INTEGRATED MODELING OF WATERSHED AND STREAM WATER QUALITY

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Abstract: A new modeling approach has been developed to evaluate the response of stream water quality to man-induced changes in watersheds, such as deforestation, urbanization, and changes in agricultural practices. The approach is based on the integration of watershed and channel network models for the continuous simulation of transport and fate of nutrients and other pollutants. The method of model integration utilizes terrain analysis and GIS technology to define a conceptual description of the watershed and its channel network. The watershed model AGNPS is used to compute runoff, soil erosion, and nutrient loads originating from upland areas. The CCHE1D one-dimensional model is used to route unsteady flows and compute transport and fate of pollutants in channel networks, with emphasis on the simulation of the aquatic cycles of nitrogen and phosphorus compounds. The model integration concept is demonstrated through an application to the Goodwin Creek watershed, in north Mississippi. A ten-year long integrated simulation was conducted, in which the watershed model AGNPS was used to determine water, sediment, and nutrient loads that would reach the channels, and CCHE1D computed the concentrations of nitrogen and phosphorus compounds along the channels of the network. The proposed modeling system was also used in a typical watershed management scenario to determine how prescribed changes in land use could affect the concentration of pollutant in streams.

INTRODUCTION

In 1991, the United States Geological Survey (USGS) initiated the National Water-Quality Assessment (NAWQA) Program, which was aimed at understanding the spatial extent of water quality, how water quality changes with time, and how human activities and natural factors affect water quality across the country. The study (USGS, 1999) revealed that much of the resources spent on water-pollution were directed toward municipal and industrial point sources, while control of contaminated runoff from nonpoint sources in both agricultural and urban areas was still lacking. The U.S. Environmental Protection Agency's (USEPA) biennial reports on the Nation's water quality have been showing that sedimentation and excessive concentrations of nutrients and pathogens are the leading causes of impairment in rivers and streams, while nutrients and metals are the main pollutants in lakes and reservoirs (USEPA, 2002). These assessments show clearly that nonpoint sources now account for the great majority of degraded surface waters, and agriculture is the leading source of pollution.

The spatially distributed nature of nonpoint source pollution, in which many different factors combine to cause degradation, requires the analysis of complex systems, larger areas, and for longer periods of time. By using a physically-based systematic approach and taking into account the most important processes and mechanisms, numerical models can help determine the reasons for impairment, the location of the main pollution sources, and how they relate to human activity. Since nonpoint source pollution is primarily water-driven, the choice of a catchment or watershed to define spatial extent is logical and virtually undisputed.

INTEGRATING WATERSHED AND STREAM MODELS

Because most water quality problems are responses to pollutant generation processes that occur in the upland and riparian zones of the river system, it is impossible to isolate the channel system from its corresponding watershed if water quality issues are to be considered. It is common practice to employ a "watershed model" to simulate the hydrologic processes that lead to runoff, to estimate soil erosion, and to determine amounts of nutrients and other pollutants that are transported in runoff or with eroded sediment. Similarly, stream water quality models are often used to determine pollutant concentrations for given inflow conditions and known pollutant loadings. However, in most cases these models are used independently of each other. The main objective of the work presented here is to establish a framework for integration of stream and watershed models so that it would be possible to determine, in a efficient and convenient manner, space and time-dependent concentrations of pollutants in streams, for known watershed characteristics and hydrological events. While watershed models are excellent tools to determine the pollutant loads (sediment, nutrients, pesticides, etc.) from various fields, they cannot accurately predict how pollutants affect water bodies. To evaluate how these water bodies are being impaired, it is necessary to predict the concentrations of the most relevant constituents for natural conditions of the streams. Because of the temporal variability resulting from the rainfall-runoff process, continuous, unsteady flow simulations are necessary. Processes that occur in stream waters, such as biogeochemical transformations, storage, dilution, etc, are also important in the determination of water quality conditions. In some cases, erosion of channel beds and banks, excess turbidity and sedimentation, and changes in water temperature are important in the degradation of stream habitats. Furthermore, pollutant concentrations can vary significantly due to the presence of tributaries and other water and pollutant sources. Coupling the watershed simulation with a channel network simulation would allow an analysis of the water quality in the aquatic environment that would capture the basic physical processes, clearly revealing the cause-effect relationships among the several processes.

