

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

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9

10 **Abstract**

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

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

28

### 29 **Keywords**

30 Bank erosion, sediment, sinuosity, vegetation, catchment.

31

### 32 **Introduction**

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

48 Sediment fingerprinting techniques have been applied to a number of catchments  
49 worldwide to understand the relative importance of different sources of sediment,  
50 including eroded bank material. These suggest that bank erosion contributes

51 significantly to catchment sediment budgets, in some cases representing up to 48%  
52 of total sediment supply (Walling, 2005; Walling et al, 2008). Furthermore, where  
53 channel banks contain contaminated sediments the contribution of bank erosion to  
54 pollutant supply has also been noted to be significant; for example, lead supply from  
55 banks of  $9 \text{ kg m}^{-1} \text{ yr}^{-1}$  (Glengonnar Water, Scotland UK, Rowan et al, 1995) and  
56 mercury supply of  $2.7 \text{ kg km}^{-1} \text{ yr}^{-1}$  (South River, Virginia USA, Rhoades et al, 2009).

57 The severity of bank erosion is influenced by numerous factors such as the  
58 presence of bank vegetation (through both mechanical and hydrological factors)  
59 (Micheli and Kirchner, 2002; Bartley et al, 2008; Simon and Collison, 2002);  
60 discharge and flow regime (Julian and Torres, 2006; Hooke, 2008; Surian and Mao,  
61 2009); lithology (Hooke, 1980); channel confinement (Lewin and Brindle, 1977;  
62 Janes et al, 2017); and anthropogenic influences (Winterbottom and Gilvear, 2000;  
63 Michalková et al 2011). As such rates of channel bank erosion are both highly  
64 temporally and spatially variable (Hooke, 1980; Bull, 1997; Lawler et al, 1999;  
65 Couper et al, 2002).

66 Management of sediment and other diffuse pollution issues at a catchment scale  
67 is imperative due to the connectivity of the system. Models provide a valuable means  
68 of estimating sediment generation and transport at catchment scales, potentially  
69 providing insights into the spatio-temporal generation and transport of sediment and  
70 the system responses to longer term changes such as climate change. However,  
71 many existing catchment-scale hydrological and water quality models contain no  
72 explicit representation of channel bank erosion processes; CREAMS - Chemicals,  
73 Runoff and Erosion from Agricultural Management Systems (Knisel, 1980),  
74 ANSWERS - Areal Nonpoint Source Watershed Environment Simulation (Beasley  
75 and Huggins, 1980), EPIC - Erosion Productivity Calculator (Sharpley and Williams,

76 1990), SWAT – Soil and Water Assessment Tool (Arnold et al, 1998), and PSYCHIC  
77 – Phosphorus and Sediment Yield Characterisation In Catchments (Davison et al,  
78 2008). Additionally, those models which do contain representations of bank erosion  
79 only account for few of the numerous aforementioned factors controlling channel  
80 bank erosion rates which limits their ability to simulate the observed spatial and  
81 temporal variation of sediment generation through bank erosion processes. For  
82 example, the semi-distributed INCA-Sed model (Jarritt and Lawrence, 2007)  
83 accounts for bank eroded sediment within in-stream sediment sources using a power  
84 law relationship incorporating discharge and calibration parameters. As  
85 acknowledged by the authors, a range of sub-reach scale processes are not  
86 included within the model and therefore only a broad range of seasonal trends can  
87 be observed, rather than finer temporal and spatial variation. The model SedNet  
88 provides a mean-annual sediment budget (Prosser et al, 2001; Wilkinson et al,  
89 2009). Riverbank erosion within the model is based on an empirical relationship  
90 related to stream power, the extent of channel bank vegetation, and non-erodible  
91 surfaces. Whilst this method incorporates some factors influencing the spatial  
92 variation of bank erosion rates and provides an estimate of annual sediment  
93 generation, it does not account for finer-scale temporal variability or provide an  
94 indication of event-based bank erosion. Whilst a dynamic version of the model (D-  
95 SedNet, Wilkinson et al, 2014) exists, this model disaggregates longer term data to  
96 provide daily output this model, meaning the model is unable to fully capture the  
97 temporal variability observed in sediment loads.

