

Development of Nutrient Sub-Modules for Linkage with Hydraulic and Hydrologic Modeling Systems

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Cover Figure: Agricultural Field

Introduction

The concept of watershed planning is not new to the U.S. Army Corps of Engineers. Throughout its history, the Corps has incorporated watershed planning into the process by which it manages water resource systems. Even the Corps geographic organization, along watershed boundaries rather than State and County lines in most cases, supports the historic understanding of the need to manage water within a watershed context. However, this understanding and organizational concept alone are not sufficient to ensure proper protection and responsible development of the Nation's water resources in the future.

This country is facing a looming water crisis. It is seeing frequent regional droughts, disputes over allocation brought on by growing population demands, environmental degradation due to changing land uses, and widespread disagreement over competing purposes for water resources use. The problems of rapid growth in certain areas are worse because responsibilities to address water needs are distributed among a multitude of government agencies and private companies, so the problem solving efforts are typically fragmented. The results are predictable: instead of broadly supported regional solutions that address multiple needs, balance competing uses, and can be quickly implemented, we get narrowly focused, contentious and slowly implemented, uncertain and expensive, inferior solutions. For several years, the Nation's priorities and values related to water resources have been changing. This is a natural evolution resulting from advances in scientific knowledge, public reaction to that increase in knowledge, and an unprecedented national prosperity that allows us to consider more than the short term basics of life.

Unlike the single purpose, project driven initiatives that the Corps has been directed to accomplish in the past, the perspective of this new watershed approach is based on multi-purpose, multi-objective management, examining all water needs in the watershed and receiving waterbodies. With this broader context, watershed partners would collaborate to simultaneously address multiple objectives - environmental quality, social effects, and national and regional economic development.

In support of the Corps watershed approach, the System Wide Water Resources Research Program (SWWRP) was designed to assemble and integrate the diverse components of water resources management. Products from this program are designed to help users surpass individual project level analysis, and apply current and improved technologies for multi-disciplinary system-wide assessments. The ultimate goal, of SWWRP, is to provide the Corps, its partners, and stakeholders, the overall technological framework and analytical tools to restore and manage water resources and balance human development activities with natural system requirements.

Within SWWRP, multiple riverine, estuarine, watershed, and subsurface flow models are being modified to address issues of environmental concern. Several integration approaches are either ongoing or proposed to accomplish this task. To have a

full system-wide water quality and contaminant capability in SWWRP, the different hydrologic and hydraulic engines must utilize a common water quality and contaminant approach to prevent the arbitrary partitioning of constituents. The goal of this development effort is to upgrade existing hydrologic and hydraulic models (i.e., water engines) using a common water quality approach in order to facilitate their linkage and application on a system wide basis.

In keeping with a common water quality approach to model development, a library of water quality kinetics is being developed and integrated within a variety of water transport engines. The library of algorithms are able to deal with a multi-species, multi-phase, multi-reaction system, and includes both fast (equilibrium-based) and slow (non-equilibrium-based or rate-based) reactions, is easily extensible to new reaction pathways, includes both common nutrient and contaminant packages, and has a simple, well-defined data interface and calling procedure, making them portable. The modules are developed such that they are data structure independent thus facilitating their integration into a wide range of modeling systems.

As research and development continues, it is anticipated that additional and improved process descriptions will be developed and as such will be integrated into the Nutrient Sub-Module (NSM) for dissemination to a number of modeling systems (Johnson and Gerald, 2006).

Soil Nutrient Processes

The complexity of nutrient transformations and transport in watershed systems has led to the use of both conceptual and mechanistic models for their description. Modeling of nutrients in the watershed consists of three distinct parts. The first part deals with simulating most of the nutrient transformations and movements in the soil nutrient cycle, whereas the second part focuses on the transport and transformation of nutrients in the overland flow. The third part simulates nutrient in-stream transport and transformation processes. The distribution of soil nutrient within a watershed can provide clues as to how nutrients are transported from soil to stream. The Nutrient Sub-Module has been developed such that it simulates the nutrient processes, in soil, overland flow and stream, for multiple species and phases.

Soil Nitrogen Cycle

Of all the mineral nutrients, N has the most complex nutrient cycle, Figure 1, largely because N can exist as a gas (both ammonia and nitrogen gas), whereas the other mineral nutrients do not exist as gases under normal soil conditions. To help understand the various components of the N cycle, definitions and molecular formulas of the numerous N forms are provided in Table 1 (Neitsch et al., 2002).

