Testing a cellular modelling approach to simulating late-Holocene sediment and water transfer from catchment to lake in the French Alps since 1826
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Lake sediments have long been used to reconstruct past changes in erosion and sediment delivery (Mackereth, 1966; Engstrom and Wright, 1984; Dearing, 1991; Dearing and Jones, 2003; Chiverrell, 2006). As human impacts on the landscape have increased during the late Holocene, the sediments preserved within lacustrine basins typically comprise a record of the erosion of catchment soils, especially in upland areas (Mackereth, 1966). Alpine lake sediments are characteristically influenced by climatically induced floods through snowmelt or intense summer thunderstorms (Foster et al., 2003), active hillslope processes such as mass movement and gullying on steep slopes (Foster et al., 2003) and avalanches which deliver sediment from highest slopes to lower altitudes rapidly. Geochemical and environmental magnetic analyses can assist the reconstruction of sediment-source linkages and the changes in the geomorphological regime of the catchment (eg, van der Post et al., 1997; Dearing et al., 2001, 2008; Foster et al., 2003, 2008; Shen et al., 2007; Chiverrell et al., 2008). The linkages between catchments and lakes are reflected in the erosion, transmission and deposition processes that produce the eventual lacustrine sedimentary record. Both coupling and connectivity between geomorphological processes in the catchment and sediment delivery to the lake govern the
extent to which externally driven events such as storms (floods) and land-use change, and longer-term climate changes are reflected in the sediment record.

Previous research has seen geomorphologists and palaeoecologists attempting to ascertain the relative contributions of these external drivers (eg, Harvey et al., 1981; Macklin, 1999; Foster et al., 2003; Arnaud et al., 2005; Chiverrell et al., 2007), but they have been hampered by the integrated nature of the meteorologically driven flood events, longer-term climate changes and land-use signals preserved in sedimentary and geomorphological archives. In addition to drivers that are extrinsic to the system, other intrinsic factors moderate the process-response to landscape change, meteorological events and long-term climate change. Variable sediment distribution, erodibility of the system, other intrinsic factors moderate the process-response to landscape change, meteorological events and long-term climate change. Variable sediment distribution, erodibility of the landscape, local storage and release of sediment (eg, floodplains), and longer-term sediment sinks (eg, higher-level lakes and alluvial fans), can all interrupt the sediment conveyor (Fryirs and Brierley, 2001; Lang et al., 2003; Fryirs et al., 2007) with the potential to significantly moderate any palaeoenvironmental signal recorded within lake sediments (Dearing and Jones, 2003; Chiverrell et al., 2008).

When considering sediment transfer from catchments to lacustrine basins, the interactions between the key components of these complex systems may be more important than the individual processes operating within each subsystem (eg, hillslope, tributaries, floodplains and deltas). Individually the sedimentary and landform archives of these subsystems are difficult to interpret and particularly difficult to correlate with changes in land use, meteorological events and/or long-term climate changes. Therefore, providing that drivers and process-responses can be incorporated, a catchment-scale modelling framework could offer a more holistic approach to understanding the sediment flux between geomorphological subsystems. Traditional methods of modelling sediment production, transport and deposition have concentrated on sediment budget approaches (Trimble, 1983) through field studies (Lang et al., 2003; Rommens et al., 2006; Hoffman et al., 2007). Whilst sediment budgets describe inputs, transfers, stores and outputs of sediment in a catchment, they cannot capture geomorphological change or interactions between catchment-scale processes. In fact, there have been few attempts to model interactions between hillslopes and fluvial systems, largely because of the non-linear behaviour and complex nature of the process interactions.

This paper addresses these issues by using and developing an established hydrogeomorphological model (CAESAR: Coulthard, 1999; Coulthard et al., 2002, 2005; Van de Wiel et al., 2007) to assess sediment transfer within a lake catchment. This paper presents a time series of modelled sediment and water discharge for the last 180 years, driven by instrumental meteorological and historical land-use time series. Previous validation of CAESAR model output has been attempted by comparison with well-dated fluvial sequences, yet these are fragmentary, discontinuous and spatially variable. A potential advantage of a lake catchment system is the availability of lacustrine sediments to provide an integrated record of sediment flux over long timescales against which model sediment outputs may be compared. Although lake sedimentary archives do not always reflect solely allogenic processes, by carefully selecting proxies that reflect detrital soil-sediment signals from the sedimentary archive, comparisons can be made with modelled CAESAR sediment records. Thus this paper presents a first attempt to cross-validate the sediment flux to a lake produced by this catchment-scale hydrogeomorphological model and to use CAESAR to explore the relative contributions of long-term climate, meteorological events and land use in forcing of this system.

CAESAR (Cellular Automata Evolutionary Slope and River model)

Landscape evolution models (eg, Tucker and Slingerland, 1994; Hancock et al., 2002), whilst useful for long term (10^3–10^4 year) simulations, are often inappropriate for geomorphological studies over timescales of years and centuries. This is in part due to the coarse spatial resolution, long time steps (days to years) and the averaging of climatic drivers and process rates over long periods. Conversely, the application of high-resolution computational fluid dynamic (CFD) models over short timescales is computationally time-consuming and in some cases they omit certain types of sediment from the simulations, for example bedload (Coulthard et al., 2007). Coulthard (1999) and Coulthard et al. (2007) developed a cellular model (CAESAR) that allowed the modelling of fluvial geomorphological processes at fine-resolution temporal and spatial scales, and this has been applied to fluvial catchments in upland Britain over 10^3–10^4 timescales (Coulthard et al., 2002, 2005, 2007), meandering reaches (Coulthard and Van De Wiel, 2006) and braided systems in New Zealand (Coulthard et al., 2007).

