum concentration of sediment that can be transported by the water (ton/m<sup>3</sup> or kg/L)</p> <p><math>V_{ch}</math> = volume of water in the reach segment (m<sup>3</sup> H<sub>2</sub>O)</p>				
<p>If <math>conc_{sed,ch,i} &lt; conc_{sed,ch,mx}</math></p> <p>then:</p> $sed_{deg} = (conc_{sed,ch,mx} - conc_{sed,ch,i}) V_{ch} K_{CH} C_{CH}$ <p>where:</p> $K_{CD} = 0.003 \exp[385 J_i]$	<p><math>sed_{deg}</math> = amount of sediment re-entrained in the reach segment (metric tons)</p> <p><math>conc_{sed,ch,mx}</math> = maximum concentration of sediment that can be transported by the water (ton/m<sup>3</sup> or kg/L)</p> <p><math>conc_{sed,ch,i}</math> = concentration of sediment in the reach at the beginning of the time step (ton/m<sup>3</sup> or kg/L)</p> <p><math>V_{ch}</math> = volume of water in the reach segment (m<sup>3</sup> H<sub>2</sub>O)</p> <p><math>K_{CH}</math> = channel erodibility factor (cm/hr/Pa)</p> <p><math>J_i</math> = jet index</p> <p><math>C_{CH}</math> = channel cover factor</p>	<p>The net amount of sediment re-entrained in the reach.</p> <p>Channel erodibility factor is determined by using a submerged jet device. The jet is set perpendicular to flow and the amount of erosion around the device is calculated as 'jet index'. See Hanson (1990), Trans ASAE, 33:132-137.</p> <p>Channel cover factor is the proportion of the channel degraded that is covered by a specific vegetative type compared to degradation of channel with no vegetation.</p>		Channel erodibility factor is calibrated from US sites.	2,14E
$sed_{ch} = sed_{ch,i} - sed_{dep} + sed_{deg}$	<p><math>sed_{ch}</math> = amount of suspended sediment in the reach ( tons)</p> <p><math>sed_{ch,i}</math> = amount of suspended sediment in the reach at the beginning of the time period (metric tons)</p> <p><math>sed_{dep}</math> = amount of sediment deposited in the reach segment (metric tons)</p>	<p>The final amount of sediment in the channel</p>			1,2

	$sed_{deg}$ = amount of sediment re-entrained in the reach segment (metric tons)				
$sed_{out} = sed_{ch} \cdot \frac{V_{out}}{V_{ch}}$	$sed_{out}$ = amount of sediment transported out of the reach (metric tons) $sed_{ch}$ = amount of suspended sediment in the reach (metric tons) $V_{out}$ = volume of outflow during the time step (m <sup>3</sup> H <sub>2</sub> O) $V_{ch}$ = volume of water in the reach segment (m <sup>3</sup> H <sub>2</sub> O)	The amount of sediment transported out of the reach			1

Model Name	Language	Output
SWAT	FORTRAN	SS transported in and out of reach, SS concentration in reach, org-N, org-P, nitrate, ammonium, nitrite, mineral-P, algae, BOD and DO concentrations transported in and out of reach.

References:

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Williams, J. R. (2005). Soil and Water Assessment Tool Theoretical Documentation.



WASP	Parameters	Description	Calibration requirements	Issues	Reference to Table 1
$\frac{\Delta(V_j C_j)}{\Delta t} = \sum_i [-Q_{ij} C_{ij} + R_{ij} (C_i - C_j)] + \sum_L W_{Lj} + \sum_B W_{Bj} + \sum_k V_j S_{Kj}$	<p><math>C_j</math>= concentration of water quality constituent in segment j  <math>t</math>=time  <math>Q_{ij}</math>= advective flow between segments i and j, defined as positive as leaving segment j, and negative when entering  <math>C_{ij}</math>=constituent concentration advected between i and j:  <math>=u C_j + (1-u) C_i</math> when entering j, and  <math>=u C_i + (1-u) C_j</math> when leaving j.  <math>R_{ij}</math>=dispersive flow between segments i and j:  <math>=E_{ij} A_{ij} / l_{ij}</math>            where:  <math>E_{ij}</math>=dispersion coefficient between segments i and j.  <math>A_{ij}</math>=cross sectional area between segments i and j  <math>l_{ij}</math>= characteristic mixing length between segments i and j.  <math>W_{Lj}</math>=point and diffuse loads into segment j  <math>W_{Bj}</math>=boundary loads into segment j  <math>S_{Kj}</math>=kinetic transformations within segment j</p>	General mass balance equation		This is the general advective equation. It does not include processes like settling, scour, sedimentation and benthic diffusion	1, point and non point sources
<b>Suspended sediment</b>					
$V_s = \frac{8.64 \cdot g}{18 \cdot \mu} \cdot (\rho_p - \rho_w) \cdot d_p^2$	<p><math>V_s</math> = Stoke's velocity for a particle with the diameter <math>d_p</math> and density <math>\rho_p</math> (m/day)  <math>g</math> = acceleration of gravity (981cm/sec<sup>2</sup>)  <math>\mu</math> = absolute viscosity of water (0.01 poise (g/cm<sup>3</sup>-sec) at 20 °C)  <math>\rho_p</math> =density of the solid (g/cm<sup>3</sup>)  <math>\rho_w</math> =density of water (1.0g/cm<sup>3</sup>)  <math>d_p</math> = particle diameter (mm)</p>	Settling velocity of the particle (Stoke's velocity)	Absolute viscosity of the water, density of the solid, density of the water, particle diameter, sediment surface area, scour velocity, sediment concentration of the sediment segment, sediment concentration of the water segment, probability of deposition upon contact with the bed, depth of the upper bed, sedimentation velocity of the upper bed, sediment velocity of the lower bed, depth of		2,14PS,14PD

$W_{Bs} = A_{ij} \cdot (W_R \cdot S_i - W_D \cdot S_j)$	$W_{Bs}$ =net sediment flux rate (g/d) $A_{ij}$ = sediment surface area (m <sup>2</sup> ) $W_R$ = scour velocity (m/day) $S$ = sediment conc. (g/m <sup>3</sup> ) $W_D$ =deposition velocity (m/d) $i$ = sediment segment $j$ = water segment	The net sediment flux rate	the lower bed		2,11,14flow, 14E
$W_D = V_s \cdot \alpha_D$	$W_D$ = deposition velocity (m/d) $V_s$ = Stoke's velocity for a particle with the diameter $d_p$ and density $\rho_p$ (m/day) $\alpha_D$ = probability of deposition upon contact with the bed	The deposition velocity			2
$d_i \frac{\delta S_i}{\delta t} = w_D S_j - (w_R + w_s) S_i$	$d_i$ = depth of the upper bed (m) $S_i$ = sediment concentration in the upper bed (g/m <sup>3</sup> ) $W_D$ = deposition velocity (m/d) $S_j$ =sediment conc. in water (g/m <sup>3</sup> ) $W_R$ = scour velocity (m/day) $w_s$ = sedimentation velocity of the upper bed (m/day)	The mass balance of the upper bed layer			2,11,14PS,14PD,14flow,14E
$d_k \frac{\delta S_k}{\delta t} = w_s S_i - w_{sk} S_k$	$d_k$ = depth of the lower bed (m) $S_k$ = sediment concentration in the lower bed (g/m <sup>3</sup> ) $w_s$ = sedimentation velocity of the upper bed (m/day) $S_i$ = sediment concentration in the upper bed (g/m <sup>3</sup> ) $w_{sk}$ = sediment velocity of the lower bed (m/day)	The mass balance of the lower bed layer			2,11,14PS,14PD,14F

