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Method for Incorporating Morphological Sensitivity into Flood Inundation Modeling

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1 **A method for incorporating morphological sensitivity into flood** 2 **inundation modelling**

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13

14 **Abstract**

15 Typically, the analysis and design of fluvial flood defence schemes is based on a single N
16 year extreme flow event using a single survey of the river channel and flood-plains. Adopting
17 this approach assumes that the channel capacity is identical for all subsequent N year events.

18 If one assumes that the typical design life for a flood defence scheme is of the order of 50
19 years, then such an approach is flawed as river channel morphology, and hence flood
20 conveyance, may change considerably over this time scale (e.g. Stover and Montgomery,
21 2001; Lane et al., 2007; Neuhold et al., 2009). Therefore, to provide a more robust estimate
22 of future flood inundation, a sensitivity analysis of these changes should be undertaken. This
23 paper proposes a modelling methodology that combines a stochastic model, for estimating
24 streamflow throughout the design period, and a 1D sediment transport model (HEC-RAS), to

25 enable this sensitivity to be included in flood inundation modelling and defence scheme
26 design. The methodology is demonstrated through conceptual implementation to evaluate the
27 change in water surface elevation (WSE) along an alluvial river (River Caldey, England)
28 reach after 50 years of sediment transport. Changes in WSE are assessed when the reach is
29 natural (no flood defences) and modified (with idealised flood defences). Results show that,
30 the construction of the flood defence scheme does not alter the overall morphological pattern
31 of the reach but can significantly increase (260%) local aggradation. Additionally, 50 years of
32 morphological change has the potential to increase WSE such that high flows, previously
33 confined within the channel, can overtop the banks and become flood events; and that, the
34 standard freeboard levels of the flood defence scheme may be insufficient to prevent
35 overtopping when morphological change is considered. The method can be considered as a
36 semi-quantitative modelling methodology to account for the sediment-related sensitivity of
37 Flood Risk Management; and provides valuable insights into the potential magnitude that this
38 has on future flood inundation.

39

40 **Keywords:** sediment transport, aggradation, flood risk, HEC-RAS

41 **Introduction**

42 When floods occur the impacts they have on the population residing within flood prone areas
43 are significant (e.g. property damage, insurance premiums, public health etc.). Common
44 practice for the analysis and assessment of flood risk and defence schemes is the use of an N
45 year extreme event and a single ‘*snapshot*’ survey of the channel and flood-plains. This
46 approach suggests that the river will accommodate every N year event in an identical manner,
47 i.e. the bathymetry is fixed. For many rivers, this approach is fundamentally flawed as it does

48 not allow inclusion of the morphological changes that will take place in the channel between
49 subsequent N year events, or during the design life of any defence scheme.

50 Using historical channel and flow data for the Skokomish River, Washington, Stover and
51 Montgomery (2001) concluded that, as there were no significant changes in flood peaks, the
52 observed increased rate of flooding was a product of the aggradation in the river and a
53 reduction in conveyance capacity. Additionally, on the River Wharfe, England, Lane et al.
54 (2007) used a combination of field data and numerical modelling to show that, even short-
55 term (16 month) morphological changes can increase flood inundation from small return
56 period (0.5 and 1 year) events. Furthermore, using a longer dataset for the River Wharfe,
57 Raven et al. (2009) proposed an increase in flood inundation due to observed in-channel
58 morphological change, using a simple flow resistance relationship at certain cross-sections.
59 Finally, recent flood events in England (Cockermouth, 2009 and the Somerset Levels,
60 2013/14) have been attributed to sediment-related flood risk, through aggradation and
61 reduction in channel capacity.

62 Whether these changes in morphology are natural or anthropogenic, there is the potential
63 for sediment yields to significantly increase under climate change (McIntyre and Thorne,
64 2013). Adding to this, the Pitt Review, commissioned by the UK Government, has
65 comprehensively identified sediment transport and morphological changes, as being one of
66 the key drivers of flood risk by the 2050s (Evans et al., 2008). All of these highlight the
67 requirement for quantitative methodologies that can address this pressing issue.

68 In response, the Environment Agency (EA) of England and Wales currently monitor
69 gravel bars at locations on rivers where aggradation may compromise current flood defence
70 levels. Although this approach is a step in the right direction, it is conducted *ad hoc* due to its
71 labour intensive nature, resulting in large spatial and temporal variability in the surveys. This
72 emphasises the desirability of numerical modelling methodologies; as a means of making

73 informed decisions regarding the implications of sediment transport on flood risk
74 management (FRM).

75 In recent years, there have numerous studies relating to methods of incorporating
76 uncertainty into flood risk analyses (e.g. Beven and Binley, 1992; Merwade et al., 2008;
77 Beven et al., 2011; Jung and Merwade, 2012). The aim of these is to include uncertainties
78 associated with input parameters to numerical flood models (e.g. selection of Manning's n ;
79 errors in geometry measurement; errors in flow prediction; climate change etc.) to build up a
80 more complete picture of the possible range of model predictions. Whilst the report of Beven
81 et al. (2011) does highlight the uncertainty associated with variable channel geometry, no
82 quantitative estimation of these changes were included in their analyses. For such refinement,
83 the work of Neuhold et al. (2009) provides one such framework, where rainfall-runoff
84 simulations for a range of 100 year events were employed to vary the discharge input
85 scenario of the Ill River, Austria. Using a 1D hydrodynamic-sediment transport modelling
86 approach (GSTARS), the sensitivity of the morphological change at peak discharge was
87 analysed specific to the variability in storm characteristics, catchment condition and sediment
88 input. Combining the output with calculated overtopping probability showed up to a 12.3%
89 increase in flood risk.

