SHETRAN: DISTRIBUTED RIVER BASIN FLOW AND TRANSPORT MODELING SYSTEM

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ABSTRACT: Physically based spatially distributed (PBSD) river basin models have been available for over 10 years. One of their strengths lies in the way the surface and subsurface are represented as coupled parts of a whole, giving ground-water flows that are controlled by such factors as realistic surface saturation and infiltration, and surface conditions that are controlled by realistic groundwater levels, discharges, and so forth. PBSD sediment and solute transport models can be integrated into PBSD river basin modeling systems, and the integrated systems are powerful tools for studying the environmental impacts associated with land erosion, pollution, and the effects of changes in land use and climate, and also in studying surface-water and ground-water resources and their management. SHETRAN takes PBSD river basin modeling a step further, in that multifraction sediment transport and multiple, reactive solute transport are handled within a single system, fully coupled to water flow, and the subsurface is modeled as a fully 3D variably saturated heterogeneous medium. SHETRAN therefore has a substantial capability for addressing environmental and water resources problems that span the traditional disciplines of river basin and ground-water modeling.

INTRODUCTION

The starting point for the development of SHETRAN was the Système Hydrologique Européen (SHE) (Abbott et al. 1986a,b), a physically based spatially distributed (PBSD) system for modeling coupled surface and subsurface water flow in river basins. SHE was also the starting point for the development of the SHESED system for coupled water flow and bulk sediment transport (Wicks and Bathurst 1996) and for the MIKE SHE system, which can, among other things, model advection and dispersion of conservative solutes in multilayer aquifers, nitrogen transformations in the root zone, soil erosion, and irrigation (Refsgaard and Storm 1995). The international team that developed SHE were specialists in modeling surface processes and were influenced by Freeze and Harlan's (1969) ''blueprint'' for a modeling system and by the pioneering work of Freeze (1971). The thinking behind the ''blueprint'' was that good physically based models exist for the main processes of water movement in river basins (such as channel flow and flow in porous media), and these can be integrated into flexible spatially distributed modeling systems that can be applied to river basins of any size and type. When considered alongside other approaches to river basin modeling [for example, Ball and Trudgill (1995) and Singh (1995)], this approach is probably the best for giving detailed 3D descriptions of flow and transport in the combined surface/subsurface.

SHETRAN is a 3D coupled surface/subsurface PBSD finite-difference model for coupled water flow, multifraction sediment transport, and multiple, reactive solute transport in river basins. A substantial part of the development funding for SHETRAN was obtained from United Kingdom Nirex Limited (Nirex) under their safety assessment research program for a potential deep underground repository for radioactive wastes. Within Nirex's program, SHETRAN is used to investigate the distribution and movement of radionuclides in the surface and near surface (top 50 m or so) of basins.

SHETRAN gives a detailed description in time and space of the flow and transport in the basin, which can be visualized using animated graphical computer displays. This makes it a powerful tool for use in studying the environmental impacts of land erosion, pollution, and the effects of changes in land use and climate, and also in studying surface-water and ground-water resources and management. SHETRAN is currently being integrated into a decision-support system to maximize its usefulness in environmental impact management.

The main differences between SHETRAN and existing PBSD river basin modeling systems lies in its comprehensive nature and capabilities for modeling subsurface flow and transport. The subsurface is treated as a variably saturated heterogeneous porous medium, and fully 3D flow and transport can be simulated for combinations of confined, unconfined, and perched systems. The ''unsaturated zone'' is modeled as an integral part of the subsurface, and subsurface flow and transport are coupled directly to surface flow and transport. So, for example, it is possible to model flow and transport in ''deep'' ground water, while at the same time modeling flow and transport in complex near-surface regions that respond rapidly to rainfall and strongly affect recharge and surface runoff.

River basin and ground-water modeling have traditionally been thought of as separate disciplines with different aims. In reality, however, surface water, soil-water, and ground-water are coupled parts of a whole. There is an increasing awareness of the importance of the role of ground-water storage and flow in the processes of runoff generation, and ground-water modelers increasingly acknowledge that they often treat the surface in an overly simple way in their calculations of recharge (Ledoux et al. 1989; Anderson and Burt 1990; Sudicky 1996). Two of the strengths of SHETRAN are the simple, direct way the surface and subsurface are coupled and the detail with which flow and transport in the subsurface are represented. Combined, these strengths give capabilities that blur the distinction between river basin and ground-water modeling, and provide a modeling system capable of being used for both.

SHETRAN

Three main components lie at the core of SHETRAN, one each for water flow, sediment transport, and solute transport. Flow is assumed not to be affected by transport and sediment transport not to be affected by solute transport, so the three components lie in a natural hierarchy (Fig. 1). The components model physical processes (Table 1) represented by PBSD equations, most of which are partial differential equations (Table 2), and extensive data sets are required for model pa-