CAESAR is considered to be a reduced complexity model (Coulthard et al., 2007) that operates in a cellular automata style. CAESAR uses relatively simple representations of fluvial and hillslope processes that allow the generation of complex non-linear system behaviour. Simple parameterisation of soil creep, soil erosion and slope failure within CAESAR enables coupling of hillslope sediment sources with the fluvial model. Fluvial sediment transport is simulated using multiple grain sizes with either the Einstein–Brown (Einstein, 1950) or the Wilcock and Crowe (2003) bedload transport formulae, and these interact with an ‘active layer’ system that allows suspended sediment, bed armouring, selective transport and the development of stratigraphy (Van de Wiel et al., 2007). One limitation is that CAESAR does not currently deal with the erosion of cohesive aggregates.

The inputs needed to run CAESAR are simple and require little parameterisation or empirical data when compared with other hydrological models (eg, Mike-SHE: Abbot et al., 1986; Refsgaard, 1997). In CAESAR, landscapes are represented as a mesh of grid cells of uniform size (Coulthard, 1999) based on a digital elevation model (DEM). Each cell holds a set of initial values representing the elevation, water depth, vegetation and sediment/soil grain size distribution. The nature of the cellular model allows interactions between the cells of a DEM to generate feedbacks and complex responses to relatively simple inputs. A series of process-based rules governing hydrological routing, hydraulic routing, slope processes (mass movement, soil creep and soil erosion), fluvial erosion and deposition are applied to each cell. Importantly this catchment-scale modelling approach incorporates the zones of sediment production, transport and deposition (Schumm, 1977) within a single model. Further details on the programme structure and process representation are available from the CAESAR website (http://www.coulthard.org.uk/).

To simulate landscape evolution for large areas, such as a river catchment, there is a trade off between computer processing capacity and what is feasible in terms of spatial resolution and model time-step. Here we have been limited to a 50 m × 50 m grid resolution, but forced model runs using hourly resolution meteorological data in order to incorporate the responses to high magnitude flood events. Although model simulations operate using a variable time step or iteration (operating between 10^2 and 10^4 seconds), they are driven using hourly precipitation and land-use data derived from historical, proxy and instrumental records (Coulthard et al., 2005).
Petit lac d'Annecy

Lac d'Annecy (Lat 45°48′ N; Long 06°08′ E) is situated in the Haute Savoie region of southeastern France at an altitude of ~447 m. The lake (area 26.5 km²) comprises two basins, the Grand lac and Petit lac, and receives drainage from a mountainous catchment (area 251 km²) that reaches altitudes above 2200 m. The Petit lac d'Annecy, (Figure 1), has a long history of research that has focused on historical documentation of land-use changes (Crook et al., 2002, 2004), geomorphological assessment of the catchment (Foster et al., 2003) and lake sediment reconstruction of environmental changes (Higgit et al., 1991; Thordyrcraft et al., 1998; Dearing et al., 2001; Noël et al., 2001; Foster et al., 2003). The Petit lac catchment (area 170.4 km²) is drained by three main tributary systems, the Eau Morte, Ire and Bornette (Figure 1). River systems from five subcatchments (Table 1) drain into and cross an extensive lowland floodplain before entering the lake as the three main tributaries. The catchment is free of glaciers and there is no permanent snow cover, but annual peak discharges March–April reflect snowmelt (Foster et al., 2003).

This paper focuses on two contrasting styles of subcatchment: the Ire, a bedrock-confined mountain torrent; and the Tamie, also a steep-sided system but with a wider floodplain. Altitude and terrain are the main controls upon land use (Foster et al., 2003), with subalpine grasslands on lower gradients above 1500 m in part maintained as summer pasture. Below ~1500 m these grasslands become extensive coniferous forests, and the steep valley sides are covered by deciduous and coniferous forest. On the flatter lower-lying terrain, the forests have been cleared and fine-grained alluvial soils support intensive cultivation. The history of human intervention and exploitation of the landscape dates the first settlement to the Neolithic (~5000 yr BP), but evidence from palynological records suggests that these impacts remained small-scale until the region was under Roman influence c. 1700 yr BP (Noël et al., 2001). The lake sediment record suggests that changes in the spatial and temporal pattern of human activity have affected the flood and sediment regime of the catchment (Dearing et al., 2001; Noël et al., 2001).

The recent land-use history for the catchment is well constrained, with forest inventory records (woodland cover in hectares) available for seven communes back to 1730 (Figure 2b: Crook et al., 2002). The commune boundaries differ from those of the subcatchment areas, with the Ire including Chevaline, Doussard and part of Seythenex, and the Tamie mostly located within the commune of Seythenex and a small part of Faverges (Figure 1).

Figure 1 Petit lac d’Annecy: main inflows, lake basin, subcatchment boundaries, commune boundaries, elevation, major summits. Inset shows location of study area in France

<p>| Table 1 Key characteristics of subcatchments with the Petit lac d’Annecy catchment |
|-----------------------------------------|--------------------------------------------|-------------------------------------|-------------------------------------|--------|</p>
<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Dominant geology</th>
<th>Hydrology</th>
<th>Modern day vegetation cover</th>
<th>Geomorphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bormette</td>
<td>10.8</td>
<td>Cretaceous marl and limestone.</td>
<td>Mountain torrent</td>
<td>~70% forested</td>
</tr>
<tr>
<td>Ire</td>
<td>21.6</td>
<td>Cretaceous marl and upper/middle Jurassic limestone. Scree slopes</td>
<td>Mountain torrent, constrained bedrock channel</td>
<td>~60% forested</td>
</tr>
<tr>
<td>St Ruph</td>
<td>17.3</td>
<td>Cretaceous marl and limestone. Scree slopes</td>
<td>Mountain torrent</td>
<td>~60% forested</td>
</tr>
<tr>
<td>Tamie</td>
<td>24.4</td>
<td>Cretaceous marl and limestone. Quaternary glacial till</td>
<td>Lowland river system with steep headwater tributary</td>
<td>~50% forested</td>
</tr>
<tr>
<td>Montmin</td>
<td>15.5</td>
<td>Cretaceous marl and limestone</td>
<td>Perched valley with deeply incised bedrock gorge</td>
<td>~50% forested</td>
</tr>
<tr>
<td>Eau Morte Floodplain</td>
<td>42.1</td>
<td>Quaternary alluvium, glacial till and sand and gravel. Largely Cretaceous marl with some limestone</td>
<td>Limited natural meandering reaches, dominated by twentieth-century canalised channels</td>
<td>~25% forested</td>
</tr>
</tbody>
</table>