90 Although this framework provided a detailed first step towards integrating sediment
91 changes into flood risk assessment, their approach considered only a single-event (up to 24
92 hour storms), which would limit the amount of morphological change predicted for the
93 updated cross-sections. Given that the inter-flood period and subsequent flood events would
94 continue to dynamically morph the channel cross-section, it can be reasonably assumed that
95 Neuhold's approach may underestimate the actual sensitivity of flood risk to morphological
96 change. Hence, the overall aim of this paper is to propose a framework for longer-term,

97 multi-event simulations, within the constraints of available UK data and appropriate to UK
98 Flood Risk Assessment use of design discharges.

99 The structure of the method combines a stochastic model, for generating synthetic
100 streamflow sequences from gauge data, with a 1D sediment transport model (HEC-RAS) to
101 produce multiple realisations of the potential changes to channel geometry. The example
102 presented here is conceptually developed to assess the impacts that 50 years (within a typical
103 flood defence scheme design life) of morphological change has on future flood inundation.
104 The novelty in this study therefore lies in the longer-term streamflow simulation framework
105 and combination of modelling approaches.

106 The stochastic model combines a hidden-Markov model with the generalised Pareto
107 distribution to facilitate the generation of synthetic, daily mean, streamflow sequences. These
108 sequences have similar overall statistics to the measured historic flow, but differ in the order
109 in which the flow conditions occur. The current applicability of the model is limited to
110 synthetic sequences with the same statistical properties as the historic data and thus, has no
111 capability for the inclusion of variability from climate change. As the purpose of this paper is
112 to introduce the modelling concepts and discuss the potential impacts, the omission of climate
113 change using this model is considered acceptable at this stage.

114 The methodology is applied to a natural reach (no flood defence scheme) and a modified
115 reach (with a flood defence scheme); and will allow for the following key questions to be
116 answered:

- 117 • How do we best incorporate long-term morphological change into FRM?
- 118 • Does long-term morphological change affect future flood inundation?
- 119 • How does the construction of a flood defence scheme alter morphological change and
120 future risk of overtopping?

121

122 Current UK flood defence schemes incorporate a level of freeboard to provide allowance
123 to account for uncertainties in design. The freeboard height depends on a range of land use
124 factors. For urban land use with residential properties a 100 year return period freeboard
125 value is set at 0.6m. For commercial property it would be set at only 0.3m and lower values
126 may be applied in rural areas (Environment Agency, 2000). Thus, the study presented here
127 will provide an indication of whether the sensitivity in future WSE, attributed to sediment
128 transport and morphological change, has the potential to exceed this limit and cause
129 overtopping of defences; thus increasing the flood risk associated with the defended reach.
130 For the purposes of this study, ‘*idealised*’ flood defence walls will be simulated at the
131 channel banks on every cross section of the modelled domain. Their height is selected such
132 that they are never overtopped, hence changes to WSE can be compared to freeboard
133 allowance.

134 The results from the numerical simulations will demonstrate the potential sensitivity of
135 future flood inundation to morphological change. Output data should be considered as a semi-
136 quantitative (i.e. order of magnitude) assessment at this stage due to the range of uncertainties
137 from the hydraulic and sediment domain (see Neuhold et al., 2009 for comprehensive list of
138 scenario, model, natural variability and parametric uncertainties). Thus, the paper’s focus is
139 to deliver a conceptual numerical modelling study that aims to introduce a methodology for
140 accounting for sediment processes within flood risk assessments which have, up until now,
141 been omitted.

142 **HEC-RAS model**

143 HEC-RAS is a 1D hydraulic modelling package developed by the US Army Corps of
144 Engineers, Hydrologic Engineering Centre. As this study involves the modelling of sediment
145 transport and channel change, only this aspect of the software is discussed in detail. For more

146 information regarding the formulation and application of HEC-RAS, the reader is referred to
147 Gibson et al. (2006) and USACE (2010).

148 This type of sediment transport model is defined as capacity-based and therefore
149 possesses well known limitations (Cao and Carling, 2002a and b; Cao et al., 2012). Unlike
150 more advanced 1D alluvial sediment transport models (e.g. Shvidchenko and Pender, 2008;
151 Cao et al., 2012) that can simulate the unsteady nature of flood waves (e.g. finite difference
152 or finite volume), HEC-RAS uses a quasi-unsteady flow assumption. This limitation is
153 unimportant in this framework application as the 50 year long simulations to be undertaken
154 use estimations of daily mean flow (i.e. constant for 24 hours) and hence, the difference
155 between unsteady and quasi-unsteady predictions will be marginal. Additionally, the use of a
156 quasi-unsteady flow model makes HEC-RAS much more computationally efficient than
157 models that use unsteady flow; an important factor when conducting multiple long-term
158 sediment transport modelling simulations.

159 Sediment routing in HEC-RAS is determined by solving the sediment continuity
160 relationship of Eq. (1), which states that the change in sediment volume in a control volume
161 is equal to the difference between the sediment influx and outflux.

162

$$(1 - \lambda_p)B \frac{\partial \eta}{\partial t} = - \frac{\partial Q_s}{\partial x} \quad (1)$$

163

164 where: B = channel width; η = channel elevation; λ_p = active layer porosity; t = time; x =
165 distance; Q_s = transported sediment load. HEC-RAS can divide the grain size distribution into
166 up to 20 individual grain classes, ranging from 0.004mm to 2048mm in diameter, with the
167 transport potential being estimated using seven different models. Due to the empirical nature
168 of the formulae, the selection of the most appropriate is of paramount importance, with
169 different formulae providing considerably different outputs. Ideally, the most suitable

170 formula is determined to be the one that best agrees with measured field data but, should this
171 be unavailable (which is all too common in fluvial modelling), it is up to the modeller to
172 decide on the most sensible formula to provide meaningful end results. This is commonly
173 achieved through the sensitivity testing of suitable formulae, comparison with similar
174 catchments or previous studies and the experience of the modeller.