98 Detailed numerical models of bank erosion have been shown to simulate channel  
99 migration with reasonable accuracy (Darby et al, 2002, 2007; Duan 2005; Nagata et  
100 al; 2000). These models generally incorporate mathematical modelling of hydraulic

101 bank properties, shear stresses acting on channel banks and subsequent erosion.  
102 However these models lack simulation of catchment hydrology, and the high-  
103 resolution data required for such models and their computational requirements limit  
104 their application to reach scales. Therefore to provide estimates of bank-eroded  
105 sediment at a catchment scale, alternative methods are required.

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

123

124 **Methodology**

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

141

## 142 **Description of model improvements**

143 The representation of bank erosion within the basic model is based on the  
144 exceedance of critical shear stress ( $\tau_{bc}$ ) acting on the channel banks. The critical  
145 shear stress is calculated using the Shield's curve method (similarly to Simon et al,  
146 2000). Bank erosion ( $E_b$ ) is calculated as a rate of detachment of material per unit  
147 area of bank ( $\text{kg m}^{-2} \text{s}^{-1}$ ) according to:

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

148

149

150 where  $BKB$  is a bank erodibility parameter( $\text{kg m}^{-2} \text{s}^{-1}$ ), and  $\tau_b$  is the shear stress  
151 acting on the channel bank ( $\text{N m}^{-2}$ ) calculated as:

$$\tau_b = K\tau$$

152

2

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

159 Within the enhanced model, spatial variation of bank erosion is represented by  
160 way of the non-linear influence of local channel sinuosity on bank erosion. This is  
161 incorporated within the model by categorising channel sinuosity in to one of three  
162 groups (similarly to channel curvature ratio categories as detailed by Crosato, 2009);  
163 channel links with low sinuosity ( $<1.2$ ) have low erosion rates, moderately sinuous  
164 channels ( $1.2-1.5$ ) have the highest erosion rates, and highly sinuous channels  
165 ( $>1.5$ ) have erosion rates slightly lower than that of moderately sinuous channels  
166 (Janes, 2013).

167 Temporal variation of bank erosion as a result of the changing channel bank  
168 vegetation is represented within the model by varying the bank erodibility coefficient  
169 ( $BKB$ ) between minimum and maximum values over time (see Figure 3). When  
170 channel discharge at a location in the catchment exceeds a threshold value ( $Q_{Thresh}$ )  
171 for that location the bank erodibility coefficient at that location increases to a  
172 maximum value ( $BKB_{max}$ ).  $Q_{Thresh}$  represents the discharge at which vegetation within

173 some parts of the reach is expected to be removed, and hence bank erodibility is  
 174 increased. For outer-bends with little vegetation this increase in erodibility represents  
 175 de-stabilisation of channel banks.  $Q_{Thresh}$  at the catchment outlet is set by the user  
 176 (based on flood recurrence interval), and then each link is given a unique value of  
 177  $Q_{Thresh}$  calculated from the value of  $Q_{Thresh}$  at the outlet (the methodology used is  
 178 detailed in the model application section). For all subsequent time steps of the model  
 179 where the threshold value is not exceeded, the bank erodibility coefficient gradually  
 180 decreases over time to the minimum value ( $BKB_{min}$ ) at a rate set by the recovery  
 181 factor ( $R$ ):

$$BKB_t = BKB_{max} \text{ where } Q \geq Q_{Thresh}$$

182 3

$$BKB_t = BKB_{t-1} \cdot R \text{ where } BKB_t > BKB_{min}$$

183 4

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

190

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

191 5

192 where  $PE_{max}$  represents the maximum daily potential evapotranspiration ( $\text{mm s}^{-1}$ ),  
 193  $PE_{obs}$  ( $\text{mm s}^{-1}$ ) is the observed potential evapotranspiration and  $\partial t$  is the length of  
 194 the time-step (seconds). The parameter  $k$  controls the time-scale of vegetation



195 recovery and should reflect the type of vegetation in the catchment. Higher values of  
196  $k$ , leading to a quicker recovery times, are appropriate for species with the ability of  
197 rapid re-growth, such as willow (*Salix fragilis*). Table 1 shows the input parameters  
198 required for the developed bank erosion model.

