Improving bank erosion modelling at catchment scale by incorporating temporal and spatial variability

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Abstract

Bank erosion can contribute a significant portion of the sediment budget within temperate catchments, yet few catchment scale models include an explicit representation of bank erosion processes. Furthermore, representation is often simplistic resulting in an inability to capture realistic spatial and temporal variability in simulated bank erosion. In this study, the sediment component of the catchment scale model SHETRAN is developed to incorporate key factors influencing the spatio-temporal rate of bank erosion, due to the effects of channel sinuosity and channel bank vegetation. The model is applied to the Eden catchment, north-west England, and validated using data derived from a GIS methodology. The developed model simulates magnitudes of total catchment annual bank erosion (617 - 4063 t yr^{-1}) within the range of observed values (211 - 4426 t yr^{-1}). Additionally the model provides both greater inter-annual and spatial variability of bank eroded sediment generation when compared with the basic model, and indicates a potential 61% increase of bank eroded sediment as a result of temporal flood clustering. The approach developed within this study can be used within a number of distributed

hydrologic models and has general applicability to temperate catchments, yet further development of model representation of bank erosion processes is required.

Keywords

Bank erosion, sediment, sinuosity, vegetation, catchment.

Introduction

Sediment erosion and transport are natural geomorphic processes within river catchments, but high magnitude events and anthropogenic influences (such as deforestation and over-grazing) can easily disrupt the sensitive equilibrium between them. When these changes result in increased sediment loads, they may have numerous detrimental effects to the river system; increased sedimentation in channels and floodplains affecting land-use and changes in river morphology and behaviour (Owens et al, 2005), flooding (Mcintyre et al, 2012), and disruption to habitats and decreased biodiversity (e.g. salmonid spawning, Soulsby et al, 2001). Furthermore, as sediments act as a transport vector for pollutants such as heavy metals, increased sediment delivery may also change the chemical composition of the river resulting in negative impacts to the ecosystem (eutrophication, Owens and Walling, 2002; and toxicity effects, Mackin et al, 2003). Consequently, information on sediment generation and transport through river systems at a catchment scale, and their temporal and spatial variability is increasingly important to support catchment management.

Sediment fingerprinting techniques have been applied to a number of catchments worldwide to understand the relative importance of different sources of sediment, including eroded bank material. These suggest that bank erosion contributes significantly to catchment sediment budgets, in some cases representing up to 48% of total sediment supply (Walling, 2005; Walling et al, 2008). Furthermore, where channel banks contain contaminated sediments the contribution of bank erosion to pollutant supply has also been noted to be significant; for example, lead supply from banks of 9 kg m^{-1} yr^{-1} (Glengonnar Water, Scotland UK, Rowan et al, 1995) and mercury supply of 2.7 kg km^{-1} yr^{-1} (South River, Virginia USA, Rhoades et al, 2009).

The severity of bank erosion is influenced by numerous factors such as the presence of bank vegetation (through both mechanical and hydrological factors) (Micheli and Kirchner, 2002; Bartley et al, 2008; Simon and Collison, 2002); discharge and flow regime (Julian and Torres, 2006; Hooke, 2008; Surian and Mao, 2009); lithology (Hooke, 1980); channel confinement (Lewin and Brindle, 1977; Janes et al, 2017); and anthropogenic influences (Winterbottom and Gilvear, 2000; Michalková et al 2011). As such rates of channel bank erosion are both highly temporally and spatially variable (Hooke, 1980; Bull, 1997; Lawler et al, 1999; Couper et al, 2002).

