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Development and application of a prototype version of INCA-Sed: A model for simulating fine sediment delivery and transfer in catchments

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1. Introduction

This report describes the development and preliminary application of a prototype version of a catchment-scale sediment delivery model for simulating in-stream suspended sediment concentrations in response to hydrologic forcing. This model is designed with an INCA-compatible structure, so that it can be linked to the INCA-P phosphorus model to simulate transport of the particulate phase but can also be run alone to simulate sediment delivery to and transfer in stream channel reaches. At this stage of model development, the INCA-Sed prototype model code is a C++ program, written by N P Jarritt, based on model equations developed by D S L Lawrence and N P Jarritt, and the equations and applications reported here refer to this prototype. Continuing work within the context of the EUROLIMPACS project is concerned with incorporating these equations into an INCA user interface, so that the sediment delivery model can be applied by users to a wider range of users to European catchments.

The principal aim underlying the development of the prototype sediment delivery model is to develop a tool for simulating the time-dependent patterns of suspended sediment in channel reaches. In order for such a model to be a useful tool which can feasibly be applied to a range of catchments, it must satisfy the following criteria: 1) require only readily available data, rather than depend on specialised data from intensively instrument catchments; 2) use only a limited number of variables and parameters so as to avoid ‘overparameterisation’; and 3) include only the dominant processes controlling sediment delivery and transfer from slopes to channel reaches and within the channel reaches comprising the INCA-style fluvial system.

2. Background and Context

The term ‘sediment delivery’ has been widely used to describe the combined processes of sediment movement within a catchment, from soil erosion on slopes through to fluvial export at the catchment outlet (Walling,1983). Traditional approaches to empirical quantification of this set of processes include sediment rating curves (Leopold and Maddock, 1953), which treat the statistical relationship between discharge and suspended sediment concentrations as an in-stream problem, as well as sediment delivery ratios (Glymph, 1954), which estimate sediment yield as a fraction of gross erosion from catchment slopes. Although these techniques suffer from problems of spatial and temporal aggregation, the sediment ratio concept incorporates the role of catchment slopes as a source zone for sediment. This general approach has been further developed in recent years to include spatial variability in likely sediment source areas based on variables such as land use, catchment characteristics and hydrologically effective rainfall (e.g.Ferro, 1997; Naden and Cooper, 1999; Watts, et al., 2003), and these techniques often perform better than more detailed physical models (Jetten et al., 1999). The principal shortcoming of empirically-derived models continues to be the relative lack of characterisation of the processes contributing to the time-dependent patterns of suspended sediment concentrations observed in rivers. This can undermine their ability to capture hysteresis arising from sediment 'flushing' and source zone depletion on both event-based and seasonal timescales (Walling, 1977). It also can limit compatibility with more process-based time-dependent models of hydrologic and nutrient fluxes.

A variety of fully-distributed and physically-based models describing sediment erosion and transport have also been developed within the past decade, e.g. WEPP (Laflen et al., 1991), LISEM (deRoo et al., 1996), and EUROSEM (Morgan et al., 1998). Much of this work was initially motivated by detailed plot-scale investigations of soil erosion processes, and these physically-based model components have been extended to the catchment scale to provide linked hillslope/channel models for sediment flux. This modelling strategy represents a powerful tool for investigating physical processes in conjunction with field experiments or detailed monitoring programmes; however, the large number of input parameters which must be estimated or calibrated often limits the model applications to small-scale, research catchments, where sediment pathways and storage zones can be established by monitoring programmes (Jetten, et al., 1999). In particular, the rigorous demands for input data implicit in physically-based models may make their routine application for environmental management purposes unfeasible, and therefore it is difficult to extend them to larger spatial scales. Fully-distributed models also usually discretise catchment slope processes to a grid or mesh-scale resolution, which can result in long run times and numerical errors and instabilities, further undermining the viability of routine application. These limitations highlight the need for a third generation of 'integrated' catchment sediment delivery models which incorporate readily available environmental data pertaining to hydrometeorological conditions, land use, soil erodibility, and catchment and stream channel morphology at an appropriate level of spatial aggregation. This semi-distributed approach has been used for several years in hydrological modelling (Hughes and Sami, 1994) and recently in the modelling of sediment yield (Liden, et al., 2001). It is also the approach underlying the INCA-Sed model, as well as the related catchment models of nutrient dynamics, INCA-N (Whitehead et al., 1998) and INCA-P (Wade et al., 2002).

