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How sensitive are river systems to climate and land-use changes? A model-based evaluation

T. J. COULTHARD* and M. G. MACKLIN
Institute of Geography and Earth Sciences, University of Wales, Aberystwyth SY23 3DB, Wales, UK

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ABSTRACT: Simulated Holocene sediment discharges from a high-resolution cellular model of river evolution in northern England, driven by a peat-bog proxy climate and palynological based land-cover record, show a very close similarity to alluviation phases evident in British river valleys. Independent validation of the model indicates that British river systems have been surprisingly sensitive to short term (ca. 10^2 yr) climate fluctuations, although river dynamics also have been modulated by land-use change and sediment supply. This has important implications for understanding alluvial system evolution, establishing controlling factors and, most importantly, forecasting river response to future climate and land-use changes. Copyright © 2001 John Wiley & Sons, Ltd.

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KEYWORDS: numerical modelling; sediment discharge records; Holocene proxy climate records.

Introduction

For the past 25 yr, many studies have demonstrated how changes in climate and land-cover during the Holocene have affected river systems (e.g. Knox, 2000). By correlating dated alluvial sequences with proxy climate records and cultural histories, researchers have shown how deforestation and changes in agricultural practices (Knox, 1977; Brown and Barber, 1985; Trimble, 1999) and hydroclimate variability (Macklin *et al.*, 1992; Vita-Finzi, 1995) have influenced valley floor sedimentation and erosion rates. Although these studies have provided valuable information on long-term trends and patterns, the temporal resolution of alluvial sequences, and of climatic and anthropogenic records, are commonly insufficient to demonstrate an unequivocal temporal correlation. This is unfortunate, as evaluating and testing direct links could answer one of the fundamental questions within fluvial geomorphology, that is, how sensitive river systems are in relation to either, or both, climate and land-use changes?

An alternative approach is to use numerical modelling to simulate the interactions between environmental change and the catchment. Recent studies (Coulthard *et al.* 1998, 1999, 2000) have started to address this issue by using a cellular model to determine the effects of different climate and land-use scenarios on sediment discharges in an upland basin in northern England for simulations lasting up to 100 yr. This model suggested that deforestation elevated sediment discharges by 80%, whereas increasing the magnitude of all rainfall events by 33% produced a 100% rise in sediment discharge. When climate and catchment land cover were changed simultaneously, however, this produced a 1300% increase in sediment discharge, suggesting that upland river catchments are more sensitive to climatic deterioration when they are deforested (Coulthard *et al.*, 2000). Although these model runs confirmed earlier field-based investigations of Holocene river development in upland northern England (Macklin *et al.*, 1992; Merrett and Macklin, 1999), it was not known whether this modelling approach was applicable to larger, more complex catchments. In this paper we present for the first time, the results of a new simulation that spatially and temporally up-scales our previous work to model the evolution of a larger river basin over the past 9000 yr.

Method and model description

Recently, cellular computer models have been used to study the evolution of river basins (Howard, 1994; Tucker and Slingerland, 1994; Willgoose *et al.*, 1991). They represent hillslopes and river channels as a mesh of square or hexagonal cells with elevations that change according to approximations for erosion and deposition. These studies have provided fresh insights on the development of landscapes over longer time periods (generally greater than

* Correspondence to: T. J. Coulthard, Institute of Geography and Earth Sciences, University of Wales, Aberystwyth.
E-mail: T.Coulthard@aber.ac.uk

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10^5 yr), but they have rarely been applied to, or their results compared with, real river basins and actual sedimentary records. Furthermore, they have been limited by a river representation without divergent flow, routing all water to the lowest neighbouring cell, and through erosion and deposition models that do not include the effects of grain size. The model presented in this paper addresses these limitations in four ways. First, it uses flow rules that allow divergent and convergent flow, secondly it incorporates fluvial erosion and deposition over a wide range of grain sizes, thirdly runoff simulation is driven by a peat-bog-derived proxy wetness index and palynologically based land-use record, and finally, it is applied over a 9000 yr time period to a 450 km^2 catchment that includes upland, piedmont and lowland valley floor reaches.