175 Upon determination of the sediment influx and outflux at the control volumes, the
176 difference in these are then used to update the geometry. When influx is greater than outflux
177 aggradation occurs and when outflux is greater than influx degradation occurs. The volume of
178 this mismatch of influx and outflux is distributed across the channel by lowering/raising the
179 submerged points of the cross-section accordingly.

180 **Field site**

181 The methodology is implemented on the River Caldew, England. The Caldew is located in
182 Cumbria, has its source on Skiddaw Peak in the Lake District and is one of the major
183 watercourses of the River Eden catchment. The river flows north into the city of Carlisle
184 where it reaches its confluence with the Eden. The catchment is characterised by heath and
185 moorland in the headwaters, with both arable farming and urban centres in the lower reaches;
186 land-use has remained largely unchanged over the previous decades.

187 It is a relatively steep ($S_0 > 1:500$) gravel bed river, with a highly active sediment
188 transport and morphological regime where observations of aggradation have, historically,
189 been considered responsible for flooding parts of Carlisle. This has led to numerous flood
190 modelling studies involving the Caldew (e.g. Neal et al., 2009; Mason et al., 2009; Horritt et
191 al., 2010; Neal et al., 2013). After an extreme flood event in 2005, a defence scheme was
192 constructed within Carlisle to protect the city from future events on the rivers Eden, Caldew
193 and Petteril.

194 Due to the active morphological regime of the Caldew, a sediment transport modelling
195 study (Jacobs, 2007), to assess the effects of the scheme on channel morphology, was
196 commissioned by the EA. Currently they conduct a regular monitoring programme of gravel
197 bars to ensure that changes to bed levels do not compromise flood defences. Updated bar
198 surveys are then included in simple hydraulic models to determine whether failure of these
199 defences is possible. Should this be the case the bars are then physically altered. Although
200 this has proven to be a successful responsive measure, the benefit of having a predictive
201 numerical modelling method would allow for natural aggradation patterns of the river to be
202 incorporated into initial flood risk assessments and defence design. As such, this could
203 improve the management of sediment within reaches and minimise the requirements for *ad*
204 *hoc* modification of the channel, such as is currently happening.

205 **Flow data**

206 The EA operates and maintains a flow gauge on the Caldew at Cummersdale (OS grid
207 reference NY394527), approximately 5 km upstream from Carlisle (Fig. 1). However, this
208 was only opened in 2000 meaning that the record is considered too short for producing
209 reliable long-term synthetic flow sequences. Prior to this, another gauge at Holm Hill
210 approximately 11 km upstream of Carlisle (OS grid reference NY378468), was active 1968-
211 2000 (*ca.* 32 years) and therefore provides a more suitable dataset for stochastic modelling.
212 Additionally, the location of the gauge is within close proximity to the upstream boundary of
213 the model domain, meaning that the stochastic flow sequences can be directly applied as a
214 boundary condition to the HEC-RAS model.

215 **Model domain and set-up**

216 In 2012, the EA commissioned the survey of river cross-sections for the main watercourses
217 around Carlisle. This survey data include the Caldew, from its confluence with the Eden to

218 approximately 10km upstream, and has been used as the basis for the construction of the
219 model used herein.

220 In many of the commercially available sediment transport models, the interaction
221 between sediment delivery, structures, and attenuation of flood flow in urban areas have not
222 been fully tested. With this in mind, the heavily engineered reach (weirs, bridges and flood
223 defences) through Carlisle was omitted and preference afforded to the rural reach; this
224 provides greater confidence in results. Additionally, to represent attenuation during high flow
225 events the cross-sections have to be extended across the flood-plains. For purely 1D sediment
226 transport models, such as HEC-RAS, a rural reach, where the flood-plains are more
227 conducive to conveying flow downstream, is desirable. The model domain was defined as a
228 4.4km reach upstream of Carlisle (Fig. 1).

229 Common practice for the calibration of Manning's n in hydraulic models is either based
230 on comparisons with measured stage data throughout the domain, or the judgement of the
231 modeller. With the absence of suitable field data for calibration, selection of n was based on
232 photographs, values used within the EA's calibrated flood forecasting model and the
233 guidelines of Chow (1959). It was set as 0.04, for the channel, and 0.05, for the floodplains.

234 As there are no data to provide a flow-stage relationship at the downstream boundary,
235 this is defined using the recommended practice of a normal depth boundary based on channel
236 bed slope (USACE, 2010). To limit the effect of this on the hydraulics within the reach of
237 interest, the modelled domain has been extended a further 0.5km downstream.

238 **Sediment data and model set-up**

239 Crucial to the research presented herein is recognition that the methodology operates
240 within the constraints of poor sediment data availability for the UK. Single morphological
241 surveys and *ad hoc* grain size data are generally available; however, sediment supply,
242 transported load or repeat morphological survey data are rare. In keeping with this, data for

243 the Caldw through Carlisle comprised six sediment samples at locations along the river, one
244 of which is within the reach considered in this study (Fig. 1). From this data (not shown), it is
245 clear that the Caldw experiences downstream fining, typical of gravel bed rivers. This means
246 the sample taken within the modelled reach (i.e. at the downstream end of the model) is the
247 most appropriate and has therefore been applied throughout the domain. At this location the
248 sediment have $D_{10} = 3.7\text{mm}$, $D_{50} = 22.4\text{mm}$ and $D_{90} = 190.6\text{mm}$. Due to the lack of sediment
249 transport data in the UK, globally boundary conditions are commonly defined in practice
250 using an equilibrium load. The same approach has been adopted here, meaning no
251 degradation or aggradation results at the upstream section. As the sediment loading applied at
252 the upstream boundary can influence model predictions, the model has been artificial
253 extended 0.2km upstream for improved representation of the sediment dynamics within the
254 reach of interest.