Two criticisms can potentially be levelled at the ‘intermediate’ modelling approach presented here. Firstly, multiparameter models are inevitably associated with non-unique solutions in which multiple sets of parameters produce equally acceptable results. Fully-distributed, physically-based models are not immune from this weakness and, in fact, are generally even more encumbered by it (Quinton, 1997; de Roo, 1998). In this work, we have used an automated General Sensitivity Analysis in model calibration, as has previously been applied in the integrated catchment model for phosphorus dynamics, INCA-P (Wade, et al., 2001). The results of this analysis are given in the accompanying report on this procedure. This techniques enables the likely ‘envelope’ of acceptable solutions to be distinguished by multiple Monte Carlo trials and can also be used to identify the most responsive parameters, as well as aid in constraining key source zones and pathways within the study catchments. A second criticism, which tends to apply equally to monitoring and modelling approaches, is the lack of an explicit process characterisation of slope to channel linkages and floodplain storage. This is a problem that has long been recognised by geomorphologists, particularly as a limitation of slope-based soil erosion models and monitoring programmes. In many larger catchments, a full closure on sediment budgets can only be achieved by invoking process linkages on a Holocene or even longer timescale. However, the objective underlying this sediment delivery tool is not to fully delineate the functioning of the sediment delivery system in the study catchments, but rather, to characterise the ‘response’ of the fine sediment regime to hydrologic forcing, based on available suspended sediment and related time series. In the sections that follow, the model structure and key equations are presented, and the model performance is then demonstrated by contrasting the sediment response of two lowland catchments in southern England, the Lambourn and the Enborne.

2. INCA-Sed Model Structure

i) Spatial structure

INCA-Sed follows the same model structure as the INCA-N (Whitehead, et al., 1998) and INCA-P (Wade et al., 2002) models, using a semi-distributed representation of the catchment system. Catchment physical features in INCA-Sed are recognised at three spatial levels, rather than on a grid cell basis. At the first level, the main river channel is divided into a series of reaches. The land area that drains into each of these reaches is then defined as a 'sub-catchment' using a Digital Terrain Model (DTM) and Geographical Information System algorithms (Morris and Flavin, 1994). At the second level, each sub-catchment is further divided into a maximum of six land use classes. This is achieved by overlaying the sub-catchment boundaries on a land use map and the percentage of each land use type within each sub-catchment is calculated. At the third spatial level, a generic cell of unit area is applied to each land use type. A parameter set is derived for the cell by averaging the spatial parameters and is used in the processing of the model equations. Sub-catchment totals are derived by summing the results for each land use type.

The in-stream component of the model treats each reach as a fully-mixed reservoir, with inputs from upstream and the sub-catchment associated with the reach, and an output to the reach immediately downstream. The INCA models run on a daily timestep, producing output as daily averages for each sub-catchment and stream reach. The model equations using a fourth-order Runge-Kutta numerical technique. This allows the equations to be solved simultaneously, ensuring that no individual process takes precedence over any other.