The model represents a river catchment with a mesh of uniformly sized square grid cells. Each grid cell contains values for elevation, water discharge, vegetation cover and grain-size distribution. To model convergent and divergent flow, a novel scanning algorithm is used that sweeps across grid cells four times (from top, bottom, left and right) (Coulthard *et al.*, 2000). In each scan, flow from a hydrological model is routed to any (or all) of the three downstream immediate neighbours as per Murray and Paola (1994). However, unlike Murray and Paola's method, if flow exceeds the cells' subsurface hydraulic conductivity, water depth is calculated with a modification of Manning's formula (Coulthard *et al.*, 2000) using the average positive slope from all eight neighbours. If the combined elevation of the cell, and its water depth, is greater than one (or all) of the three downstream neighbours then a proportion is routed to these cells. The maximum depth calculated for all cells over each of the four scans is recorded and has been shown to be similar to calculations using multiple flow algorithms (Desmet and Govers, 1996). Any flow not removed from the basin is left, allowing hollows to fill up so they do not to interfere with subsequent scans. Although unable to represent momentum effects or secondary circulation, this procedure is several orders of magnitude faster than other methods and most importantly allows convergent and divergent flow in all directions, over local topographic highs, while maintaining mass balance and fluxes along the maximum energy gradient.

Flow depth and bed slope are used to calculate fluvial erosion between cells through the Einstein–Brown (Einstein, 1950) expression. Sediment transport is calculated for 11 separate grain-size fractions (in whole phi units from 0.001 to 0.256 m) coupled to the stream bed through 11 active layers (Hoey and Ferguson, 1994; Cui *et al.*, 1996) each 0.2 m thick, creating a 2.2 m stratigraphy for each cell. Mass movement is calculated through an iterative procedure that moves material from cell to cell when a slope threshold is exceeded. Soil creep is calculated monthly and a linear vegetation growth model allows a turf mat to develop. Changes in cell elevation resulting from fluvial erosion, mass movement and creep are updated simultaneously and time-steps chosen so that net rates are restricted to 10% of the average slope, preventing inaccuracies and computational instability. As these processes operate within the same grid, feedbacks between them are integrated automatically. This allows the simple inputs of an initial topography, vegetation cover and rainfall, to drive a complex sequence of catchment evolution.

This model was applied to the River Swale, northern England, which has a maximum basin relief of 725 m (Fig. 1). The catchment is underlain by Carboniferous sandstones and gritstones, and much is capped by a variable thickness of Pleistocene till. The Holocene valley floor is inset below and confined by Late Pleistocene glacio-fluvial terraces and moraine ridges (Howard and Macklin, 1998). To simulate the Holocene evolution of the River Swale, an initial topography, climate record and land-cover history were required. As the exact valley topography of the River Swale at the beginning of the Holocene is unknown, the present-day surface was taken as an analogue. This is not an unreasonable assumption as following large-scale valley floor incision (10–20 m) during the Late-glacial (Howard *et al.*, 2000), trunk channel bed levels have varied by only ± 3 m over the Holocene (Macklin *et al.*, 2000). This surface was represented by a 50 m by 50 m digital elevation model (DEM) of the upper 450 km^2 of the Swale catchment, extending to Great Langton (20 m OD), below which elevation changes by less than 5 m. The DEM was overlain with a 3 m thick 'soil' of homogeneous grain-size distribution capped with a turf mat. The climate input for the model is derived from a combination of two proxy wetness indices from peat bogs in northern England (Bolton Fell Moss; Barber *et al.*, 1994) and northern Scotland (Anderson *et al.*, 1998). We have used the nearer Bolton Fell Moss record (located 60 km northwest of the River Swale), which extends back to 6300 cal. yr BP, for the most recent part of the Holocene and the Scottish record, which starts at 9200 cal. yr BP, for the early Holo-