Management of sediment and other diffuse pollution issues at a catchment scale is imperative due to the connectivity of the system. Models provide a valuable means of estimating sediment generation and transport at catchment scales, potentially providing insights into the spatio-temporal generation and transport of sediment and the system responses to longer term changes such as climate change. However, many existing catchment-scale hydrological and water quality models contain no explicit representation of channel bank erosion processes; CREAMS - Chemicals, Runoff and Erosion from Agricultural Management Systems (Knisel, 1980), ANSWERS - Areal Nonpoint Source Watershed Environment Simulation (Beasley and Huggins, 1980), EPIC - Erosion Productivity Calculator (Sharpley and Williams, 1990), SWAT – Soil and Water Assessment Tool (Arnold et al, 1998), and PSYCHIC – Phosphorus and Sediment Yield Characterisation In Catchments (Davison et al, 2008). Additionally, those models which do contain representations of bank erosion only account for few of the numerous aforementioned factors controlling channel bank erosion rates which limits their ability to simulate the observed spatial and temporal variation of sediment generation through bank erosion processes. For example, the semi-distributed INCA-Sed model (Jarritt and Lawrence, 2007) accounts for bank eroded sediment within in-stream sediment sources using a power law relationship incorporating discharge and calibration parameters. As acknowledged by the authors, a range of sub-reach scale processes are not included within the model and therefore only a broad range of seasonal trends can be observed, rather than finer temporal and spatial variation. The model SedNet provides a mean-annual sediment budget (Prosser et al, 2001; Wilkinson et al, 2009). Riverbank erosion within the model is based on an empirical relationship related to stream power, the extent of channel bank vegetation, and non-erodible surfaces. Whilst this method incorporates some factors influencing the spatial variation of bank erosion rates and provides an estimate of annual sediment generation, it does not account for finer-scale temporal variability or provide an indication of event-based bank erosion. Whilst a dynamic version of the model (D-SedNet, Wilkinson et al, 2014) exists, this model disaggregates longer term data to provide daily output this model, meaning the model is unable to fully capture the temporal variability observed in sediment loads.

Detailed numerical models of bank erosion have been shown to simulate channel migration with reasonable accuracy (Darby et al, 2002, 2007; Duan 2005; Nagata et al; 2000). These models generally incorporate mathematical modelling of hydraulic bank properties, shear stresses acting on channel banks and subsequent erosion. However these models lack simulation of catchment hydrology, and the high-resolution data required for such models and their computational requirements limit their application to reach scales. Therefore to provide estimates of bank-eroded sediment at a catchment scale, alternative methods are required.

If models are to provide the more holistic representation of sediment processes at a scale that is needed to inform catchment management, further research is needed to improve two key aspects of catchment models; continuous simulation of coupled hydrological and sediment processes, and the ability to replicate both temporal and spatial variability of natural systems. This paper therefore describes the further development and application of the Système Hydrologique Européen TRANsport (SHETRAN) model (Ewen et al, 2000) to provide improved spatio-temporal representation of channel bank erosion processes within simulated catchment sediment budgets. The physically based model SHETRAN was chosen due to the ability of the model to represent both spatial and temporal variation of sediment generation through physical representation of these processes and their controlling factors. In particular, the paper shows how the modifications enable improved simulation of the temporal (through representation of bank vegetation removal and bank de-stabilisation associated with high magnitude events, and subsequent recovery) and spatial (by taking account of the influence of channel sinuosity) variation of bank eroded sediment generation within the Eden catchment in north-west England.

Methodology

SHETRAN (Systeme Hydrologique Europeen TRANsport) is a physically-based distributed model for catchment scale simulation of hydrology and transport (Ewen et al, 2000). The model operates using a grid based representation of the catchment, with channel links situated along the edges of the grid cells. An option to include a more comprehensive representation of channel bank hydraulics can also be incorporated, resulting in an additional 10m width grid cell between channel links and the adjacent grid cells. The temporal resolution of the model is typically one hour, although the timestep decreases during storm events to provide an improved representation of rapid infiltration and surface runoff processes. The processes represented within the hydrological and sediment components of the model are shown in Figure 2 and detailed within Birkinshaw et al, 2014 and Elliot et al, 2012. The following section details the development of the bank erosion component of SHETRAN and the application of the developed model is described in the subsequent section. Hereafter, the existing SHETRAN bank erosion model is termed the ‘basic’ model and the revised model implemented within this study the ‘enhanced’ model.

Description of model improvements

The representation of bank erosion within the basic model is based on the exceedance of critical shear stress (τ_{bc}) acting on the channel banks. The critical shear stress is calculated using the Shield’s curve method (similarly to Simon et al, 2000). Bank erosion (E_b) is calculated as a rate of detachment of material per unit area of bank (kg m^{-2} s^{-1}) according to:

$$E_b = BKB.\left(\frac{\tau_b}{\tau_{bc}} - 1\right) \ where\ \tau_b > \tau_{bc}$$

where *BKB* is a bank erodibility parameter(kg m^{-2} s^{-1}), and τ_b is the shear stress acting on the channel bank (N m^{-2}) calculated as:

$$\tau_b = K\tau \qquad (2)$$

where *K* is a proportionality constant calculated from channel width and flow depth and τ is the mean flow shear stress on the bed. Whilst this equation accounts for the influence of varying discharge and hence shear stress acting on channel banks, all other significant factors (including those mentioned in the previous section) are not included. Therefore the natural variation of bank erosion rates both spatially and temporally throughout catchments is likely to be underestimated.

