MODELING HYDRODYNAMICS, CHANNEL MORPHOLOGY, AND WATER QUALITY USING CCHE1D

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ABSTRACT

CCHE1D is a one-dimensional model for the simulation of unsteady flows, sediment transport, and water quality in stream networks. The model can be applied to a variety of engineering problems, but it is particularly useful in the determination of channel–watershed system responses to natural and man-made changes in both channels and upland areas. The model can be used in combination with the watershed model AGNPS in the analysis of watershed hydrology and nonpoint source pollution problems caused by erosion or pollutants such as nutrients and pesticides. CCHE1D's flow module – CCHE1D-FL – computes one-dimensional unsteady flows in dendritic channel networks of arbitrary cross-sectional shapes. The sediment transport module – CCHE1D-ST – simulates the transport of sediment mixtures using a nonequilibrium approach, predicting sediment yields and channel morphological changes. The recently developed water quality module – CCHE1D-WQ – simulates transport and fate of pollutants in streams for continuous, unsteady flow conditions. The model computes advective-dispersive transport of a number of pollutants, simulating the biogeochemical processes of the main nutrient cycles, phytoplankton growth, and the process of eutrophication. GIS-based graphical software complements the modeling system, providing automated methods for watershed delineation, channel network generation, data transfers and conversions, and visualization.

1. INTRODUCTION

CCHE1D is a modeling system for the simulation of flow, sediment transport, and water quality in a network of streams. CCHE1D consists of a group of one-dimensional models for channel processes, which are integrated and supported by a GIS-based graphical interface. This group of programs, referred as the CCHE1D model, can be applied to a variety of engineering problems, but it is particularly useful in the determination of channel-watershed system responses to agricultural management practices and man-made modifications to the channels or upland areas. The model can be used in combination with the watershed model AGNPS in the analysis of nonpoint source pollution problems caused by erosion and associated pollutants such as nutrients and pesticides. It can be used to determine long-term erosion and deposition patterns, estimate water quality parameters in streams, identify the main pollution sources and their spatial distribution, and assess the performance of control and remedial measures on sediment and pollutant loads throughout the watershed.

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2. CHANNEL-WATERSHED INTEGRATION

CCHE1D has been designed to analyze hydrodynamics, sediment transport, and water quality in channels of entire watersheds. Unlike other one-dimensional models developed in the past, the CCHE1D software has been specifically designed to integrate the modeling of channel processes to the modeling of upland processes.

There are many advantages that arise from this integration. During the past years, engineering applications of numerical models evolved from the simple routing of floods along a river, or the computation of the transport of a cloud of pollutant, to a much broader and complex analysis that might include sediment-related processes, such as erosion and sedimentation, or a variety of water quality issues. The shift to watershed-based analysis, which redirects focus to nonpoint sources of water, sediment and pollutants, was the main drive for the development of CCHE1D.

Regarding the simulation of hydrologic processes, a combined watershed–channel simulation eliminates deficiencies inherent to the design of existing modeling components. Modeling of rainfall-runoff and related processes has been developed independently from the models for hydrodynamics and transport processes in channels. Watershed models simulate upland hydrology and determine surface runoff for given precipitation or snowmelt events. Stream hydrodynamics are usually not included in most of these models, and flood routing is determined by a variety of hydrologic methods. The use of such methods may not be accurate – or even adequate – for certain types of engineering analyses, especially when they involve flood propagation and other processes determined by flow and other transport phenomena in channels.

When more accurate predictions are sought, especially when flow unsteadiness is important, or when watersheds become large, a channel hydrodynamic model can provide time-dependent predictions of the hydraulic properties for the whole channel system. Watershed models alone cannot be used to determine flow conditions when channel geometry or other features substantially affect the development and propagation of flood waves. The existence of reservoirs and other flow-controlling structures are examples of situations where a channel hydrodynamic model may be necessary.

A distinct situation occurs when engineers are primarily interested in channel processes: modern applications of river modeling software often require the analysis of the whole channel system under naturally occurring conditions, as opposed to the simulation of a few representative situations, as it was commonly done in the past. Engineers soon realize that hydraulic data required for modeling, such as measured discharges and stages, are usually available only for a few locations in the channel system, and the available data may not reflect the unsteadiness commonly present in the runoff and routing of storm water. In these situations, the hydrologic component of a watershed model can be employed to furnish spatially variable, time-dependent inflows at many locations of the watershed.