199

### 200 **Application of the enhanced model**

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

207 The model was applied with a grid resolution of 1km<sup>2</sup> (and bank cells with a  
208 length of 1km and width of 10m) with a maximum hourly temporal resolution. A 1km<sup>2</sup>  
209 grid resolution reasonably captured the OS (Ordnance Survey – UK national  
210 mapping agency) blue line channel network. The model was set-up using 30m Digital  
211 elevation model (Ordnance Survey, 2009), land-use (CEH, 2007), and soils (Wosten  
212 et al, 1999). A daily 1km<sup>2</sup> gridded daily rainfall product from 1990-2007 (Perry et al,  
213 2009) was used to specify the spatial rainfall, with tipping bucket rain gauge data  
214 then used to disaggregate the daily data to an hourly resolution to capture the  
215 shorter duration intensities. A simple nearest neighbour approach was applied to  
216 disaggregate the daily totals to hourly; for each grid cell, the shape of the nearest  
217 available hourly record was used to distribute the daily total to hourly intervals (see  
218 Lewis et al, 2016 for further details).

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

231

$$Q_T = x_T \cdot Q_{MED}$$

232

6

233

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

238 All channel links within SHETRAN representations are located between two  
239 channel bank cells and have a default sinuosity of 1. Therefore a GIS-based channel  
240 network was used to estimate sinuosity for each link. Sinuosity was measured  
241 across the catchment using WFD river waterbodies data (Environment Agency,  
242 2012) and GIS; a channel network polyline was split into reaches of equal length,  
243 and sinuosity calculation for each reach was calculated as the channel distance

244 divided by the straight-line distance between reach start and end points. As the value  
245 of sinuosity is dependent on the reach length at which it is measured, this process  
246 was repeated for a range of length scales. The length scale with the largest peak in  
247 variance of sinuosity (measurement length of 975m) was used as this best captured  
248 the variation of sinuosity across the catchment.

249

### 250 **Model calibration and validation**

251 After a one year 'start-up' period in which groundwater levels tended to an  
252 equilibrium, the model was run from 1991-2001 for parameter calibration, and 2001-  
253 2007 for validation. Similarly to previous studies using SHETRAN (Bathurst et al,  
254 2006; Lukey et al, 2000; Elliott et al, 2012) calibration parameters included the  
255 overland and channel flow resistance coefficients, with calibration conducted  
256 manually due to the computational requirements of the model. The hydrological  
257 component of the model was compared with hourly and daily hydrological data from  
258 the National River Flow Archive (CEH, 2015) gauging stations and HiFlows data sets  
259 (see Figure 4). From this a range of parameter value sets were derived (see Table 3)  
260 based on parameters to which the simulated flows were most sensitive (Lukey et al,  
261 2000 Bathurst et al, 2006). The simulation outputs were then superimposed on each  
262 other, providing an envelope of minimum and maximum model estimates of river  
263 flows.

264 Analysis of peak-over-threshold (POT) events was also conducted as part of the  
265 validation process to ensure the model could accurately reproduce high-magnitude  
266 events, using POT data from the NRFA (CEH, 2015). For each POT event the  
267 observed event maximum discharge was compared with the maximum simulated  
268 discharge within 24 hours either side of the event timing. The average percentage

269 error of simulated POT events was then calculated within the calibration/validation  
270 periods for each gauging station.