Within the enhanced model, spatial variation of bank erosion is represented by way of the non-linear influence of local channel sinuosity on bank erosion. This is incorporated within the model by categorising channel sinuosity in to one of three groups (similarly to channel curvature ratio categories as detailed by Crosato, 2009); channel links with low sinuosity (<1.2) have low erosion rates, moderately sinuous channels (1.2-1.5) have the highest erosion rates, and highly sinuous channels (>1.5) have erosion rates slightly lower than that of moderately sinuous channels (Janes, 2013).

Temporal variation of bank erosion as a result of the changing channel bank vegetation is represented within the model by varying the bank erodibility coefficient (*BKB*) between minimum and maximum values over time (see Figure 3). When channel discharge at a location in the catchment exceeds a threshold value (Q_{Thresh}) for that location the bank erodibility coefficient at that location increases to a maximum value (BKB_{max}). Q_{Thresh} represents the discharge at which vegetation within some parts of the reach is expected to be removed, and hence bank erodibility is increased. For outer-bends with little vegetation this increase in erodibility represents de-stabilisation of channel banks. Q_{Thresh} at the catchment outlet is set by the user (based on flood recurrence interval), and then each link is given a unique value of Q_{Thresh} calculated from the value of Q_{Thresh} at the outlet (the methodology used is detailed in the model application section). For all subsequent time steps of the model where the threshold value is not exceeded, the bank erodibility coefficient gradually decreases over time to the minimum value (BKB_{min}) at a rate set by the recovery factor (R):

$$BKB_t = BKB_{max} \ \ where\ Q \geq Q_{Thresh} \quad (3)$$

$$BKB_t = BKB_{t-1}.R \ \ where\ BKB_t > BKB_{min} \quad (4)$$

The difference in the magnitude of BKB_{min} and BKB_{max} represents the stabilising influence of vegetation on channel banks. The seasonal climate also influences the recovery factor (R), which reflects the potential rate of re-growth of bank vegetation and subsequent bank protection and stabilisation. R is calculated from the potential evapotranspiration (as a proxy for plant development) assuming that bank-side vegetation are not water-limited due to the shallow depth to the watertable:

$$R = 1 - \left(k.\partial t.\left(\frac{PE_{obs}}{PE_{max}}\right)\right) \quad (5)$$

where PE_{max} represents the maximum daily potential evapotranspiration (mm s^{-1}), PE_{obs} (mm s^{-1}) is the observed potential evapotranspiration and $\boldsymbol{\partial t}$ is the length of the time-step (seconds). The parameter $\boldsymbol{k}$ controls the time-scale of vegetation recovery and should reflect the type of vegetation in the catchment. Higher values of *k*, leading to a quicker recovery times, are appropriate for species with the ability of rapid re-growth, such as willow (Salix fragilis). Table 1 shows the input parameters required for the developed bank erosion model.

Application of the enhanced model

The model was applied to the 2400km^2 predominately rural Eden catchment in north west England, UK (see Figure 4). Topographical variation across the catchment (788m AOD at the highest point, to 15m at the outfall at the Sheepmount gauge) results in significant variation of average annual rainfall; the lower Eden receives approximately 800mm yr^{-1} whilst upper reaches receive in excess of 2800 mm yr^{-1}(Mayes et al, 2006).

The model was applied with a grid resolution of 1km^2 (and bank cells with a length of 1km and width of 10m) with a maximum hourly temporal resolution. A 1km^2 grid resolution reasonably captured the OS (Ordnance Survey – UK national mapping agency) blue line channel network. The model was set-up using 30m Digital elevation model (Ordnance Survey, 2009), land-use (CEH, 2007), and soils (Wosten et al, 1999). A daily 1km^2 gridded daily rainfall product from 1990-2007 (Perry et al, 2009) was used to specify the spatial rainfall, with tipping bucket rain gauge data then used to disaggregate the daily data to an hourly resolution to capture the shorter duration intensities. A simple nearest neighbour approach was applied to disaggregate the daily totals to hourly; for each grid cell, the shape of the nearest available hourly record was used to distribute the daily total to hourly intervals (see Lewis et al, 2016 for further details).