ii) Process linkages

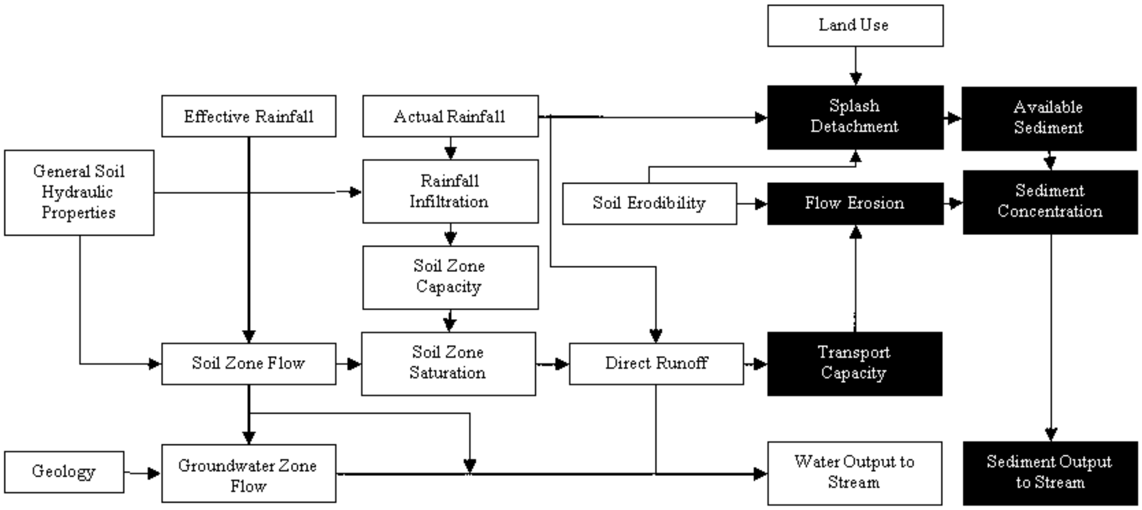

Figure 1. The components of and linkages between the processes driving the sub-catchment generation and delivery of sediment in INCA-Sed.

The set of processes is considerably simplified relative to soil erosion models such as EUROSEM (Fig. 1). For each sub-catchment of the model, material for transport (available sediment) is generated on the catchment slopes. Given sufficient direct runoff, this material is transported from the land to the in-stream phase of the model. Direct runoff can also further erode sediment from the surface once this supply is depleted. As such, the sediment concentration in the direct runoff is a combination of the sediment stored on the slope and that generated by flow erosion. The principal simplifications relative to detailed soil erosion models include the omissions of 1) an interception component; 2) explicit modelling of runoff flow hydraulics; and 3) a distinction between rill and interrill erosion. Within the channel, the average uniform conditions generated by the hydrological model are used to represent the average bulk movement of sediment within the channel (Fig. 2).

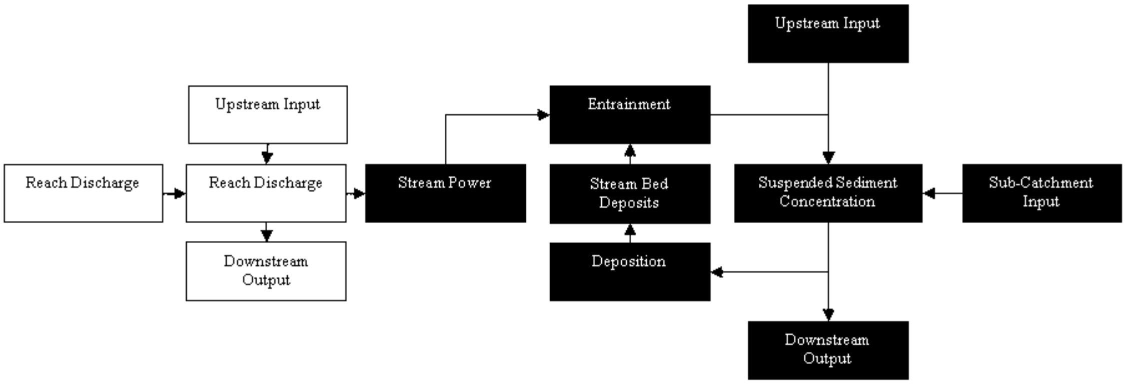

Figure 2. The components of and linkages between the processes driving the in-stream storage and transport of sediment in INCA-Sed.

The bulk entrainment and deposition of sediment is governed by the flow capacity, specified in terms of stream power. Suspended sediment concentration in the flow increases with stream power, given the presence of available material either delivered from the subcatchments or entrained from the bed. With decreasing stream power, the sediment in suspension will settle and be deposited on the stream bed, but is available for further in-stream resuspension.

3. INCA-Sed Model Equations

i) Hydrological processes

The INCA hydrological model is driven by a single input timeseries, the daily effective rainfall, derived from the MORECS soil moisture and evaporation accounting model. The MORECS model produces estimates of evapotranspiration, soil moisture deficit and hydrologically effective rainfall on a 40 x 40 km grid basis (Gardner and Field, 1983). The hydrological model consists of two components, a land phase for the sub-catchment zones and an in-stream phase for the river reaches.

The land phase of the hydrological model considers three principal water flux pathways within a catchment: direct runoff, shallow soil zone drainage, and flow through the groundwater zone, i.e. baseflow generation. The flux of water through each of these zones is modelled using mass balance equations. The use of three hydrological fluxes in the INCA-P model (Wade et al., 2002) is an extension of the original INCA model (Whitehead et al., 1998) in which only the soil and groundwater zones are included.