271 The bank erodibility parameters (see Table 2) were calibrated by comparison with  
272 observed bank erosion values derived using an historical map overlay methodology  
273 in GIS, further details of which can be found in Janes et al (2017). Channel banklines  
274 were digitised for the Eden and main tributaries Caldew, Irthing, Lyvennet, Eamont  
275 and Petteril from Historical OS maps for the 5 available years (1880, 1901, 1956,  
276 1970, and 2012) with consecutive banklines overlaid to provide an area of bank  
277 erosion. As smaller tributaries are often represented on OS maps as a single line  
278 (particularly on older maps) it is not possible to calculate bank erosion values for  
279 these channels using this methodology. To account for potential geo-referencing and  
280 mapping errors within the data, the eroded area was calculated using the simple  
281 overlay procedure, and also applying a buffer of 3.5m to the older channel, providing  
282 upper and lower erosion estimates respectively. Minimum and maximum bank height  
283 estimates were calculated from the two bank heights provided within the RHS survey  
284 data, to account for error within the estimate. Minimum and maximum estimates of  
285 annual bank eroded sediment were estimated for each sub-catchment using this  
286 procedure. Whilst alternative methods of data collection such as erosion pin  
287 methodologies can provide estimates of bank eroded sediment at a finer temporal  
288 resolution (event scale), these methods are limited spatially and cannot provide  
289 catchment wide estimates of bank erosion and are therefore unsuitable for this  
290 study.

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

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

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

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

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

327

## 328 **Results**

### 329 **Hydrological assessment**

330 Table 4 shows the average hourly hydrological performance statistics of the  
331 model for the validation period (and daily statistics at Kirkby Stephen where hourly  
332 flow data were unavailable). All hourly NSE and  $R^2$  values are above 0.55 and 0.7  
333 respectively, indicating satisfactory model performance at all sites (Moriasi et al,  
334 2007). The simulated absolute percentage bias is below 25% at all gauging stations  
335 (indicating satisfactory model performance according to Moriasi et al, 2007) and at 5  
336 of the 8 stations is less than 8%.

337 The POT analysis indicates the model's ability to predict high-magnitude events  
338 (see Figure 5 and Table 5). Although the model under-estimates event peak flow at  
339 most locations, as is common with other hydrological models (Butts et al, 2004; Van  
340 Liew et al, 2003), 65% of POT events were within the simulated uncertainty range at  
341 the catchment outlet at Sheepmount (Table 4 and Figure 5). It should be noted that  
342 the gauging station on the Irthing at Greenholme is often affected by backwater from

343 the Eden at medium-high flows, which could partially explain the lower peak over  
344 threshold simulation accuracy observed at this location (Table 5).

### 345 **Bank erosion**

346 The GIS overlay methodology indicates the total mass of sediment generated  
347 through bank erosion processes within the catchment is between 539-2346 t yr<sup>-1</sup>  
348 (Table 6). The estimates from both GIS methodologies provide an uncertainty range  
349 between 211-4426 t yr<sup>-1</sup>. Total annual simulated bank erosion in Table 7 is higher  
350 than the most recent observed average annual bank erosion rates (1970-2012 –  
351 Table 6) but within the observed uncertainty range over the historical. Additionally,  
352 Table 7 indicates the enhanced model simulates a greater inter-annual variability of  
353 average annual bank erosion rates than the basic model. The enhanced model  
354 simulates a greater range of spatial variation of bank erosion throughout the  
355 catchment than the basic model. The basic version of the model was parameterised  
356 so that the total catchment average annual mass of bank eroded sediment  
357 generation was similar to the enhanced model to enable comparison of spatial bank  
358 erosion simulation in Figure 6. The observed data used for comparison here is taken  
359 from the upper estimate. The basic version of the model (Figure 6A) simulates a  
360 fairly spatially constant magnitude of bank erosion throughout the catchment in  
361 comparison to the enhanced model (Figure 6B) and the observed data (Figure 6C).  
362 The model was also validated at a sub-catchment scale using Water Framework  
363 Directive sub-catchment boundaries by correlating the total simulated bank eroded  
364 sediment of the basic and enhanced versions of the model with the observed data.  
365 Correlations between simulated and observed data indicate the enhanced model  
366 provides a more accurate spatial estimation of bank erosion at the sub-catchment  
367 level (R=0.500, p=0.007) compared to the basic model (R=0.367, p=0.048). These

368 correlation values indicate an improvement in the spatial variability of bank erosion  
369 simulated by the developed model, but nevertheless the overall predictive ability of  
370 the spatial variability is poor due to reasons detailed within the discussion.