When investigating sediment-related problems, a similar situation exists. Coupled to many existing watershed models are complex soil erosion models which can estimate losses from agricultural fields, given the characteristics of topography, soils, land use, and agricultural operations. Although these estimates are extremely useful, they do not account for erosion and sedimentation that take place in streams. In some watersheds, channel bed and bank erosion contributes significantly to the overall sediment balance. The simulation of sediment transport in channels can provide a more realistic account of sedimentation processes in watersheds. On the other hand, when focus is shifted to the modeling of sediment transport in channels, upland soil erosion modeling can be a convenient method to determine loads at different locations in the watershed, accounting for both space and time variations that are difficult to be estimated without upland modeling.

When analyzing water quality problems, the integration of channel and watershed models provides advantages similar to those described for water and sediment. The combined use of models allows the determination of pollutant concentration in streams as a function of loadings from upland areas – such as agricultural fields – which are computed by the watershed model for storm events that generate runoff. This feature is particularly useful when determining the impact of land use changes on stream water quality. Modeling pollutant loads with the aid of a watershed model can also be useful in identifying locations or practices that are the main sources of pollution.

3. CCHE1D MODEL DESIGN

The combined use of a sophisticated watershed model and a stream water quality model requires considerable effort assembling and preparing the large amounts of descriptive data both models require. Another complicating factor is that existing stream and watershed models were developed separately, and their combined use was not considered in their design. These two factors alone make this type of application to real-world engineering problems very difficult, requiring tedious manipulation of input and output data from each modeling program, often tailored to a particular application.

In CCHE1D, both GIS and terrain analysis methods are employed to define a common data structure that allows the combined use of distinct modeling programs. These technologies are also instrumental in helping define the spatial distribution of the many physical properties and parameters that make the bulk of the input data the models require.

Figure 1 shows the general data flow and order of operations for the current system. 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. Only after these steps are concluded, the modeling process can begin. The upland modeling must be performed first: using data from the terrain analysis phase, complemented with other user-supplied information, the watershed model can determine nutrient loadings for each subcatchment for the duration of the simulation. After this is done, upland simulation results are processed or converted accordingly, and transferred to the channel network model, which of course will compute how the upland loadings affect the pollutant concentrations in the network of streams for the duration of the simulation.

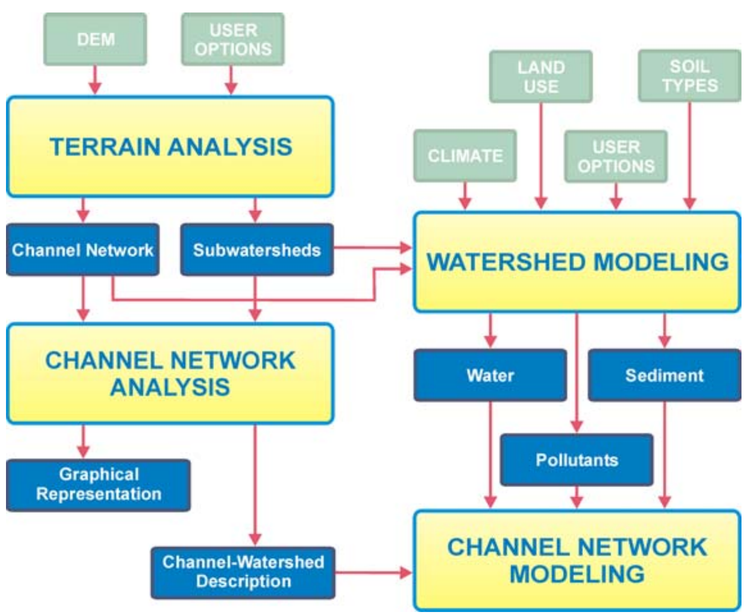

Figure 1 Integrated Modeling Approach – Operations and Data Flow.

CCHE1D utilizes landscape analysis techniques to create the spatial description of watershed and channels. The model TOPAZ – TOpographic PArameteriZation – (Garbrecht and Martz, 1995) is used to extract the drainage network and corresponding subbasins from elevation data contained in a Digital Elevation Model (DEM) data file. TOPAZ's results are used as the basis for the generation of a logical representation of the channel–watershed system. Besides the determination of obvious physical traits such as lengths, slopes, etc., a topological description of the system is established in order to allow the transfer of information among the several programs of the modeling system. This logical description is used by all modeling programs and by tools that implement automated data manipulation methods. Examples of automated data analysis tasks would be the generation of computational meshes, the establishment of relationships between channel reaches and the corresponding drainage areas, conversion of daily runoff volumes into inflow discharges, etc.

Figure 2(a) shows typical watershed subdivision obtained from terrain analysis from TOPAZ, which corresponds to the channel network shown in 2(b). Because channel simulations use a computational mesh with many computational nodes, it is often necessary to redistribute the lateral inflows computed by the watershed model among all nodes of the channel network. CCHE1D has functions that automate this redistribution.