255 From the sediment transport formulae available in HEC-RAS the Ackers-White, Meyer-
256 Peter-Muller and Yang can be considered the most suitable for the grain size distribution of
257 the Caldw. Sensitivity testing of these showed that the Ackers-White formula gave the
258 lowest estimates of sediment discharge; this is preferable in testing the proposed
259 methodology as it minimises any ‘forcing’ of substantial changes to the geometry and
260 subsequently, WSE. The Ackers-White formula was also considered most suitable for the
261 Caldw in a previous sediment transport study conducted by the EA (Jacobs, 2007).

262 **Methodology**

263 **Stochastic modelling**

264 The stochastic model used to generate the synthetic flow sequences is that proposed by
265 Pender et al. (2015) which combines a hidden Markov model (HMM) with the generalised
266 Pareto distribution (GP); hereafter referred to as the HMM-GP model.

267 Baum and Petrie (1966) first proposed the use of a HMM for modelling time-series in
268 situations where a standard Markov model was shown to be limited. Since then it has been
269 successfully applied to the modelling of a wide range of time series data (e.g. Rabiner, 1989;
270 Hughes et al., 1999; Thyer and Kuczera, 2000; Ghahramani, 2001; Jenkins et al., 2014). The
271 basic structure and implementation of the HMM-GP, for simulating daily streamflow, is
272 described below, with the reader being referred to Pender et al. (2015) for a detailed
273 description of the model and its application.

274

- 275 1. Identify discrete states (S) in the flow record
- 276 2. Define the set of N unobserved states to account for all possible values between the
277 discrete state limits. For example if state A were between $5\text{m}^3/\text{s} - 15\text{m}^3/\text{s}$ the
278 unobserved states correspond to 5, 6, 7, 8, ..., $15\text{m}^3/\text{s}$ and so on. Each discrete state has
279 N unobserved states
- 280 3. Define the state transition probability matrix. For S states this is an $S \times S$ matrix with
281 the value in row i and column j corresponding to the probability of flow transition
282 from state S_i to state S_j .
- 283 4. Define the emission probability matrix that contains the occurrence probabilities of all
284 unobserved states that correspond to each observed state. i.e. an $S \times N$ matrix
- 285 5. Define a set of S initial probabilities for each discrete state following the method of
286 (Rabiner, 1989).

287

288 The main difference between a standard HMM and the HMM-GP is that the estimates of the
289 extreme flows (above 99th percentile) are from a fitted GP model. To test the robustness of
290 the HMM-GP model Pender et al. (2015) applied it to three rivers in the UK with distinctly
291 varying hydrological characteristics. The results showed the model is capable of producing an

292 accurate representation of the historic flow climate and could sufficiently represent the entire
293 range of flows that occur in the rivers.

294 During these tests the model was applied to the Caldew, using the Holm Hill data set
295 discussed previously. The basic testing of the model conducted by Pender et al. (2015) was to
296 compare the statistics of the measured flow regime with that of 100 synthetically generated
297 regimes of the same duration. The assessment is in the form of a comparison of probability
298 densities, between the recorded and synthetic sequences, along with a more specific
299 comparison at certain percentiles. To allow for a better visual comparison, the probability
300 densities have undergone a log transform. At the individual percentiles, the percentage
301 difference between the mean value from the 100 synthetic sequences and the corresponding
302 measured value is determined using Eq. (2).

303

$$\% \text{ Difference} = \frac{\text{mean}(Q_{p,\text{synthetic}}) - Q_{p,\text{recorded}}}{Q_{p,\text{recorded}}} \quad (2)$$

304

305 where: $Q_{p,\text{synthetic}}$ and $Q_{p,\text{recorded}}$ are the synthetic and recorded flow values at percentile p
306 respectively.

307 The results from this assessment are provided in Fig. 2 and, by accurately representing
308 the historic flow regime, confirm the suitability of using the HMM-GP model for generating
309 synthetic flow sequences, to be used as a boundary condition, in this study.

310 **Sediment transport modelling**

311 Due to the stochastic nature of the HMM-GP model every time a sequence is generated it will
312 be inherently different, although the average statistics will be similar. This means that the
313 modelling of a single N year sequence is insufficient to deduce the bed change that will occur
314 during N years (Pender et al., 2014). To overcome this, a bootstrapping-type approach is

315 proposed. This involves the simulation of numerous flow sequences to allow for a more
316 complete representation of the potential N year bed level change as an envelope of data.
317 Whilst similar approaches have been adopted for coastal erosion modelling (Ranasinghe et
318 al., 2011; Ranasinghe et al., 2013; Callaghan et al., 2013) the empirical nature of the models
319 used in these instances (i.e. low computational effort) meant that many thousands of
320 simulations were feasible, allowing convergence of erosion estimates at the 95% confidence
321 intervals. However, as this study is prediction of flood risk (i.e. after 50 years of
322 morphological change) updated channel cross-section geometry is required to build a model
323 that represents the predicted channel. As such, it is not feasible to produce a geometry based
324 on confidence intervals of morphological change.