The parameter Q_{Thresh}, which determines the discharge that leads to significant bank de-stabilisation and erosion, was derived in a three stage process and has a unique value for each link scaled from the value of Q_{Thresh} at the outlet. Firstly, the model was run using the long term average daily rainfall (temporally constant, but spatially variable across the catchment) to derive steady state simulated discharge at the catchment outlet, from which scaling factors were calculated for all links based on the ratio of local link flow to the outlet discharge. Secondly, the discharge magnitude at the catchment outlet for a flood of a return interval to represent Q_{Thresh} event was calculated using the annual maximum (AMAX) dataset (CEH, 2015) covering 46 hydrological years (1966-2012), the median of annual maximum values (Q_{med}) and a Generalised Logistic growth curve (estimated using L-moments, see Flood Estimation Handbook, Faulkner 1999). For a given return period T:

$$Q_T = x_T . Q_{MED} \tag{6}$$

where Q_T is the discharge for an event with return interval ($_T$), x_T is the growth factor (the value of the growth curve at a given return period). Finally the corresponding Q_{Thresh} values throughout the catchment were calculated by multiplying Q_{Thresh} valueat the catchment outlet by the scaling factors.

All channel links within SHETRAN representations are located between two channel bank cells and have a default sinuosity of 1. Therefore a GIS-based channel network was used to estimate sinuosity for each link. Sinuosity was measured across the catchment using WFD river waterbodies data (Environment Agency, 2012) and GIS; a channel network polyline was split into reaches of equal length, and sinuosity calculation for each reach was calculated as the channel distance divided by the straight-line distance between reach start and end points. As the value of sinuosity is dependent on the reach length at which it is measured, this process was repeated for a range of length scales. The length scale with the largest peak in variance of sinuosity (measurement length of 975m) was used as this best captured the variation of sinuosity across the catchment.

Model calibration and validation

After a one year ‘start-up’ period in which groundwater levels tended to an equilibrium, the model was run from 1991-2001 for parameter calibration, and 2001-2007 for validation. Similarly to previous studies using SHETRAN (Bathurst et al, 2006; Lukey et al, 2000; Elliott et al, 2012) calibration parameters included the overland and channel flow resistance coefficients, with calibration conducted manually due to the computational requirements of the model. The hydrological component of the model was compared with hourly and daily hydrological data from the National River Flow Archive (CEH, 2015) gauging stations and HiFlows data sets (see Figure 4). From this a range of parameter value sets were derived (see Table 3) based on parameters to which the simulated flows were most sensitive (Lukey et al, 2000 Bathurst et al, 2006). The simulation outputs were then superimposed on each other, providing an envelope of minimum and maximum model estimates of river flows.

Analysis of peak-over-threshold (POT) events was also conducted as part of the validation process to ensure the model could accurately reproduce high-magnitude events, using POT data from the NRFA (CEH, 2015). For each POT event the observed event maximum discharge was compared with the maximum simulated discharge within 24 hours either side of the event timing. The average percentage error of simulated POT events was then calculated within the calibration/validation periods for each gauging station.

The bank erodibility parameters (see Table 2) were calibrated by comparison with observed bank erosion values derived using an historical map overlay methodology in GIS, further details of which can be found in Janes et al (2017). Channel banklines were digitised for the Eden and main tributaries Caldew, Irthing, Lyvennet, Eamont and Petteril from Historical OS maps for the 5 available years (1880, 1901, 1956, 1970, and 2012) with consecutive banklines overlaid to provide an area of bank erosion. As smaller tributaries are often represented on OS maps as a single line (particularly on older maps) it is not possible to calculate bank erosion values for these channels using this methodology. To account for potential geo-referencing and mapping errors within the data, the eroded area was calculated using the simple overlay procedure, and also applying a buffer of 3.5m to the older channel, providing upper and lower erosion estimates respectively. Minimum and maximum bank height estimates were calculated from the two bank heights provided within the RHS survey data, to account for error within the estimate. Minimum and maximum estimates of annual bank eroded sediment were estimated for each sub-catchment using this procedure. Whilst alternative methods of data collection such as erosion pin methodologies can provide estimates of bank eroded sediment at a finer temporal resolution (event scale), these methods are limited spatially and cannot provide catchment wide estimates of bank erosion and are therefore unsuitable for this study.

Preliminary magnitudes of differences in erosion rates between vegetated and non-vegetated banks, and parameters influencing the length of recovery time were based on literature of riparian growth rates of vegetation types found in the area

(Environment Agency, 1998). The recovery factor was calibrated as 3 months during summer according to bank vegetation growth rates in Environment Agency, 1998. The return period of an event used to calibrate the Q_{Thresh} parameter was guided by literature evidence and was based on an event with return period of greater than 12 years. The variation of bank erodibility with channel sinuosity was parameterized based on Janes et al (2013); bank erosion rates at channel sinuosities around the threshold value of sinuosity (~1.5) are approximately 2.75 times greater than straight channels (low sinuosities), and in highly sinuous channels (>1.5) approximately 2 times greater.