Algae Cycle					
$S_{k4} = (G_{p1} - D_{p1} - k_{s4}) \cdot P$	$S_{k4}$ = reaction term (mg C/L-d) $G_{p1}$ = growth rate constant (d <sup>-1</sup> ) $D_{p1}$ = death plus respiration rate constant (d <sup>-1</sup> ) $k_{s4}$ = settling rate constant (d <sup>-1</sup> ) $P$ = phytoplankton population size (mg C/L)	The change in the concentration of phytoplankton	Net settling velocity of phytoplankton, herbivorous zooplankton population grazing on phytoplankton, grazing rate on phytoplankton per unit zooplankton population, death rate, parasitisation rate, endogenous respiration rate at 20 °C,		2,3,6
$G_{p1} = k_{1c} \cdot X_{RT} \cdot X_{RI} \cdot X_{RN}$	$G_{p1}$ = growth rate constant (d <sup>-1</sup> ) $k_{1c}$ = maximum growth rate (d <sup>-1</sup> ) $X_{RT}$ = temp adjustment factor $X_{RI}$ = light limitation factor as a function of I, f, D, and K <sub>e</sub> $X_{RN}$ = nutrient limitation factor as a function of (DIP) and (DIN) T = ambient water temp (°C) I = incident solar radiation (ly/day) f = fraction of day that is daylight D = depth of water column (m) K = total light extinction coefficient (m <sup>-1</sup> ) DIP = dissolved inorganic phosphorus (orthophosphate) available for growth (mg/L) DIN = dissolved inorganic nitrogen (ammonia plus nitrate) available for growth (mg/L)	The phytoplankton growth rate	temperature coefficient, ambient water temperature, Michaelis half saturation constant for Phosphorus, Michaelis half saturation constant for Nitrogen, dissolved inorganic phosphorus (orthophosphate) available for growth, dissolved inorganic nitrogen (ammonia plus nitrate) available for growth, phytoplankton chlorophyll concentration, light extinction coefficient, depth of the water column, average incident light intensity during daylight hours just below the surface, maximum growth rate, extinction coefficient per unit of chlorophyll,		6A,13T,13sun, 13nuts
$X_{RT} = \Theta_{1c}^{(T-20)}$	$X_{RT}$ = temp adjustment factor $\Theta_{1c}$ = temperature coefficient T = ambient water temp (°C)	The temperature adjustment factor	quantum yield, saturating light intensity of phytoplankton, fraction of day that is daylight, settling rate constant, phytoplankton population size, phosphorus to carbon ratio, concentration of phytoplankton carbon		13T
$\overline{X_{RI}} = \frac{e}{K_e \cdot D} \cdot f \cdot \left[ \exp\left\{-\frac{I_a}{I_s} \exp(-K_e \cdot D)\right\} - \exp\left(-\frac{I_a}{I_s}\right) \right]$	$\overline{X_{RI}}$ = instantaneous, depth averaged, growth rate reduction e = natural log (2.71828) D = depth of water column (m) f = fraction of day that is daylight	The instantaneous, depth averaged, growth rate reduction		Assumed average incident light intensity during daylight hours.	6A,13sun

	$I_a$ = average incident light intensity during daylight hours just below the surface (assumed to average 0.9 l/f, ly/day) $I_s$ = saturating light intensity of phytoplankton (ly/day) $K_e$ = light extinction coefficient				
$K_{eshd} = 0.0088 \cdot P_{Chl} + 0.054 \cdot P_{Chl}^{0.67}$	$P_{Chl}$ = phytoplankton chlorophyll concentration (µg/L)	Phytoplankton self shading attenuation			13sun
$\Theta_c = 0.3 \cdot \frac{\Phi_{max} \cdot K_c \cdot f_u \cdot I_a}{k_{1c} \cdot X_{RT} \cdot e} \cdot \left[ \frac{1 - e^{-K_e \cdot D}}{K_e \cdot D} \right]$	$\Theta_c$ = ratio of C to chl-a in the phytoplankton (mg C/mg chl a) $\Phi_{max}$ = quantum yield (mg C fixed per mole of light quanta absorbed) $K_c$ = extinction coefficient per unit of chlorophyll (m <sup>2</sup> /mg chl a) $f_u$ = units conversion factor (0.083, assuming 43% incident light is visible and 1 mole of photons is equivalent to 52,000 cal) (mole photons/m <sup>2</sup> -ly) $k_{1c}$ = maximum growth rate (d <sup>-1</sup> ) $X_{RT}$ = temp adjustment factor $e$ = natural log (2.71828) $I_a$ = average incident light intensity during daylight hours just below the surface (assumed to average 0.9 l/f, ly/day) $D$ = depth of water column (m) $K_e$ = light extinction coefficient	The carbon to chlorophyll ratio		Units conversion factor (0.083, assuming 43% incident light is visible and 1 mole of photons is equivalent to 52,000 cal)	6A,13sun
$X_{RN} = Min \left( \frac{DIN}{K_{mN} + DIN}, \frac{DIP}{K_{mP} + DIP} \right)$	$X_{RN}$ = nutrient limitation factor as a function of dissolved inorganic DIP = dissolved inorganic phosphorus (orthophosphate) available for growth (mg/L) DIN = dissolved inorganic nitrogen (ammonia plus nitrate) available for growth (mg/L)	The nutrient limitation factor			6A,13nuts

	$K_{mN}$ = Michaelis half saturation constant for Nitrogen $K_{mP}$ = Michaelis half saturation constant for P				
$k_{1R}(T) = k_{1R}(20^{\circ}C) \cdot \Theta_{1R}^{(T-20)}$	$k_{1R}(T)$ = temp corrected endogenous respiration rate(d <sup>-1</sup> ) $k_{1R}(20^{\circ}C)$ = endogenous respiration rate at 20 °C (day <sup>-1</sup> ) $\Theta_{1R}$ = temperature coefficient T = ambient water temp ( °C)	The endogenous respiration rate of the algae adjusted to local water temperature			6A,13T
$D_1 = k_{1R}(T) + k_{1D} + k_{1G} \cdot Z(t)$	$D_1$ =biomass reduction rate(d <sup>-1</sup> ) $k_{1R}(T)$ = temperature corrected endogenous respiration rate (d <sup>-1</sup> ) $k_{1D}$ = death rate, representing the effect of parasitisation i.e. the infection of algal cells by other microorganisms, and toxic materials such as chlorine residual (day <sup>-1</sup> ) $k_{1G}$ = grazing rate on phytoplankton per unit zooplankton population (L/mg C-day) $Z(t)$ = herbivorous zooplankton population grazing on phytoplankton (mg C/L)	The biomass reduction rate for phytoplankton			3
$k_{s4j} = \frac{v_{s4ij}}{D_j}$	$k_{s4j}$ = effective phytoplankton settling or loss rate (day <sup>-1</sup> ) $v_{s4ij}$ = net settling velocity of phytoplankton from segment j to segment i (m/day) $D_j$ = depth of segment j (equal to volume/surface area) (m)	The settling rate for phytoplankton			2
<b>Phosphorus Cycle</b>					
$\frac{\partial C_{4a_{pc}}}{\partial t} = \left( G_P - D_P - \frac{v_{s4}}{D} \right) C_{4a_{pc}}$	$\frac{\partial (C_{4a_{pc}})}{\partial t}$ = change in the concentration of phytoplankton phosphorus (mg P/L/day)	Change in the concentration of phytoplankton phosphorus	Net settling velocity of phytoplankton, herbivorous zooplankton population grazing on phytoplankton, grazing rate on phytoplankton		2,6A