The use of stream water quality models is often made difficult by the lack of reliable measurements or accurate knowledge of what the pollution sources are, and how they vary from location to location and during the various seasons of the year. Integration of stream and watershed models permits the estimation of the magnitude of these sources based on physical parameters of the watershed that are well known and easily measurable. Perhaps the greatest advantage of the model integration approach being presented is the capability of identifying the pollution sources and evaluating the response of the ecosystem to remedial measures. Agricultural practices have very large influence on the amount of chemicals that are released from fields. An integrated modeling system is helpful in identifying which agricultural practices are less efficient in retaining nutrients and pesticides. Models are often used to help in long-term planning to determine the Best Management Practices (BMP's) to reduce nonpoint source pollution and maintain water quality. Accurate modeling is essential in determining how various BMP's will affect water quality in a watershed scale.

INTEGRATED MODELING FRAMEWORK

The integration of watershed and channel network models requires a formal system that includes the definition of modeling procedures, the establishment of communication protocols, and the implementation of data management services. The design of the integration procedure must resolve many practical problems. Data requirements from all components should be compatible with each other, although in some cases assumptions would have to be made to allow the combined use of the models. More importantly, an unequivocal relationship between the several spatial and temporal discretization methods must be established. In the present method, terrain analysis techniques, coupled with specialized data processing algorithms, are used as the backbone for model integration. The modeling procedure starts with the terrain analysis phase, in which the location of the channels and the definition of subcatchments are inferred from the digital elevation data. The outcome of this analysis is further processed to establish a digital description of the watershed. All spatial data are converted into a relational database, and some data elements are further processed to match data requirements of the watershed and channel models. Using data from the terrain analysis phase, complemented with other user-supplied information, the watershed model determines nutrient loadings for each subcatchment for the duration of the simulation. After the upland simulation is done, results are processed or converted accordingly, and transferred to the channel network model, which of course will compute how the upland loadings affect the nutrient concentrations in the network of streams for the duration of the simulation. Figure 1 shows the flow of information among the several phases of the modeling process.

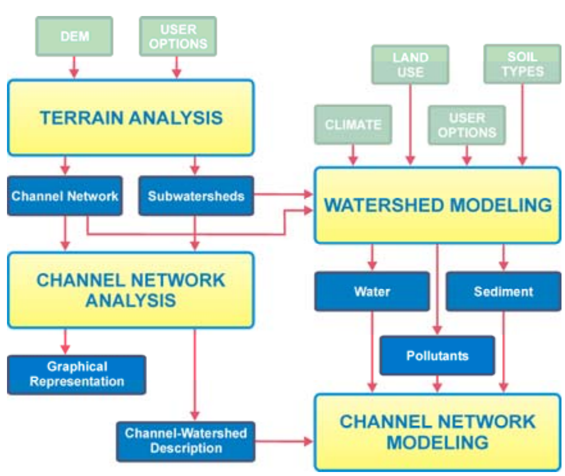


Figure 1 Integrated modeling procedure: operations and data flow.

MODELING COMPONENTS

Channel Network Model: CCHE1D is a one-dimensional model for the simulation of unsteady flows in dendritic channel networks of arbitrary cross-sectional shapes (Wu et al., 2002). The flow model contains special procedures for the computation of flow across hydraulic structures like dams, culverts, low and high-drop structures, bridges and measuring flumes. Its sediment transport module simulates the transport of sediment mixtures using a nonequilibrium approach, predicting sediment yields and channel morphological changes. CCHE1D's data structure has been designed to work with watershed models effectively: the model was developed following the same philosophy of data integration through automated terrain analysis that is adopted here for the pollutant transport model. The CCHE1D model is controlled from a GIS-based graphical interface that creates the computational mesh for the channel simulations, and manages most of the input data, such as channel cross sections, options and parameters, etc. (Vieira and Wu, 2002).