Model simulations with the sediment component were conducted across the range of hydrological parameters specified in Table 3, so that the simulated suspended sediment load and bank erosion values incorporate the effects of the hydrological parameter uncertainty. Similarly to the hydrological component of the model, minimum and maximum parameter values were set for sensitive sediment parameters, and simulations were conducted using a range of parameter values within this range (see Table 3). Simulated annual sediment loads were calculated and compared to those predicted by sediment rating curves, derived using grab samples and turbidity data collected from several locations between November 2006 and March 2009 (see Figure 4) by the CHASM (Catchment Hydrology And Sustainable Management) project (Mills, 2009). These were then used in conjunction with either gauging station data or simulated discharge to provide estimates of annual sediment loads at these locations.

The sensitivity of the enhanced model to temporal flood clustering was analysed with respect to the magnitude of bank eroded sediment. To do this the model was run with a one year start-up period, and then three days of rainfall (taken from the

January 2005 event, 6/01/2005 – 8/01/2005 inclusive with a peak discharge at Sheepmount of 1516.3 m^3s^{-1}, as this was a notable high magnitude event). A temporally constant rainfall was then used for one week before a second smaller rainfall event that did not exceed Q_{Thresh}. The model was then re-run with 2, 4, 6, 8 and 12 week gaps between the two events. Constant temporal rainfall input between the two events was used to ensure identical antecedent hydrological conditions prior to the second event so that simulated differences in the magnitude of bank eroded sediment were due solely to event timing.

Results

Hydrological assessment

Table 4 shows the average hourly hydrological performance statistics of the model for the validation period (and daily statistics at Kirkby Stephen where hourly flow data were unavailable). All hourly NSE and R^2 values are above 0.55 and 0.7 respectively, indicating satisfactory model performance at all sites (Moriasi et al, 2007). The simulated absolute percentage bias is below 25% at all gauging stations (indicating satisfactory model performance according to Moriasi et al, 2007) and at 5 of the 8 stations is less than 8%.

The POT analysis indicates the model's ability to predict high-magnitude events (see Figure 5 and Table 5). Although the model under-estimates event peak flow at most locations, as is common with other hydrological models (Butts et al, 2004; Van Liew et al, 2003), 65% of POT events were within the simulated uncertainty range at the catchment outlet at Sheepmount (Table 4 and Figure 5). It should be noted that the gauging station on the Irthing at Greenholme is often affected by backwater from the Eden at medium-high flows, which could partially explain the lower peak over threshold simulation accuracy observed at this location (Table 5).

Bank erosion

The GIS overlay methodology indicates the total mass of sediment generated through bank erosion processes within the catchment is between 539-2346 t yr^{-1} (Table 6). The estimates from both GIS methodologies provide an uncertainty range between 211-4426 t yr^{-1}**.**Total annual simulated bank erosion in Table 7 is higher than the most recent observed average annual bank erosion rates (1970-2012 – Table 6) but within the observed uncertainty range over the historical. Additionally, Table 7 indicates the enhanced model simulates a greater inter-annual variability of average annual bank erosion rates than the basic model. The enhanced model simulates a greater range of spatial variation of bank erosion throughout the catchment than the basic model. The basic version of the model was parameterised so that the total catchment average annual mass of bank eroded sediment generation was similar to the enhanced model to enable comparison of spatial bank erosion simulation in Figure 6. The observed data used for comparison here is taken from the upper estimate. The basic version of the model (Figure 6A) simulates a fairly spatially constant magnitude of bank erosion throughout the catchment in comparison to the enhanced model (Figure 6B) and the observed data (Figure 6C). The model was also validated at a sub-catchment scale using Water Framework Directive sub-catchment boundaries by correlating the total simulated bank eroded sediment of the basic and enhanced versions of the model with the observed data. Correlations between simulated and observed data indicate the enhanced model provides a more accurate spatial estimation of bank erosion at the sub-catchment level ($R=0.500$, $p=0.007$) compared to the basic model ($R=0.367$, $p=0.048$). These correlation values indicate an improvement in the spatial variability of bank erosion simulated by the developed model, but nevertheless the overall predictive ability of the spatial variability is poor due to reasons detailed within the discussion.