The hydrological system is driven by an effective rainfall flux (p_{eff}, $m^3s^{-1}m^{-2}$) into the soil zone:

$$\frac{dq_{sw}}{dt} = \frac{p_{eff} - q_{sw}}{T_2} \qquad \textbf{[1]}$$

where q_{sw} ($m^3s^{-1}m^{-2}$) is the soil zone flow and T_2 (days) is the soil water zone residence time. A portion of the soil zone flow percolates downwards into the groundwater zone, as controlled by the baseflow index, c_3 (dimensionless):

$$\frac{dq_{gw}}{dt} = \frac{c_3 q_{sw} - q_{gw}}{T_3} \qquad \textbf{[2]}$$

where q_{gw} ($m^3s^{-1}m^{-2}$) is the groundwater zone flow and T_3 (days) is the residence time. In the INCA-Sed model, direct runoff (overland flow) can be generated as either saturation excess overland flow or infiltration-limited overland flow. Direct runoff derived from a saturation excess is represented as a proportion, c_1, of the soil zone flow in excess of the saturation threshold, q_{sat}, as given by:

$$\frac{dq_{dr}}{dt} = \frac{c_1(q_{sw} - q_{sat}) - q_{dr}}{T_1} \qquad \textbf{[3]}$$

The soil zone saturation flow, $q_{sat,}$ is related to the soil type, a spatially distributed parameter within INCA-Sed. The proportion of the excess soil zone flow that does not contribute to direct runoff input is assumed to be lost to surface depressions and subsequent evaporation. This water loss is therefore given by

$$(1 - c_1)(q_{sw} - q_{sat}) \qquad \textbf{[4]}$$

Direct runoff is also generated when the rainfall rate exceeds the infiltration rate (*i.e.* infiltration-limited overland flow), such that

$$\frac{dq_{dr}}{dt} = \frac{c_2(p - i) - q_{dr}}{T_1} \qquad \textbf{[5]}$$

where p ($m^3s^{-1}m^{-2}$) is the rainfall rate, i ($m^3s^{-1}m^{-2}$) is the variable infiltration rate and c_2 (dimensionless) is the proportion of the rainfall excess that becomes direct runoff. The infiltration rate is directly proportional to the hydraulic conductivity of the soil and inversely proportional to the water content of the soil. INCA-Sed does not model the volumes of water within each of the sub-catchment flow zones; but rather, calculates the flux rates within each zone. To accommodate this, the effective degree of saturation is calculated from the relative magnitudes of the soil zone flow and the saturation threshold flow. The full equation governing the direct runoff within INCA-Sed is obtained by combining equations [3] and [5] to yield:

$$\frac{dq_{dr}}{dt} = \frac{c_1 \langle q_{sw} - q_{sat} \rangle + c_2 (p - i) - q_{dr}}{T_1} \qquad \textbf{[6]}$$

The total discharge from the sub-catchment into the reach (Q_{SC}, m^3 s^{-1}) is then given by

$$Q_{SC} = A\left(q_{dr} + (1 - c_3) q_{sw} + q_{gw}\right) \qquad \textbf{[7]}$$

where A is the subcatchment area. The discharge within the channel is governed by the equations previously derived and presented by Whitehead et al. (1998) and the reader is referred to that work for details.

ii) Sediment generation and slope to channel delivery model

As illustrated in Fig. 1, sediment is generated in the model by splash detachment and erosion by direct runoff, and equations must be developed to represent these processes. The transport capacity of the direct runoff also needs to be specified, as does a mass balance for the sediment in each subcatchment. The detachment of soil particles by raindrop impact is a function of the energy imparted to the soil surface by the individual drops (Sharma *et al.*, 1993), and in terms of available data, the best available proxy for this is the daily rainfall total. Splash detachment (S_{SP}, kg m^{-2}s^{-1}) is therefore modelled as a function of the rainfall (p, m^{3}s^{-1}m^{-2}), a soil erodibility parameter spatially linked to soil type, E (kgm^{-2}s^{-1}) and a vegetation cover index linked to land use, V (dimensionless):

$$S_{SP} = pE^{\frac{p}{V}} \qquad \textbf{[8]}$$

The transport capacity of surface runoff is of critical importance in the modelling of sediment delivery in models that are driven by direct runoff (Ferro, 1998), as it acts as an upper limit to the potential contribution of each sub-catchment to sediment concentrations in the channel. In INCA-Sed, this is modelled as a simple power law relationship given by