Water Quality Module: A water quality module for CCHE1D has been recently developed (Vieira, 2004). It has been designed to compute time-dependent concentrations of a series of constituents, which are primarily governed by the processes of advection, dispersion, and chemical reactions. Its main purpose is the simulation of nonpoint source pollution in primarily agricultural watersheds. Therefore, emphasis is given to the simulation of the biogeochemical transformations that determine the fate of nutrients, in particular the simulation of the aquatic cycles of nitrogen and phosphorus compounds. The model also includes procedures for the determination of growth of phytoplankton in response to high concentrations of nutrients and other environmental conditions. At the present stage of development, the model simulates the nitrogen and phosphorus cycles, the decay of biochemical oxygen demand (BOD), and the growth of phytoplankton. Dissolved oxygen and water temperature modeling are currently being implemented into the model. Figure 2 illustrates the overall structure of the model.

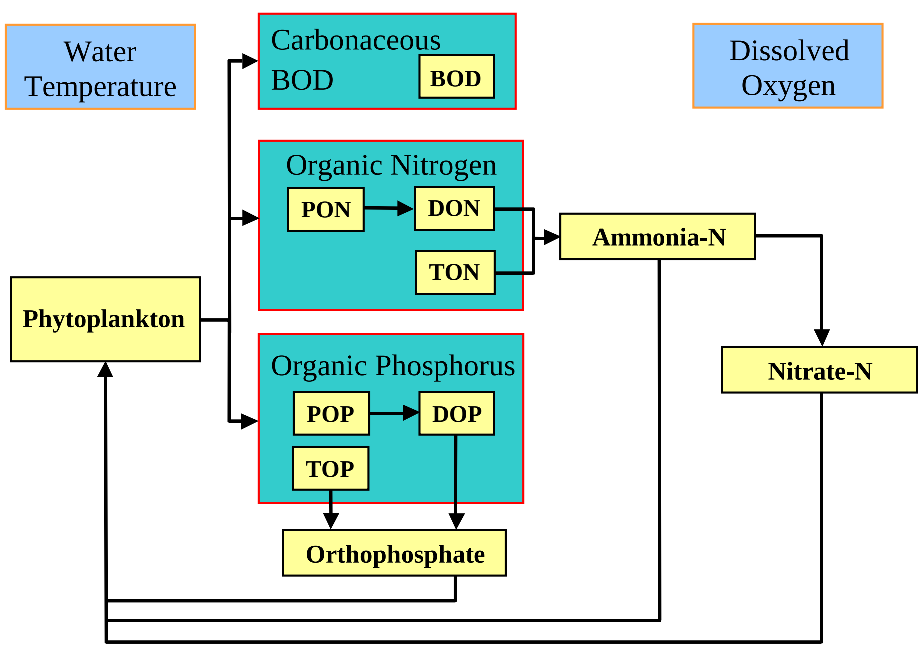


Figure 2 State variables used in the water quality module for CCHE1D.

The nitrogen cycle is simulated through four state variables: particulate organic nitrogen (PON), dissolved organic nitrogen (DON), ammonia nitrogen, nitrate nitrogen. For phosphorus, three state variables are used: particulate organic phosphorus (POP), dissolved organic phosphorus (DOP), and total inorganic phosphorus (orthophosphate). Alternatively, organic phosphorus can also be modeled using a single state variable, total organic phosphorus (TOP). The chemical kinetics of the several transformation processes represented in the model are approximated by first order reactions, where the reaction rate is proportional to the concentration of the reactant to the first power. Reaction rates are temperature dependent, and other limitation factors are also used. The model also includes the modeling of phytoplankton dynamics and eutrophication.

