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A method for incorporating morphological sensitivity into flood inundation modelling

Douglas Pender[a], Sandhya Patidar[a], Kazi Hassan[a] and Heather Haynes[a]

[a] Institute for Infrastructure and Environment

Heriot-Watt University

Edinburgh

UK

EH14 4AS

Email: d.pender@hw.ac.uk; s.patidar@hw.ac.uk; k.hassan.1@research.gla.ac.uk; h.haynes@hw.ac.uk

Corresponding author: Douglas Pender (d.pender@ymail.com)

Abstract

Typically, the analysis and design of fluvial flood defence schemes is based on a single *N* year extreme flow event using a single survey of the river channel and flood-plains. Adopting this approach assumes that the channel capacity is identical for all subsequent *N* year events. If one assumes that the typical design life for a flood defence scheme is of the order of 50 years, then such an approach is flawed as river channel morphology, and hence flood conveyance, may change considerably over this time scale (e.g. Stover and Montgomery, 2001; Lane et al., 2007; Neuhold et al., 2009). Therefore, to provide a more robust estimate of future flood inundation, a sensitivity analysis of these changes should be undertaken. This paper proposes a modelling methodology that combines a stochastic model, for estimating streamflow throughout the design period, and a 1D sediment transport model (HEC-RAS), to enable this sensitivity to be included in flood inundation modelling and defence scheme design. The methodology is demonstrated through conceptual implementation to evaluate the change in water surface elevation (WSE) along an alluvial river (River Caldew, England) reach after 50 years of sediment transport. Changes in WSE are assessed when the reach is natural (no flood defences) and modified (with idealised flood defences). Results show that, the construction of the flood defence scheme does not alter the overall morphological pattern of the reach but can significantly increase (260%) local aggradation. Additionally, 50 years of morphological change has the potential to increase WSE such that high flows, previously confined within the channel, can overtop the banks and become flood events; and that, the standard freeboard levels of the flood defence scheme may be insufficient to prevent overtopping when morphological change is considered. The method can be considered as a semi-quantitative modelling methodology to account for the sediment-related sensitivity of Flood Risk Management; and provides valuable insights into the potential magnitude that this has on future flood inundation.

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

Introduction

When floods occur the impacts they have on the population residing within flood prone areas are significant (e.g. property damage, insurance premiums, public heath etc.). Common practice for the analysis and assessment of flood risk and defence schemes is the use of an *N* year extreme event and a single '*snapshot*' survey of the channel and flood-plains. This approach suggests that the river will accommodate every *N* year event in an identical manner, i.e. the bathymetry is fixed. For many rivers, this approach is fundamentally flawed as it does not allow inclusion of the morphological changes that will take place in the channel between subsequent *N* year events, or during the design life of any defence scheme.

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

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

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

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

Although this framework provided a detailed first step towards integrating sediment changes into flood risk assessment, their approach considered only a single-event (up to 24 hour storms), which would limit the amount of morphological change predicted for the updated cross-sections. Given that the inter-flood period and subsequent flood events would continue to dynamically morph the channel cross-section, it can be reasonably assumed that Neuhold's approach may underestimate the actual sensitivity of flood risk to morphological change. Hence, the overall aim of this paper is to propose a framework for longer-term, multi-event simulations, within the constraints of available UK data and appropriate to UK Flood Risk Assessment use of design discharges.

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

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

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

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

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

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

HEC-RAS model

HEC-RAS is a 1D hydraulic modelling package developed by the US Army Corps of Engineers, Hydrologic Engineering Centre. As this study involves the modelling of sediment transport and channel change, only this aspect of the software is discussed in detail. For more information regarding the formulation and application of HEC-RAS, the reader is referred to Gibson et al. (2006) and USACE (2010).

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

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

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

where: B = channel width; η = channel elevation; λ_p = active layer porosity; t = time; x = distance; Q_s = transported sediment load. HEC-RAS can divide the grain size distribution into up to 20 individual grain classes, ranging from 0.004mm to 2048mm in diameter, with the transport potential being estimated using seven different models. Due to the empirical nature of the formulae, the selection of the most appropriate is of paramount importance, with different formulae providing considerably different outputs. Ideally, the most suitable formula is determined to be the one that best agrees with measured field data but, should this be unavailable (which is all too common in fluvial modelling), it is up to the modeller to decide on the most sensible formula to provide meaningful end results. This is commonly achieved through the sensitivity testing of suitable formulae, comparison with similar catchments or previous studies and the experience of the modeller.