325 There are two possible ways that this future channel can be developed: (i) simulate M
326 flow sequences and use M final channel geometries; or (ii) simulate M flow sequences and
327 use the results to define potential ‘*best*’ and ‘*worst*’ case future channel configurations. This
328 concept of using best- and worst-case channel geometries, means that conservative upper and
329 lower bounds on future flood inundation can be established and only two detailed hydraulic
330 models are then required for flood risk assessment. For the remainder of this paper these
331 methods of defining the geometry are referred to as All and Min/Max respectively; and
332 summarised below for clarity.

333

334 i. **All:** This method uses the final (i.e. modified after 50 years of sediment
335 transport) channel geometries from all M sequences. Each of the M new
336 geometries are used to assess future flood inundation via running a hydraulic
337 inundation model for all M modified channels. The benefit of this approach is
338 that the method is conservative with regard to sediment volume; however, it is
339 time and resource intensive to perform M inundation models as a sensitivity

340 assessment. Although this is not the case with the 1D model used here, many
341 of flood inundation modelling studies are now implemented with 1D-2D
342 models, which are considerable more computationally expensive.

343 ii. **Min/Max:** This method creates two new channel geometries. Each of the
344 simulated final cross-sections (i.e. from all M sequences) is reviewed to
345 identify the cross-section which showed the maximum aggradation (or
346 minimum degradation) and that which showed the minimum aggradation (or
347 maximum degradation). These cross-sections are extracted for use in the new
348 Max and Min geometry files, respectively. The same process is repeated for
349 each cross-section until the two new geometry files (Max and Min) are fully
350 populated. The inundation model is then run for the two new geometries. This
351 means that the Max channel will result in the worst-case potential future flood
352 inundation; and the Min channel, the best-case. This approach benefits from
353 only two inundation models being needed for a sensitivity analysis. However,
354 although it considers the extreme scenario of the maximum change viable in
355 the reach; it suffers from non-conservation of sediment volume. As this may
356 be considered unrepresentative of reality, the statistical properties of this
357 approach (the simplest of which is the arithmetic mean of the Max and Min
358 data) are also considered.

359 For the demonstration of the methodology here, 100 flow sequences will be modelled;
360 this number of sequences tends towards <1.5% variability in the mean aggradation. Upon
361 generation of the 100 flow sequences using the HMM-GP model, the sediment transport and
362 morphological changes along the reach are estimated using the HEC-RAS model set-up
363 discussed previously. To validate the concept of using best and worst future channel

364 geometries, a comparison will be made with results produced using all 100 potential future
365 channel configurations.

366 Upon creation of the new geometries the future flood inundation is assessed by using
367 these to estimate WSE from design flood events. In this study, this is determined using
368 extreme event peak flows (i.e. a steady-state simulation) estimated from the Flood Estimation
369 Handbook (FEH). It should be noted that, although only the peak flows are modelled in the
370 demonstration presented here, to fully understand the effects of the morphological changes
371 the entire design hydrograph should be simulated and assessed. Additionally, this is
372 conducted in keeping with the current adopted approach of using a fixed-bed model in the
373 UK. Whilst Neuhold et al. (2009) showed that sediment transport during flood events can
374 significantly affect inundation during the event in some rivers, this is not the case for the
375 Caldeu where sensitivity testing using during flood hydrographs showed that the
376 morphological changes during single events are insignificant compared to those over 50
377 years.

378 For the purpose of this analysis future (i.e. after 50 years of morphological change) flood
379 depth is analysed via the differences in WSE that occurs between the original and new
380 channel geometries. This will be conducted for eight flood events with return periods (RP) of
381 1, 2, 5, 10, 25, 50, 100 and 200 years, to establish trends between morphological response
382 and different levels of flow.

383 **Results and analysis**

384 **Morphological response**

385 One of the most widely used (e.g. Jacobs, 2007; Shvidchenko and Pender, 2008; Ayres, 2010;
386 Cao et al., 2012) indicators of morphological change in hydraulic engineering is the elevation
387 of the channel invert (lowest point). Here however, it is proposed that the net change in

388 sediment volume is more suitable as this will provide a better insight into the
389 degradation/aggradation patterns and subsequently, channel capacity along the reach. Net
390 change in sediment volume is the difference between volume entering (to) and leaving (from)
391 a reach; in HEC-RAS, such reach is bounded by two consecutive cross-sections. This is in
392 line with previous analyses of field measurements of morphological response (e.g. Lane et
393 al., 2007; Raven et al., 2009).

394 To assess the morphological variation, the ‘*envelope*’ of sediment volume change was
395 plotted. This envelope consists of the results from all 100 simulations, thus providing a
396 maximum and minimum value at all locations, from all flow sequences. The envelopes for
397 the sediment volume change, for the natural (no flood defences) reach, are provided in Fig. 3.

398 Although all of the sequences generated from the HMM-GP stochastic model have
399 similar overall properties, the size of the envelopes in Fig. 3 highlights the importance of
400 conducting multiple simulations to build up a better understanding of potential morphological
401 change. This importance can further be demonstrated by analysing the results at an individual
402 cross-section. For example, at the section located 2.16km from the downstream boundary
403 (Fig. 3), the minimum and maximum changes in sediment volume, from all 100 flow
404 sequences, were estimated to be -754m^3 and 508m^3 respectively. The fact that these indicate
405 the section has the potential to degrade and aggrade, depending on the flow sequence, further
406 emphasises the insufficiency of only using one flow sequence for FRM purposes.

407 **Future flood inundation**

408 As discussed previously, the final channel configurations from the 100 simulations are used
409 to produce new geometries to assess future flood inundation. Fig. 4 shows the WSE change
410 envelopes along the modelled reach for all return periods, using the Min/Max and All
411 methods for determining new channel geometries. There is a general tendency towards

412 channel aggradation, supporting the public consensus that this was a contributing factor in
413 historical floods.