<p><i>Growth- Death - Settling</i></p>	<p><math>G_p</math> = Specific phytoplankton growth rate (day<sup>-1</sup>)  <math>a_{pc}</math> = P to C ratio (mg P/mg C)  <math>C_4</math> = phytoplankton carbon concentration (mg C/L)  <math>D_p</math> =phytoplankton loss rate  <math>v_{s4}</math> = settling velocity (m/day)  <math>D</math> = segment depth (m)</p>		<p>per unit zooplankton population, death rate, parasitisation rate, endogenous respiration rate at 20 °C, temperature coefficient, ambient water temperature, Michaelis half saturation constant for Phosphorus, Michaelis half saturation constant for Nitrogen, dissolved inorganic phosphorus</p>		
<p><math display="block">\frac{\partial C_8}{\partial t} = D_p(1 - f_{op})a_{pc}C_4 - k_{83}\theta_{83}^{T-20}\left(\frac{C_4}{K_{mpc} + C_4}\right)C_8</math></p> <p><math display="block">- \frac{v_{s3}(1 - f_{d8})}{D}C_8</math></p> <p><i>Death-mineralisation-settling</i></p>	<p><math>\frac{\partial C_8}{\partial t}</math> = change in the concentration of organic phosphorus (mg P/L/day)  <math>D_p</math> = phytoplankton loss rate (day<sup>-1</sup>)  <math>a_{pc}</math> = P to C ratio (mg P/mg C)  <math>f_{op}</math> = fraction of dead and respired phytoplankton recycled to the organic phosphorus pool  <math>C_4</math> = phytoplankton Carbon concentration (mg C/L)  <math>k_{83}</math> =dissolved organic P mineralization at 20 °C (day<sup>-1</sup>)  <math>\theta_{83}</math> = temperature coefficient  <math>T</math> = water temperature ( °C)  <math>K_{mpc}</math> = half saturation constant for phytoplankton limitation of P recycle (mg C/L)  <math>C_8</math> = conc of organic P  <math>v_{s3}</math> = organic matter settling velocity (m/day)  <math>f_{d8}</math> =fraction dissolved organic phosphorus in the water column  <math>D</math> = segment depth (m)</p>	<p>Change in the concentration of organic phosphorus</p>	<p>(orthophosphate) available for growth, dissolved inorganic nitrogen (ammonia plus nitrate) available for growth, phytoplankton chlorophyll concentration, light extinction coefficient, depth of the water column, average incident light intensity during daylight hours just below the surface, maximum growth rate, extinction coefficient per unit of chlorophyll, quantum yield, saturating light intensity of phytoplankton, fraction of day that is daylight, settling rate constant, phytoplankton population size, phosphorus to carbon ratio, concentration of phytoplankton carbon, fraction of dead and respired phytoplankton recycled to the organic phosphorus pool, dissolved organic phosphorus mineralization at 20 °C, temperature coefficient, water temperature, half</p>		<p>2,3,10T</p>

$\frac{\partial C_3}{\partial t} = D_p(1 - f_{op})a_{pc}C_4 + k_{83}\theta_{83}^{T-20}\left(\frac{C_4}{K_{mpc} + C_4}\right)C_8$ $- G_p C_4 a_{pc} - \frac{v_{s5}(1 - f_{d3})}{D}C_3$ <p><i>Death + mineralization – growth – settling</i></p> <p>And:</p> $C_3 = C_{DIP} + C_{PIP}$ <p>Fraction of particulate inorganic phosphorus</p> $f_{p3} = \frac{C_{PIP}}{C_3} = \frac{K_{PIP}M}{1 + K_{PIP}M}$ <p>Fraction of dissolved inorganic phosphorus</p> $f_{d3} = \frac{C_{DIP}}{C_3} = \frac{1}{1 + K_{PIP}M}$	$\frac{\partial C_3}{\partial t}$ = change in the concentration of inorganic phosphorus (mg P/L/day) $D_p$ = phytoplankton loss rate (day <sup>-1</sup> ) $a_{pc}$ = P to C ratio (mg P/mg C) $f_{op}$ = fraction of dead and respired phytoplankton recycled to the organic phosphorus pool $C_4$ = concentration of phytoplankton carbon (mg C/L) $k_{83}$ = dissolved organic P mineralization at 20°C (day <sup>-1</sup> ) $\theta_{83}$ = temperature coefficient $T$ = water temperature (°C) $K_{mpc}$ = half saturation constant for phytoplankton limitation of P recycle (mg C/L) $C_8$ = conc of organic P (mg P/L) $G_p$ = specific phytoplankton growth rate (day <sup>-1</sup> ) $v_{s5}$ = inorganic matter settling velocity (m/day) $f_{d3}$ = fraction dissolved inorganic phosphorus $f_{p3}$ = fraction of particulate inorganic phosphorus $D$ = segment depth (m) $K_{PIP}$ = partition coefficient for particulate phosphorus $C_{PIP}$ = conc. of particulate inorganic phosphorus $C_{DIP}$ = conc. of dissolved inorganic phosphorus	The change in the concentration of inorganic phosphorus	saturation constant for phytoplankton limitation of phosphorus recycle, concentration of organic phosphorus, organic matter settling velocity		2,3,10T,12
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	$M$ =conc. of solids (kg/L)				
<b>Nitrogen Cycle</b>					
$\frac{\partial C_4 a_{nc}}{\partial t} = \left( G_p - D_p - \frac{v_{s4}}{D} \right) C_4 a_{nc}$ <p style="text-align: center;"><i>Growth – Death – Settling</i></p>	$\frac{\partial (C_4 a_{nc})}{\partial t}$ <p>= change in phytoplankton nitrogen conc. (mg N/L/day)  <math>G_p</math> = specific phytoplankton growth rate (day<sup>-1</sup>)  <math>a_{nc}</math> = N to C ratio (mg N/gm C)  <math>C_4</math> = phytoplankton C conc. (mg C/L)  <math>D_p</math> = phytoplankton loss rate (day<sup>-1</sup>)  <math>v_{s4}</math> = settling velocity (m/day)  <math>D</math> = segment depth (m)</p>	Change in the concentration of phytoplankton nitrogen	Net settling velocity of phytoplankton, herbivorous zooplankton population grazing on phytoplankton, grazing rate on phytoplankton per unit zooplankton population, death rate, representing the effect of parasitisation, endogenous respiration rate at 20 °C, temperature coefficient, ambient water temperature, Michaelis half saturation constant for Phosphorus, Michaelis half saturation constant for Nitrogen, dissolved inorganic phosphorus (orthophosphate) available for growth, dissolved inorganic nitrogen (ammonia plus nitrate) available for growth, phytoplankton chlorophyll concentration, light extinction coefficient, depth of the water column, average incident light intensity during daylight hours just below the surface, maximum growth rate, extinction coefficient per unit of chlorophyll, quantum yield, saturating light intensity of phytoplankton, fraction of day that is daylight, settling rate constant, phytoplankton population size, half saturation constant for phytoplankton limitation of phosphorus recycle, nitrate nitrogen		2,3,6A
$\frac{\partial C_7}{\partial t} = D_p f_{on} a_{nc} C_4 - k_{71} \theta_{71}^{T-20} \left( \frac{C_4}{K_{mpc} + C_4} \right) C_7$ $- \frac{v_{s3}(1 - f_{d7})}{D} C_7$	$\frac{\partial C_7}{\partial t}$ <p>= change in organic nitrogen conc. (mg N/ L/day)  <math>D_p</math> = phytoplankton loss rate (day<sup>-1</sup>)  <math>a_{nc}</math> = N to C ratio (mg N/gm C)  <math>f_{on}</math> = fraction of dead and respired phytoplankton recycled to the organic nitrogen pool  <math>C_4</math> = phytoplankton carbon concentration (mg C/L)  <math>k_{71}</math> = organic nitrogen mineralization rate at 20 °C (d<sup>-1</sup>)  <math>\theta_{71}</math> = temperature coefficient  <math>T</math> = water temperature (°C)  <math>K_{mpc}</math> = half saturation constant for phytoplankton limitation of P recycle (mg C/L)  <math>C_7</math> = organic N conc. (mg N/ L)  <math>v_{s3}</math> = organic matter settling velocity (m/day)</p>	Change in the concentration of organic nitrogen			2,3,10T,13nuts, 16