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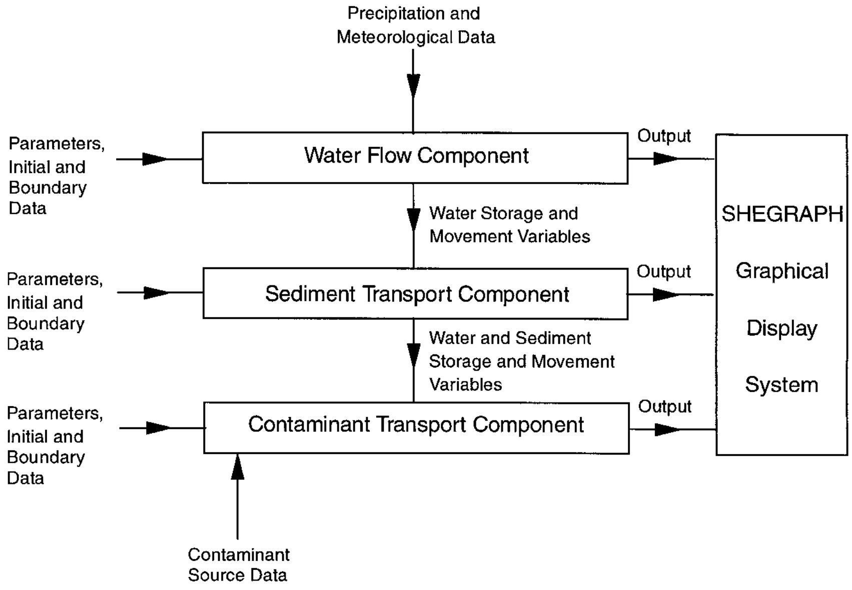

FIG. 1. Information Flows in SHETRAN

TABLE 1. Main Processes Represented in SHETRAN

Component (1)	Processes (2)
Water flow: Surface water flow on ground surface and in stream channels; soil-water and ground-water flow in unsaturated and saturated zones, including systems of confined, unconfined, and perched aquifers	• Canopy interception of rainfall • Evaporation and transpiration • Infiltration to subsurface • Surface runoff (overland, overbank, and in channels) • Snowpack development and snowmelt • Storage and 3D flow in variably saturated subsurface • Combinations of confined, unconfined, and perched aquifers • Transfers between subsurface water and river water • Ground-water seepage discharge • Well abstraction • River augmentation and abstraction • Irrigation
Sediment transport: Soil erosion and multifraction transport on ground surface and in stream channels	• Erosion by raindrop and leaf drip impact and overland flow • Deposition and storage of sediments on ground surface • Total-load convection with overland flow • Overbank transport • Erosion of river beds and banks • Deposition on river bed • Down-channel advection • Infiltration of fine sediments into river bed
Solute transport: Multiple, reactive solute transport on ground surface and in stream channels and subsurface	• 3D advection with water flow • Advection with sediments • Dispersion • Adsorption to soils, rocks, and sediments • Two-region mobile/immobile effects in soils and rocks • Radioactive decay and decay chains • Deposition from atmosphere • Point or distributed surface or subsurface sources • Erosion of contaminated soils • Deposition of contaminated sediments • Plant uptake and recycling (simple representation only) • Exchanges between river water and river bed

TABLE 2. Flow and Transport Equations for SHETRAN

Process (1)	Equation (2)
Subsurface flow	Variably saturated flow equation (3D) (P)
Overland flow	Saint-Venant equations, diffusion approximation (2D) (A)
Channel flow	Saint-Venant equations, diffusion approximation (flow in a network of 1D channels) (A)
Canopy interception and drip	Rutter equation (A)
Evaporation	Penman-Monteith equation (PME) (or as fraction of potential evaporation rate) (A)
Snowpack and melt	Accumulation equation and energy budget melt equation (or degree-day melt equation) (A)
Overland sediment transport	Advection-dispersion equation (2D) with terms for deposition and erosion by raindrop and leaf drip impact and overland flow (W)
Channel sediment transport	Advection-dispersion equation (transport in network of 1D channels) with terms for deposition and erosion and for infiltration into bed (W)
Land surface and subsurface solute transport	Mobile/immobile advection-dispersion equation (3D) with terms for adsorption, dead space, radioactive decay, erosion of contaminated soil, deposition of contaminated sediments, plant uptake, and deposition from above (E)
Channel solute transport	Advection-dispersion equation (transport in network of 1D channels) with terms for adsorption to sediments, radioactive decay, erosion and deposition of contaminated bed materials, overbank transport, and deposition from above (E)

Note: (A) = Abbott et al. (1986b); (E) = Ewen (1995); (P) = Parkin (1996); and (W) = Wicks and Bathurst (1996) and Purnama and Bathurst (1991).

rameterization (Table 3). The development of SHETRAN took many man-years of effort, and so far five man-years have been spent on testing. SHETRAN was created by integrating upgraded versions of the evapotranspiration, snowmelt, and surface water flow components from SHE (Abbott et al. 1986b), the variably saturated subsurface flow component of Parkin (1996), a revised version of the sediment transport component of SHESED (Wicks and Bathurst 1996), which allows multifraction transport using the approach proposed by Purnama and Bathurst (1991), and the component developed by Ewen (1995) for combined surface/subsurface multiple, reactive solute transport. Further SHETRAN developments currently under way are listed in Table 4.