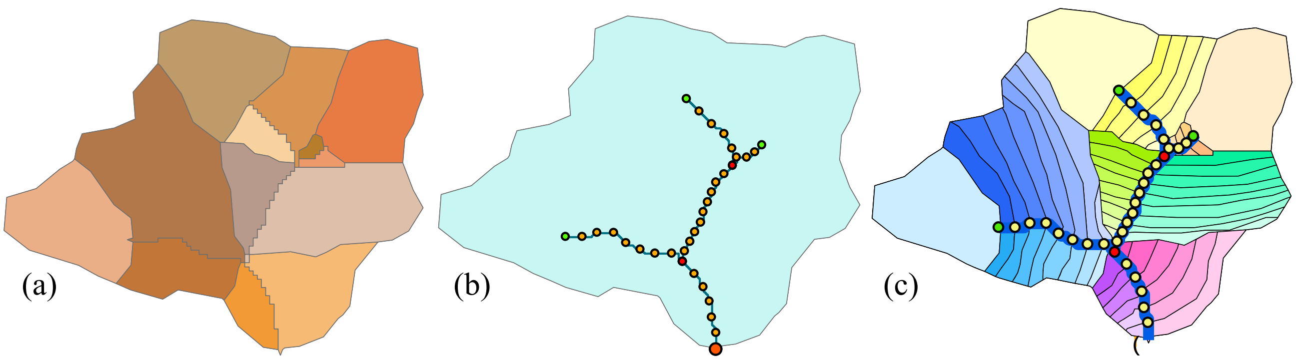

Figure 2 (a) Subbasins created from DEM analysis, used for hydrologic, erosion and pollutant loading modeling; (b) computational channel network for stream processes modeling; (c) redistribution of computed upland inflows among computational nodes.

The integrated simulation is controlled by a software module implemented using the ArcView GIS program. Besides providing a graphical interface to the modeling system, the software controls the execution of the other programs, executes the necessary data conversions and transfers, and provides support for standard GIS data formats. The watershed model AGNPS (Bingner et al., 2003) has been selected to compute runoff, soil erosion, and nutrient loads originating from upland areas. Figure 3 shows the layout of the CCHE1D graphical interface.

4. CCHE1D-FL HYDRODYNAMICS MODULE

CCHE1D's flow module – CCHE1D-FL – computes one-dimensional unsteady flows in dendritic channel networks of arbitrary cross-sectional shapes. The governing equations of the 1-D dynamic wave model for open-channel flows are the de Saint Venant equations (Wu and Vieira, 2002):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \qquad (1)$$

$$\frac{\partial}{\partial t}\left(\frac{Q}{A}\right)+\frac{\partial}{\partial x}\left(\frac{\beta Q^2}{2A^2}\right)+g\frac{\partial h}{\partial x}+g\left(S_f-S_0\right)=0 \quad (2)$$

where x and t are the spatial and temporal axes; A is the flow area; Q is the flow discharge; h is the flow depth; S_0 is the bed slope; β is a correction factor for the momentum due to the nonuniformity of velocity distribution on the cross section; g is the gravitational acceleration; and q is the side discharge per unit channel length; S_f is the friction slope, defined as $S_f = Q|Q|/K^2$, with K being the conveyance.