	$f_{D7}$ = fraction of dissolved organic nitrogen D = segment depth (m)		equation, Michaelis constant for denitrification, denitrification rate at 20 °C, phytoplankton carbon concentration, nitrogen to carbon ratio, ammonia nitrogen concentration, half saturation constant for oxygen, dissolved oxygen concentration, water temperature, temperature coefficient, nitrification rate, organic nitrogen concentration, organic nitrogen mineralization rate at 20 °C, fraction of dead and respired phytoplankton recycled to the organic nitrogen pool, organic matter settling velocity, fraction of dissolved organic nitrogen		
$\frac{\partial C_1}{\partial t} = D_p(1 - f_{on})a_{nc}C_4 - k_{71}\theta_{71}^{T-20}\left(\frac{C_4}{K_{mpc} + C_4}\right)C_7$ $- G_p a_{nc} P_{NH3} C_4 - k_{12}\theta_{12}^{(T-20)}\left(\frac{C_6}{K_{NIT} + C_6}\right)C_1$ <p>Where</p> $P_{NH3} = C_1\left(\frac{C_2}{(K_{mN} + C_1)(K_{mN} + C_2)}\right)$ $+ C_2\left(\frac{K_{mN}}{(C_1 + C_2)(K_{mN} + C_2)}\right)$	$\frac{\partial C_1}{\partial t}$ = change in concentration of ammonia (mg N/L/day) $D_p$ = phytoplankton loss rate (day <sup>-1</sup> ) $a_{nc}$ = N to C ratio (mg N/gm C) $f_{on}$ = fraction of dead and respired phytoplankton recycled to the organic nitrogen pool $C_4$ = phytoplankton carbon concentration (mg C/ L) $k_{71}$ = organic nitrogen mineralization rate at 20 °C (d <sup>-1</sup> ) $\theta_{71}$ = temperature coefficient $T$ = water temperature (°C) $K_{mpc}$ = half saturation constant for phytoplankton limitation of P recycle (mg C/L) $K_{mN}$ = coefficient to estimate the amount of ammonia taken up by phytoplankton compared to nitrate (given as 25µg/L) $C_7$ = organic N conc. (mg N/L) $G_p$ = specific phytoplankton growth rate (day <sup>-1</sup> ) $k_{12}$ = nitrification rate (day <sup>-1</sup> ) $\theta_{12}$ = temperature coefficient $C_6$ = dissolved oxygen concentration (mg O <sub>2</sub> /L) $K_{NIT}$ = half saturation constant for oxygen limitation of nitrification (mg O <sub>2</sub> /L) $C_1$ = ammonia conc. (mg-N/L)	The change in the concentration of ammonia nitrogen			3,5,6A,10T, 10DO, 13nuts, 16

	$C_2$ =nitrate conc. (mg-N/L)				
$\frac{\partial C_2}{\partial t} = k_{12} \theta_{12}^{T-20} \left( \frac{C_6}{K_{NIT} + C_6} \right) C_1$ $- G_P a_{nc} (1 - P_{NH3}) C_4 - k_{2D} \theta_{2D}^{(T-20)} \left( \frac{k_{NO3}}{k_{NO3} + C_6} \right) C_2$ <p>Where</p> $P_{NH3} = C_1 \left( \frac{C_2}{(K_{mN} + C_1)(K_{mN} + C_2)} \right)$ $+ C_2 \left( \frac{K_{mN}}{(C_1 + C_2)(K_{mN} + C_2)} \right)$	$\frac{\partial C_2}{\partial t}$ = change in the concentration of nitrate nitrogen (mg N/L/day) $k_{12}$ = nitrification rate (day <sup>-1</sup> ) $\theta_{12}$ = temperature coefficient $T$ = water temperature (°C) $C_6$ = DO concentration (mg O <sub>2</sub> /L) $K_{NIT}$ = half saturation constant for O <sub>2</sub> limitation of nitrification (mg O <sub>2</sub> /L) $C_1$ = ammonia conc. (mg N/L) $G_P$ = specific phytoplankton growth rate (day <sup>-1</sup> ) $a_{nc}$ = N to C ratio (mg N/gm C) $C_4$ = phytoplankton carbon concentration (mg C/L) $k_{2D}$ = denitrification rate at 20 °C (day <sup>-1</sup> ) $k_{NO3}$ = Michaelis constant for denitrification (mg O <sub>2</sub> /L) $C_2$ = nitrate conc. (mg N/L) $K_{mPc}$ = half saturation constant for phytoplankton limitation of phosphorus recycle (mg C/L) $K_{mN}$ =coefficient to estimate the amount of ammonia taken up by phytoplankton compared to nitrate (given as 25µg/L)	Change in the concentration of nitrate nitrogen			4,5,6A,10T, 10DO
Model Name	Language	Output			
WASP	FORTRAN	Inorganic P, organic P, unavailable P, available P, ammonia, nitrate, total inorganic N, organic N, total nitrogen, phytoplankton growth, death rates, phytoplankton growth limitation, BOD conc., DO conc., BOD decay rate.			

References:

Wool, T. A., Ambrose, R. B., Martin, J. L., Comer, E. A. Water Quality Analysis Simulation Program (WASP): Version 6. Draft User's Manual

KINEROS	Parameters	Description	Calibration requirements	Issues	Reference to Table 1
<b>Suspended Sediment</b>					
$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_c(x, t)$	$q_c(x, t)$ = net lateral inflow per unit length of channel $A$ = cross sectional area of the channel $Q$ = channel discharge	The net lateral inflow per unit length of channel	Bottom width of the channel, rate of lateral sediment inflow for channels, concentration at equilibrium transport capacity, hydraulic depth, particle diameter, kinematic viscosity of water, particle specific gravity, critical shear stress, bed shear stress, channel discharge, cross sectional area of flow, sediment concentration, rate of lateral sediment inflow for channels, rate of erosion of the soil bed, hydraulic radius		1, non-point source
$\frac{\partial A}{\partial t} + \frac{dQ}{dA} \cdot \frac{\partial A}{\partial x} = q_c(x, t)$	$q_c(x, t)$ = net lateral inflow per unit length of channel $A$ = cross sectional area of the channel $Q$ = channel discharge	The channel discharge expressed as a function of the cross sectional area of the channel and the net lateral inflow per unit length of channel			1
$Q = \alpha \cdot R^{m-1} \cdot A$	$R$ = hydraulic radius $A$ = cross sectional area of the channel $Q$ = channel discharge	Relationship between cross sectional area and channel discharge			1
$\frac{\partial(AC_s)}{\partial t} + \frac{\partial(QC_s)}{\partial x} - e(x, t) = q_s(x, t)$	$C_s$ = sediment conc. ( $L^3/L^3$ ) $A$ = cross sectional area of flow ( $L^2$ ) $e$ = rate of erosion of the soil bed ( $L^2/T$ ) $q_s$ = rate of lateral sediment inflow for channels ( $L^3/T/L$ ) $Q$ = channel discharge	The sediment dynamics at any point along the channel is determined using the following equation			1, 11, 14E, 14F
$g_h = c_g \cdot (C_{mx} - C_s) \cdot A$	$g_h$ = hydraulic erosion rate $c_g$ is a transfer rate coefficient ( $T^{-1}$ ) $C_{mx}$ = concentration at equilibrium transport capacity $C_s$ = sediment conc. ( $L^3/L^3$ ) $A$ = cross sectional area of flow ( $L^2$ )	The hydraulic erosion rate			14E, 14F

$q_m = C_{mx} \cdot Q - w \cdot S^\beta \cdot Q^\gamma \cdot r^\delta \cdot \left[ 1 - \frac{\tau_c}{\tau_o} \right]^\epsilon$ $\tau_o \geq \tau_c$	$q_m$ =transport capacity (L <sup>2</sup> T <sup>-1</sup> ) $C_{mx}$ = concentration at equilibrium transport capacity $Q$ = channel discharge $S$ =slope of stream $r$ =rainfall rate $\tau_o$ = bed shear stress (L <sup>2</sup> /T) $\tau_c$ = critical shear stress (L <sup>2</sup> /T) $w$ is a coefficient $\beta$ , $\gamma$ , and $\epsilon$ are exponents that have values of 0 or between 1 and 2 $\delta$ is an exponent with a value that varies from 0 to -2.24	The transport capacity of the stream			1, 11, 14E, 14F, 14S
$v_s^2 = \frac{4}{3} \cdot \frac{g \cdot (S_s - 1) \cdot d}{C_D}$	$v_s$ = particle fall velocity $g$ is gravitational acceleration (LT <sup>-2</sup> ) $S_s$ is particle specific gravity $C_D$ = drag coefficient $d$ = particle diameter (L)	Calculation of the particle fall velocity			2, 14PD, 14PS
$C_D = \frac{24}{R_n} + \frac{3}{\sqrt{R_n}} + 0.34$	$C_D$ = drag coefficient $R_n$ = Reynold's number	The drag coefficient calculated as a function of Reynold's number			2
$R_n = v_s d / \nu$	$v_s$ = particle fall velocity $d$ = particle diameter (L) $\nu$ is kinematic viscosity of water (L <sup>2</sup> /T)	Definition of Reynold's number			2, 14PD, 14PS
$c_g(\text{deposition}) = \frac{v_s}{h_D} \cdot \left[ 1 - \frac{C_{mx}}{C_s} \right]$	$c_g$ = transfer rate coefficient $h_D$ = hydraulic depth	Calculation of the transfer rate coefficient			2, 14PD

	$v_s$ = particle fall velocity $C_{mx}$ = concentration at equilibrium transport capacity $C_s$ = sediment conc. (L <sup>3</sup> /L <sup>3</sup> )				
$C_s(0,t) = \frac{q_s}{q_c + v_s \cdot BW}$	$C_s$ = sediment conc. (L <sup>3</sup> /L <sup>3</sup> ) $q_s$ = rate of lateral sediment inflow for channels (L <sup>3</sup> /T/L) $q_c(x,t)$ = net lateral inflow per unit length of channel $v_s$ = particle fall velocity $BW$ = bottom width of the channel	The sediment concentration for the upper boundary condition			2

Model Name	Language	Output
KINEROS	FORTRAN 77	Suspended solid concentration, deposition and scour

References:

Woolhiser, D. A., Smith, R. E., Goodrich, D. C. (1990). KINEROS, a Kinematic Runoff and Erosion Model: Documentation and user manual. U.S. Department of Agriculture, Agricultural Research Service, ARS-77, 130 pp.