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Initial conditions and model setup

Digital elevation model
For the Petit lac subcatchments, a 50 m × 50 m grid cell digital elevation model (DEM) was used (Institut Géographique National, France). This resolution does not capture the finer detail of the topography, but was sufficient to model catchment sediment output for comparison with the lake sediment records. The principal model inputs, precipitation and forest cover (land use), were applied uniformly across the catchment DEM. The larger Petit lac catchment has been divided into subcatchments primarily to speed up model simulation time with model runs completed independently for the Ire and Tamie systems. Clearly these simulations do not include the Eau Morte floodplain (Figure 1), where there has been extensive deposition and storage of both coarse- and fine-grained sediments during the Holocene. The principal implication is that the simulations of the Ire and Tamie should overpredict absolute sediment flux to the lake, but the temporal pattern of sediment supply should be unaffected. Sediment provenance analyses comparing catchment soils and sediments with the lake sediments show a strong connectivity between hillslope zones and the lake basin (Dearing and Zolitschka, 1999; Foster et al., 2003).

Soil/sediment depth model
The distribution of unconsolidated sediment and soils was incorporated through the use of a second DEM, which reflected the elevation of the bedrock surface. Essentially the depth between the surface and the bedrock controls the amount of sediment potentially available for erosion. Depth to the bedrock was estimated by both a field-based assessment and an empirical model using the relationship between sediment thickness recorded in the field and slope angle. Therefore the DEM was used to identify ranges of slope angle, which were assigned a soil/sediment depth. This process produced spatially variable sediment depths ranging from 0.1 to 20 m, with less on the steeper cliffs and slopes. After several sensitivity tests, all surfaces above ~1400 m were assigned a soil/sediment depth of 1 m to ensure the summit regions had a realistic depth of sediment and to ensure there was sufficient residual sediment on these slopes after the model spin-up period (60 years). The objective with these high-altitude sites was for a patchwork cover of relatively shallow sediments (<1 m) and bare ground on steeper slopes and cliffs. Comparison with the field data shows these estimated sediment/soil thicknesses after the model spin-up period to be broadly realistic.

Meteorological: precipitation and temperature
An hourly precipitation series was produced using the hourly data recorded between 1991 and 2005 for Albertville (c. 25 km away) as a 5 year template. This short time series was repeated back to 1826, and adjusted to monthly precipitation totals from an integrated Annecy and Geneva precipitation record (Nicholson and Thompson, 2000). Sequentially the 5 year series has been adjusted to the Annecy-Geneva monthly totals to provide an hourly time series back to 1826. The limitation of this approach is that whilst monthly totals will reflect the climate history for the last 180 years, the frequency, duration and relative magnitude of stochastic meteorological events (rainfall) will repeat on cycles of five years. In essence the approach allows modelling of the response of the catchment to both short-timescale (meteorological) events and longer-term climate variations imparted through the Annecy-Geneva series.

Comparison between preliminary CAESAR simulations using a constant value to represent land use (the ‘m’ value, section 4.4) \(m = 0.010\) and hourly recorded discharge data available for the
Ire subcatchment in 1999 revealed a lack of correlation between recorded instrumental and modelled water discharge particularly during months of snow accumulation and snowmelt. At these times, CAESAR underpredicts discharge during snowmelt and overpredicts during the winters, because snow accumulation and melt are not parameterised in CAESAR. Thus, snow storage and melt have been incorporated by creating a simple mass-balance programme to modulate the precipitation into a snow-adjusted series using temperature data available to 1826 from Meythet (Figure 3). The programme uses hourly precipitation and temperature data inputs, and employs user-defined values to set a freeze threshold, freeze percentage, melt threshold and melt rate. The annual snow storage cycle produced was similar to empirical data recorded from the Alps, with winter storage (November–March) and a mid-March snowmelt pulse. Thus the adjusted precipitation series incorporates changes in both thermal- and hydroclimate since AD 1826. Limitations to this approach stem from discrepancies between the Albertville time series and actual events in the Petit lac catchment. The adjusted precipitation series was applied uniformly across the DEM grid as currently it is not possible in CAESAR to vary meteorological inputs on a spatial basis. The complexity of the flow routing algorithm (as described in Coulthard et al., 2002) renders alternative approaches (eg, lapse based) difficult and would almost certainly require a redesign of CAESAR. Thus characteristics of the hydroclimate regime, for example greater quantities of precipitation and snow storage at higher altitudes or zones of rain-shadow cannot be captured. Whilst this arguably could produce discrepancies between modelled and real-world water discharges or flow regime this is not apparent from data-model comparisons.

Figure 3  Exemplary diagram of how the snow mass balance programme works. (a) Original precipitation data, (b) Temperature data, (c) Snow storage taking place during processing, (d) Temperature modified precipitation data, (e) Modelled daily average discharge data (post-snow modifications) compared with observed average daily instrumental discharge from Ire (1999)
Land-use changes: land-use parameter

CAESAR runs are driven in part by land cover changes, which are represented by the parameter \( m \); a modification of the vegetation parameter used in TOPMODEL (Beven, 1997). Essentially, the \( m \) values are derived from the effect that they have on the recession limb of the flood hydrograph. A high \( m \) value such as 0.013 slows the rate of decline of the recession limb of the hydrograph (Figure 4) and reduces the transmissivity within the soil, therefore imitating the effect that vegetation cover would have on the catchment. A lower \( m \) value (sparser vegetation) such as 0.005 allows more transmissivity through soil as there is a quicker decline in soil moisture deficit; it imitates all the factors associated with water movement and water storage with regard to vegetation. Figure 4 shows modelled discharge data under different \( m \) conditions in relation to the same precipitation event.