### 371 **Sediment load accuracy**

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

### 380 **Sensitivity to temporal flood clustering**

381 Values of bank eroded sediment generation for each of the five temporal flood  
382 cluster scenarios was calculated by summing the total catchment bank erosion for 31  
383 days, starting from the date of the second rainfall event (see Table 9). The model  
384 indicates bank eroded sediment generated from a single flood event may be up to  
385 61% greater if the event occurs within 2 weeks of a large flood event. As the  
386 temporal separation of the two flood events increases the magnitude of bank erosion  
387 caused by the second event decreases. Once channel bank vegetation has  
388 recovered from the first event, subsequent events below the threshold discharge do  
389 not result in increased magnitudes of bank erosion.

390

### 391 **Discussion**



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

399 The GIS dataset also indicates significant temporal variability of average annual  
400 bank erosion rates between the four time-periods analysed, but does not fully  
401 capture the inter-annual variability. Several previous studies have noted significant  
402 inter-annual variability of bank erosion processes (Hooke, 2008; Kronvang et al,  
403 2013). Simulated bank eroded sediment generation using the enhanced model  
404 shows greater inter-annual variation of bank erosion rates than those of the basic  
405 model (Table 7), with the highest values during the year 2005. This is expected as  
406 the largest event discharge recorded during the study period (and 2<sup>nd</sup> largest to date)  
407 at this station occurred during the January of this year (8/1/2005 1516.3 m<sup>3</sup>s<sup>-1</sup>).  
408 Previous studies have indicated the significance of high magnitude events to bank  
409 erosion (Hooke, 1979; Julian and Torres 2006; Henshaw et al, 2012; Palmer et al,  
410 2014). The developed representation of bank erosion processes enables model  
411 sensitivity to high magnitude events, and therefore replication of observed temporal  
412 (inter-annual) variability of sediment generation.

413 The observed average annual bank erosion rates for the years 1970-2012 shown  
414 in Table 6 are lower than average simulated values for 2001-2006. The observed  
415 data present an average annual bank erosion value across several years and inter-  
416 annual variation within time periods, as a result of flood rich and poor years, is not

417 represented. The average annual maximum discharge recorded at Sheepmount from  
418 1970-2012 was considerably lower than between 2001-2006 ( $647\text{m}^3\text{s}^{-1}$  and  $764\text{m}^3\text{s}^{-1}$   
419 respectively). Therefore bank erosion rates between 2001-2006 would be expected  
420 to be higher than the 1970-2012 average. Furthermore, observed data show total  
421 bank erosion within 6 main channels of the Eden catchment, additional smaller  
422 tributaries have not been included, yet simulated values include the whole catchment  
423 as represented by the model. The lower estimates of observed bank erosion are  
424 taken from the GIS overlay methodology with a 3.5m buffer applied to account for  
425 errors within the mapping process, which for more recent maps (such as 1970 and  
426 2012) should be less significant than for earlier maps. Therefore the lower estimate  
427 of actual bank erosion for the 1970-2012 time-period is potentially a significant  
428 underestimate of reality.

429 The enhanced model simulates sensitivity to flood clustering, by incorporating an  
430 element of catchment recovery following a large event. The results indicate bank  
431 eroded sediment generation for an event of the same magnitude may vary  
432 depending on the event timing. Previous studies have noted the importance of  
433 antecedent conditions to bank erosion processes; Hooke (1979) noted that whilst  
434 event-based bank erosion at certain sites was correlated with discharge of the  
435 previous peak, the influence of this variable is complex. Previous high flows can  
436 weaken banks by undercutting but can also remove loose bank material leaving the  
437 bank more resistant to subsequent high flows. Thorne (1982) observed that mass  
438 failure of banks can result in an increase in bank stability due to supply of sediment  
439 to the basal zone, unless critical shear stress for removal of this basal material is  
440 exceeded. The enhanced model developed in this study provides an additional  
441 element of catchment memory for bank erosion and enables simulation of the effects

442 of event clustering, and influence of antecedent conditions. The frequency of high  
443 magnitude events within the UK is expected to increase with projected climatic  
444 changes (Bell et al, 2012; Kay et al, 2014; Madsen et al, 2014). Therefore, to enable  
445 climate-proof catchment management practices models will be required to represent  
446 the effects of flood clustering.