EPDRIV1	Parameters	Description	Calibration requirements	Issues	Reference to Table 1
<b>Water Quality Governing Equations</b>					
$\frac{\partial \alpha}{\partial t} + \bar{\mu} \frac{\partial \alpha}{\partial x} = D \frac{\partial^2 \alpha}{\partial x^2} + \frac{q}{A} (\gamma - \alpha) - K_s \alpha + SINKS$	$\alpha$ = mass concentration $\bar{\mu}$ = average velocity $x$ = longitudinal distance $D$ = dispersion coefficient $q$ = lateral inflow rate $A$ = cross sectional area (m <sup>2</sup> ) $\gamma$ = concentration of the runoff input to the channel by distributed flow $q$ $K_s$ = biochemical uptake or decay rates (+) & growth rates (-) $SINKS$ = biochemical sources (+) and sinks (-)	The general equation to be solved for mass balance concentrations			1, point sources, non-point sources
$D = D_0 + g^{0.5} \cdot k_D \cdot n \cdot  u  \cdot \left( \frac{A}{B} \right)^{\frac{5}{6}}$	$D$ = rate of dispersion (m <sup>2</sup> sec <sup>-1</sup> ) $D_0$ = constant (time-invariant) rate of dispersion (m <sup>2</sup> sec <sup>-1</sup> ) $g$ = gravitational acceleration (9.817m s <sup>-2</sup> ) $k_D$ = dispersion coefficient $n$ = roughness coefficient (Manning's n) $u$ = velocity $A$ = cross sectional area (m <sup>2</sup> ) $B$ = width (m)	The rate of dispersion			1
<b>Nitrogen Cycle</b>					

$\left( \begin{array}{c} \text{Rate of loss of org} - N \\ \text{due to hydrolysis to} \\ \text{ammonia and settling} \\ g - N / m^3 / \text{day} \end{array} \right) =$ $\left( K1N + KDN + \frac{XONS}{H} \right) ORGANS$ <p>where:</p> $K1N = ACK * TH\_K1N^{(T-20)} * \left( \frac{1 + KOCB1}{DO} \right)$ <p>and:</p> $KDN = ADN \left( TH\_KDN^{(T-20)} \right) * \left( \frac{KOCBDN}{DO + KOCBDN} \right) * \left( \frac{NO_3 - N}{DO + KOCBDN} \right)$	<p><math>K1N</math> = temperature and DO corrected rate coefficient for organic-N, day<sup>-1</sup></p> <p><math>KDN</math> = temperature corrected rate coefficient for nitrate reduction and anaerobic CBOD oxidation, day<sup>-1</sup></p> <p><math>XONS</math> = the settling rate for organic nitrogen (m/day)</p> <p><math>H</math> = stream depth (m)</p> <p><math>ORGAN</math> = concentration of organic nitrogen (g-N/m<sup>3</sup>)</p> <p><math>KOCB1</math> = Monod half velocity constant for oxygen-limited aerobic systems (g O<sub>2</sub>/m<sup>3</sup>)</p> <p><math>DO</math> = dissolved oxygen conc.</p> <p><math>ACK</math> = rate coefficient for organic nitrogen decay to NH<sub>3</sub> (day<sup>-1</sup>)</p> <p><math>TH\_K1N</math> = temperature coefficient for organic-N decay</p> <p><math>T</math> = temperature (°C)</p> <p><math>ADN</math> = uncorrected rate coefficients for denitrification of organic matter (day<sup>-1</sup>)</p> <p><math>TH\_KDN</math> = temperature coefficient for denitrification</p> <p><math>KOCBDN</math> = denitrification inhibition half-velocity constant, g O<sub>2</sub>/m<sup>3</sup></p> <p><math>NO_3 - N</math> = local nitrate concentration, g-N/m<sup>3</sup></p>	<p>Equation to calculate the rate of loss of organic nitrogen due to mineralization (hydrolysis) and settling.</p>	<p>Monod half velocity constant for oxygen limitation of macrophyte decay and oxygen limited aerobic systems, cross sectional area, average dissolved oxygen concentration, width, macrophyte specific decay rate, macrophyte density, specific macrophyte growth rate, hydraulic depth, light extinction coefficient for the particular reach, light intensity (net short-wave radiation) at the water surface, maximum specific algal decay rate, algal concentration, half velocity constant relating phosphate concentration to algal growth rate, phosphate concentration, half velocity constant relating inorganic nitrogen to algal growth, nitrate + ammonia concentration, light growth adjustment factor, maximum specific growth rate, sediment denitrification rate, conversion factor coefficient for oxygen to nitrogen equivalents, temperature, temperature coefficient for ammonia release, benthic release rate,</p>	<p>2,3,4 10DO, 10OM, 10T, 16</p>
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$\left( \begin{array}{l} \text{Rate of increase of organic} - N \\ \text{due to algal / macrophyte decay} \end{array} \right) =$ $g - N / m^3 / \text{day}$ $(ANCONT * ALGADK + MNCONT * MDEATH)$	<p><i>ANCONT</i> = nitrogen to biomass ratio in algae (g/g)</p> <p><i>ALGADK</i> = rate of algal decay (g/m<sup>3</sup>/day)</p> <p><i>MNCONT</i> = nitrogen to biomass ratio in macrophytes (g/g)</p> <p><i>MDEATH</i> = rate of macrophyte decay (g/m<sup>3</sup>/day)</p>	The increase in the concentration of organic nitrogen as a result of algal and macrophyte decay	nitrogen to biomass ratio in macrophytes, nitrogen to biomass ratio in algae, concentration of nitrate nitrogen, concentration of ammonium nitrogen, Monod half velocity constant for oxygen limitation of nitrification, temperature		3
$\left( \begin{array}{l} \text{Net rate of accumulation} \\ \text{of organic nitrogen} \end{array} \right) = (ANCONT * ALGADK +$ $MNCONT * MDEATH) - \left( K1N + KDN + \frac{XONS}{H} \right) * ORGANS$	<p><i>KDN</i> = temperature corrected rate coefficient for nitrate reduction and anaerobic CBOD oxidation (day<sup>-1</sup>)</p> <p><i>K1N</i> = temperature and DO corrected rate coefficient for organic-N, day-1</p> <p><i>XONS</i> the settling rate for organic nitrogen (m/day)</p> <p><i>H</i> = stream depth (m)</p> <p><i>ORGAN</i> = concentration of organic nitrogen (g-N/m<sup>3</sup>)</p> <p><i>ANCONT</i> = nitrogen to biomass ratio in algae (g/g)</p> <p><i>ALGADK</i> = rate of algal decay (g/m<sup>3</sup>/day)</p> <p><i>MNCONT</i> = nitrogen to biomass ratio in macrophytes (g/g)</p> <p><i>MDEATH</i> = rate of macrophyte decay (g/m<sup>3</sup>/day)</p>	The net accumulation of organic nitrogen	coefficient for ammonium oxidation (suggested value is 1.1), uncorrected rate coefficient for nitrification, temperature coefficient for organic nitrogen decay, rate coefficient for organic nitrogen decay to NH <sub>3</sub> , concentration of organic nitrogen, settling rate for organic nitrogen		2,3,16
$\left( \begin{array}{l} \text{Rate of nitrification} \\ \text{of ammonia to nitrate} \end{array} \right) = -KN * NH_4^+ - N$ $g - N / m^3 / \text{day}$	<p><i>KN</i> = nitrification rate coefficient (d<sup>-1</sup>)</p> <p><i>NH<sub>4</sub><sup>+</sup> - N</i> = ammonia conc. (g-N/m<sup>3</sup>)</p> <p><i>AKN</i> = uncorrected rate</p>	The rate of nitrification of ammonia to nitrate			5, 10T, 10DO