CAESAR has been adapted to allow \( m \) to vary on an hourly basis thereby following the meteorological input series, and this is applied uniformly to every cell across the catchment. As the DEM has been split into subcatchments, land-use histories can be varied between subcatchment, which at present is the only viable method by which land use can be varied on a spatial basis. As the commune boundaries differ from the subcatchment boundaries (outlined in section ‘Petit lac d’Annecy’), an area-weighted mean forest cover has been calculated using the commune coverage in each subcatchment, and these forest cover estimates were calibrated (Figure 2a) to contemporary forest cover discerned from aerial photographs (©2008 Google – Imagery). Limitations to this approach stem from discrepancies between forest inventory data (1826–1999) and the aerial photography (1999), and errors arising in the historical record particularly from forested areas not being declared as forest. Nonetheless, these data (Figure 2a) were used to provide a history of the land use for each subcatchment in the CAESAR model runs.

The forest cover data for each subcatchment (Figure 2b) have been used to produce equivalent \( m \) value (Figure 2a) series extending back to 1826. Given the role the \( m \) value plays in governing the shape of the flood hydrograph it is important to calibrate modelled discharge against recorded discharge in order to obtain an appropriate \( m \) value for the present-day land cover. A series of CAESAR simulations were completed using a precipitation time series for 1999 but varying the \( m \) value across the range 0.002–0.02 (Coulthard, personal communication, 2005; Beven, 1997). Comparison of the modelled data and hourly recorded discharges suggests that contemporary (1999) \( m \) values for the Iree were ~0.011 (eg, Figure 3e), and the close match between recorded and modelled water discharges provide some validation of the model set-up (eg, Figure 3e). A sensible range for \( m \) in these subcatchments appears to be 0.016, –dense forest, extending to 0.005, –grassland. Clearly it is possible to postulate a wide variety of linear and non-linear models to summarise the relationship between forest cover and the \( m \) parameter, but in the absence of empirical data to substantiate the nature of this relationship for past land use \( m \) has been scaled against forest cover on a linear basis (Figure 4 inset). This approach is similar to that applied in previous simulations using CAESAR (eg, Coulthard et al., 2002).

Lake sediment record

In 1995, a 814 cm Kullenberg core (LA13) was taken from the flat central basin of the Petit lac in 55 m of water. Previously published lake sediment accumulation rates in this core were based on tuning a magnetic proxy of erosion in the lake records to the meteorological time series for the past few centuries (Foster et al., 2003). Here, an alternative chronology for LA13, which avoids the linkage to meteorological data and circularity of reasoning, integrates ages obtained from absolute dating techniques (\(^{137}\)Cs, \(^{210}\)Pb and \(^{14}\)C) and marker chronological horizons identified in magnetic and palynological proxy data (R.T. Jones, J.A. Dearing, R.C. Chiverrell, G. Foster, P.G. Appleby, D.S. Crook, H. Noël, E. Vergès and J.L. de-Beaulieu, unpublished data, 2006). The period from the early nineteenth century to the present (1995) is represented within the upper 1 m of sediment. Mean sediment ages from a cubic polynomial age–depth model provide temporal control for the sediment proxy data. We have also made use of the dry mass sediment accumulation rates calculated from the \(^{137}\)Cs and \(^{210}\)Pb depth–age model assuming constant rate of supply (Appleby and Oldfield, 1978). These age–depth models are an interpretation of the chronology, and include inherent error and uncertainty. In comparisons between the lake sediment record and modelled sediment discharge we have no expectation of a ‘perfect’ temporal match, but a broad similarity in the overall pattern might be expected around a possible uncertainty of ±10 years for these timescales.

A proxy for sediment transport to the lake is provided by paramagnetic susceptibility (\(\chi_{\text{para}}\)). This is the high field (800–1000 mT) susceptibility measured on a Molspin vibrating sample magnetometer (eg, Snowball et al., 1999), expressed in mass specific units (10\(^{-5}\) m\(^3\)/kg). Unlike measurements of low field susceptibility (\(\gamma LF\)), \(\chi_{\text{para}}\) records all Fe-containing minerals in a sample.
Fe-containing paramagnetic clay minerals are ubiquitous in the soils and glacial sediments of the Petit lac and, quantitatively, more important than ferrimagnetic minerals. The use of $\chi_{\text{para}}$ as a proxy for detrital sediment transport also avoids the complications of non-catchment authigenic minerals, such as bacterial magnetosomes and iron sulphides dominating the sediment magnetic record (Dearing, 1999; Dearing et al., 2001).

**Methodology**

Two model simulations were undertaken for the period 1826 to 2005 for the Tamie and Ire subcatchments. The simulations were driven using an hourly ‘snow mass balance’-adjusted rainfall series derived by modulating hourly precipitation by temperature (as described in section ‘Meteorological: precipitation and temperature’) (Figure 5a). The simulations used hourly $m$ value series that reflected the land-use history of each subcatchment (Figure 5b). Both simulations included a 60 year run up period (not shown), 1765–1825, to allow the model to stabilise. The outputs from CAESAR simulations are aggregated to produced hourly water (Figure 5c) and sediment discharge (m$^3$/s) time series from flows leaving the right-hand side of a DEM. Although the model outputs hourly data, during flood events the calculations are resolved at a much finer time step and aggregated to hourly outputs. Sediment distribution was subdivided into nine grain size fractions (boundaries: 62.5 μm, 250 μm, 500 μm, 1000 μm, 2000 μm, 4000 μm, 8000 μm, 32 000 μm, 128 000 μm) the finest of which <62.5 μm, coarse silt, was handled as suspended sediment and used for comparison with the lake sediment record (Figure 5d–h). The finest grain size fraction modelled in CAESAR was used for comparison against the lake sediment record as this is the dominant grain size fraction in lake sediments. Generally, the nine grain size fractions used in CAESAR follow a similar pattern of temporal sediment discharge, with all the largest events captured within all nine grain size fractions, but amplified in the finest grain sizes. Changes in surface elevation were recorded as a series of DEMs at a pre-determined interval (decadal) and reveal the spatial and temporal pattern of erosion and deposition.