Watershed Model: A nutrient analysis model requires information about hydrology, soil erosion, and field characteristics to predict nitrogen and phosphorus moving in runoff, with sediment, and by leaching. The hydrologic model provides estimates of the volume of runoff, percolation, soil and water temperature, and water use, while the erosion model provides estimates of sediment loss. The determination of nutrient losses must be tightly connected to both the runoff and erosion counterparts. The present context of nonpoint source pollution in entire watersheds requires a model that performs continuous simulations and utilizes a spatially distributed approach. For the current work, the annualized version of watershed model AGNPS was selected for the simulation of nutrient loadings from upland areas. This model has been revised recently, and it includes improved routines for the determination of nutrient loadings, as well as an output format especially designed for channel flow modeling. The current version of the CCHE1D model is capable of directly importing simulation results from the AGNPS model, although other watershed models (SWAT, WEPP, etc.) can be used if the user adapts the watershed model results to one of the data formats supported by CCHE1D.

DATA INTEGRATION PROCEDURES

The terrain analysis model TOPAZ (Garbrecht and Martz, 1995) is used to define a channel network and to delineate corresponding drainage areas. In order to facilitate data management, two additional logical descriptions are used. The first subwatershed description is a modification of the original TOPAZ configuration, in which areas from the left- and right-hand sides of the channels are considered separately. This is used for watershed modeling, since lands at different sides of streams commonly have distinct uses. In addition, areas that drain into the head of streams (source areas) are represented separately. A second subwatershed type is derived by regrouping the drainage areas that contribute to each channel link; this subdivision is used to facilitate the connection between subwatersheds and channel links. The subwatersheds are then divided into portions called Incremental Areas, which are drainage areas that correspond to the segments of channel between two neighboring nodes used in the channel computations. The purpose of incremental areas is mainly computational: they provide easy means of subdividing the outflow from a subwatershed among all nodes of its channel. Figure 3 shows examples of watershed subdivisions, the channel network with its computational nodes, and the Incremental Areas used to match data from the watershed modeling with the computational mesh used for the channel simulations.

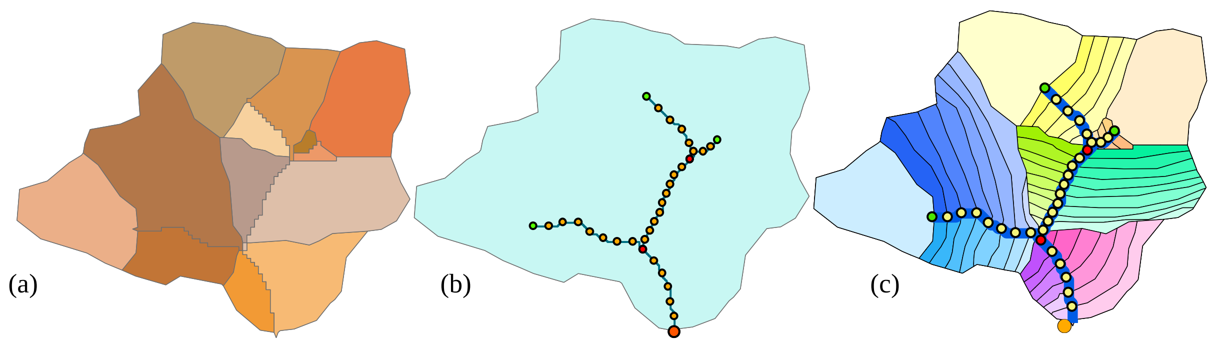


Figure 3 (a) Subbasins created from DEM analysis, used for hydrologic, erosion and pollutant loading modeling; (b) computational channel network for stream processes modeling; (c) redistribution of computed upland inflows among computational nodes (Incremental Areas).

Utilizing results from the watershed model AGNPS with the channel network flow and pollutant transport models requires special considerations regarding the spatial and temporal distribution of runoff and pollutant loadings. In AGNPS, computed runoff and pollutant loads are expressed as the total mass of water, sediment, and nutrients. These must be converted to mass fluxes that represent the distributed lateral inflows into the channels. Hydrographs produced by rainfall events in catchments of small areas have the typical shapes shown in Figure 4(a). In order to approximate this behavior, the daily volumes of water computed by AGNPS are converted into triangular hydrographs, as seen in Figure 4(b). After the peak discharge and duration for the storm are determined, the total water volume is converted into flow rates, for each subwatershed, for each simulation day. When the inflow data are transferred to the channel model, these hydrographs are redistributed among the computational nodes of the channel network, using the watershed subdivision types described above. In order to convert daily amounts of nutrients (expressed as mass) into equivalent concentrations of each constituent, it is assumed that during a rainfall event at a subwatershed, higher flows will carry larger amounts of pollutants, that is, the pollutant concentration is constant in time for that particular event.