In normal use, SHETRAN models a single complete river basin, and data for the basin are drawn from some or all of the following hard and soft sources:

- Records from weather stations, rain gauges, evaporation pans, and so forth
- River gauging records
- Contour and digital maps of surface elevation
- Maps of geology and land use
- Satellite images and surface surveys of land use and vegetation cover

TABLE 3. Main Data for Physical Properties and Initial and Boundary Conditions in a SHETRAN

Component (1)	Data (2)
Water flow	• Precipitation and meteorological data for each station • Station numbers for each column and river link • Size and location of columns, river links, and finite-difference cells • Soil/rock types and depths for each column • Land-use/vegetation for each column • Man-controlled channel flow diversions and discharges • Rates of borehole pumping, artificial recharge, flow diversions, and so forth • Initial hydraulic potentials for subsurface • Initial overland and channel flow depths • Initial snowpack thicknesses and temperatures • Boundary hydraulic potentials (or flow rates) • Boundary stream inflow rates • Canopy drainage parameters and storage capacities • Ground cover fractions • Canopy resistances and aerodynamic resistances (for PME) • Vegetation root density distribution over depth • Porosity and specific storage of soils/rocks • Matric potential functions for soils/rocks • Unsaturated hydraulic conductivity functions for soils/rocks • Saturated hydraulic conductivity of soils/rocks • Snow density, zero-plane displacement, and roughness height
Sediment transport	• Raindrop size distribution • Drop sizes and fall distances for canopy drainage • Proportion of canopy drainage falling as leaf drip • Initial thickness of sediments and channel bed materials • Sediment concentrations in waters entering via inflowing streams • Sediment porosities and particle size distributions • Erodibility coefficients
Solute transport	• Initial concentrations in surface and subsurface waters • Concentrations in rainfall • Dry deposition rates • Concentrations in flows entering at boundaries • Dispersion coefficients for soils/rocks • Adsorption distribution coefficients (and exponents, if nonlinear) • Mobile fractions for soils/rocks • Fractions of adsorption sites within mobile regions in soils/rocks • Exchange coefficients for mobile and immobile regions in soils/rocks • Decay constants (e.g., for radioactive decay) • Plant-uptake constants

- Surveys of channel cross-sectional dimensions and bed and bank conditions
- Logs created during borehole drilling, digging soil pits, soil coring, and examining existing exposures
- Soil permeametry and borehole pumping test records
- Laboratory soil/rock/sediment particle size and hydraulic test records
- Geophysical logs for borehole and surface tests
- Water supply extraction licenses
- Farm records and historical records of flooding
- Plot and hillslope experimental results, including erosion and tracer tests
- Data for nearby or similar basins
- Hydrogeological/hydrological reasoning and experience
- Previous experience with PBSD modeling

It usually takes at least a few weeks to create a preliminary data set for a new basin.

As well as single complete basins, SHETRAN can be applied to parts of basins or to a group of contiguous basins [e.g., Adams (1995)]. It can, for example, be applied to a single hillslope plot or to all the subbasins in a large (e.g., 5,000 km^2) river basin.

SHETRAN has not followed the ‘‘layered’’ approach to computation used in SHE (i.e., ground surface, unsaturated zone, and saturated zone). The main computational structures in SHETRAN are ‘‘stream links’’ and ‘‘columns’’ (Figs. 2 and 3): River networks are modeled as networks of stream links, and the rest of the basin is modeled as a set of columns, each containing its own part of the ground surface and vegetation. This structure was developed originally for the solute transport component (Ewen 1995), within which there are only two main algorithms: One for transport along stream links, and another for vertical transport in a column (the method used to represent the lateral flow and transport between columns is described later). Each column comprises many finite-difference cells, stacked one above the other, and there may be a different soil or rock associated with each cell. There is lateral transport between cells in neighboring columns, as well as

TABLE 4. Continuing Development Work Involving SHETRAN

Status (1)	Description (2)
Under test	• Nitrate component; simulates nitrogen transformations and leaching and transport of nitrate • Landslip component; simulates landslip triggering and sediment quantities released
Under development	• User-friendly graphical interface for data input, editing, and displaying results • Decision-support system for planning and environmental impact assessment, containing SHETRAN as one of set of models
Designed	• Cold regions component that models ground and river freezing and their effects on solute transport
Under design	• River network component based on solution of full Saint-Venant equations; will improve flood modeling • Regional groundwater component to sit below variably saturated subsurface flow model • Capability for preferential flow in subsurface

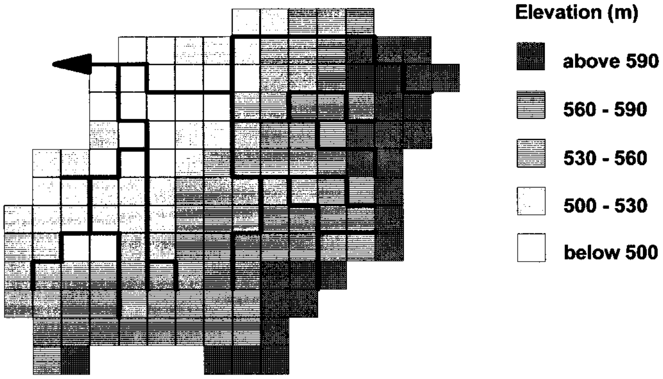

FIG. 2. SHETRAN Grid for Rimbaud Basin, France, Showing Tops of SHETRAN Columns, River Link Network, and Ground Surface Elevations

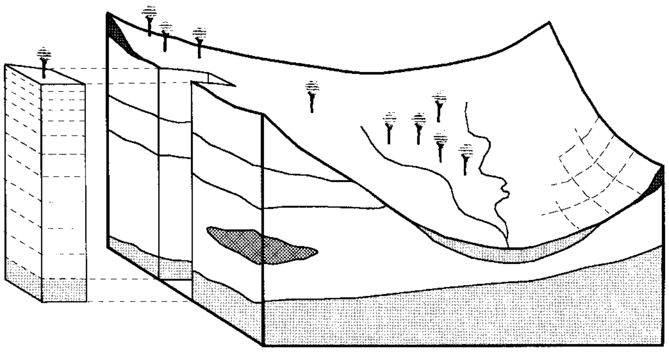

FIG. 3. Schematic Illustration Showing SHETRAN Column and Its (Sub-Column) Cells

vertical transport in each column, thus giving solute transport in three dimensions.