**Results and interpretation**

**Overall patterns**

Figure 5 shows the water discharge ($Q_w$) (Figure 5c) and the modelled sediment discharges for the finest grain size (62.5 μm) for the Ire and Tamie which have been totalled on both annual and a 5-year basis for comparability (Figure 5d–h) with likely temporal precision of the lake sediments. The overall trend of $Q_w$ in both catchments shows high values in the periods 1840–1860, 1920–1930 and 1955–1970, though values for the period 1920–1930 in the Ire are proportionately lower. The sediment peaks in the Tamie (Figure 5d,e) appear more pronounced, yet the level of ‘background’ sediment discharge in the Tamie is lower than in the Ire (Figure 5f,g), which may be exaggerating the appearance of the peaks. The Ire has greater annual sediment discharge than the Tamie, and this is reflected in the model outputs for the two catchments.
discharge than the Tamie, exemplified by the period between 1880 and 1910 when the Tamie has extremely low amounts of sediment discharge. In both subcatchments, the largest floods eg.1850, 1865, 1870, 1885, 1922, 1933, and 1971 were produced by the largest precipitation/snowmelt events. However, the magnitude of flood events was not solely a function of precipitation input as forest cover ($m$ value) clearly amplifies (during deforestation) or reduces (during afforestation) the hydrological response to precipitation/snowmelt events of broadly equivalent magnitude, for example 1850 and 1940, respectively (Figure 5c).

**Ire**

The total suspended sediment ($Q_s$) discharge from the Ire remained relatively high throughout the 180 years, which suggests the system was well-coupled and regularly flushed with materials from valley-side and montane source areas. $Q_s$ was relatively low from 1826 to 1842, with a sustained peak from 1842 to 1862 and then declining gradually to lows in 1862–1868 (Figure 5d). Further peaks in $Q_s$ occurred 1868–1878, 1888–1897, 1912–1932, 1942–1947 and 1962–1977 (Figure 5d). Almost all of these coincided with a single year or series of years with substantial floods. Considerably large floods (eg. 1848 and 1850) produced a greater sediment response, and this also appeared to leave a legacy of sediment in the channel which was available for transport in the years after. The 1850 event rendered the system particularly sediment-rich, with even relatively small subsequent floods producing large sediment peaks in the period 1850–1865. Similarly the flood event at 1971 had an initial peak of sediment, followed by another large peak at 1982, which was a response to a much smaller flood event reflecting that the channel remained sediment-rich following the 1971 flood.

The steep valley sides and restricted floodplain of the Ire provide relatively little accommodation space for sediment storage. Figure 6a–c shows that the channel was mainly eroding throughout the time period 1836–1866, but there was localised temporary sediment storage in and around the channel (within the constraints of a 50 m × 50 m DEM). Figure 6a shows the spatial pattern of erosion and deposition at decadal time-steps through the substantial peak in $Q_s$ at 1850–1864 (Figure 5g). Slope processes, for example soil creep and soil erosion, occur gradually and at a uniform rate (approximately 7 mm/yr for soil creep and 5 mm/yr for soil erosion) throughout the modelled period, only varying with slope angle, and are visible as the minor amounts of erosion and deposition of sediment across the DEM (Figure 6a–c). Soil erosion rate calculations in CAESAR are similar to the slope length term within the USLE, and imitate a slope wash term (Coulthard, personal communication, 2007). In the comparative lull of $Q_s$ between 1836 and 1846 the rates of erosion and deposition associated with channel processes were an order of magnitude greater than on the hillslopes (Figure 6a). Prior to the 1848 and 1850 flood-induced peaks in $Q_s$ the system experienced incision (c. 10 cm erosion) in the main channel and tributary systems, with localised temporary storage in zones along the main channel (<1 m deposition).

During the 1848–1850 floods (Figure 5c) there was greater erosion in the hillslope tributary systems (Figure 6b.1), with deposition and growth of tributary junction alluvial fans (Figure 6b.1) particularly at broader sections of the valley floor. There was also
localised storage of materials in and adjacent to main channel and tributary systems (Figure 6b.3). Supply of sediments at this time exceeded the transport capacity of the system creating local depocenters (Figure 6b.4). In the years 1850–1864, the river channels and more substantial tributaries experienced flows and remained sediment-rich (Figure 6c.1), which may explain the higher background sediment discharge outside of the flood-induced sediment peaks (Figure 5f).

Assessing the impact of forest cover on sediment and water discharge is difficult owing to the relatively minor changes in forest cover since 1826. However, the falls in forest cover (m value) 1892–1915 and 1953–1975 both coincide with minor increases in $Q_{ss}$ and coincide with a time when peak discharges were low. The slightly flashier nature of the flood hydrograph under lower m values was sufficient to mobilise sediments. These impacts are clearer for the 1892 to 1915 phase than 1953 to 1975 when the system was perhaps starved of sediment because of low flood discharges from 1930 to 1953. This further highlights the importance of conditioning and sediment history in controlling the response of the fluvial system to flood events.

**Tamie**

The annual total suspended sediment discharge ($Q_{ss}$) was relatively low and somewhat discontinuous throughout the 180 year record perhaps indicating that this system had a better capacity to store sediment and that under low flows the channel was poorly coupled to sediment source zones. $Q_{ss}$ was low during 1826–1845 (Figure 5f,g) followed by large peaks which were sustained during 1845–1866 before a subsequent decline in $Q_{ss}$ during 1866–1920. Three other clear peaks in $Q_{ss}$ occurred during 1920–1932, 1960–1965 and 1967–1972, all of which coincided with large flood peaks demonstrating the strong link between floods and $Q_{ss}$. The larger floods, as with the Ire, produced the largest sediment responses eg, 1850, 1885, 1924, 1925 and 1934. The peaks in 1848 and 1850 may have rendered the channel sediment-rich for a similar period of time as seen in the Ire (c. 14 years) because there were large peaks in sediment discharge until c. 1864 (Figure 5g). The broad valley floor of the Tamie is less restricted than in the Ire and provides a greater capacity for sediment storage, but areas, particularly the valley floor, are not mobilised by the channel on an annual basis creating a greater potential for sediment storage. These circumstances enabled the valley floor to accrete, evidence of which is seen in local valley floor depocenters and particularly in the tributary alluvial fans (Figure 6d.1).