<p>where:</p> $KN = AKN \cdot [TH\_KNH3^{(temp-20)}] \cdot \left( \frac{DO}{DO + KON} \right)$	<p>coefficient for nitrification (day<sup>-1</sup>)  <math>TH\_KNH3</math> = temperature coefficient for ammonium oxidation (suggested value is 1.1)  <math>DO</math> = dissolved oxygen conc.  <math>KON</math> = Monod half velocity constant for oxygen limitation of nitrification (g O<sub>2</sub>/m<sup>3</sup>)</p>				
$\left( \begin{array}{l} \text{Rate of Ammonium - N} \\ \text{decrease due to} \\ \text{algal/macrophyte uptake} \\ \text{g - N/m}^3/\text{day} \end{array} \right) = - \left( \frac{NH_4^+ - N}{NH_4^+ - N + NO_3 - N} \right) \cdot (ANCONT \cdot ALGRO + MNCONT \cdot MGRATE)$	<p><math>NH_4^+ - N</math> = concentration of ammonium (g-N/m<sup>3</sup>)  <math>NO_3 - N</math> = concentration of nitrate (g-N/m<sup>3</sup>)  <math>ANCONT</math> = nitrogen to biomass ratio in algae  <math>ALGRO</math> = growth rate of the algae (g/m<sup>3</sup>/day)  <math>MNCONT</math> = nitrogen to biomass ratio in macrophytes  <math>MGRATE</math> = growth rate of the macrophytes (g/m<sup>3</sup>/day)</p>	The rate of ammonia decrease due to algal/macrophyte uptake			6A, 6M, 13nuts
$\left( \begin{array}{l} \text{Benthic rate of ammonium - N} \\ \text{release by sediments} \\ \text{g - N/m}^3/\text{day, KBNNH3} \end{array} \right) = \frac{BENNH3}{H} TH\_BENN^{(T-20)}$	<p><math>BENNH3</math> = benthic release rate g-N/ (m<sup>2</sup>/day)  <math>H</math> = depth (m)  <math>TH\_BENN</math> = temperature coefficient for ammonia release  <math>T</math> = temperature (°C)</p>	The rate of benthic release of ammonia by sediments			15,10T,11

<p>Net rate of accumulation of ammonium g - N/m<sup>3</sup>/day</p> $= (K1N + KDN) \cdot ORGAN$ $- ANCONT \cdot \left(1 - \frac{NH_4 - N}{NH_4 - N + NO_3 - N}\right)$ $\cdot (ALGRO - ALGADK) - MNCONT \cdot \left(1 - \frac{NH_4 - N}{NH_4 - N + NO_3 - N}\right)$ $\cdot (MGRATE - MDEATH) + KBNNH3 - KN \cdot NH_4^+ - N$	<p><b>KBNNH3</b> = rate of benthic release of ammonia by sediments  <b>K1N</b> = temperature and DO corrected rate coefficient for organic-N, day<sup>-1</sup>  <b>ORGAN</b> = concentration of organic nitrogen (g-N/m<sup>3</sup>)  <b>NH<sub>4</sub><sup>+</sup> - N</b> = concentration of ammonium nitrogen (g-N/m<sup>3</sup>)  <b>NO<sub>3</sub> - N</b> = concentration of nitrate nitrogen (g-N/m<sup>3</sup>)  <b>ANCONT</b> = nitrogen to biomass ratio in algae  <b>ALGRO</b> = growth rate of the algae (g/m<sup>3</sup>/day)  <b>MNCONT</b> = nitrogen to biomass ratio in macrophytes  <b>MGRATE</b> = growth rate of the macrophytes (g/m<sup>3</sup>/day)  <b>KDN</b> = temperature corrected rate coefficient for nitrate reduction and anaerobic CBOD oxidation (day<sup>-1</sup>)  <b>KN</b> = nitrification rate coefficient (day<sup>-1</sup>)</p>	<p>The net rate of accumulation of ammonia</p>			<p>3, 5, 6A, 6M, 11, 15, 16</p>
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$\left( \begin{array}{l} \text{Net rate of} \\ \text{accumulation} \\ \text{of nitrate} - N \\ \text{g} - N / m^3 / \text{day} \end{array} \right) = KN * NH_4 - N -$ $(ONEQUI * KDN * CBOD) - (ANCONT * ALGRO +$ $MNCONT * MGRATE) * \left( \frac{NO_3 - N}{NH_4 - N + NO_3 - N} \right) -$ $(KDNO_2 * NO_3 - N)$	<p><i>ONEQUI</i> is a conversion factor coefficient for oxygen to nitrogen equivalents</p> <p><i>KDNO2</i> = sediment denitrification rate (day<sup>-1</sup>)</p> <p><math>NH_4^+ - N</math> = concentration of ammonium nitrogen (g-N/m<sup>3</sup>)</p> <p><math>NO_3 - N</math> = concentration of nitrate nitrogen (g-N/m<sup>3</sup>)</p> <p><i>ANCONT</i> = nitrogen to biomass ratio in algae</p> <p><i>ALGRO</i> = growth rate of the algae (g/m<sup>3</sup>/day)</p> <p><i>MNCONT</i> = nitrogen to biomass ratio in macrophytes</p> <p><i>MGRATE</i> = growth rate of the macrophytes (g/m<sup>3</sup>/day)</p> <p><i>KDN</i> = temperature corrected rate coefficient for nitrate reduction and anaerobic CBOD oxidation (day<sup>-1</sup>)</p> <p><i>KN</i> = nitrification rate coefficient (day<sup>-1</sup>)</p>	The net rate of accumulation of nitrate			4,5,6A, 6M, 10T,10DO,11
<b>Phosphorus Cycle</b>					
$\left( \begin{array}{l} \text{Release of organic P} \\ \text{by algal/macrophyte} \\ \text{decay g} - P / m^3 / \text{day} \end{array} \right) = APCONT \cdot ALGADK + MPCONT \cdot MDEATH$	<p><i>APCONT</i> = phosphorus to biomass ratio in algae</p> <p><i>ALGADK</i> = death rate of algae (g/m<sup>3</sup>/day)</p> <p><i>MPCONT</i> = phosphorus to biomass ratio in macrophytes</p> <p><i>MDEATH</i> = death rate of macrophytes (g/m<sup>3</sup>/day)</p>	The release of organic phosphorus by algae/macrophytes	Monod half velocity constant for oxygen limitation of macrophyte decay, cross sectional area, average dissolved oxygen concentration, depth, width, macrophyte specific decay rate, macrophyte density,	Does not account for particulate-P	3,13nuts