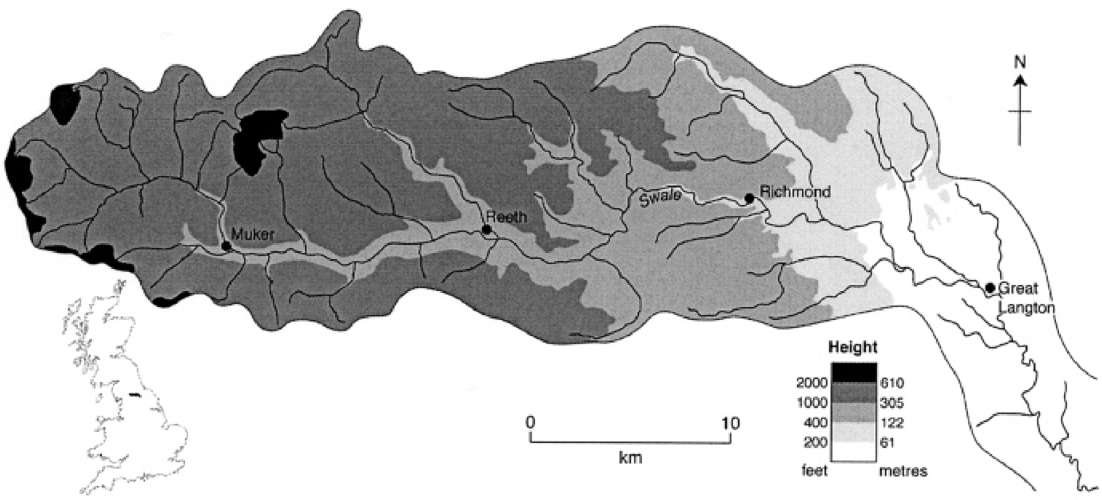

Figure 1 Relief and location of the River Swale catchment

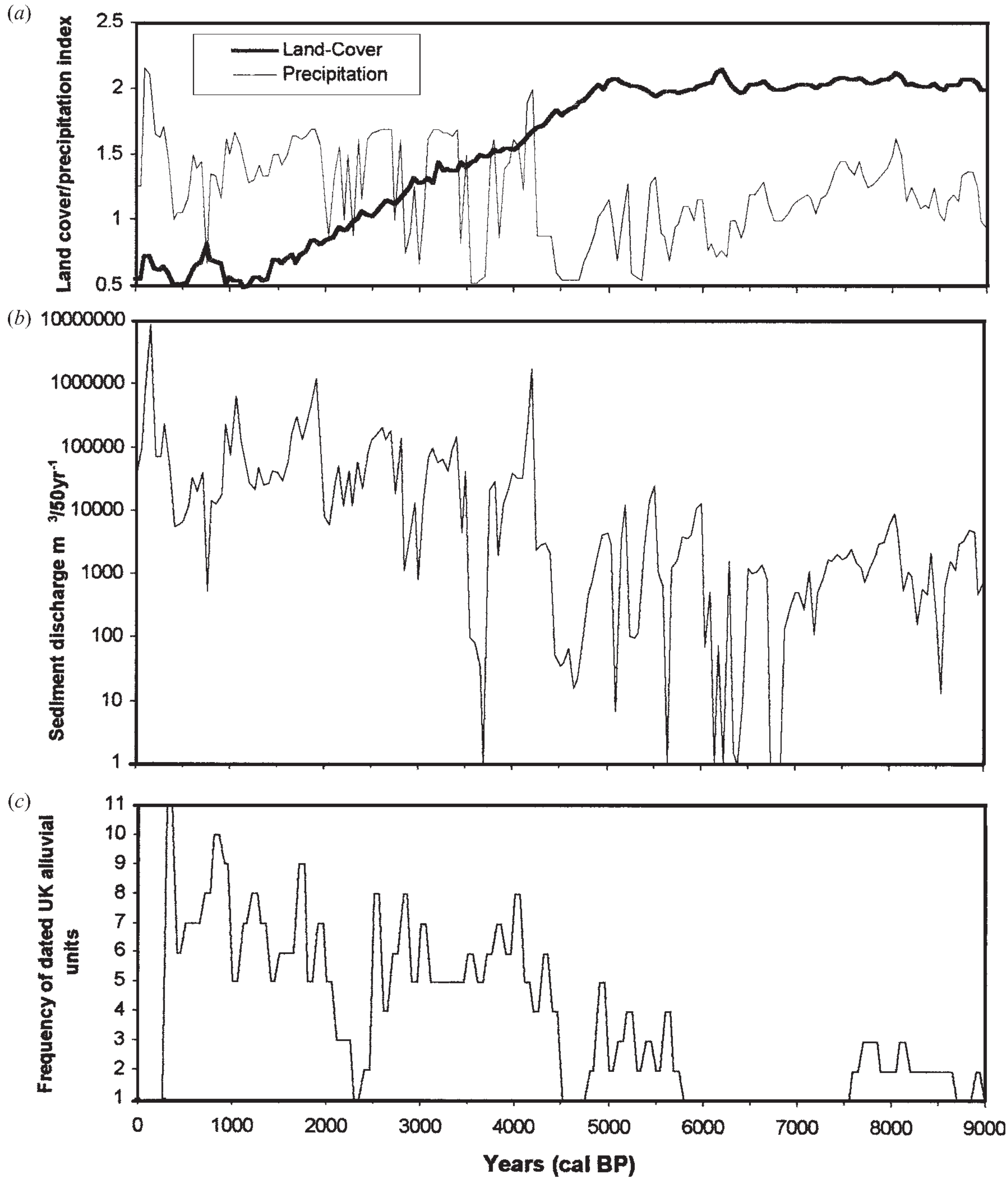

Figure 2 (a) Land-cover and precipitation indices used to drive the Holocene simulation. (b) Log simulated sediment discharge. (c) Frequency of dated alluvial units in the UK, including the River Swale (after Macklin, 1999).

cene. This combined sequence was resampled at 50 yr intervals, and based on previous applications (Coulthard *et al.*, 2000), normalised to values between 0.75 and 2.25 (Fig. 2a) to create a rainfall index. To drive the model, a 10-yr hourly rainfall record (1985–1995) located in the lower part of the Swale catchment (SE 515370) was duplicated five times to span 50 yr, and multiplied by the index, generating a proxy hourly rainfall record for the past 9000 yr. Changes in land cover are poorly documented in the Swale catchment and we have used local palynological records (Tinsley, 1975; Smith, 1986) to develop a land cover index ranging from 2 (forested) to 0.5 (grassland) (Fig. 2a). This simulated the effects of different land-cover on catchment hydrology by altering a parameter, within the hydrological model, controlling the magnitude and duration of the flood hydrograph for a given storm event (Coulthard *et al.*, 2000). During the simulation, continuous sediment discharge data for each grain-size fraction were recorded and at 50-yr intervals, grid-elevation and grain-size data were saved, from which, detailed topographic, runoff and sediment discharge records of the River Swale catchment were produced.

Analysis

Figure 2 shows (a) the climate and land-cover indices, (b) the log simulated sediment discharge and (c) the frequency of dated Holocene alluvial units in the Yorkshire Ouse basin (of which the River Swale is a major tributary) and other British river systems (Macklin, 1999). This demonstrates a rapid catchment response to climate change, with 50-yr sediment discharge peaks corresponding with periods of wetter climate. Furthermore, these peaks are of short duration and deliver over 90% of the total sediment discharge in less than 1000 yr. After ca. 5000 cal. yr BP, as tree cover gradually declines, there is an increase in sediment discharge, suggesting that decreasing vegetation cover enhances sediment supply and erosion. This relationship, however, is not linear, with similarly wet peaks at 1000, 1800, 2700 and 3200 cal. yr BP generating very different sediment discharges. This may be the result of sediment storage and remobilisation in the valley floor. Regression analysis between the log simulated sediment discharge and alluvial unit frequency (Fig. 3) shows a statistically significant positive relationship, which would be expected as periods of accelerated floodplain sedimentation are likely to equate to increases in catchment sediment discharge.