When the solute transport component was first developed (Ewen 1990), it was coupled directly to SHE, effectively using SHE as the water flow component. In SHE, subsurface water flow is described by the 2D Boussinesq equation for vertically averaged lateral flow in a single phreatic aquifer, and the 1D Richards equation for vertical flow in the unsaturated zone. The system thus created is an interim version of SHETRAN, called SHETRAN Version 3. It uses the ''layered'' (SHE) approach for flow and the column/link approach for transport. To allow 3D solute transport to be simulated in Version 3, a 3D velocity field is derived from the Boussinesq and Richards results (Ewen 1995).

To create SHETRAN Version 4, the subject of this paper, the column approach was extended to subsurface flow (Parkin 1996). The key to the capability to model complex combinations of confined, unconfined, and perched systems lies in the way lateral flow and transport are modeled. To minimize computational difficulties, yet give a very flexible system, each cell in each column is assumed to exchange water and solute with a maximum of only two cells in each neighboring column (Fig. 4).

All the flow calculations for the basin for a given time step are completed before the solute transport calculations begin. The solution procedure for both water flow and solute transport involves sweeping through the basin, column by column, and carrying out implicit finite-difference calculations for vertical flow/transport within each column. This involves solving a tridiagonal matrix equation that is a finite-difference analog for the governing partial differential equation for flow/transport in a vertical column. Although these calculations are for 1D flow/transport, the result is a fully 3D solution. This is achieved by including a source term in the analog equations to account for the lateral flow/transport taking place between each cell and the associated cells in the neighboring columns. The analog equations are therefore strictly analog for the 3D partial differential equations for flow/transport, derived in a form suitable for use in the column-by-column sweeping procedure. For the water flow calculations, several sweeps are made during each time step to reduce the errors arising from the inherent nonlinearity of variably saturated flow.

One advantage of the column approach is that the coupling between surface and subsurface solute transport is strong and simple, as the surface is an integral part of the columns. For water flow, the coupling is achieved via the top boundary conditions for the columns, which are controlled by surface conditions. The surface flows are handled in the fashion developed for SHE by Abbott et al. (1986b) (Tables 1 and 2), using an implicit finite-difference approach. To capture some of the fast dynamics near the channels, a degree of gird refinement is incorporated in SHETRAN in the form of stream banks, which are narrow columns that lie on either side of each river link (Fig. 4). The coupling between subsurface flow and transport and flow and transport in river links is handled in the same fashion as intercolumn lateral flow and transport, but the efficiency of this coupling is partly controlled by a channel-bed hydraulic resistance calculated from the physical properties of the bed materials.

A typical run-time for a 1 year SHETRAN simulation is around 2 h of processing on a high-performance UNIX workstation for a simulation involving water flow and the transport of five solutes in a basin comprising 250 columns, 50 links, and 50 cells per column. The simulation time step is usually less than 2 h and is automatically reduced during and immediately after rainfall; steps as short as a few minutes are usual during heavy rainfall. For simplicity, a common time step is used in all three components.

Run times can be reduced using parallel processing computers [Parkin (1996) measured a 3.5 speed-up rate using six processors, with one processor for water flow and one each for five solutes]. Although tests have not yet been carried out, SHETRAN was designed so that different processors can be used for each column, thus allowing it to be run on massive multiprocessing computers.

RESULTS

The main phase of work on testing SHETRAN is nearing completion, and the new results described here are drawn from this work. One project involves modeling flow in complex subsurface sequences of Quaternary deposits at a monitored field site (Fig. 5). In the figure, the high lateral velocities close to the ground surface indicate interflow, and the moderate lateral velocities at depth indicate saturated ground-water flow.

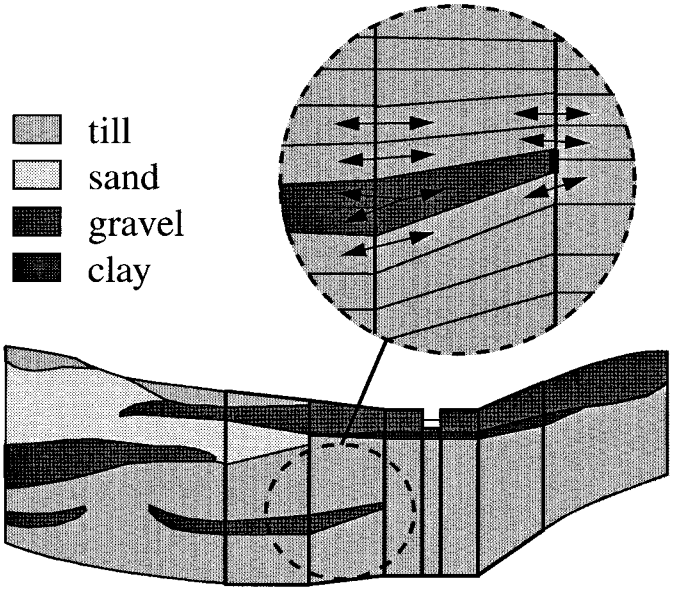

FIG. 4. Schematic Illustration of Vertical Cross-Section through Sequence of Quaternary Drift Deposits, Showing Several SHETRAN Columns, and Exploded View Showing Lateral Connections between SubColumn Cells