447 The spatial variation of bank erosion simulated by the basic model was controlled  
448 solely by flow variation (and hence variation of shear stress) throughout the  
449 catchment. As shown in Figure 6A this resulted in little variation of simulated bank  
450 erosion across the catchment. Significant spatial variation was observed from the  
451 GIS analysis within this study (Figure 6C), and has been observed within several  
452 additional UK catchments (Bull, 1997; Lawler et al, 1999). The inclusion of sinuosity  
453 within the enhanced model enables simulation of some spatial variability of bank  
454 erosion rates within the catchment (Figure 6B). Correlation of sub-catchment totalled  
455 bank erosion rates indicate that bank erosion predicted by the enhanced model is  
456 more accurate than the basic model, yet still provides a weak fit of the observed  
457 bank erosion rates throughout the catchment. Several factors such as anthropogenic  
458 influences, lithology, channel confinement, bank height, and slope influence bank  
459 erosion rates resulting in the significant observed spatial variability within  
460 catchments. Whilst sinuosity is known to be one factor influencing the spatial  
461 variation of bank erosion (Janes 2013; Micheli and Kirchner 2002) many of these  
462 additional factors are not included within the developed model due to current limited  
463 understanding of their behaviour, complex interactions, and lack of spatial data  
464 coverage. Therefore some differences between the simulated and observed bank  
465 erosion rates are to be expected due to the omission of many of these factors and  
466 the widely recognised difficulty of capturing the naturally high variability in bank

467 erosion rates. Comparisons of observed and model simulated bank erosion values  
468 such as those in Figure 6 are rarely performed but these types of analyses are  
469 required if models are to be judged useful in management at the local scale. The  
470 model can be used to assist identification of areas where bank erosion would be  
471 expected to occur naturally, and comparison with observational data can indicate  
472 areas where bank erosion is prevented/accelerated due to anthropogenic factors not  
473 included within the model.

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

481

## 482 **Conclusions**

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

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

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

515

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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.**

<b>Parameter</b>	<b>Units</b>	<b>Description</b>
$BKB_{min}$	$kg\ m^{-1}\ s^{-1}$	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 $BKB_{min}$ to $BKB_{max}$
$k$	N/A	Vegetation recovery speed (high values = rapid growing vegetation types)

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

<b>Parameter</b>	<b>Calibrated value</b>
<i>Return period of <math>Q_{Thresh}</math></i>	12
<i>k</i>	0.03
Factoral difference between $BKB_{min}$ and $BKB_{max}$	20

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<b>Sinuosity</b>	<b>Straight channels &lt;1.2</b>	<b>Meandering channels 1.2-1.5</b>	<b>Highly sinuous channels &gt;1.5</b>
$BKB_{min}$	3.5E-11	9.6E-11	7.0E-11
$BKB_{max}$	7.0E-10	1.9E-09	1.4E-09

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

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

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

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

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

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

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830 **Table 6: Observed bank erosion rates (t yr<sup>-1</sup>) from each overlay time period.**

831 **Values shown are averages from all methodological estimates,**

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<b>Channel</b>	<b>1880-1901</b>	<b>1901-1956</b>	<b>1956-1970</b>	<b>1970-2012</b>
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
<b>Total</b>	<b>2346</b>	<b>1186</b>	<b>2849</b>	<b>539</b>

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848 **Table 7: Annual bank erosion for the whole catchment as simulated by both**  
 849 **the basic and enhanced models during the validation period. Values are in t yr<sup>-1</sup>**  
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		<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>
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

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**Table 8: Observed and simulated average annual sediment loads (t yr<sup>-1</sup>).**

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

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889 **Table 9: Model sensitivity to temporal sequencing of flood events. Bank**  
890 **erosion values shown are summed from the whole catchment over a period of**  
891 **31 days, starting from the beginning of the second rainfall event.**

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

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