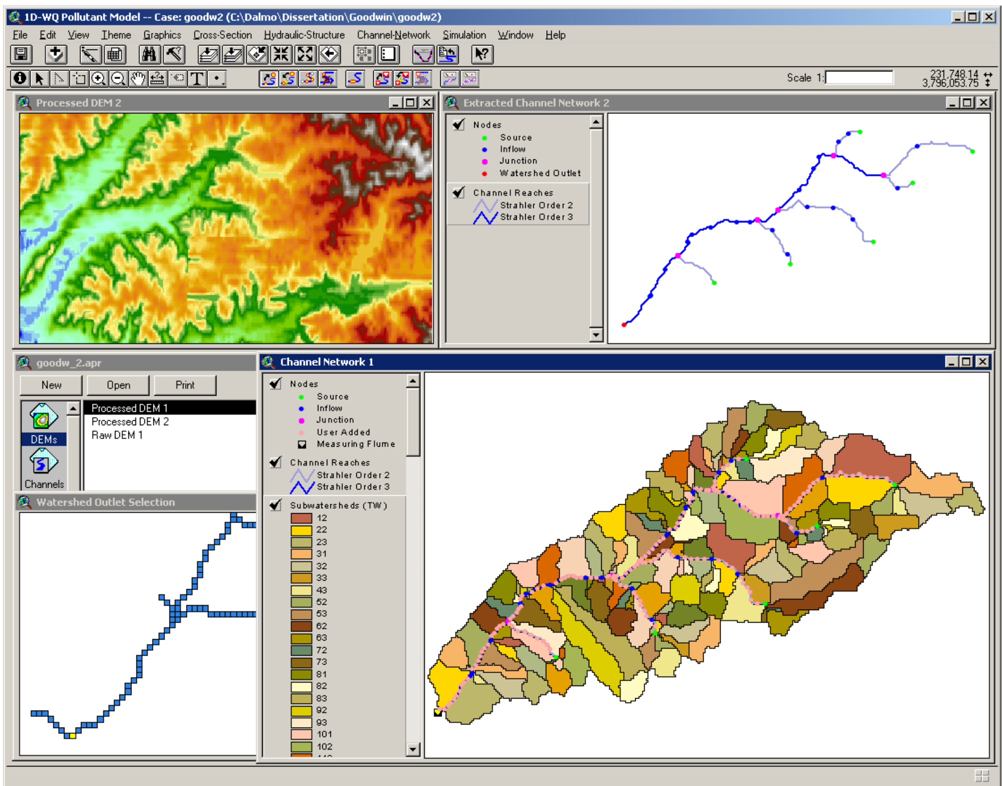

Figure 3 CCHE1D Graphical Interface.

Because the hydraulic properties in the main channel and in the flood plains are usually noticeably different, a channel cross-section is divided into three subsections: a main channel, and optional right and left flood plains. The flow equations are discretized with the four-point implicit scheme of Preissmann, and the resulting pentadiagonal matrix is solved with the Double Sweep method (Thomas algorithm).

CCHE1D contains special procedures for the computation of flow across hydraulic structures like dams, culverts, low and high-drop structures, bridges and measuring flumes. Usually, in-stream structures determine the local flow hydraulics, also affecting erosion and sedimentation processes in their neighborhood. Some of these structures are built as erosion control devices; therefore it is important that the model simulates their effect on flow and sediment transport with reasonable accuracy.

5. CCHE1D-ST SEDIMENT TRANSPORT MODULE

CCHE1D predicts channel morphological changes and sediment yields, computing variations of the bed material gradation and simulating hydraulic sorting and armoring processes. These processes are common in natural river systems, and their correct representation is necessary especially for long-term predictions of channel evolution.

The model computes the transport of nonuniform sediment using the nonequilibrium approach. In the traditional equilibrium (or saturated) transport model, the actual sediment transport rate is assumed equal to the sediment transport capacity at every cross section – the assumption of local equilibrium – and the bed change is calculated by the sediment continuity equation. However, in many cases, such as in strong sediment overloading, for example, the inflow sediment discharge imposed at the inlet can be significantly different from the transport capacity, which might lead to difficulties in the calculation of bed changes near the inlet. The nonequilibrium transport model adopts the mass transport equation to determine the actual sediment transport rate, which should be more suitable for the simulation of sediment transport in natural rivers, often in nonequilibrium state.

The governing equation for the nonequilibrium transport of nonuniform sediment is (Wu and Vieira, 2002):

$$\frac{\partial(AC_{tk})}{\partial t}+\frac{\partial Q_{tk}}{\partial x}+\frac{1}{L_s}\left(Q_{tk}-Q_{t*k}\right)=q_{lk} \tag{3}$$

where C_{tk} is the section-averaged sediment concentration of size class k; Q_{tk} is the actual sediment transport rate; Q_{t*k} is the sediment transport capacity or the so-called equilibrium transport rate; L_s is the nonequilibrium adaptation length of sediment transport; and q_{lk} is the side inflow or outflow sediment discharge from bank boundaries or tributary streams per unit channel length.

Eq. (3) is a generalized governing equation that can be applied to bed load, suspended load, and wash load separately, or to total load, depending on how the sediment transport rate and the adaptation length are defined. The CCHE1D model does not distinguish bed load and suspended load, but treats them together as bed-material load. Therefore, Eq. (3) is applied to the sum of bed and suspended loads, where the transport rate Q_{tk} is the sum of bed load and suspended load transport rates. Eq.(3) is also applied to wash load, where the adaptation length L_s is assumed to be infinitely large and then the exchange term on the left-hand side is zero.

The sediment transport capacity can be written as a general form

$$Q_{t*k}=p_{bk}Q_{tk}^{*} \tag{4}$$

where p_{bk} is the availability factor of sediment, which is defined here as the bed material gradation; Q_{tk}^{*} is the potential sediment transport rate for size class k, which can be determined with the help of established relations. The bed deformation due to size class k is determined with

$$\left(1-p'\right)\frac{\partial A_{bk}}{\partial t}=\frac{1}{L_s}\left(Q_{tk}-Q_{t*k}\right) \tag{5}$$

where p' is the bed material porosity and $\partial A_{bk}/\partial t$ is the bed deformation rate of size class k.