Table 1: Definitions of each N form

Nitrogen Form	Molecular Formula	Notes
Nitrogen gas	N_2 (g)	-
Ammonia gas	NH_3 (g)	-
Ammonium	NH_4^+	Plant available, attracted to exchange sites on clay particles
Nitrate	NO_3^-	Very mobile, requires more energy by plant than ammonium
Nitrite	NO_2^-	Mobile, generally low concentrations
Organic N	-	Slowly supplies available N to soil solution

Nitrogen exists in a number of chemical forms and undergoes chemical and biological reactions. Unlike other nutrients, only a small amount of N is contributed from the mineral part of the soil (i.e., rocks). Most naturally occurring N enters the soil either as NO_3^- or NH_4^+ in rainfall (atmospheric deposition) or by special plants, such as alfalfa, ceanothus, and red alder, that are called "nitrogen fixers". Humans also increase the N in soils by fertilizing with either chemical or organic fertilizers. Once in the soil, the N will transform through the processes of mineralization, immobilization, volatilization, nitrification, denitrification, plant uptake, and sorption. Two of these transformations—volatilization and denitrification—result in losses of N from the soil. N is also lost through leaching and runoff. Because most of the transformations and losses are caused by microbial action, all the processes are slowed down considerably when temperatures are low.

The basic concept in the soil N module is the mass balance which was employed to formulate governing equations for each of the soil N state variables (Figure 1). Soil N state variables simulated in NSM in each soil layer include:

1. Fresh Organic N ($orgN_{frs}$)
2. Active Organic N ($orgN_{act}$)
3. Stable Organic N ($orgN_{sta}$)
4. Ammonium N (NH_4^+)
5. Sorbed Ammonium N (PNH_4^+)
6. Nitrate N (NO_3^-)

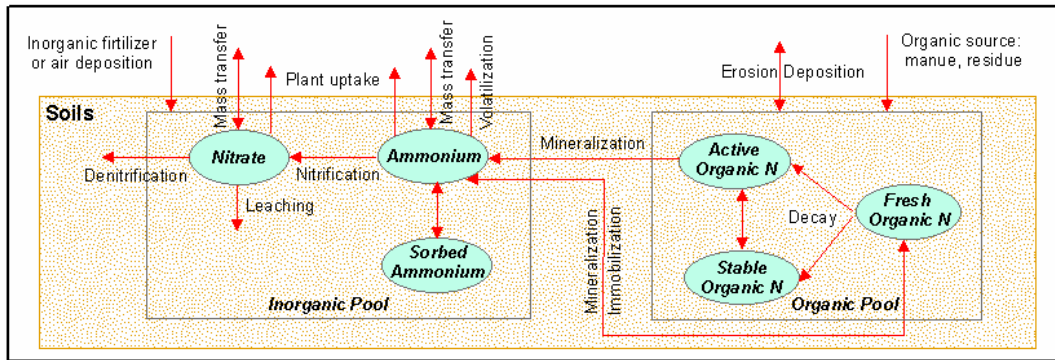


Figure 1: NSM soil nitrogen cycle

Soil Phosphorus Cycle

Phosphorus can exist in the soil as phosphate (HPO_4^{-2} or $H_2PO_4^{-}$), particulate P, organic P, or in P minerals. Phosphate is the only form that plants can take up, yet in most agricultural soils there is less than 1 mg/L (ppm) of phosphate in solution, which represents much less than 1% of the total soil P. Organic P, which is P bound in organic matter, has been found to represent between about 25% and 65% of total P in surface soils, with mineral P (such as calcium phosphate minerals) and sorbed P, representing the remainder (Brady, 1984).