$$S_{TC} = a_4 \left(\frac{Aq_{dr}}{L} - a_5 \right)^{a_6} \quad \textbf{[9]}$$

where L is the length of the channel reach, a_4 (kg m^{-2}), a_5 (m^2 s^{-1}) and a_6 (dimensionless) are calibration parameters.The erosion of sediment by direct runoff is represented in a similar manner, although the erosive potential of the flow is given in terms of the total transport capacity, less the current sediment load. Direct runoff flow erosion S_{FL} (kg s^{-1}) is therefore given by:

$$S_{FL} = a_1 E \frac{(S_{TC} - S_C)}{S_{TC}} \left(\frac{Aq_{dr}}{L} - a_2 \right)^{a_3} \quad \textbf{[10]}$$

where a_2 (m^2 s^{-1}) and a_3 (dimensionless) are calibration parameters and S_C (kg s^{-1}) is the sediment transport rate. Finally, a mass balance accounting is used for each sub-catchment to determine the mass of sediment remaining on the slope and removed to the channel during each time step.

iii) In-stream sediment dynamics

The suspended sediment flux within the stream channel can be conceptualised as having two components: 1) lateral downstream transfer through reaches; and 2) vertical exchange with the bed material.

Downstream movement can be readily linked to the hydrologic flux; however, the vertical exchange is much more complex, as sediment is potentially entrained, deposited and reentrained during its migration through channel reaches. In order to accommodate this, the relative rates of entrainment from and deposition to the bed must be linked to the hydrologic equations. A key variable controlling this is the grain size distribution of the sediment, and INCA-Sed incorporates the effects of sediment grain size by calculating a mass balance for each of five grain size classes (with boundaries at 2, 60, 200 and 600 μm). The grain size of the material delivered to the stream from the slopes is assumed to be related to the soil texture of the subcatchment contributing to a reach and this texture, together with the distribution of soil types within each subcatchment is used to estimate the proportion of each of the five grain size classes delivered to the stream.

Entrainment is driven by the boundary shear velocity, which for equilibrium flow in a wide rectangular channel is given by:

$$v_* \approx \sqrt{gd \sin\theta} \qquad \textbf{[12]}$$

Within INCA-Sed, this is applied in the form

$$v_* \approx \sqrt{gda_7 \sin\theta} \qquad \textbf{[13]}$$

where a_7 (dimensionless) is a calibration parameter introduced to accommodate the departure from ideal conditions in natural channels. Inman (1949) related the sediment grain diameter to the threshold shear velocity required to entrain a particle into the flow from the bed, and the following approximation to the Inman curve is applied in INCA-Sed to determine when particular grain size classes are vulnerable to entrainment:

$$D_{\max} = x_1 v_*^{x_2} \qquad \textbf{[14]}$$

where D_{max} is the maximum grain diameter that can be entrained at a given shear velocity, and x_1 and x_2 are constants of regression with values of 9.9941 and 2.5208, respectively. Once suspended, sediment particles will tend to fall towards the bed under the force of gravity, although the turbulent structure of the flow can locally enhance the suspension. As a first approximation, though, INCA-Sed calculates a potential deposition rate for each grain size class based on the terminal settling velocity for that median grain size of each class.

The volume of sediment stored on the reach bed is increased by deposition from the flow and is decreased by the material entrainment. Therefore, for a timestep of length T seconds, the mass balance equation is:

$$\frac{dm_{bed}}{dt} = (m_{dep} - m_{ent}) \qquad \textbf{[15]}$$

The mass balance for the sediment in suspension within a reach is more complex. In addition to local exchange with the bed, the suspended ‘store’ in each reach receives sediment from upstream and from the contributing sub-catchment and releases suspended sediment downstream. The mass balance equation, for a timestep of length *T*, is thus:

$$\frac{dM_{sus}}{dt} = \left(M_{out} + LW(m_{ent} - m_{dep}) + M_{up} - Qm_{ses}\right) \quad \textbf{[16]}$$

where M_{sus} (kg) is the total mass of sediment in suspension in the reach, M_{out} (kg s^{-1})is the mass delivered to the reach from the subcatchment, *W*(m) is the width of the channel reach, M_{up} (kg s^{-1}) is the input from upstream reach, *Q* is the flow discharge (m^{-3} s^{-1}) and m_{sus} (kg m^{-3}) is the suspended sediment concentration given as:

$$m_{sus} = \frac{M_{sus}}{Vol} \quad \textbf{[17]}$$

where *Vol* is the volume of water (m^{-3}) in the reach.