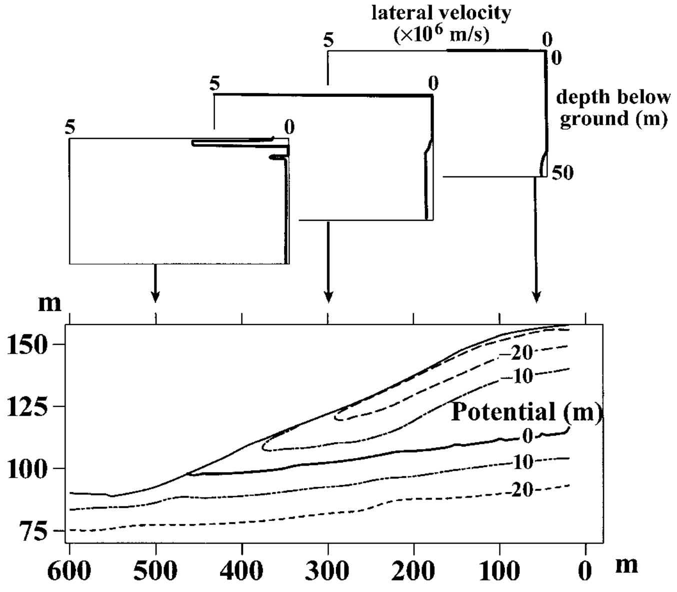

FIG. 5. Vertical Slice through Hillslope Comprising Sandstone Overlain with Complex Sequence of Quaternary Deposits, Showing Simulated Subsurface Water Potentials and Three Profiles of Lateral Velocity

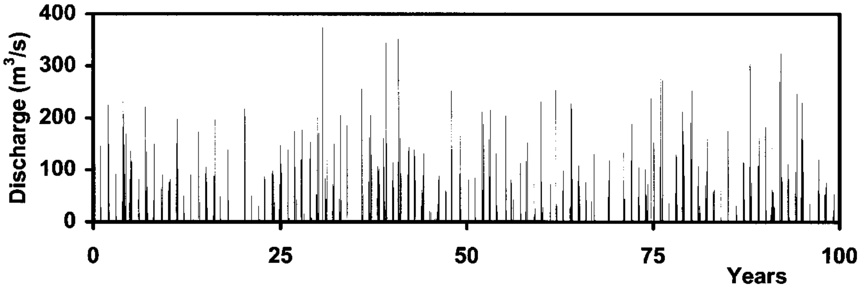

FIG. 6. 100 Year Discharge Hydrograph Simulated for Cobres Basin, Portugal, for Rainfall Data Created Using Stochastic Rainfall Simulator

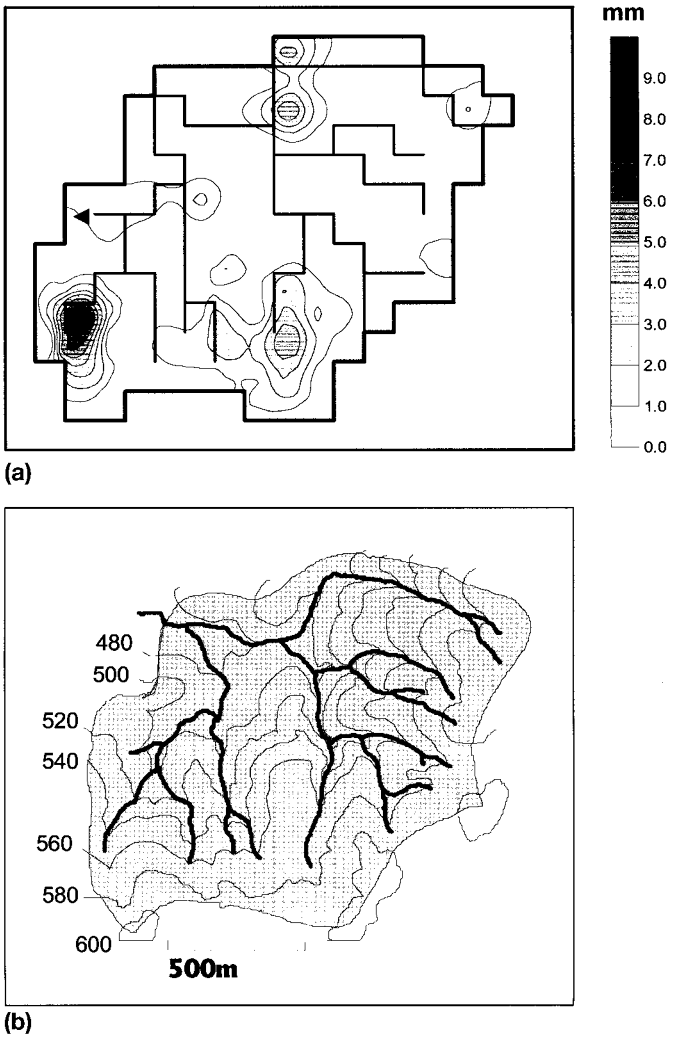

FIG. 7. (a) Spatial Distribution of Cumulative Simulated Erosion for Rimbaud Basin, France, for August 1990–July 1991, inclusive. (b) Elevation in Meters

The peaks in the leftmost velocity profile are for two layers of gravel lying in a sequence of alternating clay and gravel deposits. The aim of the project is to predict the saturated areas and the associated discharge rate for contaminated ground water discharging to the surface. This is a modeling problem where the heterogeneity of the subsurface structure must be represented explicitly, and where very strong coupling is required between the surface and subsurface if the dynamics of the interactions between the regions are to be captured.