Phosphorus is generally much less mobile than N, being strongly adsorbed to soil particles as well as organic matter. Figure 2 shows the major components of the Soil P cycle. Soil P is divided into an organic and mineral component that can receive inputs via inorganic fertilizers, organic manure, waste, and sludge. Organic P in the soil is divided into three pools: the fresh organic P pool ($orgP_{frs}$), the active organic P pool ($orgP_{act}$) and the stable organic P pool ($orgP_{sta}$). The $orgP_{frs}$ represents the organic matter that can be easily mineralized (e.g. manures, decayed plants, and microbial biomass). The $orgP_{act}$ constitutes materials with slower rate of mineralization, whereas $orgP_{sta}$ is composed of P in stable organic matter i.e. humus. Organic pools are differentiated on the basis of C:P ratios. Inorganic P is divided into labile (soluble) inorganic P (P_{sol}), active inorganic P ($minP_{act}$) and stable inorganic P ($minP_{sta}$) pools. P_{sol} is in rapid equilibrium with $minP_{act}$ which in return is in slow equilibrium with $minP_{sta}$. When inorganic fertilizer P is added, it rapidly equilibrates between P_{sol} and $minP_{act}$. The slow reaction between $minP_{act}$ and $minP_{sta}$ then follows. The six soil P forms simulated by NSM for each soil layer are:

1. Fresh Organic P ($orgP_{frs}$)
2. Active Organic P ($orgP_{act}$)
3. Stable Organic P ($orgP_{sta}$)
4. Labile (Soluble) Inorganic P (P_{sol})
5. Active Inorganic P ($minP_{act}$)
6. Stable Inorganic P ($minP_{sta}$)

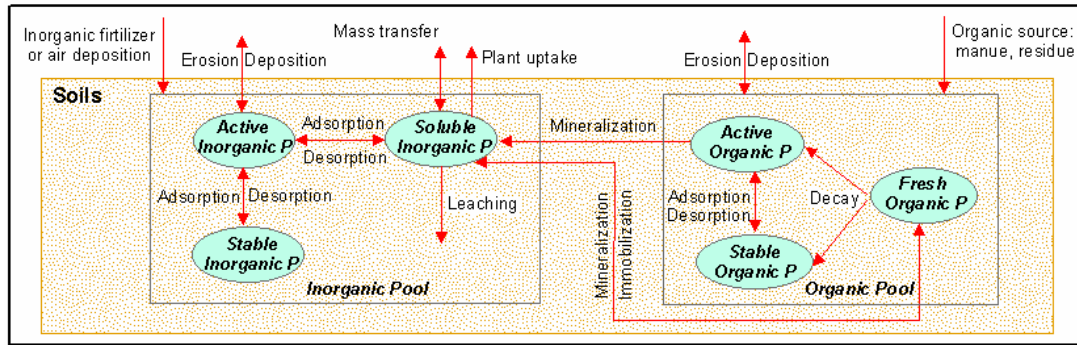


Figure 2: NSM soil phosphorus cycle

The P transformations in soils involve complex mineralogical, chemical, and biological processes. Main transformation processes in the soil include decomposition and mineralization of organic P, immobilization of labile P and sorption of labile P to/from soil particles. P dissolved in soil water and P adsorbed to soil particles can be transported to surface water. Microorganisms deeply affect soil P transformation through mineralization-immobilization processes. The knowledge of P transformations is essential to understand the P behavior in soils.

Overland Flow Nutrient Processes

Nutrient storage in the soil occurs primarily in the uppermost few centimeters where it is accessible to shallow-rooted vegetation. Surface water fluxes interact with this layer and can dissolve some of the soluble nutrient stores, as well as causing erosion of the organic and adsorbed stores. Water serves as a solvent and physical/chemical transport medium for dissolved and particulate materials and thus overland flow can be an important mechanism of nutrient transport from soils to streams (Sharpley et al., 1992; Goulding et al., 1996).

Overland Nitrogen Transformation and Transport

Surface runoff can remove large quantities of nutrients from the soil in both dissolved and particulate forms. In the case of N, the dissolved inorganic component is further discriminated into of NO_3^- and NH_4^+ . The loss of dissolved nutrients in surface runoff is the result of rainfall mixing with the dissolved nutrients in the upper portion of the soil that interacts with surface runoff and once in water, they are transported. Suspended nutrients, which are assumed to be either organic or adsorbed inorganic components, attach to eroded sediment material derived from erosion or from bed erosion in the stream channel, and are transported with water. The concentration of suspended nutrients in overland flow is largely determined by soil texture, infiltration rate, rainfall intensity, slope, and ground cover. However, the high degree of temporal and spatial variability in the distribution of surface runoff makes it difficult to conduct studies on nutrient transport by this process. Some of the challenges in conducting nutrient mass balance studies are in determining the unmeasured amounts of nutrients removed

from the water and stored in aquatic organisms and sediments, and nutrients added to the water from resuspension, erosion, and dissolution processes.