$\left( \text{Loss of org - P due to hydrolysis to phosphate and settling g - P/m}^3/\text{day} \right) = (ORG - P) \cdot \left( KPDK + \frac{KPSET}{H} \right)$	<p><i>ORG - P</i> = organic P concentration (g/m<sup>3</sup>)  <i>KPDK</i> = organic P hydrolysis rate (day<sup>-1</sup>)  <i>KPSET</i> = organic P settling rate (m/day)  <i>H</i> = depth (m)</p>	The loss of organic nitrogen due to hydrolysis to phosphate	specific macrophyte growth rate, hydraulic depth, light extinction coefficient for the particular reach, light intensity (net short-wave radiation) at the water surface, maximum specific		2,3
$\left( \text{Net rate of accumulation of org - P g/m}^3/\text{day} \right) = -(ORG - P) \cdot \left( KPDK + \frac{KPSET}{H} \right) + (APCONT \cdot ALGADK + MPCONT \cdot MDEATH)$	<p><i>ORG - P</i> = organic P concentration (g/m<sup>3</sup>)  <i>KPDK</i> = organic P hydrolysis rate (day<sup>-1</sup>)  <i>KPSET</i> = organic P settling rate (m/day)  <i>H</i> = depth (m)  <i>APCONT</i> = P to biomass ratio in algae  <i>ALGADK</i> = death rate of algae (g/m<sup>3</sup>/day)  <i>MPCONT</i> = phosphorus to biomass ratio in macrophytes  <i>MDEATH</i> = death rate of macrophytes (g/m<sup>3</sup>/day)</p>	The net rate of accumulation of organic phosphorus	algal decay rate, algal concentration, half velocity constant relating phosphate concentration to algal growth rate, phosphate concentration, half velocity constant relating inorganic nitrogen to algal growth, nitrate + ammonia concentration, light growth adjustment factor, maximum specific growth rate, phosphorus to biomass ratio in algae, phosphorus to biomass ratio in macrophytes		2,3,13nuts
$\left( \text{Uptake of phosphate - P by algal/macrophyte growth g - P/m}^3/\text{day} \right) = -APCONT \cdot ALGRO - MPCONT \cdot MGRATE$	<p><i>APCONT</i> = phosphorus to biomass ratio in algae  <i>ALGRO</i> = growth rate of algae (g/m<sup>3</sup>/day)  <i>MPCONT</i> = phosphorus to biomass ratio in macrophytes  <i>MGRATE</i> = growth rate of macrophytes (g/m<sup>3</sup>/day)</p>	The uptake of phosphate by algae/macrophytes	to biomass ratio in macrophytes, organic P concentration, organic P hydrolysis rate, organic P settling rate, benthic release rate, temperature coefficient for phosphate release, phosphate loss rate, temperature coefficient for		6A, 6M, 13nuts
$\left( \text{Benthic rate of Phosphate - P release by sediments g - P/m}^3/\text{day, KBENPO4 and loss due to decay} \right) = \frac{BENPO4}{H} \cdot TH\_BENPO4^{(T-20)} - APO4 \cdot TH\_SORP^{(TEMP-20)} \cdot OPO4$	<p><i>BENPO4</i> = benthic release rate (g-P/ (m<sup>2</sup> day))  <i>H</i> = depth (m)  <i>TH\_BENPO4</i> = temperature coefficient for phosphate release  <i>T</i> = temperature (°C)  <i>APO4</i> = phosphate loss</p>	The rate of benthic release of phosphate	phosphate sorption or loss, phosphate concentration		15, 10T, 12, 11

	<p>rate (1/day)</p> <p><math>TH\_SORP</math> =</p> <p>temperature coefficient for phosphate sorption or loss</p> <p><math>TEMP</math> = temperature (°C)</p> <p><math>OPO4</math> = phosphate concentration (mg/L)</p>				
<p>(Net rate of accumulation of phosphorus P g - P/m<sup>3</sup>/day)</p> $= ORG - P \cdot KPDK + KBENPO4$ $- (APCONT \cdot ALGRO + MPCONT \cdot MGRATE)$ $- APO4 \cdot TH\_SORP^{(TEMP-20)} \cdot OPO4$	<p><math>APO4</math> = phosphate loss rate (1/day)</p> <p><math>KPDK</math> = organic P hydrolysis rate (day<sup>-1</sup>)</p> <p><math>ORG - P</math> = organic P concentration (g/m<sup>3</sup>)</p> <p><math>TH\_SORP</math> =</p> <p>temperature coefficient for phosphate sorption or loss</p> <p><math>TEMP</math> = temperature (°C)</p> <p><math>OPO4</math> = phosphate concentration (mg/L)</p> <p><math>APCONT</math> =</p> <p>phosphorus to biomass ratio in algae</p> <p><math>ALGRO</math> = growth rate of algae (g/m<sup>3</sup>/day)</p> <p><math>MPCONT</math> =</p> <p>phosphorus to biomass ratio in macrophytes</p> <p><math>MGRATE</math> = growth rate of macrophytes (g/m<sup>3</sup>/day)</p>	The net accumulation of phosphorus			3, 6A, 6M, 11, 12, 13nuts, 15
<b>Algae/Macrophyte Cycle</b>					
<p><math>ALGRO = C(12, I) \cdot ALG1 \cdot FL \cdot FN \cdot FP</math></p> <p>where:</p> $FL = \frac{1}{KEXT * H}$	<p><math>ALGRO</math> = algal growth rate corrected for light, temperature, and nutrient availability (g-biomass/m<sup>3</sup> day<sup>-1</sup>)</p> <p><math>C(12, I)</math> = algal concentration at node I at time t (g-biomass/m<sup>3</sup>)</p> <p><math>ALG1</math> = maximum specific growth rate (day<sup>-1</sup>)</p> <p><math>FL</math> = light growth adjustment factor</p>	The growth rate of the algae			6A, 13sun, 13nuts

	<p><math>FN</math> = nitrogen growth adjustment factor</p> <p><math>FP</math> = phosphorus growth adjustment factor</p> <p><math>KEXT</math> =light extinction coefficient, m<sup>-1</sup>, corrected for algal self-shading</p> <p><math>H</math> = hydraulic depth</p>				
$FN = \frac{NPOOL}{(NPOOL + KNPOOL)}$	<p><math>FN</math> = N growth adjustment factor</p> <p><math>NPOOL</math> = nitrate + ammonia concentration (g/m<sup>3</sup>)</p> <p><math>KNPOOL</math> = half velocity constant relating inorganic nitrogen to algal growth (g/m<sup>3</sup>)</p>	Calculation of the nutrient adjustment factor for nitrogen			6A, 13nuts
$FP = \frac{PO_4}{(PO_4 + KPO_4X)}$	<p><math>FP</math> = phosphorus growth adjustment factor</p> <p><math>PO_4</math> = phosphate conc. (g/m<sup>3</sup>)</p> <p><math>KPO_4X</math> = half velocity constant relating phosphate concentration to algal growth rate (g/m<sup>3</sup>)</p>	Calculation of the nutrient adjustment factor for phosphorus			6A, 13nuts
$(ALGADK) = C(12, I) \cdot KALGDK \cdot \left( \frac{DO}{DO + KOALDK} \right)$	<p><math>ALGADK</math> = algal decay rate g/(m<sup>3</sup>/day)</p> <p><math>C(12, I)</math> = algal concentration at node i (g/m<sup>3</sup>)</p> <p><math>KALGDK</math> = maximum specific algal decay rate (day<sup>-1</sup>)</p> <p><math>DO</math> = dissolved oxygen concentration</p> <p><math>KOALDK</math> = DO half velocity constant for algal decay (g/m<sup>3</sup>)</p>	The algae respiration and death rate			3, 10DO

$MGRATE = \frac{B \cdot MACRO \cdot SWALG \cdot e^{(-KEXT \cdot H)}}{A}$ $+ \left( \frac{2}{KEXT \cdot A} \right) \cdot MACRO \cdot SWALG \cdot [1 - e^{(-KEXT \cdot H)}]$	<p><b>MGRATE</b> = net macrophyte growth along the channel</p> <p><b>B</b> = stream top width (m)</p> <p><b>MACRO</b> is MACGRO (m<sup>2</sup>/watt/day)*MACROB (g/m<sup>2</sup>) (g/watt*day)</p> <p><b>SWALG</b> = light intensity (net short-wave radiation) at the water surface (watt/m<sup>2</sup>)</p> <p><b>A</b> = channel cross sectional area (m<sup>2</sup>)</p> <p><b>KEXT</b> = light extinction coefficient for the particular reach (m<sup>-1</sup>)</p> <p><b>H</b> = hydraulic depth (m)</p> <p><b>MACROB</b> = macrophyte surface density (g/m<sup>2</sup>)</p> <p><b>MACGRO</b> = specific macrophyte growth rate (m<sup>2</sup> W<sup>-1</sup> day<sup>-1</sup>)</p>	<p>Is the net macrophyte growth rate along the channel</p>			6M, 13sun
$MDEATH = MACROB \cdot MACDKY \cdot TH\_MDIE^{(TEMP-20)}$ $\cdot (B(I) + 2H) \cdot A(I) \cdot \frac{DOX}{1 + KOALDK}$	<p><b>MDEATH</b> = macrophyte decay rate (g/m<sup>3</sup>/day)</p> <p><b>MACROB</b> = macrophyte density (g/m<sup>2</sup>)</p> <p><b>MACDKY</b> = macrophyte specific decay rate (day<sup>-1</sup>)</p> <p><b>TH\_MDIE</b></p> <p><b>TEMP</b></p> <p><b>B</b> = width (m)</p> <p><b>H</b> = depth (m)</p> <p><b>A</b> = cross sectional area (m<sup>2</sup>)</p> <p><b>DOX</b> = average dissolved oxygen concentration (g/m<sup>3</sup>)</p> <p><b>KOALDK</b> = Monod half velocity constant for oxygen limitation of macrophyte decay (g/O<sub>2</sub>/m<sup>3</sup>)</p>	<p>Is the rate of macrophyte decay due to respiration and death</p>			3, 10T, 10DO