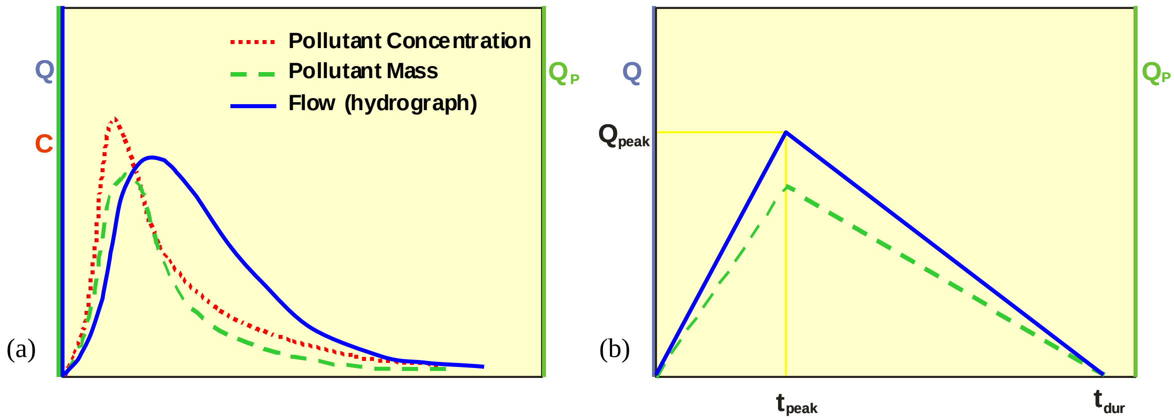


Figure 4 Natural and hypothetical hydrographs.

APPLICATION TO GOODWIN CREEK

The combined use of the watershed model AGNPS, the channel flow model CCHE1D, and the newly developed nutrient transport model allows the estimation of the amounts of nutrients that are removed from the diverse agricultural fields and transported through overland and channel waters. This application demonstrates how the several models are used together to estimate soil erosion and pollution loading that are caused by rainfall events. Goodwin Creek is a small watershed in North Mississippi of about 21 km^2 covered by pastures, forests and crops. The watershed has been selected because it is an experimental watershed of the U.S. Department of Agriculture National Sedimentation Laboratory (NSL), and has being extensively surveyed and monitored during the past twenty-five years. The watershed contains an array of stream flow and sediment transport measuring instruments, weather stations, and a rich database that includes soil properties, agricultural practices, stream sediments, etc. The site has been the focus of numerous scientific studies, and extensive information is available on the hydrologic, erosion, and sedimentation processes of the watershed.

Although detailed and reliable data are available for most physical aspects, data regarding nutrients present in streams are somewhat limited. Nutrient sampling is not performed on a continuous basis, and most data are derived from sampling at unknown hydrological conditions. For Goodwin Creek, detailed soils, crops, and management operations were gathered by the NSL (Bingner, 2001). In Goodwin Creek, soils are silty in texture and susceptible to erosion if vegetative cover is removed. Climate data for Goodwin Creek was obtained from one of the weather stations inside the watershed, which is located approximately at the its center. Rainfall is assumed uniform throughout the watershed.

The channel extraction process, based on a 30-meter resolution Digital Elevation Model (DEM), created a channel network with eleven channels of Strahler order two or greater, with a total length of 17 km; 217 subwatersheds were defined for the watershed simulation. In order to avoid routing of flow through very small channels, those of Strahler order equal to one were removed from the channel network. For the numerical simulations, a computational mesh containing 203 nodes was created, with extra nodes being added along the channels to create a relatively uniform mesh with an average element length of 89.3 meters.