4. Model Demonstration

To provide a preliminary test of model performance, INCA-Sed was applied to two neighbouring catchments, the Lambourn and the Enborne, both tributary to the River Kennet in Berkshire, England. The River Lambourn drains the Berkshire Downs to the north of Newbury and has a catchment area of 234 km^2. The catchment is highly permeable, baseflow-dominated system, being underlain almost entirely by chalk. It is dissected by an extensive network of dry valleys, giving rise to comparatively steep slopes, particularly in the north of the catchment. The catchment is dominated by arable farmland and also mown/grazed turf, serving the horse breeding industry located in the Lambourn valley. The River Enborne drains the area immediately to the south of Newbury and is slightly smaller than the Lambourn catchment, with an area of 153 km^2. In contrast with the Lambourn catchment, the chalk in the Enborne is overlain by low-permeability Tertiary clays and gravels throughout most of the catchment. The catchment is characterised by much gentler slopes than the Lambourn, but the runoff response tends to be very rapid, due to the low permeability of the surface materials. Land use is also largely comprised of arable farmland with some zones of woodland.

To apply INCA-Sed, the catchments were partitioned into contributing sub-catchments using a digital terrain map for the area. The percentage distribution of soil type, land use and geology were derived for each sub-catchment by using GIS overlays for each of these physical characteristics. The reach lengths of the main river channel were also derived from the GIS database. The discharge time series were obtained from 15-minute records from the Environment Agency gauging stations at Shaw (O.S. Grid Reference SU 470682) and Brimpton (O.S. Grid Reference SU 568648), for the Lambourn and Enborne, respectively. The daily suspended sediment time series used for the model demonstration extend from 21 March 1999 to 20 March 2000 and were sampled approximately 2 km north of the gauging station for the Lambourn and a few hundred metres upstream of the gauging station at Brimpton for the Enborne. The samples were taken using an EPICS automatic sampler and the water samples were processed using vacuum filtration with 0.45 μm Whatman filter papers (Evans, *et al*. 2003). Two daily samples were available for each site and the average of those two values was used in the work presented here.

Comparisons between the observed suspended sediment concentrations and the model results are illustrated in Figs. 3 and 4 for the two catchments.

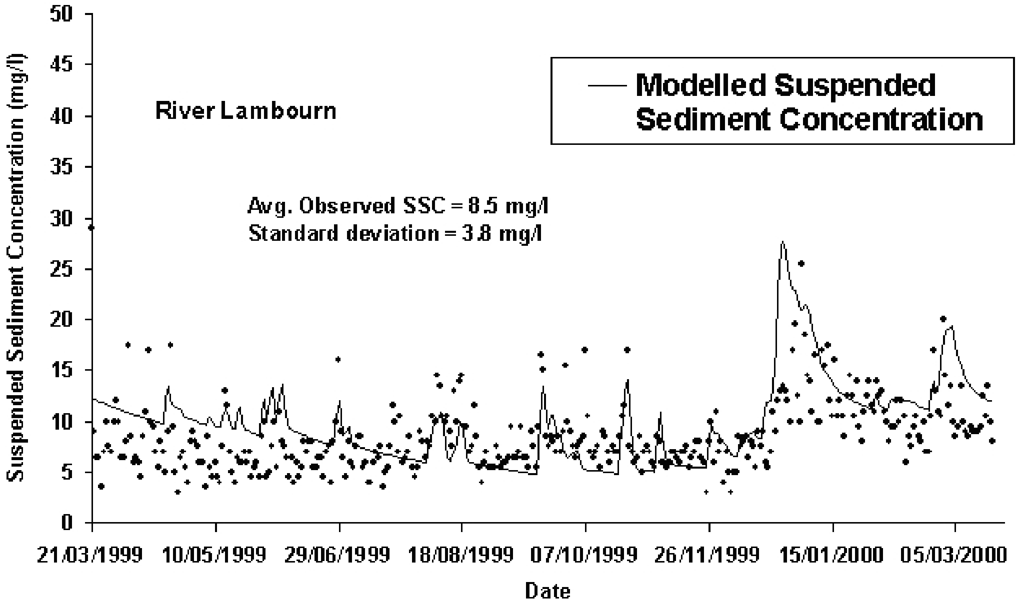

Figure 3. Observed and simulated in-stream suspended sediment concentrations (mg l^{-1}) in the River Lambourn (predominantly chalk).