There is a striking similarity between the simulated and observed records, not only in terms of their overall form, but also in the strong correspondence between submillennial scale changes in simulated sediment discharge and the number of dated alluvial units over the past 9000 yr. For example, the consistently low simulated sediment discharges between ca. 6000–7000 cal. yr BP in the Swale model matches the paucity of dated alluvial units evident in British river systems during this period. Similarly the step-like and sustained increases in sediment discharges between ca. 4500 and 4000, at ca. 2000 and at ca. 400 cal. yr BP are also features of the British Holocene alluvial record. The model also appears to be robust enough to reproduce some of the short-term (10^2 yr) variations in Holocene fluvial activity. Thus periods in the past 4000 yr where simulated river sediment discharges exceeded 500 000 m^3 per 100 yr (ca. 4000, 2500, 1800, 1100 and 400 cal. yr BP) equate with frequency maxima of dated alluvial units. The timing of these phases is very similar to discontinuities identified in fluvial systems in both Europe (Starkel, 1991; Macklin and Lewin, 1993) and the USA (Knox, 1983, 1993), which have been shown to correspond to regional- and hemispheric-scale climate changes. This would strongly indicate that climate-related variations in flood frequency and magnitude is the principal factor governing long- and short-term river sediment discharges in both this simulation and British catchments during the Holocene.

High-resolution modelling of the River Swale over the past 9000 yr presented several new challenges. With previous model applications to small upland catchments, using a much smaller grid size (2 m), it was reasonably assumed that channels could not be narrower than a single grid cell. Within the Swale catchment many tributaries are smaller than the 50 m grid size, and to compensate the thresholds at which the water depth is calculated and erosion initiated were lowered. In addition, precipitation and land cover were changed uniformly over the catchment, which is a reasonable assumption for a small catchment but is likely to be an oversimplification for the Swale, with a drainage area of several hundred square kilometres and significant relative relief. Because of these limitations, model results should be viewed as preliminary and the number, timing and relative magnitude of the simulated sediment discharge peaks of more significance than predicted sediment volumes.

There are also small differences between the timing and magnitude of sediment discharge peaks and the number of dated alluvial units. This was not unexpected, as undoubtedly there are errors in the dating of the alluvial units and the peat-bog proxy climate record. Considering potential inaccuracies and model assumptions, it is perhaps all the more surprising that there is such a good relationship between simulated sediment discharges and number of alluvial units. This would imply that the model is functioning correctly and that climate is the dominant control of Holocene river systems. Otherwise, we would not expect to find such a strong correspondence between model simulations from a single catchment and British Holocene alluvial histories in general.

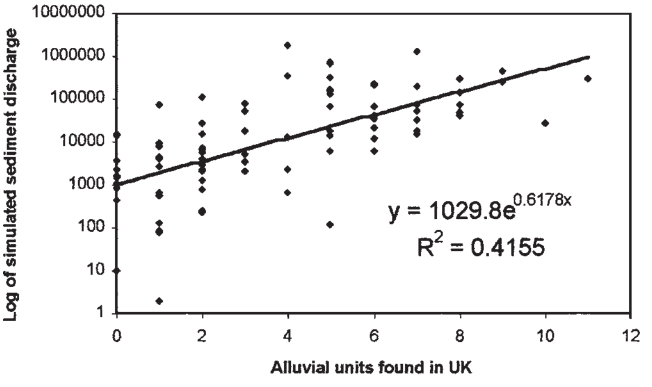

Figure 3 Chart showing the relationship between the log simulated sediment discharge and frequency of dated alluvial units in the UK (after Macklin, 1999). Here the sediment data are aggregated into 100 yr totals.

Conclusions

The results from this simulation show how Holocene river evolution in temperate catchments is driven primarily by climate change, but influenced by land-cover and sediment storage effects. The simulation is based on an integration of unrelated climate and land-cover data sets, validated with independent data that have a good statistical and logical credence. This model is not calibrated by the validation data, suggesting that the process representation, parameterisation and model dynamics are correct. Therefore, it may be a powerful new tool for investigating Holocene river dynamics and landscape evolution, which will allow us to examine linkages and rates of catchment change that we cannot presently achieve owing to the poor spatial and temporal resolution of field studies. This is not a replacement for field study, however, more a complementary technique, suggesting areas to investigate, possible causalities and raising new research questions.

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