414 The most obvious result observed in Fig. 4 is the considerable differences between the
415 magnitude of change in WSE that occurs between the Min/Max and All approaches for
416 defining future channel geometry. Unsurprisingly, the Max geometry creates the worst-case
417 aggradation and greatest increase in WSE. Although the WSE produced by the Max channel
418 are important in their own right (i.e. they provide a conservative upper limit for decision
419 making), to provide a more realistic comparison with the All approach, the key values
420 presented in Table 1 are based on the mean of the Min/Max envelope, indicated in Fig. 4.

421 The results from the simulations using All geometries helps to reinforce the previous
422 recommendation of using the Min/Max channel geometries to provide an upper and lower
423 limit on potential future WSE. These show that, when 100 sequences are simulated, the
424 maximum change in WSE along the reach is between 0.25-0.48m (across all RPs). Based
425 upon typical levels of freeboard in flood defence walls (Environment Agency, 2000), these
426 changes are significant; defences in rural or commercial zones would be overtopped (+0.3m)
427 whilst defences in residential zones (+0.6m) would remain with WSE within freeboard
428 tolerance (assuming surface waves are minimal).

429 Although the Min/Max approach may give an unrepresentative morphological change
430 (i.e. no sediment conservation), the sediment modelling results indicate that each section in
431 the reach has the potential for this level of morphological change along the reach. As such, by
432 providing this extreme envelope of change in water surface elevations it allows decision
433 makers to infer a level that they deem appropriate on a case-by-case basis.

434 It can be seen from the upper envelope limits (resulting from the Max geometry) in Fig. 4
435 that, although conservative, there is the potential for an increase in WSE along the reach
436 between 0.85-1.58m, across all return periods. This, combined with Max geometry (upper

437 envelope limit) reach-averaged increases of 0.33-0.71m (across all RPs), is significant for
438 future flood inundation. Even when the conservative nature of the Max geometry is reduced
439 through the mean of the Min/Max envelope (Table 1), maximum changes in WSE along the
440 reach are still significant (0.52-0.81m across all RPs).

441 Taking the results for individual events, the general trend is that, with increasing RP the
442 difference in WSE reduces. As the changes in morphology only occur within the channel
443 these have a lesser effect on the predicted WSE for higher RP events, when the flow is
444 additionally distributed across the floodplains.

445 The results from the Max channel geometry, at the cross-section that experiences the
446 greatest variation in WSE (1.97km from the downstream boundary) can address this
447 significance. Fig. 5 shows the Max geometry configuration at this section and the effects that
448 this has on 1 year and 200 year flood peaks. This shows that, after 50 years of sediment
449 transport, a regularly occurring (annual probability), flood peak has the potential to increase
450 WSE up to 1.58m along the reach. Due to the probability of these events occurring, the
451 potential of such increases will significantly exacerbate flood inundation and thus, risk
452 associated with future small magnitude events.

453 This concept is demonstrated by Fig. 5a, which shows the aggradation of the channel
454 results in a previously in-bank, 1 year RP event, becoming an out-of-bank flood event. This
455 also reinforces the findings of Stover and Montgomery (2001) and shows that the effects of
456 channel morphology can be just, if not more, significant than any increase in flood magnitude
457 and frequency as a result of climate change. Additionally, at the 200 year RP, Fig. 5b
458 explains how, when the flow is out-of-bank and distributed across the floodplain, the increase
459 in WSE is less significant.

460 **After construction of flood defence scheme**

461 ***Morphological response***

462 Comparing results from the natural (no defence scheme) and modified (defence scheme)
463 reaches shows that based on the HEC-RAS predictions, the construction of idealised flood
464 walls has little effect on the overall morphological regime of the reach. The results are
465 presented in Fig. 6a and show that, for all 100 simulations the reach-averaged (i.e. average at
466 every cross-section) change in volume increases by only 40m³, when the flood defence
467 scheme is introduced. However, although the overall morphological regime does not
468 experience significant change, there is substantial local variation in the size (i.e. difference
469 between maximum and minimum) of the envelope, compared to those of the natural reach
470 (Fig. 3). This increase in local variability in the morphological response demonstrates an
471 increased level of uncertainty in future flood levels. Where flood defences exist, and failure
472 has severe consequences, an increase in uncertainty of future WSE is a pressing issue. This
473 further reinforces the requirement for more quantitative methods to incorporate sediment-
474 related sensitivity into FRM.

475 This increase in envelope variation after the construction of the defences can be
476 attributed to an increase in variation of shear stress during high magnitude flow events. When
477 high flow events are constrained within the channel by the defences, there is a significant
478 variation in the bed shear stress, compared to when the reach is in its natural state and flow
479 allowed on floodplains. This is demonstrated by Fig. 6b which shows the variation in bed
480 shear stress, between the natural and modified reach, for a 200 year flood peak. As the bed
481 shear stress is a key component to the calculation of sediment transport rate, the differences
482 that occur during high flow events are responsible for the variation in the morphological
483 envelope.

484 Although the reach-averaged effect of flood wall construction has been shown to be
485 limited, significant local variation in the response at individual locations can occur. Taking
486 the same location as before (2.16km from the D/S boundary) shows that, with flood walls in
487 place, all simulations now result in net aggradation at the section. In addition, the maximum
488 volume of aggradation, at this location, has increased by 260% of that when the reach was in
489 its natural state; an increase of 1331m³ compared to 508m³.