Some long-term simulations have been run (Fig. 6) to study the effects of climate change on water resources and to examine interyear variability of basin response. It has been found that if a basin has moderate ground-water storage, the pattern of variability can be quite complex. With the ever-increasing power of computer processors, it is becoming increasingly practical to run simulations of 100 years or more.

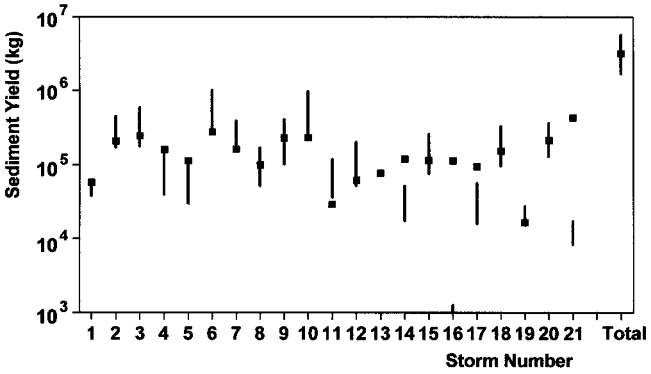

FIG. 8. Validation Result for Erosion during 21 Storms in Laval Badlands Gully Basin, Draix, France

Studies of land-use change have included a before-and-after study for the Rimbaud basin, France, which was denuded by fire in August 1990, affecting its erosion characteristics (Fig. 7). The areas of high erosion in the basin tend to have steep slopes and thin soils overlying impermeable rock. [The validation method of Ewen and Parkin (1996) was applied to water flow in this basin, prefire, using SHETRAN Version 3.] Fig. 8 shows results from a validation exercise for sediment transport. The squares in the figure are measurements for storm sediment yield. The vertical lines are SHETRAN prediction bands derived by running SHETRAN twice, once with low estimates for the sediment erodibility coefficients, and once with high estimates.

To validate the solute transport modeling in SHETRAN, hillslope plot tracer experiments have been run, and the results are being used to validate the modeling of lateral transport and dispersion of conservative and nonconservative solutes in a leaky perched system.

An important element of the SHETRAN simulation work for Nirex involves simulating the migration of radionuclides in the near surface and surface zones of hypothetical basins under future climates (Figs. 9 and 10). The background to this work is described in Thorne (1995). The source of solute for the top basin shown in Fig. 9 is a field of poorly permeable soil contaminated with unit concentration of a highly sorbing solute. The source for the lower basin is contaminated regional ground water entering the subsurface of the basin with unit concentration of a conservative solute. The solute discharge for the top basin is controlled by erosion and sediment transport, and for the lower basin is controlled by solute storage and transport in the subsurface. Fig. 10 shows a strong vertical flow and transport through a break in a confining layer (thick line).