Sediment load accuracy

Table 8 shows observed annual sediment loads with upper and lower 95% confidence intervals (calculated from the coefficient of the rating curve equations from Mills, 2009), and simulated annual sediment loads with upper and lower bounds based on the parameter set used for simulation. The confidence intervals of the observed sediment loads incorporate both hydrological and sediment parameterisation uncertainty and are of a similar magnitude to the uncertainty bounds of simulated sediment loads. Furthermore, the ranges of simulated and observed sediment loads overlap at all locations.

Sensitivity to temporal flood clustering

Values of bank eroded sediment generation for each of the five temporal flood cluster scenarios was calculated by summing the total catchment bank erosion for 31 days, starting from the date of the second rainfall event (see Table 9). The model indicates bank eroded sediment generated from a single flood event may be up to 61% greater if the event occurs within 2 weeks of a large flood event. As the temporal separation of the two flood events increases the magnitude of bank erosion caused by the second event decreases. Once channel bank vegetation has recovered from the first event, subsequent events below the threshold discharge do not result in increased magnitudes of bank erosion.

Discussion

Observed bank erosion rates within this study determine the significance of channel bank erosion as a sediment source within the Eden catchment, Cumbria. Based on average annual simulated sediment load at Sheepmount, the data collected indicate that bank erosion represents 5-11% of the annual catchment sediment budget. This value is at the lower end of the range observed within other UK catchments (Walling, 2005; Walling et al 2006; Bartley et al 2007) which could be partly due to the predominance of grassland within the catchment.

The GIS dataset also indicates significant temporal variability of average annual bank erosion rates between the four time-periods analysed, but does not fully capture the inter-annual variability. Several previous studies have noted significant inter-annual variability of bank erosion processes (Hooke, 2008; Kronvang et al, 2013). Simulated bank eroded sediment generation using the enhanced model shows greater inter-annual variation of bank erosion rates than those of the basic model (Table 7), with the highest values during the year 2005. This is expected as the largest event discharge recorded during the study period (and 2nd largest to date) at this station occurred during the January of this year (8/1/2005 1516.3 m^3s^{-1}). Previous studies have indicated the significance of high magnitude events to bank erosion (Hooke, 1979; Julian and Torres 2006; Henshaw et al, 2012; Palmer et al, 2014). The developed representation of bank erosion processes enables model sensitivity to high magnitude events, and therefore replication of observed temporal (inter-annual) variability of sediment generation.

The observed average annual bank erosion rates for the years 1970-2012 shown in Table 6 are lower than average simulated values for 2001-2006. The observed data present an average annual bank erosion value across several years and inter-annual variation within time periods, as a result of flood rich and poor years, is not represented. The average annual maximum discharge recorded at Sheepmount from 1970-2012 was considerably lower than between 2001-2006 ($647m^3s^{-1}$ and $764m^3s^{-1}$ respectively). Therefore bank erosion rates between 2001-2006 would be expected to be higher than the 1970-2012 average. Furthermore, observed data show total bank erosion within 6 main channels of the Eden catchment, additional smaller tributaries have not been included, yet simulated values include the whole catchment as represented by the model. The lower estimates of observed bank erosion are taken from the GIS overlay methodology with a 3.5m buffer applied to account for errors within the mapping process, which for more recent maps (such as 1970 and 2012) should be less significant than for earlier maps. Therefore the lower estimate of actual bank erosion for the 1970-2012 time-period is potentially a significant underestimate of reality.

The enhanced model simulates sensitivity to flood clustering, by incorporating an element of catchment recovery following a large event. The results indicate bank eroded sediment generation for an event of the same magnitude may vary depending on the event timing. Previous studies have noted the importance of antecedent conditions to bank erosion processes; Hooke (1979) noted that whilst event-based bank erosion at certain sites was correlated with discharge of the previous peak, the influence of this variable is complex. Previous high flows can weaken banks by undercutting but can also remove loose bank material leaving the bank more resistant to subsequent high flows. Thorne (1982) observed that mass failure of banks can result in an increase in bank stability due to supply of sediment to the basal zone, unless critical shear stress for removal of this basal material is exceeded. The enhanced model developed in this study provides an additional element of catchment memory for bank erosion and enables simulation of the effects of event clustering, and influence of antecedent conditions. The frequency of high magnitude events within the UK is expected to increase with projected climatic changes (Bell et al, 2012; Kay et al, 2014; Madsen et al, 2014). Therefore, to enable climate-proof catchment management practices models will be required to represent the effects of flood clustering.