The bed material is divided into several layers to allow the computation of changes in bed material gradation due to erosion or deposition. The variation of bed material gradation at the mixing layer (surface layer) is determined by:

$$\frac{\partial(A_m p_{bk})}{\partial t} = \frac{\partial A_{bk}}{\partial t} + p_{bk}^*\left(\frac{\partial A_m}{\partial t} - \frac{\partial A_b}{\partial t}\right) \tag{6}$$

The equations of the sediment transport model are discretized using the Preissmann scheme, resulting in a solution method in which the nonequilibrium sediment transport, bed deformation, and bed material sorting are solved using a coupling scheme that does not require iterations.

The model provides several well-known equations for the determination of transport capacity, and a series of options for the computation of auxiliary parameters such as bed material porosity, mixing layer thickness, nonequilibrium adaptation length, wash load size range, movable bed roughness coefficient, etc. This allows the modeler to choose which formulation suits best the case under study. An empirical bank-toe erosion model is used in conjunction with bank stability algorithms to predict bank erosion due to bed degradation.

6. CCHE1D-WQ WATER QUALITY MODULE

Modeling of transport and fate of pollutants in watersheds is a tool that overcomes the limitations of other problem-solving approaches. Such problems include the determination of the range of pollutant concentrations in rivers for given watershed characteristics and hydrological events, and the estimation of the time of permanence of high pollutant concentrations in several locations of the watershed, in response to rainfall events and seasonal variability.

From a watershed management point of view, issues include the identification of types of human activities that have the greatest impact on stream water quality, the determination of the response of river pollution indicators to changes in upland conditions, the evaluation of the performance of remedial measures planned or implemented in the watershed, and the determination the maximum admissible pollutant loadings for given watershed and hydrological conditions.

The CCHE1D-WQ water quality module (Vieira, 2004) 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.

The transport of constituents in a channel can be described by the advection-dispersion equation:

$$\frac{\partial(AC)}{\partial t} + \frac{\partial(UAC)}{\partial x} - \frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) = SA \tag{7}$$

where x and t are the spatial and temporal axes, C is the concentration of a constituent, A is the cross-section area of flow, U is the average velocity, D the longitudinal dispersion coefficient, and S is a net source term due to biochemical and physical changes, and due to distributed input to the channel by runoff.

CCHE1D utilizes a control volume method based on the exponential scheme (Spalding, 1972; Patankar, 1980), which utilizes the exact solution of the one-dimensional advection-diffusion equation for steady flow and constant diffusion as a profile for the variation of the general variable C within the control volume. The discretized equations form a tridiagonal matrix, whose solution is obtained with the Thomas algorithm, also called the Double-Sweep Method, or TDMA – TriDiagonal-Matrix Algorithm.

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. Figure 4 illustrates the overall structure of the model. Dissolved oxygen and water temperature modeling are being implemented into the model.

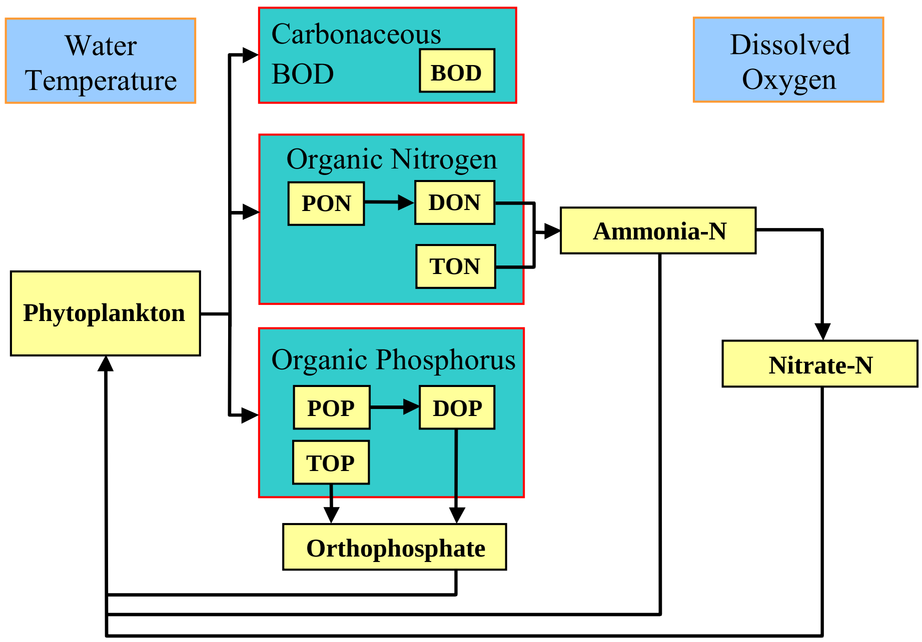

Figure 4 State variables used in the CCHE1D-WQ water quality module.