Prior to the large flood-induced $Q_{ss}$ peaks in 1848 and 1850 (Figure 5f), channel erosion was 10–90 cm in the main channel and localised tributaries (Figure 6d.2). A similar amount of material was deposited in depocenters in and around the channel, particularly on the tributary alluvial fans (Figure 6d.1). The period 1846 to 1856 saw incision in localised zones of the main channel and large tributaries (Figure 6e.1) of up to 1 m; this included up to 1 m of fan-head incision on the alluvial fans (Figure 6e.2) and tributary junctions (Figure 6e.3). The large floods at 1848 and 1850 enabled the incision of a small tributary valley (Figure 6e.4) where erosion and deposition during the period 1846–1856 (c. 1–10 cm) increased by an order of magnitude compared with the erosion and deposition in this zone from 1836 to 1846 (c. 1 mm–1 cm). As with the Ire, the forest cover did not vary dramatically enough for there to be significant responses in the hydrological and sediment regime. Flood magnitudes were much more closely related to precipitation and snowmelt inputs, and this appears the primary driver of sediment flux in both subcatchments.

**Differential response in the subcatchments**

Many factors appear to have influenced the response of these two subcatchments, effectively rendering them systems that function largely on an independent basis. Whilst the precipitation inputs remain the same, and the land cover histories similar, the geomorphology of these subcatchments are different and essentially this has governed the hydrology and the response of the sediment regime. The Ire is a generally well-coupled fluvial and hillslope system, whereas the Tamie has a much wider floodplain with zones where long-term (decadal) storage of sediment is prevalent. Within the Ire opportunities for sediment storage are limited to zones in and around the channel, thus high flows regularly flush and remobilise sediment through the system. This renders the system sensitive to discharge events. The Tamie is more complex and has greater potential for the temporary storage of sediment outside of the channel. During high-magnitude flows, sediments were mobilised, transported and then deposited in temporary depocenters in the hillslope tributary systems, on alluvial fans and on the wider floodplain away from the active channel (Figure 6e.2). In short, there was greater interruption to the ‘sediment conveyor’ in the Tamie than the Ire.

The confluence of several streams in downstream reaches of the Tamie (Figure 6e.3) is particularly interesting, because many of the small sediment pulses (Figure 5f) eg, 1835 (Figure 6f), 1858 (Figure 6g), 1885 (Figure 6h), 1922 (Figure 6i), 1924 (Figure 6i) appear to be controlled by erosion at the tributary junction (Figure 6e.3). Since there was relatively little erosion elsewhere in the catchment this could explain the source of the increased sediment discharge. Both systems have exhibited storage in the lower and shallower gradient reaches of tributaries (Figure 6b.3, 6c.1, 6d.2, 6e.5), which highlights their role in storage of sediment and interruption of the sediment conveyor.

As overall forest cover reduced (Figure 7h) between 1835 and 1885, changes in the m parameter have increased flood magnitudes (Figure 7f), which in turn have produced greater peaks in sediment discharge (Figure 7c). Conversely, as forest cover increased (Figure 7b) and flood peaks reduced in magnitude (Figure 7f), the sediment transmission appears to decline (Figure 7c). These patterns reflect the conditioning of the flood hydrograph by forest cover, and this indirectly affects sediment transmission.

The response of individual catchments to a sequence of meteorological events, climate and land use is in part governed by historical changes, but the study shows that there was significant variation between adjacent systems or reaches governed by catchment morphology and sediment distribution (Coulthard et al., 2005). Thus in order to understanding the flux of sediment within a large basin there is a clear need to model all feeder subsystems on an individual basis.

**Model validation**

In order to improve the comparability of the model outputs and lake sediment magnetic parameters, the total 5 yearly modelled sediment records for the Ire and Tamie subcatchments have been totalled, representing ~30% of the total catchment area draining into the Petit lac. Several material magnetic, geochemical and bulk density parameters were available as potential detrital sediment proxies for this lake sediment record. Lake sediment measurements of $\chi_{rel}$ (low field magnetic susceptibility), SIRM (saturated isothermal remanent magnetisation) and soft remanence are significantly affected by the presence of bacterial magnetosomes or atmospheric pollution (Dearing et al., 2001). Paramagnetic susceptibility $\chi_{para}$ (Figure 7b) appears therefore the most suitable magnetic proxy for the transport of Fe-containing detrital soil/sediment to the lake. The effects of rapid urbanisation and accelerated eutrophication during the early to mid twentieth century also mean rejecting the available lake sediment geochemical and density measurements. However, a relatively precise sediment mass accumulation rate is available for 1960–1995 using the $^{210}$Pb chronology for the Petit lac.
The 210Pb-derived sediment accumulation rate tracks the $\chi_{para}$ pattern closely over the period 1960–1990 (Figure 7b) with both records displaying a peak around 1960 before declining around 1970. This internal consistency strongly implies that the two proxies reflect broad variations in the supply of catchment soil-sediment and can be used to validate the modelled $Q_{ss}$ records. It should be noted that the chronology of the lake sediment record shown (Figure 7b) has an error of ±10 years which means that model validation has to focus on the long-term pattern of change rather than the synchrony of peaks and troughs in the time series.