The spatial variation of bank erosion simulated by the basic model was controlled solely by flow variation (and hence variation of shear stress) throughout the catchment. As shown in Figure 6A this resulted in little variation of simulated bank erosion across the catchment. Significant spatial variation was observed from the GIS analysis within this study (Figure 6C), and has been observed within several additional UK catchments (Bull, 1997; Lawler et al, 1999). The inclusion of sinuosity within the enhanced model enables simulation of some spatial variability of bank erosion rates within the catchment (Figure 6B). Correlation of sub-catchment totalled bank erosion rates indicate that bank erosion predicted by the enhanced model is more accurate than the basic model, yet still provides a weak fit of the observed bank erosion rates throughout the catchment. Several factors such as anthropogenic influences, lithology, channel confinement, bank height, and slope influence bank erosion rates resulting in the significant observed spatial variability within catchments. Whilst sinuosity is known to be one factor influencing the spatial variation of bank erosion (Janes 2013; Micheli and Kirchner 2002) many of these additional factors are not included within the developed model due to current limited understanding of their behaviour, complex interactions, and lack of spatial data coverage. Therefore some differences between the simulated and observed bank erosion rates are to be expected due to the omission of many of these factors and the widely recognised difficulty of capturing the naturally high variability in bank erosion rates. Comparisons of observed and model simulated bank erosion values such as those in Figure 6 are rarely performed but these types of analyses are required if models are to be judged useful in management at the local scale. The model can be used to assist identification of areas where bank erosion would be expected to occur naturally, and comparison with observational data can indicate areas where bank erosion is prevented/accelerated due to anthropogenic factors not included within the model.

The observed bank erosion data within this study provides an estimate of annual bank eroded sediment generation with greater spatial resolution and over a longer timescale than is possible using field-based techniques (such as erosion pins). However, it is not possible to accurately estimate event-based bank eroded sediment using data derived from this methodology. Further data (such as LIDAR analysis of bank migration at a finer temporal scale) and analysis is required to calibrate the model and assess performance during individual events.

Conclusions

Channel bank erosion contributes a significant proportion of catchment sediment budgets and yet is commonly excluded or overly simplified within catchment scale models. In this study, the bank erosion component within the physically-based SHETRAN model has been further developed to incorporate both temporal and spatial variability of bank erosion by inclusion of additional controlling factors; removal of bank vegetation and bank collapse after a flood event and subsequent recovery, and channel sinuosity. The developments within this study improve the representation of natural processes influencing bank erosion rates, and enable representation of catchment sensitivity to flood event clustering.

The model has been successfully applied to the Eden catchment, north-west England, and validated using hydrological, bank erosion and suspended sediment data. The enhanced model has been shown to simulate improved inter-annual and spatial variability of catchment scale bank eroded sediment generation when compared with the basic model, yet it is noted that the developed model still provides a weak fit with observed data. Differences between the spatial variation of observed and simulated bank erosion rates are attributed to additional factors not included within the model due to limitations in current understanding and data availability. Simulated sediment loads were compared with observational data, and whilst uncertainty in both observed and predicted sediment loads is large, values were found to overlap throughout the catchment, indicating reasonable accuracy of model simulations. Whilst the accuracy of spatial bank erosion simulations is currently insufficient to support application of the model for management purposes the study represents a contribution to the research need for continuing development of sediment models. The developed representation of bank erosion processes that have been applied to the SHETRAN model in this study could also be applied to a number of existing physically based models.

The developed representation of sediment source estimation within the model provides a more holistic representation of sediment processes throughout the catchment. The resultant model provides an improved representation of the spatial and temporal variability of sediment loads, yet further development of such models is required to provide estimates of sediment loads with sufficient accuracy to support management of diffuse pollution.

Acknowledgments

We would like to thank the two anonymous reviewers for their helpful and constructive comments that assisted in improving this manuscript. This work was funded by EPSRC as part of the FloodMEMORY project EP/K013513/1. Additional thanks go to the Environment Agency for the provision of channel survey and bank height data, Cranfield University for LandIS soil data, and the CHASM project and Carolyn Mills for sediment data. The associated metadata/data presented in this research can be accessed using the following DOIs: 10.17862/cranfield.rd.4300220, 10.17862/cranfield.rd.4300202.

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Table 1: Model user input parameters required for the developed bank erosion model. Parameter Q_{Thresh} is scaled to the outlet value.