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

Field site

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

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

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

Flow data

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

Model domain and set-up

In 2012, the EA commissioned the survey of river cross-sections for the main watercourses around Carlisle. This survey data include the Caldew, from its confluence with the Eden to approximately 10km upstream, and has been used as the basis for the construction of the model used herein.

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

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

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

Sediment data and model set-up

Crucial to the research presented herein is recognition that the methodology operates within the constraints of poor sediment data availability for the UK. Single morphological surveys and *ad hoc* grain size data are generally available; however, sediment supply, transported load or repeat morphological survey data are rare. In keeping with this, data for the Caldew through Carlisle comprised six sediment samples at locations along the river, one of which is within the reach considered in this study (Fig. 1). From this data (not shown), it is clear that the Caldew experiences downstream fining, typical of gravel bed rivers. This means the sample taken within the modelled reach (i.e. at the downstream end of the model) is the most appropriate and has therefore been applied throughout the domain. At this location the sediment have D_{10} = 3.7mm, D_{50} = 22.4mm and D_{90} = 190.6mm. Due to the lack of sediment transport data in the UK, globally boundary conditions are commonly defined in practice using an equilibrium load. The same approach has been adopted here, meaning no degradation or aggradation results at the upstream section. As the sediment loading applied at the upstream boundary can influence model predictions, the model has been artificial extended 0.2km upstream for improved representation of the sediment dynamics within the reach of interest.

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

Methodology

Stochastic modelling

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

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

1. Identify discrete states (*S*) in the flow record
2. Define the set of *N* unobserved states to account for all possible values between the discrete state limits. For example if state A were between 5m^3/s – 15m^3/s the unobserved states correspond to 5, 6, 7, 8,….15m^3/s and so on. Each discrete state has *N* unobserved states
3. Define the state transition probability matrix. For *S* states this is an *S* x *S* matrix with the value in row *i* and column *j* corresponding to the probability of flow transition from state S_i to state S_j.
4. Define the emission probability matrix that contains the occurrence probabilities of all unobserved states that correspond to each observed state. i.e. an *S* x *N* matrix
5. Define a set of *S* initial probabilities for each discrete state following the method of (Rabiner, 1989).

The main difference between a standard HMM and the HMM-GP is that the estimates of the extreme flows (above 99th percentile) are from a fitted GP model. To test the robustness of the HMM-GP model Pender et al. (2015) applied it to three rivers in the UK with distinctly varying hydrological characteristics. The results showed the model is capable of producing an accurate representation of the historic flow climate and could sufficiently represent the entire range of flows that occur in the rivers.

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

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

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

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

Sediment transport modelling

Due to the stochastic nature of the HMM-GP model every time a sequence is generated it will be inherently different, although the average statistics will be similar. This means that the modelling of a single N year sequence is insufficient to deduce the bed change that will occur during N years (Pender et al., 2014). To overcome this, a bootstrapping-type approach is proposed. This involves the simulation of numerous flow sequences to allow for a more complete representation of the potential *N* year bed level change as an envelope of data. Whilst similar approaches have been adopted for coastal erosion modelling (Ranasinghe et al., 2011; Ranasinghe et al., 2013; Callaghan et al., 2013) the empirical nature of the models used in these instances (i.e. low computational effort) meant that many thousands of simulations were feasible, allowing convergence of erosion estimates at the 95% confidence intervals. However, as this study is prediction of flood risk (i.e. after 50 years of morphological change) updated channel cross-section geometry is required to build a model that represents the predicted channel. As such, it is not feasible to produce a geometry based on confidence intervals of morphological change.

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

i. **All:** This method uses the final (i.e. modified after 50 years of sediment transport) channel geometries from all *M* sequences. Each of the *M* new geometries are used to assess future flood inundation via running a hydraulic inundation model for all *M* modified channels. The benefit of this approach is that the method is conservative with regard to sediment volume; however, it is time and resource intensive to perform *M* inundation models as a sensitivity assessment. Although this is not the case with the 1D model used here, many of flood inundation modelling studies are now implemented with 1D-2D models, which are considerable more computationally expensive.

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

For the demonstration of the methodology here, 100 flow sequences will be modelled; this number of sequences tends towards <1.5% variability in the mean aggradation. Upon generation of the 100 flow sequences using the HMM-GP model, the sediment transport and morphological changes along the reach are estimated using the HEC-RAS model set-up discussed previously. To validate the concept of using best and worst future channel geometries, a comparison will be made with results produced using all 100 potential future channel configurations.