The nitrogen cycle is simulated through five state variables: particulate organic nitrogen (PON), dissolved organic nitrogen (DON), ammonia nitrogen, nitrate nitrogen, and, indirectly, nitrogen in phytoplankton. Only the aquatic phase in considered, and interactions with bed nutrients are not explicit modeled, although settling of particulate forms is included, and nutrient uptake by benthic algae and/or macrophytes are accounted for through the general uptake process. 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 Michaelis-Menten (or Monod) limitation factors are also used.

Phytoplankton dynamics are of practical importance because they are closely associated with nutrient dynamics, and algal growth is the main process that removes nutrients from the aquatic system. Conversely, the processes of respiration, excretion, and non-predatory mortality recycle nutrients back into the system. In CCHE1D-WQ, the phytoplankton population is represented as biomass, expressed in units of carbon. The relationships with phytoplankton's main elements (nitrogen and phosphorus) are established using fixed stoichiometric coefficients.

7. EXAMPLES OF MODEL APPLICATIONS

The CCHE1D model has been applied to a variety of both laboratory and field cases as part of the process of model validation and verification that has been conducted alongside the development of the software package (Wu and Vieira, 2002; Vieira and Wu, 2002). In order to illustrate typical uses of the CCHE1D model in real-life projects, a selection of model applications is presented here. The US Agency for International Development (USAID) has funded a program of technology exchange between the United States and Poland. As part of the program, the CCHE1D model has been used in several studies conducted by Polish universities and research institutions, during the years 2003 and 2004. Some examples shown here are parts of this research effort.

7.1 Flood Analysis in the Upper Narew River

The CCHE1D unsteady flow module was used to examine the influence of the hydrological processes in the Upper Narew River on the sustainable development of the region (Rowiński et al., 2005). The application of CCHE1D was part of a multi-stage process that started with a detailed recognition of the channel-floodplain system through morphometric surveys, remote sensing, and GIS analysis. For this project, detailed monitoring of flood events and flow measurements were also executed. The CCHE1D model was then used to simulate past and anticipated flood conditions, to understand their impact on that river system.

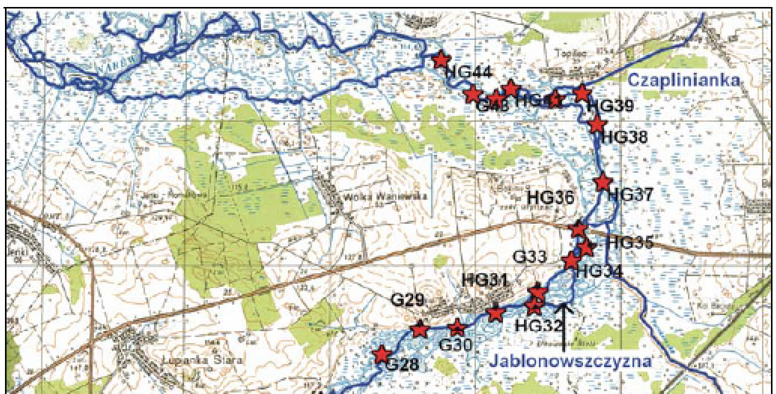

Figure 5 Study area and location of geometry and flow velocity surveys (after Rowiński et al., 2005).

Figure 5 shows the study area and the locations of where channel geometry and flow parameters were recorded. Using data derived from a rigorous hydrological analysis, CCHE1D was used to predict flooding for a variety of anticipated flow conditions. Figure 6 shows flood maps based on the model's unsteady flow computations for the 1979 flood and for return periods of 10 and 100 years.