The watershed simulation was performed for the years 1982 to 1991. For each subwatershed, the predominant soil type and land use (based on a surface area) were adopted. During the simulation, the land use for each subwatershed was not altered. Areas of crops, pastures, and forest were maintained throughout the ten years of simulation, although in reality some crops were converted into pastures.

Figure 5 shows the spatial distribution of total (dissolved and attached to sediment) nitrogen and phosphorus loadings simulated by AGNPS, shown as the 10-year average yields per unit area (in kg/ha/year). The nutrient loading is primarily related to the subwatersheds where cotton and soybeans are cultivated, followed by forested areas. Pastures provide the least amount of nutrients to the channel system.

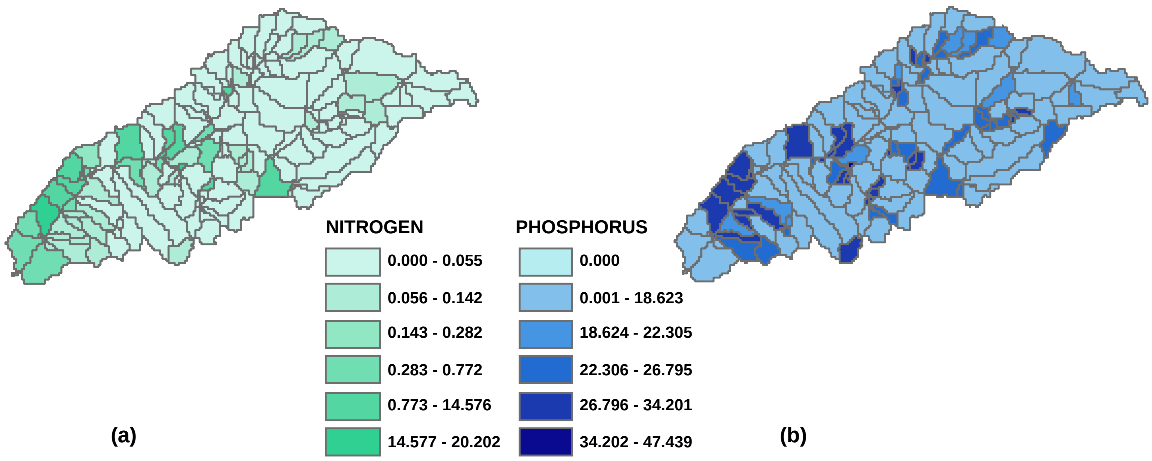
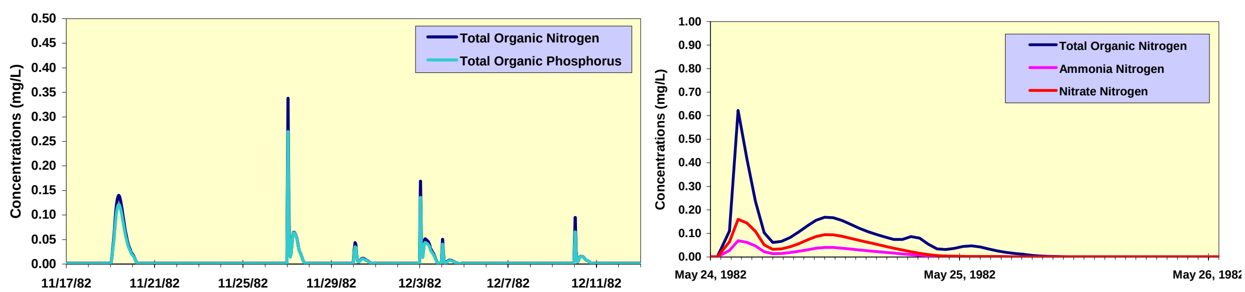


Figure 5 Simulated yields for total nitrogen and phosphorus. Ten-year average, in kg/ha/year.

For each day in which there is runoff in at least part of the watershed, computed amounts of runoff (water volume), sediment, and nutrients were saved into a data file especially designed for the channel network model. Stage-discharge rating curves from a measuring flume located at the watershed outlet were used to determine the flow boundary condition (water surface elevation) at the outlet. While other hydraulic structures exist in Goodwin Creek, they were not considered in the simulation because their effect on flow conditions is limited to a short distance. Although these structures can affect bed erosion, they do not retain water, create ponds, or modify the flow substantially to affect the transport of pollutants.