Parameter	Units	Description
BKB_{min}	kg m^{-1} s^{-1}	Minimum bank erodibility
BKB_{max}	kg m^{-1} s^{-1}	Maximum bank erodibility
Q_{Thresh}	m^3 s^{-1}	Threshold discharge at which BKB for the link increases from BKBmin to BKBmax
k	N/A	Vegetation recovery speed (high values = rapid growing vegetation types)

Table 2: Calibrated parameter values of the bank erosion model.

Parameter	Calibrated value
Return period of Q_{Thresh}	12
k	0.03
Factoral difference between BKB_{min} and BKB_{max}	20

Sinuosity	Straight channels <1.2	Meandering channels 1.2-1.5	Highly sinuous channels >1.5
BKB_{min}	3.5E-11	9.6E-11	7.0E-11
BKB_{max}	7.0E-10	1.9E-09	1.4E-09

Table 3: Validated parameter values for the Eden catchment model.

Parameter/function	Low value	High value
Hydrological		
Strickler overland flow resistance coefficient	1	3
Saturated hydraulic conductivity in channel soil (mm day^{-1})	0.1	60
Channel bank Strickler coefficients (x and y directions)	20	30
Sediment		
Overland flow erodibility (kg m^{-2} s^{-1})	0.02	0.05
Raindrop impact erodibility (J^{-1})	2E-12	1E-11

Table 4: Average performance statistics from the simulation of hourly flows across the Eden catchment (with the exception of Kirkby Stephen based on daily flows) during the validation period.

Catchment/sub-catchment	Gauging station	Upstream area (km^2)	NSE	R^2	PBIAS (%)
Eden	Sheepmount	2286	0.901	0.911	3
	Great Corby	1373	0.857	0.869	3
	Temple Sowerby	616	0.857	0.873	8
	Kirkby Stephen*	69	0.848	0.878	14
Irthing	Greenholme	334	0.726	0.809	20
Petterill	Harraby Green	160	0.630	0.796	-16
Caldew	Cummersdale	244	0.830	0.835	8
Eamont	Udford	396	0.598	0.713	-3

Table 5: Percentage of peak over threshold events within the simulated range during the validation period, and average percentage error of simulated peak discharge.

Channel	Location	Percentage of simulated events within 15% of the observed event	Average error of event discharge simulation (%)
Eden	Sheepmount	91	-1
	Great Corby Temple	88	-1
	Sowerby	47	-19
	Kirkby Stephen	22	-44
Irthing	Greenholme	8	-51
Petterill	Harraby Green	38	19
Caldew	Cummersdale	31	-37
Eamont	Udford	60	28

Table 6: Observed bank erosion rates (t yr^{-1}) from each overlay time period. Values shown are averages from all methodological estimates,

Channel	1880-1901	1901-1956	1956-1970	1970-2012
Eden	1329	682	1612	198
Petteril	136	58	209	29
Caldew	412	187	439	117
Irthing	356	216	487	166
Lyvenet	55	26	59	12
Eamont	58	17	44	16
Total	**2346**	**1186**	**2849**	**539**

Table 7: Annual bank erosion for the whole catchment as simulated by both the basic and enhanced models during the validation period. Values are in t yr^{-1}.

		2001	2002	2003	2004	2005	2006
Enhanced	Minimum	721	1655	617	1686	2842	622
	Maximum	4063	2833	2219	2682	3898	2784
	Average	2331	2120	1401	2093	3350	1400
Basic	Minimum	1951	3170	1542	2907	2356	2943
	Maximum	2126	3355	1728	3129	2539	3183
	Average	2001	3234	1588	2972	2404	3013

Table 8: Observed and simulated average annual sediment loads (t yr^{-1}).

Location	Observed average	Simulated average	Observed 95% Confidence range	Simulated range
Great Corby	21968	21254	10325-43277	11366-31956
Temple Sowerby	16016	9121	6086-26106	4871-13654
Appleby	15364	5827	1229-16747	3116-8774
Great Musgrave	5126	4263	1794-7945	2197-6479
Kirkby Stephen	1794	1528	736-3086	758-2362
Smardale	444	739	164-719	368-1147

Table 9: Model sensitivity to temporal sequencing of flood events. Bank erosion values shown are summed from the whole catchment over a period of 31 days, starting from the beginning of the second rainfall event.

Time between flood events (weeks)	Monthly bank erosion during second event (t)
1	851
2	681
4	547
6	536
8	530
12	528