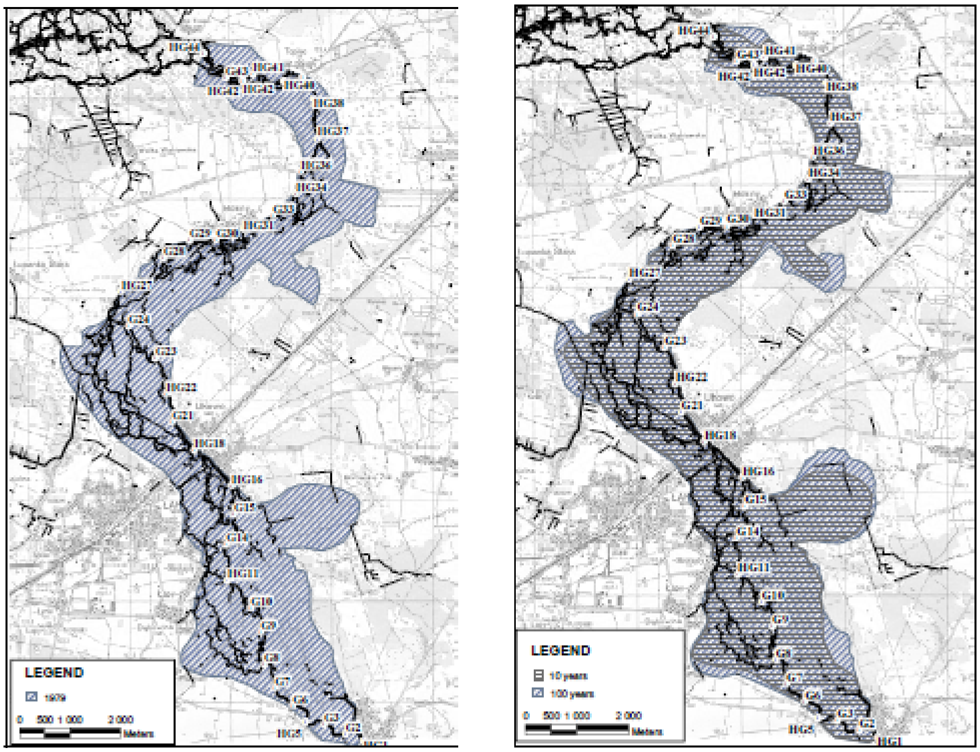

Figure 6 Flood maps prepared based on CCHE1D unsteady flow simulations (after Rowiński et al., 2005).

7.2 Sedimentation Problems in a Small Reservoir

The CCHE1D unsteady flow and sediment transport model has been used to simulate the process of sedimentation observed in the Staw Górny, a 250,000m^3, 91km^2 reservoir in Poland (Banasik et al., 2005). The 2.4km river reach, shown in Figure 7, was simulated using 26 cross sections, surveyed several times between 1979 and 2003. Inflow sediment loads were related to measured flow discharged through empirical formulas established by previous studies. The CCHE1D model was used to compute the process of reservoir sedimentation. Several sediment transport formulas of the CCHE1D-ST sediment transport module were tested. The authors also analyzed the model's sensitivity to parameters that determine nonequilibrium transport. Figure 8 compares the volumes of deposition computed with several sediment transport formulas for the period 1980-2003.

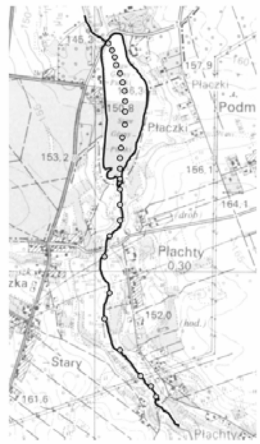

Figure 7 Staw Górny Reservoir (after Banasik et al., 2005).

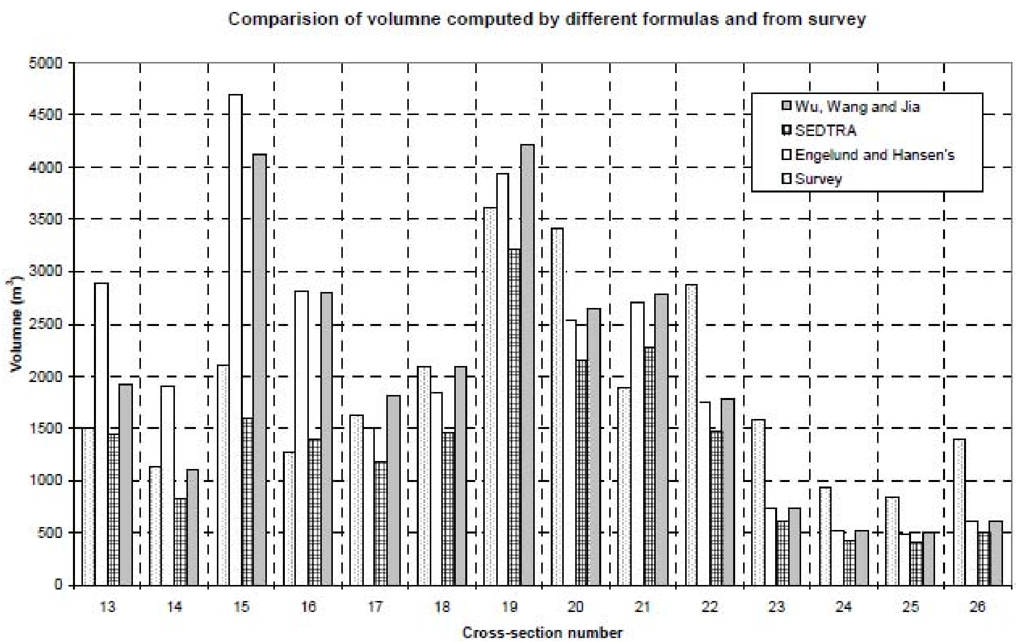

Figure 8 Measured and simulated sedimentation volumes between 1980 and 2003 (after Banasik et al., 2005).