The channel simulation included both the nitrogen and phosphorus cycles. Phytoplankton growth was not considered because there were no data available regarding phytoplankton population. Water temperature and dissolved oxygen levels were prescribed according to recorded data. For nitrogen, three state variables were used. Organic nitrogen was simulated with a single variable for both dissolved and particulate forms. Inorganic nitrogen was computed as ammonia and nitrate. In order to determine the inputs for each of these variables, certain assumptions had to be made. The amounts of nitrogen attached to sediment computed by AGNPS were considered in the channels as Total Organic Nitrogen (TON). Dissolved nitrogen was arbitrarily distributed as 20% ammonia and 80% nitrate nitrogen. For phosphorus, two state variables were used: Total Organic Phosphorus (TOP), and Orthophosphate (inorganic phosphorus). In this application, attached phosphorus was added to TOP, and the dissolved amounts were considered as orthophosphate. Since there was no site-specific information on the rates of chemical kinetics, values suggested in the literature were adopted (Vieira, 2004).



(a) (b)

Figure 6 (a) Concentrations of total organic nitrogen and phosphorus near the watershed outlet, between November 17 and December 13, 1982; (b) concentrations of total organic, ammonia and nitrate nitrogen for a storm on May 24, 1982.

Figure 6 shows typical concentration variations of total organic nitrogen and phosphorus near the watershed outlet with the passage of rainfall events (15 to 50mm) during the winter of 1982. The figure shows the flashy nature of the watershed, which has short and somewhat steep channels. A detailed look at a single storm event is shown in Figure 6(b), which shows the computed concentrations of the nitrogen constituents near the watershed outlet.

Linking Nutrient Loadings to Land Use Changes in Small Watersheds: A hypothetical land use change, in which pasture and idle lands were converted to soybean and cotton crops, was used to show how a combined watershed–channel simulation can be used to estimate the impact of the increased cultivated area on nutrient concentrations in the streams. This exercise exemplifies the application of the modeling system in watershed management, where different scenarios are used to evaluate the impact of man-induced changes on the overall water quality within the watershed. Figure 7 shows the actual land use for the watershed and the hypothetical situation, which adds areas of soybeans and cotton fields.

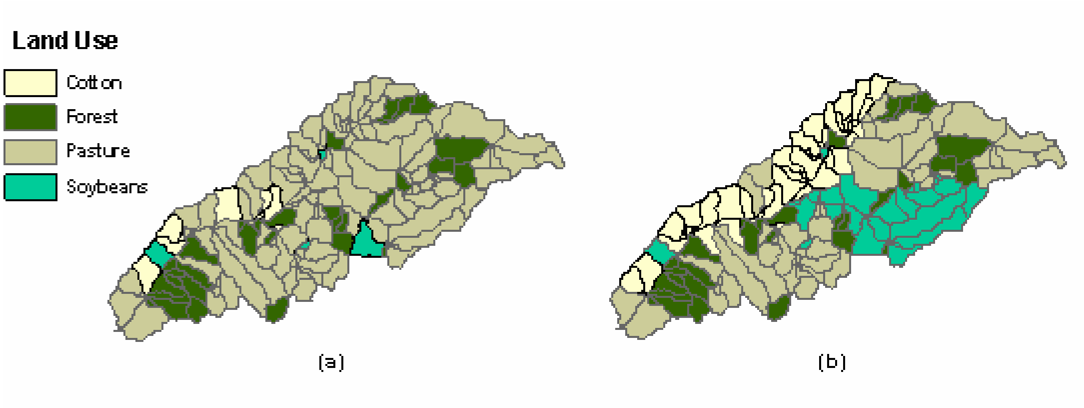


Figure 7 Watershed subdivisions and land use; (a) actual, (b) hypothetical.