Modelled total $Q_{ss}$ (Figure 7c) rises from 1826 to a peak around 1850 before declining around 1885. The peak appears to correlate with the $\chi_{para}$ record (Figure 7b), which shows a maximum around 1850 before declining to a minimum around 1865–1880. The period from 1835–1880 has the lowest forest cover (Figure 7b) which may have led to larger floods, thus amplifying the peaks in $Q_{ss}$ and increasing the amount of detrital soil-sediment. These conditions provide a plausible mechanism for explaining the high levels of $\chi_{para}$ around 1850. Modelled $Q_{ss}$ (Figure 7c) increases from c. 1910 to a smaller peak around 1935 before declining, a pattern paralleled by the $\chi_{para}$ values (Figure 7b). A decline in $Q_{ss}$ (Figure 7c) occurs from 1940 with a slight increase around 1950 which tails off before another increase in $Q_{ss}$ around 1960–1980, again broadly tracking the $\chi_{para}$ curve (Figure 7b). This peak is also mirrored in the 210Pb sediment accumulation rate (Figure 7a). All three sets of broad peaks match within the errors of the age–depth model.

Whilst the precipitation inputs remain high between 1925 and 1960 (Figure 7g), the response of the fluvial system (Figure 7f) is diminished, which is a result of increased forest cover (and therefore $m$ value) within the modelled catchments (Figure 7h). Whilst a reduction in water discharge was expected because of the nature of the hydrological model, the peaks in sediment were also reduced at this time. The match between $Q_{ss}$ (Figure 7c) and $\chi_{para}$ record (Figure 7b) between 1925 and 1960 perhaps reflects that the increased forest cover did diminish the response of the fluvial
system and therefore the sediment discharge. The Ire $Q_{wm}$ record (Figure 7e) appears more comparable with $\chi_{para}$ than the Tamie $Q_{wm}$ record (Figure 7d). This is particularly noticeable around 1920 where the peaks in Ire $Q_{wm}$ and $\chi_{para}$ were less pronounced. These differences may reflect that the Ire was more efficient in delivering sediment with an almost instantaneous response in $Q_{wm}$ to flood events. For the Tamie the sedimentary response is likely to be masked and more complex as a result of the greater opportunities for sediment storage. The similarity between the $\chi_{para}$ and Ire-style $Q_{wm}$ in turn perhaps signifies that the lake was more sensitive to inputs from efficient flashy systems (eg, Ire) and that the lake sediment sequence is strongly coupled with flood sediment supply.

Crook et al. (2002) collated documentary evidence showing flood frequency (but not magnitude of events) within the Tamie (Figure 7i) and Ire (Figure 7j) since the late seventeenth century. These events are regarded as severe enough to cause damage to land and thus were reported in order to receive compensation for loss (Crook et al., 2002). There are inaccuracies in the historical record as not all events may have been recorded because some land owners may not have reported the incident or damages to their land. No documentary records are available specifically for the Tamie, but records exist from the Eau Morte catchment into which the Tamie flows downstream of Faverges (Figure 1). These may be used as a substitute record for flood events in the Tamie although localised flash flooding does not always propagate downstream with the same intensity (Crook et al., 2002). The modelled water discharges (Figure 7f) are a function of the engineered precipitation input series (snowmelt pulses) and also $m$ value, nevertheless there are some striking parallels between high $\chi_{para}$ and historical floods around 1850 and 1870 strengthening the suggestion that $\chi_{para}$ is a proxy for detrital catchment, sediment that is mobilised under the highest flows. Similarities in peak $Q_{wm}$ (Figure 7c) and the historical records for (large) floods in the Tamie (Figure 7i) and Ire (Figure 7j) occur at 1850, 1865–1875, ~1900, 1960 and ~1970 in particular, which suggests that CAESAR has captured the behaviour typical of the larger flood and sediment events.

**Model validation and understanding hydrogeomorphic processes**

In order to apply a numerical model to any real-world problems, validation and sensitivity testing of the model is essential. Previous attempts to validate long-term landscape evolution models have assessed valley long profiles (Tucker and Slingerland, 1994; Hancock et al., 2002) and undertaken hillslope plot experiments (Hancock et al., 2002), both of which are fraught with problems when modelling beyond the recent past (Coulthard et al., 2005). Coulthard et al. (2005) used a well constrained (radioisotopic-bond-dated) investigation of both sedimentation style or rate discerned from the timing of geomorphologically significant changes in river activity for comparison with the CAESAR record for four tributaries of the River Ouse, Yorkshire (England). An alternative to validation or corroboration by comparison with geomorphological histories is to compare lake sediment evidence with (CAESAR) modelled sediment discharge. The good correspondence between the Petit lac magnetic proxy ($\chi_{para}$) and modelled sediment record for both subcatchments is encouraging, despite the fact that the lake sediment record is a catchment-wide record of erosion and deposition, whereas the totalled sediment record ($Q_{wm}$) presented here depicts time series for two subcatchments. The lake sediment record has been smoothed using a moving average (nine point) to eliminate short-term variability and highlight the long-term trends that are the focus of this paper. As the resolution of the lake sediment chronology is ±10 years, it is logical to smooth the sediment record to some extent; we regard subdecadal as the best possible chronological resolution. In the case of non-annually laminated sediments, precise comparisons cannot be made owing to the chronological uncertainty in the lake sediment proxies, but the parallelism shown here suggests the model is capturing the timing and magnitude of changes over longer timescales (bi-decadal) and to some extent on an event basis. In addition these $Q_{wm}$ data incorporate neither the three other subcatchments (Montmin, St Ruph and Bornette) nor sediment transmission through the sensitive Eau-Morte floodplain/delta (Figure 1).

The overall match between the modelled and lake sediment proxies highlights the potential for producing a modelled catchment-wide sediment record for comparison with lake sediments. The match appears slightly better for the Ire subcatchment, which perhaps suggests that this style of system and sediment transport behaviour dominate the lake sediment detrital record. The characteristics of this system are flashy flood-induced sediment transmission and it is likely that the other mountain-torrent subcatchments (eg, Bornette, St Ruph) may behave in a similar manner. The lower reaches of the Ire traverse across a floodplain (not yet modelled) and may have had significant storage potential in the nineteenth century before dyking and canalisation of the reach was introduced in the early twentieth century. The management schemes put in place since the early twentieth century certainly reduced flooding as the lower canalised reaches allowed direct transporting of sediment from the Ire to the lake. The match between $\chi_{para}$ and total $Q_{wm}$ suggests a similar forcing; therefore one may conclude that higher flows drive the $\chi_{para}$ record in the lake sedimentary sequence. The lake may also be more strongly coupled to mountain torrent hydrology/sediment movements than the behaviour of storage-release-storage systems like the Tamie. Alternatively, the close proximity of the Ire system to the lake (4 km versus 12 km) may mean that the lake record is more sensitive to local inputs. However, resolving these questions requires further modelling of sediment storage on floodplain reaches.