A diagrammatic representation of the overland flow N storages and fluxes modeled in NSM is shown in Figure 3. Within the model the following overland flow N state variables may be simulated:

1. Particulate Organic Nitrogen (*PON*)
2. Dissolved Organic Nitrogen (*DON*)
3. Particulate Ammonium Nitrogen (PNH_4^+)
4. Ammonium Nitrogen (NH_4^+)
5. Nitrate Nitrogen (NO_3^-)

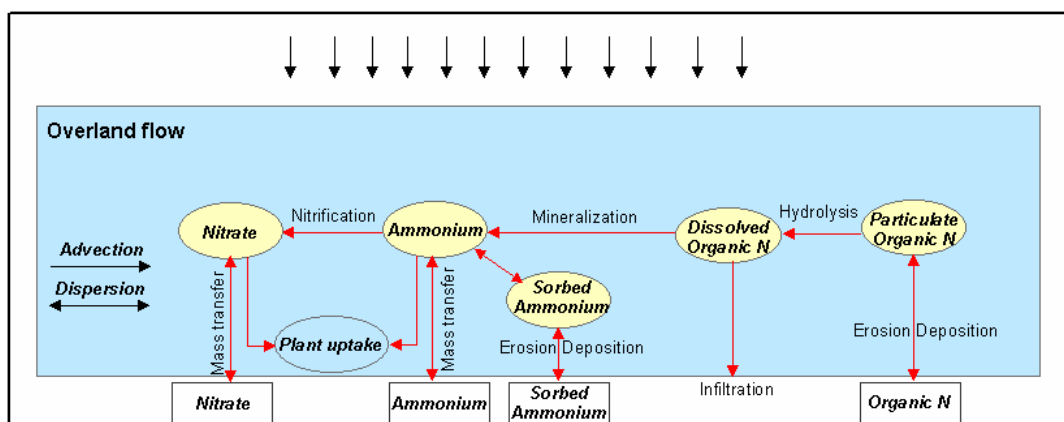


Figure 3: Overland nitrogen transformation and transport

Overland Phosphorus Transformation and Transport

Unlike N which is highly mobile, P solubility is limited in most environments. P combines with other ions to form a number of insoluble compounds that precipitate out of solution. These characteristics contribute to a build up of P near the soil surface that is readily available for transport in surface runoff. In addition to precipitating, P adsorbs to soil particles and can be transported via soil erosion. Sharpley and Syers (1979) observed that surface runoff is the primary mechanism by which P is exported from most watersheds. P movement in runoff occurs as particulate P and dissolved P. Particulate P is attached to mineral and organic sediment as it moves with the runoff. Dissolved P is in the water solution. In terms of their impact on eutrophication of water bodies, particulate P becomes less available to algae and plant uptake than dissolved P because of the chemical form it has with the mineral (particularly iron, aluminum, and calcium) and organic compounds. Dissolved P is readily available for plants, and consists of inorganic orthophosphate ($H_2PO_4^-$, HPO_4^{2-} , PO_4^{3-}) and organic phosphorus-containing compounds. The movement of dissolved P begins with the sorption, dissolution, and extraction of P from the soil, plant, and organic material. These processes occur when rain and runoff water interact with the upper soil layer. Some water infiltrates into the soil and

percolates through the profile where desorption of P will result in a low dissolved concentration in subsurface and return flow. High dissolved P concentration can be expected in the water percolating through organic, coarse-textured, and oxygen depleted, water-logged soils. The particulate P consists of organic P (POP), mineral P and phosphate adsorbed on mineral surfaces. Particulate P can be found in suspension or on the sediment. The adsorption and desorption of phosphate from mineral surfaces forms a buffering mechanism that regulates dissolved phosphate concentrations in waterbodies.