490 ***Future risk of overtopping***

491 This section presents the results after the construction of the idealised flood defence scheme
492 (i.e. at the river bank stations on every cross-section). For simplicity, and ease of comparison,
493 only the changes in WSE using Min/Max channel geometries are presented and discussed.
494 The changes in WSE, compared to the original channel, are provided in Table 2 with Fig. 7
495 showing the distribution of these changes along the reach. These changes are defined as the
496 mean values of the Min/Max WSE change envelopes, as before. If we assume the same
497 design flow event probabilities, an increase in WSE demonstrates a potential increase in flood
498 risk from overtopping of the defences. Thus, changes in WSE are discussed as changes in risk
499 in this context.

500 From Fig. 7, comparing the increase in WSE between the natural and modified reaches,
501 the general trend indicates that aggradation has a greater influence on WSE after flood
502 defence construction. This change is consistent across the range of RPs tested here, with the
503 magnitude of these differences increasing with increasing RP. The results for the natural
504 reach (Fig. 4) show that, when the RP is small (i.e. 1-2 years) and flow is confined to the
505 channel, the effects of aggradation on WSE is greater than at higher RPs. As the flow is
506 mainly in-bank during these events, and the walls have little influence on WSE, the reach-
507 averaged difference between channels with and without defences is small (increase of 0.06m
508 at a 1 year RP). However, as the flow magnitude increases, the reduction in the overall width

509 of the river system, resulting from the defences, leads to the morphological changes having a
510 greater influence on reach-averaged future flood levels (increase of 0.34m at a 200 year RP).
511 This is due to all of the flow now being confined within the modified channel, rather than
512 previously being allowed to inundate the floodplains. When flood walls are present such
513 potential increases in WSE can considerably increase the likelihood that defences could
514 become overtopped during their design life.

515 In addition to this increased risk of overtopping are the risks to the integrity of the
516 structures themselves. An increase in WSE during all flood events will induce more stresses
517 on the structures meaning that the design of these will have to account for this additional
518 loading. Emphasising that, should the influence of morphological change not be considered in
519 scheme design, an additional increase in failure potential from excess loading exists.

520 **Conclusions and recommendations**

521 This paper has presented a combined stochastic and numerical modelling methodology to
522 allow for the variability of long-term (50 years) morphological changes in river channels to
523 be accounted for in FRM. To demonstrate the implementation of the methodology, the effects
524 that 50 years of morphological change could have on the WSE of future floods was assessed
525 for a 4.4km rural reach of the River Caldey, England.

526 At this point it is worth reiterating that the purpose of this study is not to say that '*The*
527 *WSE on the Caldey will increase by Xm after 50 years of sediment transport and*
528 *morphological change*', but to introduce a method to assess changes in flood inundation
529 associated with sediment-related sensitivity by providing an envelope of predicted water
530 levels. As such, the results presented here demonstrate a potential order of magnitude
531 assessment for the increase in future WSE that is currently omitted from flood modelling
532 studies.

533 From the results presented and discussed, we can now address the key questions outlined
534 in the introduction.

535 • **How do we best incorporate long-term morphological change into FRM?**

536 It has been shown that considerable differences in future WSE arise from adopting the
537 Min/Max or All approaches for defining the future channel geometry. While the All
538 approach provides the best representation of the actual changes in channel geometry,
539 the conservative nature of many flood modelling studies means that many thousands
540 of simulations (sediment transport and hydraulic) would be required to determine a
541 confident future upper limit of WSE. By simulating 100 flow sequences and
542 producing upper and lower bounds (Min/Max approach) on future channel geometry a
543 conservative range of future WSE can be provided much more efficiently. However,
544 with this increase in efficiency comes a compromise that the Min/Max channels are an
545 amalgamation of morphological changes and thus physical process representation is
546 compromised. If computational constraints did not exist then many thousands of
547 sediment transport simulations could be conducted and probabilities of morphological
548 change could be estimated using an All approach. However, such a time consuming
549 approach is rarely possible for many flood risk practitioners. As such, it is believed
550 that using the mean the Min/Max approach is a more efficient method for
551 incorporating the sediment-related changes to WSE into flood risk decision making.
552 For the 100 simulations presented here this is more in line with the physically sound
553 All method for defining the future channel geometry.

554 This is important where the infrastructure to be protected is of a critical nature, i.e.
555 electricity sub-stations, water treatment plants, hospitals etc.

556 The answer to the above question is therefore in the hands of individual decision
557 makers, on a case-by-case basis. However, the mean of the Min/Max approach is

558 suggested as a starting point for assessing the impact of morphological change on
559 WSE. The decision can then be made to whether the detailed consideration of using
560 All geometries should be investigated.

561 • **Does long-term morphological change affect future flood inundation?**

562 The results have shown that, failing to account for the sensitivity of inundation to
563 sediment transport and morphology could lead to significant underestimation of WSE
564 during future floods. These increases in WSE during flood peaks were shown to be
565 evident in, both, natural and modified reaches. In natural reaches, the magnitude of
566 this increase is greater for smaller RP events, when the flow is mainly in-bank. For
567 these, more frequently occurring flow events, the significance of this on inundation is
568 also much greater; as previously in-bank high flow events may become out-of-bank
569 flood events. Although the magnitude of single events is not a major concern, the
570 potential increase in occurrence of flooding is. During high RP events, there is already
571 significant inundation of the floodplains, so a relatively small increase in WSE as
572 predicted here is not considered as important as a potential increase in the likelihood
573 of regular flooding.