The role played by forest cover on the sediment regime is at present captured through the moderation of the flood hydrograph; CAESAR perhaps at present fails to capture this completely because of the simplistic and static representation of hillslope processes. This impression is perhaps compounded or obscured by the lack of dramatic changes within the forest cover of the two subcatchments. However, the magnetic proxy records suggest that forest cover increases and stabilises in the late nineteenth century a reduction in sediment delivery to the lake is reflected in the $\chi_{para}$ record, a trend that has been replicated using CAESAR. In addition, the greatest amounts of modelled sediment are moved during the periods of lowest forest cover, which suggests that even minor changes in forest cover can have significant perturbations on the sediment regime. The geomorphology of the catchment plays a large role in modulating the impacts of meteorology, long-term climate and land use. The Tamie displays a more complex set of responses as a result of longer duration sediment storage in that
subcatchment. The response of total sediment flux from the Ire is rapid, whereby sediment is moved from the hillslopes into the channel through well coupled tributaries with the only storage in the channel and of a temporary nature producing efficient transmission of sediment from this subcatchment. Understanding systems such as the Ire should be easier than systems such as the Tamie where storage and release of sediment must be considered. Although the changes in forest cover are subtle for both subcatchments, there is some evidence that forest cover conditions the response of the hydrological system and sediment regime even for small-scale perturbations. When forest cover is increased in CAESAR by 10–15%, peak flood discharges appear to reduce by around 35%. These values are within a similar order of magnitude and broadly realistic when compared with previous research into the effects of land use on fluvial systems, which suggests that reducing forest cover increases water yield (Brown et al., 2005). Should the changes in forest cover be more pronounced, perhaps the response in the sediment regime within CAESAR will also be more pronounced, but longer temporal simulations with greater switches in forest cover are needed.

At present the representation of hillslope processes within CAESAR is relatively simplistic, which reflects a necessary reduction in complexity to allow computational time to be spent on fluvial processes, the focus of research and development in the past (Coulthard and Van De Wiel, 2006; Coulthard et al., 2007). Clearly there is scope to increase the level of slope process representation in CAESAR for studies such as this where hillslopes to fluvial system coupling is very important. Once the hillslope processes are developed, this may allow a more sensitive analysis of the role of changing land use at catchment scale. The importance of spatially distributed numerical modelling cannot be overestimated. If a DEM had not been used to represent topography for this type of study, then important sediment conditioning effects such as storage and release of sediment (e.g., Tamie) or seemingly more rapid sediment transmission (e.g., Ire) would not be identified and the temporal data alone would have provided only part of the story.

Implications

The study shows that a cellular hydrogeomorphological model can realistically simulate the complex interactions between climate, meteorological events, land use, flooding, and sediment transport and storage for a subalpine catchment over decadal timescales. This modelling tool may become vital for anticipating future changes. IPCC reports (2007) suggest that for European Alpine catchments, such as Annecy. At present, a large proportion of the winter precipitation is stored as snow and consequently released during April and May. This study shows that snow cover and snowmelt are critical conditioning components of the subalpine hydrogeomorphological regime. If winter precipitation increases 10–20% as suggested by the IPCC (2007), the predicted increase in the frequency and magnitude of large flood events in winter and spring can be expected to be amplified further as water storage, in the form of snow, is reduced. These climatic projections affect a landscape that is experiencing changing land-use needs (e.g., declining numbers of winter ski resorts, changes in EU Agricultural Policy) and CAESAR allows modelling of these drivers in an integrated framework.

Conclusions

CAESAR has allowed the investigation of drivers of landscape change; meteorological events, climate and land use, and assessed the impact that they have on hydrological and sedimentological regimes. Conclusions from this research suggest that:

1. Catchment morphometry and sediment distribution play a significant role modulating the pattern of sediment transmission. Thus spatially distributed numerical modelling is of fundamental importance to understand the pattern of sediment transmission at catchment scale and to identify storage and release within the hill slope–fluvial system.

2. Peaks in sediment discharge appear to be largely a function of flood magnitude driven by precipitation and snowmelt, but this may be in part conditioned by the control forest cover (land use) exerts over the hydrological regime.

3. Data-model comparisons suggest that the Petit lac d’Annecy lake sediment record may be more sensitive to systems where the linkages between hill slope and lake basin are well-coupled whereas significant sediment storage interrupts the sediment conveyor and encourages this relationship to breakdown.

4. Palaeorecords such as lake sediments and in particular environmental magnetic proxies for detrital sediment supply can provide a robust methodology to validate the modelled sediment flux. Conversely modelled sediment discharge provides an experimental framework for testing hypotheses about drivers of the lake sediment record.

5. There is a clear need for further model development, for example improving and coupling hill slope processes with land use, storm events and long-term climate as this would capture the hydrological and sedimentological regime more effectively.

Future research will attempt to improve representation of hillslope processes within CAESAR, to allow a fuller understanding of the role of forest cover. Here we have tested the capability for CAESAR to be used as a tool to predict geomorphological change and sediment flux from a catchment under varying meteorological events, climate and land-use scenarios. To assess longer-term impacts of change, for example wet/dry shifts in climate and more dramatic changes in land use, model runs are needed that address longer time periods (>2000 years) to comprehend system drivers over these timescales. The eventual aim is to provide and test a framework for understanding the annual to decadal changes in flooding and sediment transmission that may take place in the future so that approaches to adaptation and mitigation of flood hazards and shifts in sediment movement can be assessed.

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