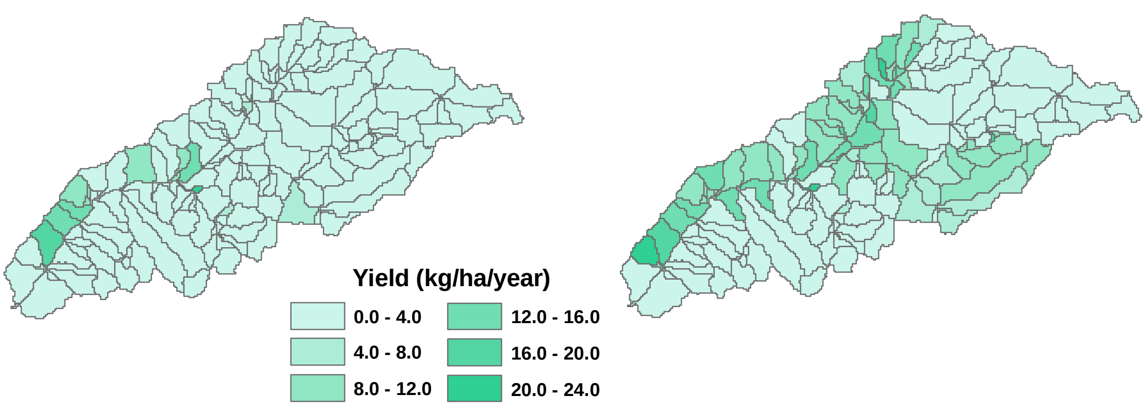


Figure 8 Simulated average nitrogen yields for actual and hypothetical land uses.

The presence of crops increases the amounts of nitrogen and phosphorus that are removed from upland areas and transported through the streams. Figure 8 compares the average nitrogen yields for the both simulations. The increase in nutrient loads is of course reflected in the concentrations of the nutrients in the streams. Figure 9 compares the concentrations of organic, ammonia nitrogen, and nitrate nitrogen for a particular storm event, for actual and hypothetical land uses. It can be seen that the increase in cultivated area causes a substantial increase in the nutrient concentrations in the streams.

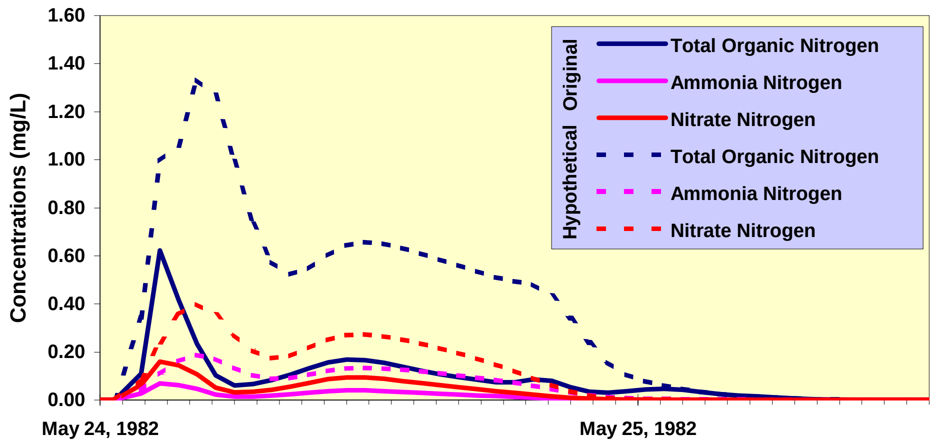


Figure 9 Simulated concentrations of organic, ammonia, and nitrate nitrogen, for actual and hypothetical land uses, near the watershed outlet.

CONCLUSIONS

Managers and scientists now recognize that models are valuable tools not only in assessing current conditions, but also in defining management policy, devising short and long-term plans, and establishing goals and targets for improvement. The proposed modeling approach can be remarkably useful in quantifying the environmental benefits of conservation practices. By simulating several scenarios, it is possible to identify Best Management Practices for a particular watershed, that is, determine what modifications in current practices can help reduce the impact of human activities on the quality of the environment, while maintaining healthy economic growth.

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