574 • **How does the construction of a flood defence scheme alter morphological change
575 and future flood risk?**

576 The results show that, whilst the construction of the flood defence scheme can have
577 significant local impacts on the channel morphology (potential 260% increase in
578 sediment volume) at certain locations, it does not alter the overall morphological
579 patterns of the reach. In addition, the multiple simulations indicate that, after the
580 construction of flood defences, the size of the morphology envelopes increase. This
581 shows that this modified reach is more susceptible to the sequence and characteristics
582 of the flow regime and therefore induces a greater degree of sediment-related

583 sensitivity. In terms of future flood risk, the trend associated with the increase in WSE
584 reverses (more significant at higher RPs) compared to when the reach has no defence
585 scheme. This is due to all of the flood water now being constrained within the
586 defences and channel. At the smaller RPs, when the flood is mainly within the
587 channel, the influence of the flood walls on increasing water level is less than when
588 the flow is large enough to be constrained by the walls.

589

590 Overall this conceptual implementation has introduced a modelling methodology that has
591 the potential to provide valuable insight into the effects of sediment transport and
592 morphology on future flood inundation modelling. The numerical simulations have
593 reinforced previous studies (e.g. Stover and Montgomery, 2001; Lane et al., 2007; Raven et
594 al., 2009; Neuhold et al., 2009) which showed that the morphological change in alluvial
595 rivers can result in increased flood inundation. It is proposed that, after some further
596 comprehensive case-study validation, this type of method has the potential to provide an
597 invaluable tool that can be used in future FRM decision-making.

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712

713 **Tables**

		Min/Max Geometry			All Geometries		
		Change in WSE (m)			Change in WSE (m)		
RP	Peak Q (m ³ /s)	Min	Mean	Max	Min	Min	Max
1	55.0	-0.02	0.37	0.81	-0.18	0.12	0.48
2	111.5	-0.07	0.28	0.71	-0.08	0.09	0.41
5	141.3	0.02	0.25	0.68	-0.07	0.08	0.4
10	164.2	-0.01	0.22	0.54	-0.06	0.07	0.36
25	192.7	0.00	0.20	0.49	-0.05	0.06	0.28
50	218.2	0.02	0.19	0.45	-0.06	0.06	0.25
100	248.2	-0.03	0.18	0.53	-0.07	0.06	0.30
200	284.9	-0.03	0.17	0.52	-0.09	0.05	0.30

714 **Table 1: Summary of changes in WSE elevation after 50 years of morphological change for the Min/Max and All**
 715 **approaches for defining new geometry. The values are those of the minimum, mean and maximum changes in WSE**
 716 **along the modelled reach entire reach; with the Min/Max value being that of the envelope mean**
 717

RP	Peak Q (m ³ /s)	Min WSE Change (m)	Mean WSE Change (m)	Max WSE Change (m)
1	55.0	-0.03 (-0.02)	0.43 (0.37)	1.00 (0.81)
2	111.5	0.04 (-0.07)	0.41 (0.28)	1.00 (0.71)
5	141.3	0.04 (0.02)	0.42 (0.25)	1.03 (0.68)
10	164.2	0.06 (-0.01)	0.43 (0.22)	1.06 (0.54)
25	192.7	0.05 (-0.00)	0.45 (0.20)	1.12 (0.49)
50	218.2	0.05 (-0.02)	0.46 (0.19)	1.17 (0.45)
100	248.2	0.05 (-0.03)	0.48 (0.18)	1.23 (0.53)
200	284.9	0.06 (-0.03)	0.51 (0.17)	1.31 (0.52)

719 **Table 2: Summary of variation of WSE elevation after 50 years of morphological change for the modified reach (with**
720 **flood defences). The results show the average of the Min/Max geometry envelope along the entire modelled reach,**
721 **with the corresponding values for the natural reach (no flood defences) provide in brackets**

722

723 **Figures**

724 **Fig. 1:** Location of the HEC-RAS model domain along the River Caldeu and (inset) the grain size distribution for the
725 sediment measured by the EA. The background map was provided by Ordnance Survey (Digimap license) and is not
726 to scale
727

728 **Fig. 2:** Results from the HMM-GP model applied to the Holm Hill data set. (a) a comparison of the log transformed
729 flows, for the recorded values (solid line), and the range of synthetic sequences (grey shaded region); (b) the
730 percentage error between the mean of the synthetic sequences and the recorded values for a range of percentiles, the
731 grey dashed lines indicate the $\pm 10\%$ error range
732

733 **Fig. 3:** Change in sediment volume along the reach from the morphological simulations of 100x50 years of flow.
734 Dashed line defines the location of interest (2.16km from the downstream boundary) discussed in the text.
735

736 **Fig. 4:** Results from the future flood risk simulations using FEH estimated peak flows. The change in WSE, along the
737 reach, for the Min/Max; and All methods for new channel geometries are provided by the grey and black envelopes
738 respectively. The average WSE along the reach using the Min/Max channels is indicated by the white line. Arrow
739 denotes the location of interest (1.97km from the downstream boundary) discussed in the text.
740

741 **Fig. 5:** Influence of 50 years of morphological change on the WSE of (a) 1 year and (b) 200 year peak flood flows on a
742 section located 1.97km from the downstream boundary. The black and dashed black lines represent the original and
743 Max channel geometries respectively; with the grey and dashed grey lines indicating the corresponding WSE
744

745 **Fig. 6:** (a) Sediment volume envelope after 50 year of sediment transport for the modified (with flood defences) reach
746 and (b) a comparison of bed shear stress for a 1:200 year flood peak for the natural (grey line) and modified (black
747 line) reaches. The dashed grey lines indicate the section located 2.16km from the downstream boundary, used for
748 analysis. It should be noted that, after construction of the flood defences, the majority of sections experience an in
749 crease in bed shear stress for a 1:200 year flood peak
750

751 **Fig. 7:** Results from the future flood risk simulations using FEH estimated peak flows for the modified reach. The
752 results shown are the average of the Min/Max envelope with the black and grey lines showing the variation in WSE
753 for the modified and natural reach respectively
754