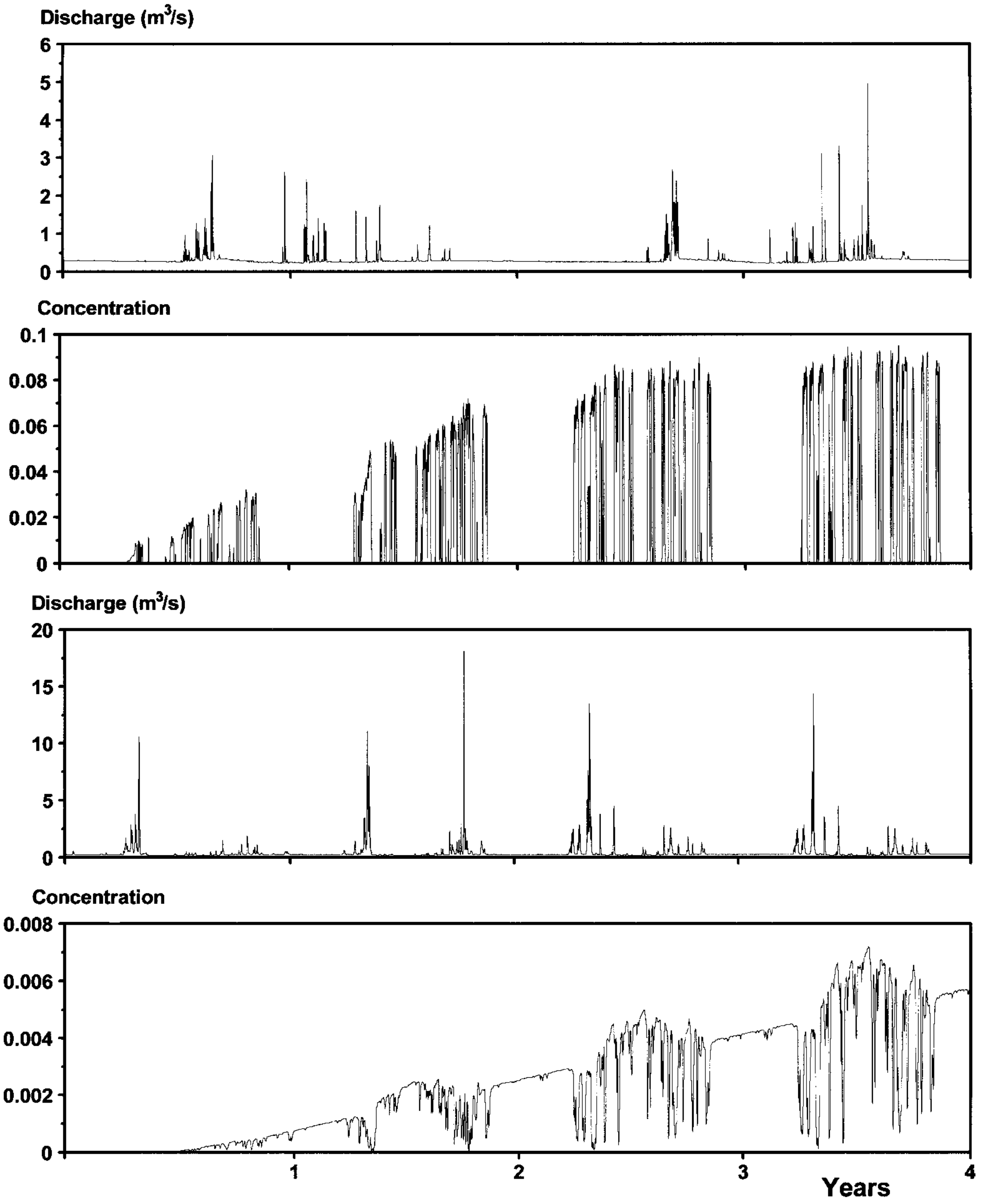

FIG. 9. Simulated Flow and Solute Discharge from Two Basins (Not Identical) that Develop Substantial Snowpacks in Winter

Most of the above studies make full use of the PBSD nature of SHETRAN, with its unique flexibility and strong surface/subsurface coupling. SHETRAN is proving to be a powerful tool for hydrological research and engineering applications and will, we hope, lead to some new insights into river basin behavior. Full details of many of the above studies will be reported at a later date.

DISCUSSION

There are many situations where PBSD river basin models are necessary and the substantial effort required to set up and run a PBSD model is warranted. This includes studies involving environmental impact assessment and surface-water and ground-water resources management and pollution, but also includes hydrological research into whole-basin behavior, surface-subsurface interactions, process interactions, runoff generation mechanisms, extreme events, water resources management strategies, and many other topics. Recently, approaches have been developed to extend the use of PBSD modeling to very large areas, up to the continental scale (Ewen 1997).

The treatment of sediments as separate but interacting classes has advantages for the simulation of both sediment and solute transport. The usual way to define sediment classes in SHETRAN is by particle size, and classes of ‘‘fine’’ sediments will be transported more efficiently with flow than classes of ‘‘coarse’’ sediments. Solute adsorption to sediments often depends strongly on sediment particle size, so the particle-size approach to choosing classes allows the simulation of the preferential sorption and transport of solutes by fine sediments.

The only interaction allowed between simultaneously transported solutes is for first-order decay and generation, as is required if the solutes are members of a radioactive decay chain. Other interactions are currently being considered for inclusion in the solute transport component, and a nitrogen transformation component has been developed and is currently under test (Table 4). The capability to simulate the simultaneous transport of several solutes has practical advantages in itself. For example, provided the adsorption behavior is linear, the consequences of pollution by a single solute released at several points within a basin can be predicted using a single simulation in which a nominally different solute is released from each source; the contribution of each source to the pollution of the basin can then be inferred from the resulting

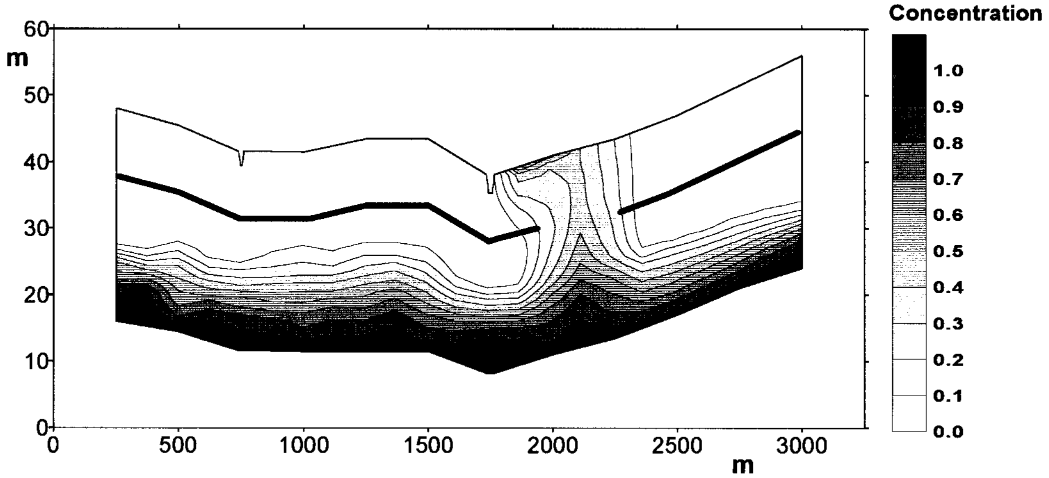

FIG. 10. Vertical Slice Showing Simulated Concentrations in 3D Plume of Solute that Entered Basin from Below with Inflowing Regional Ground Water

concentration distributions of the several nominally different solutes. (This avoids the expense of running the full water flow and sediment transport simulations several times, as would be required if separate full simulations were run for each source.) In a similar fashion, a different highly adsorbed solute can be associated with each of several sediment source locations, and the source location of the sediments deposited on a flood plain after a flood (say) can be inferred from the concentrations of the solutes in the deposited sediments.