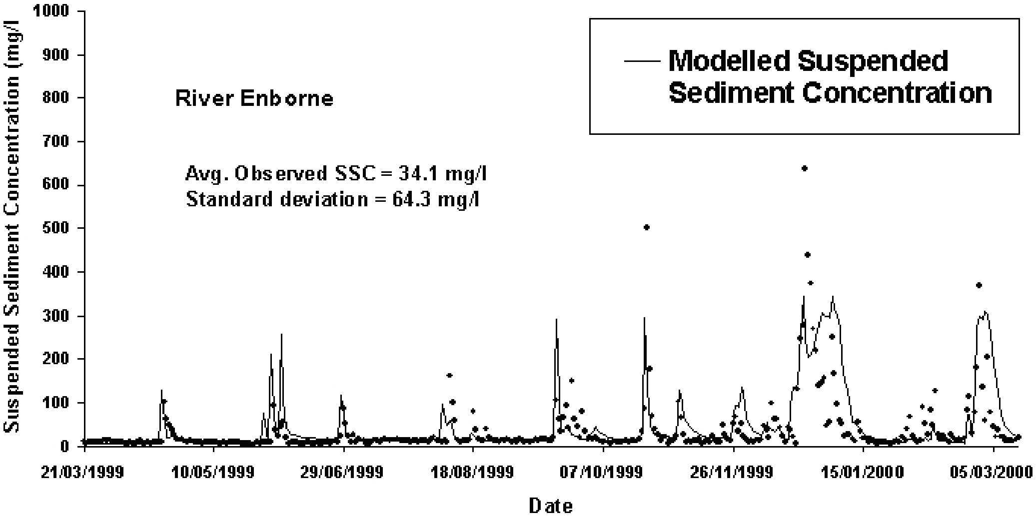

Figure 4. Observed and simulated in-stream suspended sediment concentrations (mg l^{-1}) in the River Enborne (predominantly clay).

The observed SSC values vary significantly between the two sites with annual average SSCs of 8.5 and 34.1 mg l^{-1} for the Lambourn and Enborne, respectively. The Enborne also exhibits much greater variability in concentrations with a standard deviation of 64.3 mg l^{-1}, relative to the 3.1 mg l^{-1} observed for the Lambourn. The model very effectively reproduces the flashy sediment response trends seen at the Enborne (Fig. 4), although the actual peak value is difficult to model precisely and would require a recalibration of the model with this calibration objective as the target. The model appears to perform slightly less well for the Lambourn (Fig. 3), although this is in part due to the scale at which the data are displayed relative to the Enborne. However, within the range of the Lambourn data, the series exhibits a lower degree of autocorrelation and only during the period between November 1999 and January 2002 is a consistent peak response observed. This is not surprising, given the catchment hydrology, which is baseflow dominated. It is therefore likely that much of the sediment suspended in the water column is the product of resuspended in-channel sources, including organic material derived from stream vegetation, rather than from direct runoff. During the period in which there is a distinct sediment response, the model in fact reproduces the observed trend fairly well. Given the low values of suspended sediment in this stream, the mean values and range are well represented by the model results, although the temporal structure of the response requires further investigation.

5. Continuing and other work

This report has outlined the model equations used in the prototype version of INCA-Sed developed by N P Jarritt and D S L Lawrence and has demonstrated the model by applying it to two lowland catchments in southern England, both of which are tributary catchments of the Kennet catchment. A generalised sensitivity analysis based on the application of the prototype INCA-Sed model to a hypothetical catchment to determine the relative significance of the model parameters in controlling model behaviour has also been undertaken, and this is presented in a separate report. Further work on INCA-Sed, to be undertaken within the context of EUROLIMPACS WP 6, include:

1. Incorporation of the equations developed for the prototype model into an INCA interface, and as appropriate, incorporation of the sediment transport equations into INCA-P, so that particulate transport can be represented in that model in a more physically realistic. This process will involve some modification to the spatial coverages (*e.g.* geology, land use and soil type) that are used and the sediment transport equations may also be simplified in light of the results of the generalised sensitivity analyses.
2. Application of INCA-Sed to other catchments within the EUROLIMPACS project. The data required for these further applications include daily suspended sediment concentration and stream discharge series, daily actual and effective rainfall series, topographic data for delineating subcatchments, spatial distribution of land use and soil type within the catchment, and soil texture for the soil groups used in the model. At present, further applications of the INCA-Sed model are planned for catchments in Denmark and Finland.

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