A diagrammatic representation of the overland flow P storages and fluxes modeled in NSM is shown in Figure 4. Within the model the following overland flow P state variables may be simulated:

1. Particulate Organic Phosphorus (*POP*)
2. Dissolved Organic Phosphorus (*DOP*)
3. Particulate Inorganic Phosphorus (*PIP*)
4. Dissolved Inorganic Phosphorus (*DIP*)

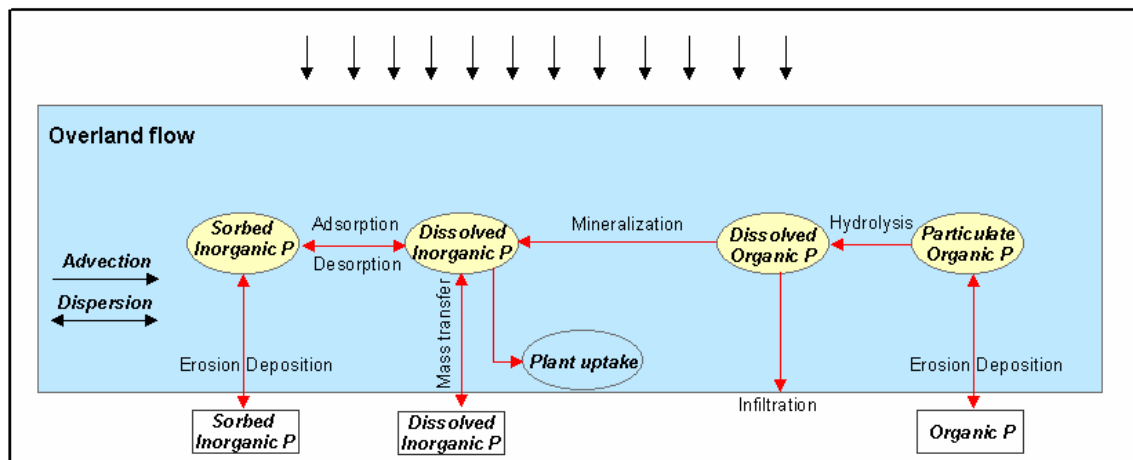


Figure 4: Overland phosphorus transformation and transport

Plant Dynamics

In order to accurately simulate the removal of water and nutrients from the root zone, transpiration, and biomass/yield production, a plant dynamics module has been developed. The plant dynamic algorithms have been taken from the SWAT/EPIC model, (Neitsch et al., 2002) as well as selected process descriptions from the Ecological Dynamic Simulation (EDYS) model (Childress et al., 2002).

The process descriptions utilize a single plant growth model to simulate all types of land covers. The algorithms are able to differentiate between annual and perennial plants. Annual plants grow from the planting date to the harvest date or until the accumulated heat units equal the potential heat units for the plant. Perennial plants maintain their root systems throughout the year, becoming dormant in the winter months.

They resume growth when the average daily air temperature exceeds the minimum, or base, temperature required.

For each increment of time, potential plant growth, i.e. plant growth under ideal growing conditions, is calculated. Ideal growing conditions consist of adequate water and nutrient supply and a favorable climate. In order to more realistically simulate plant growth, a number of stress factors are also considered: 1) Water Stress; 2) Temperature Stress; 3) Nitrogen Stress; and 4) Phosphorus Stress.

Channel Nutrient Processes

The in-stream nutrient transformation processes formulations, that follow, are adapted, in part, from the QUAL2E, QUAL2K, CE-QUAL-RIV1 (RIV1), CE-QUAL-W2 (W2), and CE-QUAL-ICM (ICM) models. Both QUAL2 and RIV1 are one-dimensional (1D) comprehensive stream water quality models. W2 is a water quality and hydrodynamic model in 2D (longitudinal-vertical) for rivers, estuaries, lakes, reservoirs and river basin systems (Cole and Wells, 2003). W2 models basic eutrophication processes such as temperature-nutrient-algae-dissolved oxygen-organic matter and sediment relationships. ICM is a finite volume eutrophication model that can be used to simulate 1-, 2-, 3-dimensional water quality variables including multiple forms of algae, carbon, nitrogen, phosphorus, and silica; and dissolved oxygen (Cercio and Cole, 1995). QUAL and similar 1D models lack a clear operational definition of water quality parameters within the model. For example, it is known that there are many forms of organic N present in natural waters. QUAL2 combines it all under 'organic N' and does not specify further whether it is TON, Kjeldahl N, particulate, dissolved, or other. In contrast, the ICM model contains a precise specification of the N, P and C variables. Since ICM contains more processes, it also contains more parameters. Only the most important in-stream nutrient processes are considered in the current NSM. The model was simplified on the basis of selecting the most dominant biochemical processes that may occur in the river under consideration. Improvements will be made in the future as better means of describing the aquatic ecosystem in mathematical terms and time for incorporating the changes into the model become available. Within the model the following in-stream nutrient state variables may be simulated:

1. Nitrate Nitrogen (NO_3^-)
2. Ammonium Nitrogen (NH_4^+)
3. Particulate Ammonium Nitrogen (PNH_4^+)
4. Dissolved Organic Nitrogen (DON)
5. Particulate Organic Nitrogen (PON)
6. Dissolved Inorganic Phosphorus (DIP)
7. Particulate Inorganic Phosphorus (PIP)
8. Dissolved Organic Phosphorus (DOP)
9. Particulate Organic Phosphorus (POP)
10. Dissolved Inorganic Carbon (DIC)

11. Dissolved Organic Carbon (*DOC*)
12. Particulate Organic Carbon (*POC*)
13. Dissolved Oxygen (*DO*)
14. Phytoplankton group (*A_p*)

Additional state variables such as benthic algae, zooplankton will be added in the future version. These model state variables can then be used to compute the following composite variables:

1. Total Nitrogen (TN)
2. Total Kjeldahl Nitrogen (TKN)
3. Total Phosphorus (TP)
4. Total Organic Carbon (TOC)
5. Ultimate Carbonaceous BOD (CBOD)

Channel Nitrogen Kinetics

Nitrogen is transported into stream systems from airborne, land surface, underground, and in situ sources. Much of the N entering streams is transported with eroded sediments and SOM and dissolved in surface runoff. The N forms commonly found in river water are: NO_3^- , NO_2^- , NH_4^+ , DON, and PON (Meybeck, 1982). These forms are reactive in the framework of the N cycle. The N cycle includes the additional processes of denitrification, nitrification and N_2 fixation that are not in the carbon and phosphorus cycles. NO_2^- concentrations are not tracked by the model because the amount of NO_2^- present in the stream is usually very small relative to NO_3^- . A schematic process representation of in-stream N dynamics modeled in NSM is illustrated in Figure 5, where the system is represented as two compartments. The main processes involved in nitrogen transformations in the sediments and water column are:

- Mineralization of DON to NH_4^+
- Nitrification of NH_4^+ to NO_3^-
- Biological uptake of NH_4^+ and NO_3^- by phytoplankton and algae
- Biological respiration of NH_4^+ by phytoplankton and algae
- Dissolved sediment fluxes of NH_4^+ , NO_3^- , and DON
- Adsorption/desorption of NH_4^+ onto suspended sediments
- Hydrolysis of PON to DON
- Biological mortality and excretion into the DON and PON pools
- Settling/resuspension of PON and sediment attached inorganic N.

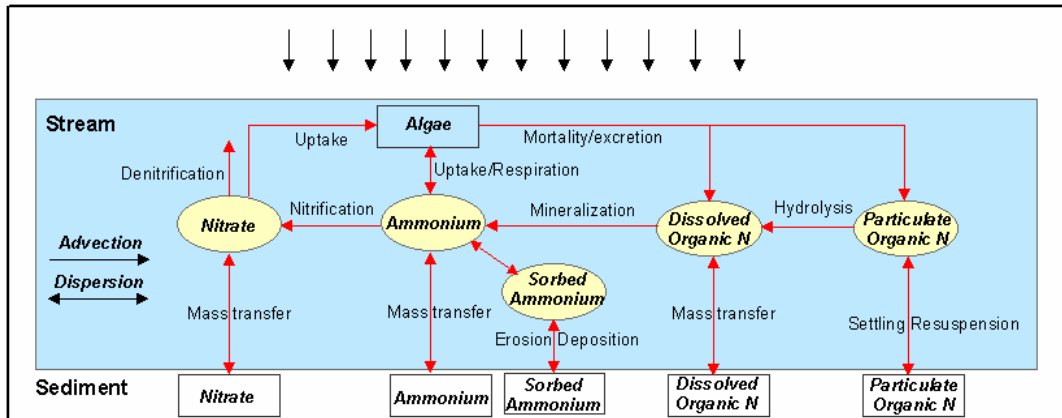


Figure 5: Schematic representation of in-stream nitrogen dynamics

Channel Phosphorus Kinetics

In contrast to nitrogen and carbon, there is no gaseous atmospheric source. P enters rivers primarily as particulate matter and secondarily as DIP also known as “ortho-P” (H_3PO_4 and its conjugate base forms). The phosphorus forms simulated in NSM are DIP, DOP, and POP. A schematic process representation of in-stream P dynamics modeled in NSM is illustrated in Figure 6, where the system is represented as two compartments. The main processes involved in phosphorus transformations in the sediments and water column are:

- Mineralization of DOP to DIP
- Biological uptake and respiration of DIP by phytoplankton and algae
- Dissolved sediment fluxes of DIP and DOP
- Adsorption/desorption of DIP onto suspended sediments
- Hydrolysis of POP to DOP
- Biological mortality and excretion into the DOP and POP pools
- Settling/resuspension of POP and PIP.

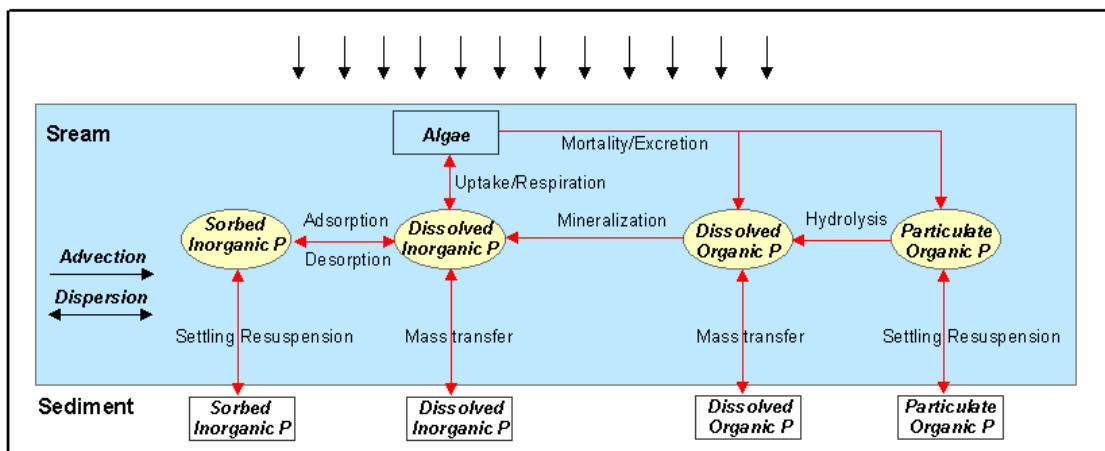


Figure 6: Schematic representation of in-stream phosphorus dynamics

Channel Dissolved Oxygen Kinetics

DO concentration is generally viewed as an indicator of the overall well-being of streams and their associated ecosystems. DO dynamics include atmospheric exchange, the sediment oxygen demand (SOD), microbial use during organic matter mineralization and nitrification, photosynthetic oxygen production and respiratory oxygen consumption, and respiration by other optional biotic components. The figure below (Figure 7) illustrates the DO storages and fluxes modeled in NSM. The following processes are considered as part of the model for the DO state variable:

- Exchange to and from the air/water interface
- Utilization of oxygen at the sediment/water interface (i.e. SOD)
- Utilization of oxygen as bacteria degrade organic matter
- Utilization of oxygen in the process of nitrification
- Photosynthetic oxygen production and respiratory consumption by phytoplankton and algae.