Over the past several years, there has been a debate about the value of PBSD river basin modeling (Abbott et al. 1986a; Beven 1989; Loague 1990; Bathurst and O'Connell 1992; Grayson et al. 1992 and 1994; Smith et al. 1994; Blöschl and Sivapalan 1995; O'Connell and Todini 1996). The main criticisms commonly leveled at PBSD river basin modeling are listed and discussed below:

1. The true rather than theoretically potential capabilities of PBSD models have not been investigated and reported.
2. PBSD models inevitably give unphysical results as a consequence of the ''scale problem'' and the large size of the grids used.
3. Some important processes are not included in PBSD models.

From our experience in building and using PBSD river basin models, we know there is some substance to these criticisms (and also that equivalently substantial criticisms can be made for all existing types of river basin models). At the root of criticism 1 are claims made by PBSD modelers that, since their models are physically based and use data for physical properties, it is possible to use their models to predict the discharge from ungauged basins, the moisture conditions on uninstrumented hillslopes, the effects of changes in land use and climate, and so forth. This criticism has been addressed in Ewen and Parkin (1996) and Parkin et al. (1996). In that work, a ''blind'' validation method was proposed and tested, with the central aim of developing a method to establish how good PBSD models are when used to make predictions of these kinds.

The ''scale problem'' is a problem for hydrology, hydrogeology, soil physics, geophysics, and so forth, as a whole, rather than a problem for PBSD modelers alone. The essence of the problem is that the values obtained by measuring a physical property (e.g., the saturated hydraulic conductivity) at several points in a region usually cannot simply be ''averaged'' to get a single value that properly reflects the physics of the relevant process viewed at the scale of the region (Beven 1993; Blöschl and Sivapalan 1995). One element of criticism 2 that can properly be leveled at PBSD modelers is that they use very large grids, exacerbating the scale problem. It is, however, good practice in PBSD modeling, partly to minimize numerical discretization errors, to use as fine a grid as possible, taking into account the size of the basin, the duration of simulation required, and the power of the computer available.

To give an example of criticism 3, preferential flow through the unsaturated zone is not modeled in SHETRAN, yet it is known to be an important process for the movement of water, sediments, and solute in the subsurface (Beven and Germann 1982; White 1985), and several methods for modelling preferential flow have been available for several years (Germann 1988). [Preferential solute transport is modelled in SHETRAN, using the two-region mobile/immobile advection-dispersion equation of van Genuchten and Wierenga (1976).] It is clear that preferential flow is important, and a capability to model preferential flow should be added to SHETRAN. The problem faced, however, is choosing the right approach, since soil physics has not yet come to a conclusion about how best to model preferential flow. Current research in soil physics is concentrating on multiregion flow and transport models [Durner and Flühler (1996); Ewen (1996a,b)], but these are, as yet, impractical for incorporation in PBSD river basin models. The previous generation of models [e.g., the two-region models of Yeh and Luxmoore (1982) and Gerke and van Genuchten (1993)] probably could be adapted for use in PBSD river basin models; however, these models are not widely accepted or used. One approach that could readily be used is to treat preferential flow as bypass flow, with empirical values giving the fraction of the surface water that ''jumps'' to given depths in given times, but the use of such an empirical approach has so far been resisted since it is not in the spirit of PBSD modeling.

When they presented their ''blueprint,'' Freeze and Harlan (1969) discussed, and appeared to share, reservations raised by Amorocho and Hart (1964) and Crawford and Linsley (1966) about the concept of PBSD river basin modeling. The reservations related to the then incomplete nature of the current understanding of physical processes and their interactions, and to the impracticality of creating data sets that describe the basins in sufficient detail. These are still concerns today, but much progress has been made in physical hydrology, remote sensing, computing hardware, GIS, and so forth in the past 30 years. Indeed, models matching and exceeding the specifications in Freeze and Harlan's ''blueprint'' have successfully been applied in a wide range of tests and applications [Bathurst 1986; Jain et al. 1992; Refsgaard et al. 1992; Lohani et al. 1993; Connolly and Silburn 1995; Bathurst and Cooley 1996; Parkin et al. 1996)]. The extensive work that has been done in model development, testing, and application has ensured that PBSD river basin modeling is now widely accepted as an important and powerful tool for use in environmental impact assessment and water resources studies and management, and this work will continue with the use and further development of SHETRAN.

CONCLUSIONS

It has been demonstrated that the SHETRAN physically based, spatially distributed modeling system is suitable for studying the environmental impacts of land erosion, pollution, climate change, and land use change within river basins. The development of SHETRAN has taken river basin modeling a step beyond previous models: Multifraction sediment transport and multiple, reactive solute transport are handled within a single system, fully coupled to surface and subsurface water flow, and the subsurface is modeled as a fully 3D variably saturated heterogeneous medium. SHETRAN therefore has a substantial capability for addressing environmental and water resources problems that span the traditional disciplines of river basin and ground water modeling.

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