Model Name	Language	Output
EPD-RIV1	FORTRAN	For each reach, predicted concentrations of BOD, Organic-N, NH3, NO3, TN, Organic-P, PO4, TP, DO, Algal biomass and growth and death rate, macrophyte growth and death rate, BOD decay rate, Chlorophyll-a

References:

Martin, J. L., Wool, T. (2002). A dynamic one-dimensional model of hydrodynamics and water quality- EPD RIV1 version 1.0 User's manual. Prepared for Roy Burke III from the Georgia Environmental Protection Division, Atlanta, Georgia, BY.



EFDC1D	Parameters	Purpose of equation	Calibration requirements	Issues	Reference number from Table 1
$\partial_t(AC) + \partial_x(QC) = \partial_x(AD_C \partial_x C) + q_L C_L + q_T C_T + q_S C_S + W_B J_{CB} - W_s J_{CS}$	<p>C = concentration  A = cross-section area  Q = discharge  C<sub>L</sub> = concentration of lateral runoff inflow  C<sub>S</sub> = concentration associated with pore water component of water column-sediment bed exchange  C<sub>T</sub> = concentration of tributary inflow  D<sub>C</sub> = longitudinal dispersion coefficient  W<sub>S</sub> = surface width of channel  W<sub>B</sub> = bed depositional width of channel  J<sub>CS</sub> = surface outflux of C  J<sub>CB</sub> = bed influx of C  q<sub>L</sub> = lateral runoff per unit channel length  q<sub>S</sub> = rate of change of cross-sectional area due to sediment bed resuspension and deposition  q<sub>T</sub> = tributary inflow per unit channel length</p>	Advection equation	concentration of solutes from upstream, tributaries, lateral flows, channel dimensions, flow velocity		1, point and non point sources
Non cohesive suspended sediments					

$\frac{w_{soj}}{\sqrt{g'd_j}} = \begin{cases} \frac{R_{dj}}{18} : d_j \leq 100\mu m \\ \frac{10}{R_{dj}} (\sqrt{1+0.01R_{dj}} - 1) : 100 \leq d_j \leq 1000\mu m \\ 1.1 : d_j > 1000\mu m \end{cases}$ <p>where:</p> $g' = g \left( \frac{\rho_{sj}}{\rho_w} - 1 \right)$ $R_{dj} = \frac{d_j \sqrt{g'd_j}}{v}$	<p>w<sub>soj</sub>=settling velocity of a discrete particle d=sediment diameter g=gravity g'=reduced gravitational acceleration R<sub>dj</sub>=sediment grain densimetric Reynolds number ρ<sub>sj</sub>=density of particle size j ρ<sub>w</sub>=density of water j=non-cohesive sediment class v= kinematic molecular viscosity of water w<sub>sj</sub>=settling velocity n=2-4 S<sub>i</sub>=sediment concentration θ<sub>csj</sub>=empirical value of critical stress of sediment τ<sub>csj</sub>=critical stress τ<sub>b</sub>=bed stress u*<sub>csj</sub>=bed critical shear velocity u*=bed shear velocity</p>	Equation to determine settling at low concentrations	Sediment particle diameter, sediment particle density, kinematic molecular viscosity of water, critical shear stress, bed shear stress	The bed transport equations have not been included.	2, 14PS,14D, 14F
$w_{sj} = \left( 1 - \sum_i \frac{S_i}{\rho_{si}} \right)^n w_{soj}$		Equation to determine settling at high concentrations			
$\theta_{csj} = \begin{cases} 0.24(R_{dj}^{2/3})^{-1} : R_{dj}^{2/3} < 4 \\ 0.14(R_{dj}^{2/3})^{-0.64} : 4 \leq R_{dj}^{2/3} < 10 \\ 0.04(R_{dj}^{2/3})^{-0.1} : 10 \leq R_{dj}^{2/3} < 20 \\ 0.013(R_{dj}^{2/3})^{0.29} : 20 \leq R_{dj}^{2/3} < 150 \\ 0.055 : R_{dj}^{2/3} \geq 150 \end{cases}$ $\theta_{csj} = \frac{\tau_{csj}}{g'd_j}$		Range of equations to determine critical stress of sediment at different particle size and density.			14PS, 14F
$u^*_{csj} = \sqrt{\tau_{csj}} = \sqrt{g'd_j \theta_{csj}}$		Calculation of bed critical shear velocity from critical stress.			14F
$u^* = \sqrt{\tau_b}$		Calculation of bed shear velocity from bed stress.			14F

$u_{csj}^* < u^* < w_{soj}$		The relationship between critical shear stress, bed shear stress and settling.			14F
When bed velocity is less than critical stress velocity, no erosion or resuspension takes place and sediment in suspension under this condition will deposit to the bed. When the bed shear velocity exceeds the critical shear velocity but remains less than the settling velocity sediment will be eroded from the bed and transported as bed load. Sediment in suspension under this condition will deposit to the bed. When the bed shear velocity exceeds both the critical shear velocity and the settling velocity, bed load transport ceases and the eroded or resuspended sediment will be transported as suspended load.					
$J_{CB} = J_{SB} = w_s \left( \frac{2(1+R)}{2+R(1-z_{eq})} \right) \bar{S}_{eq}$ $R = \frac{w_s}{u^* \kappa}$	R=Rouse parameter $u^*$ =shear velocity $\kappa$ =von Karman's constant $z_{eq}$ =dimensionless vertical coordinate varying 0 at bed to 1 at surface (at equilibrium) $w_s$ =settling velocity $\bar{S}_{eq}$ =mean suspended solid concentration at height $z_{eq}$ . $J_{SB}$ =sediment bed flux	Near bed equilibrium sediment concentration	settling velocity, von Karman's constant.		2, 14F
<b>Cohesive suspended sediment concentrations</b>					
$J_0^d = \begin{cases} -w_s S_d T_d : \tau_b \leq \tau_{cd} \\ 0 : \tau_b \geq \tau_{cd} \end{cases}$ $T_d = \left( \frac{\tau_{cd} - \tau_b}{\tau_{cd}} \right)$	$J_0^d$ =depositional flux $\tau_b$ =stress exerted by flow on bed $\tau_{cb}$ =critical stress for deposition $S_d$ =near bed depositing sediment concentration	Equation to calculate depositional flux for cohesive sediments	critical depositional stress, near bed depositing sediment concentration, settling velocity		2, 14F

$J_{CB} = J_{SB} = - \left( T_d + \frac{\ln(z_d^{-1})}{(z_d^{-1} - 1)} (1 - T_d) \right)^{-1} w_s \bar{S} : R = 1$ $J_{CB} = J_{SB} = - \left( T_d + \frac{((z_d^{-1})^{1-R} - 1)}{(1 - R)(z_d^{-1} - 1)} (1 - T_d) \right)^{-1} w_s \bar{S} : R \neq 1$	J <sub>SB</sub> =sediment bed flux z <sub>d</sub> =dimensionless vertical coordinate varying 0 at bed to 1 at surface subscript d = deposition $\bar{S}$ =mean suspended solid concentration w <sub>s</sub> =settling velocity	Equation to measure total sediment flux.			2, 14F
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Model Name	Language	Output
EDFDC1D	FORTRAN	concentration of non-cohesive and cohesive sediments

#### References

Hamrick, J.M. 2001. EDFDC1D: A One-Dimensional Hydrodynamic and Sediment Transport Model for River and Stream Networks. Model Theory and User's Guide. Technical Report EPA/600/R-01/073, U.S. EPA National Exposure Research Laboratory, Athens, Washington, DC.