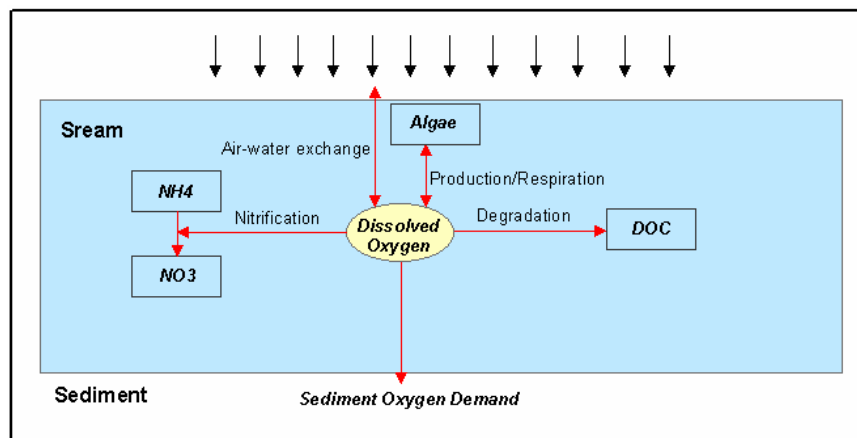


Figure 7: Schematic representation of in-stream dissolved oxygen dynamics

Channel Phytoplankton Kinetics

Algal involvement in the nutrient cycles is depicted schematically in the previous sections. Phytoplankton reduces the concentration of nutrients in the water by consuming phosphates, nitrate, and ammonium. Through assimilation these nutrients are transformed into organic materials which serve as a food source. A portion of the organic matter that is not used for food decomposes, which further affects the oxygen and nutrient levels in the water. The activities of the phytoplankton are in turn affected by the physical environment. Figure 8 provides an overview of algal dynamics modeled in NSM. Algal biomass can be simulated either in units of chlorophyll-a ($\mu\text{g Chla L}^{-1}$) or carbon (mg C L^{-1}) for phytoplankton. Algal biomass can be represented in the model either for the

entire phytoplankton assemblage, or as the individual contributions by certain groups, e.g., cyanobacteria, diatoms and other phytoplankton such as chlorophytes. Due to the lack of information to specify the kinetics rate for individual algal species in a natural environment, this model characterizes the population as a whole by the total biomass of the phytoplankton present.

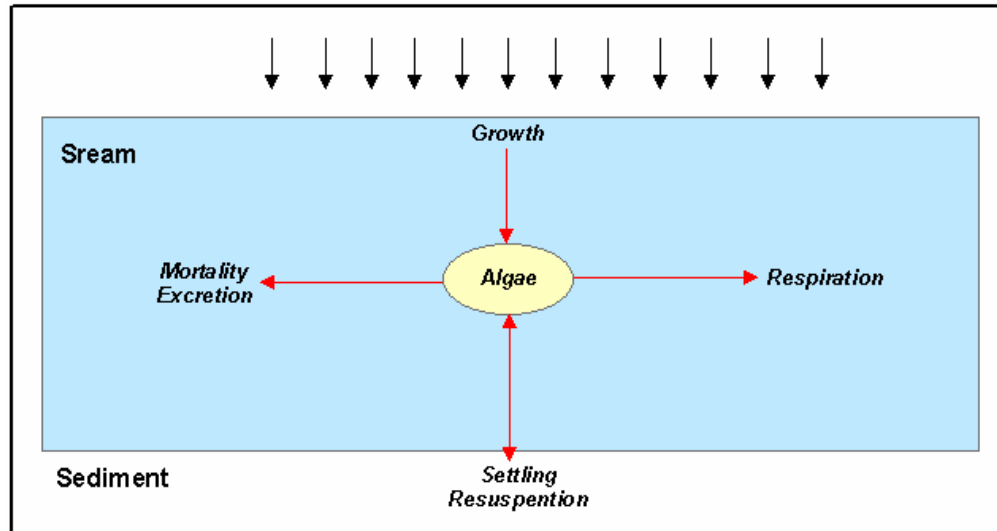


Figure 8: Schematic representation of in-stream phytoplankton dynamics

Future Development

Development efforts are currently underway to further enhance the channel kinetics modules. Processes from CE-QUAL-W2 and CE-QUAL-ICM are being evaluated in an effort to incorporate the latest process descriptions and to facilitate the linkage of USACE H&H models in a system wide framework.

The EDYS model is being evaluated in an attempt to create a robust plant dynamics module that will encompass both agricultural as well as natural landuses. Plant process descriptions for a wide range of plant life will be included within the NSM kinetics modules.

Two modeling systems are currently integrating the NSM package: 1) Gridded Surface Subsurface Hydrologic Analysis (GSSHA); and 2) Adaptive Hydraulics (ADH) model. GSSHA is a physically based finite volume and finite difference two dimensional distributed hydrologic model (Downer and Ogden, 2003). ADH is a three dimensional finite element hydraulics model (Stockstill and Berger, 2000). In the near future, work should commence to integrate NSM into the Hydrologic Engineer Center's riverine model, HEC-RAS, and watershed model, HEC-HMS.

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