7.3 Linking Nutrient Loadings to Land Use Changes in Small Watersheds

The CCHE1D modeling software was used to determine how land use changes can affect the amounts of nutrients that reach the streams of a small watershed (Vieira, 2004). The CCHE1D-WQ module was used to compute concentrations of organic and inorganic nitrogen and phosphorus compounds in the streams of the Goodwin Creek watershed, in North Mississippi. Nutrient loadings were computed using the AGNPS watershed model (Bingner, 2001) for a series of storm events. 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.

In this application, the channel network and watershed subdivision was determined from terrain elevations using TOPAZ through the CCHE1D graphical interface. AGNPS was used to simulate hydrology, soil erosion, and nutrient loading for a 10-year record of storm events. Figure 9 shows the watershed subdivision used in the computations, for the actual and hypothetical land uses.

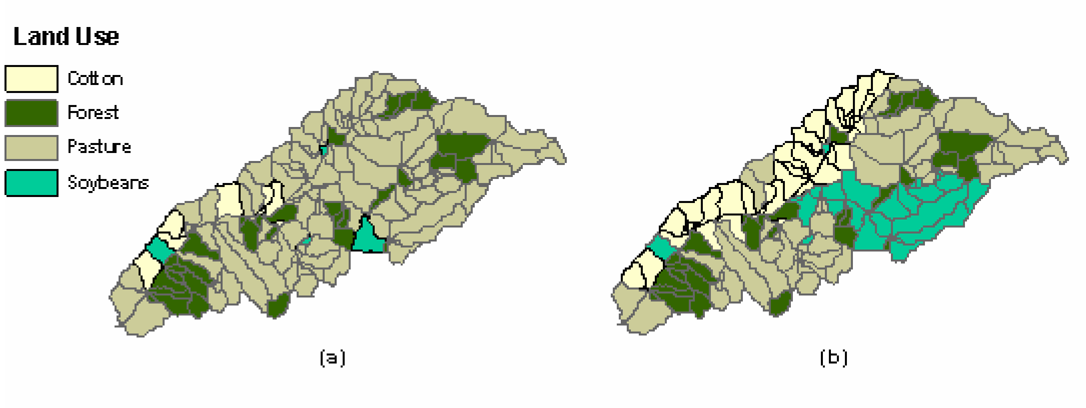

Figure 9 Watershed subdivision and land use; (a) actual, (b) hypothetical.

Figure 10 shows how the increased cultivated area may affect the concentrations of nitrogen compounds in the Goodwin Creek channel, especially during large storm events.

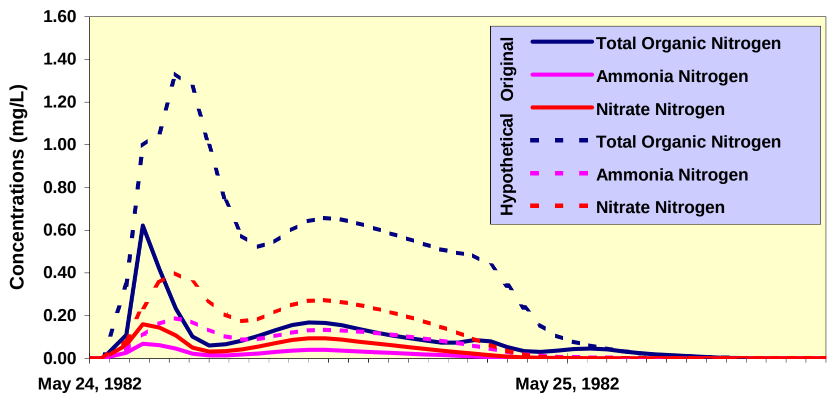

Figure 10 Computed concentrations of total organic nitrogen, ammonia nitrogen, and nitrate nitrogen at the watershed outlet for the storm event of May 24, 1984.

8. CONCLUSIONS

This paper describes the main capabilities of the CCHE1D channel network model. As illustrated by the application examples, the model can be a valuable tool in a wide variety of engineering problems in the areas of hydrology and flood analysis, sediment transport, and water quality. It also shows that integrated watershed–channel modeling permits the study of the behavior of channels in response to changes in land use or to the implementation of sediment or pollutant control measures. The approach is useful in the identification of pollutant sources, in the analysis of the performance of both in-stream and upland erosion control works and Best Management Practices (BMPs), and in the determination of pollutant-related problems, such as the definition of TMDL's.

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