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

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

Results and analysis

Morphological response

One of the most widely used (e.g. Jacobs, 2007; Shvidchenko and Pender, 2008; Ayres, 2010; Cao et al., 2012) indicators of morphological change in hydraulic engineering is the elevation of the channel invert (lowest point). Here however, it is proposed that the net change in sediment volume is more suitable as this will provide a better insight into the degradation/aggradation patterns and subsequently, channel capacity along the reach. Net change in sediment volume is the difference between volume entering (to) and leaving (from) a reach; in HEC-RAS, such reach is bounded by two consecutive cross-sections. This is in line with previous analyses of field measurements of morphological response (e.g. Lane et al., 2007; Raven et al., 2009).

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

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

Future flood inundation

As discussed previously, the final channel configurations from the 100 simulations are used to produce new geometries to assess future flood inundation. Fig. 4 shows the WSE change envelopes along the modelled reach for all return periods, using the Min/Max and All methods for determining new channel geometries. There is a general tendency towards channel aggradation, supporting the public consensus that this was a contributing factor in historical floods.

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

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

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

It can be seen from the upper envelope limits (resulting from the Max geometry) in Fig. 4 that, although conservative, there is the potential for an increase in WSE along the reach between 0.85-1.58m, across all return periods. This, combined with Max geometry (upper envelope limit) reach-averaged increases of 0.33-0.71m (across all RPs), is significant for future flood inundation. Even when the conservative nature of the Max geometry is reduced through the mean of the Min/Max envelope (Table 1), maximum changes in WSE along the reach are still significant (0.52-0.81m across all RPs).

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

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

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

After construction of flood defence scheme

Morphological response

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

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

Although the reach-averaged effect of flood wall construction has been shown to be limited, significant local variation in the response at individual locations can occur. Taking the same location as before (2.16km from the D/S boundary) shows that, with flood walls in place, all simulations now result in net aggradation at the section. In addition, the maximum volume of aggradation, at this location, has increased by 260% of that when the reach was in its natural state; an increase of 1331m^3 compared to 508m^3.

Future risk of overtopping

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

From Fig. 7, comparing the increase in WSE between the natural and modified reaches, the general trend indicates that aggradation has a greater influence on WSE after flood defence construction. This change is consistent across the range of RPs tested here, with the magnitude of these differences increasing with increasing RP. The results for the natural reach (Fig. 4) show that, when the RP is small (i.e. 1-2 years) and flow is confined to the channel, the effects of aggradation on WSE is greater than at higher RPs. As the flow is mainly in-bank during these events, and the walls have little influence on WSE, the reach-averaged difference between channels with and without defences is small (increase of 0.06m at a 1 year RP). However, as the flow magnitude increases, the reduction in the overall width of the river system, resulting from the defences, leads to the morphological changes having a greater influence on reach-averaged future flood levels (increase of 0.34m at a 200 year RP). This is due to all of the flow now being confined within the modified channel, rather than previously being allowed to inundate the floodplains. When flood walls are present such potential increases in WSE can considerably increase the likelihood that defences could become overtopped during their design life.

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

Conclusions and recommendations

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

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

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

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

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

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

  The answer to the above question is therefore in the hands of individual decision makers, on a case-by-case basis. However, the mean of the Min/Max approach is suggested as a starting point for assessing the impact of morphological change on WSE. The decision can then be made to whether the detailed consideration of using All geometries should be investigated.

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

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

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

  The results show that, whilst the construction of the flood defence scheme can have significant local impacts on the channel morphology (potential 260% increase in sediment volume) at certain locations, it does not alter the overall morphological patterns of the reach. In addition, the multiple simulations indicate that, after the construction of flood defences, the size of the morphology envelopes increase. This shows that this modified reach is more susceptible to the sequence and characteristics of the flow regime and therefore induces a greater degree of sediment-related sensitivity. In terms of future flood risk, the trend associated with the increase in WSE reverses (more significant at higher RPs) compared to when the reach has no defence scheme. This is due to all of the flood water now being constrained within the defences and channel. At the smaller RPs, when the flood is mainly within the channel, the influence of the flood walls on increasing water level is less than when the flow is large enough to be constrained by the walls.

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

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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

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

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)

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

Figures

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

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

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

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

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 section located 1.97km from the downstream boundary. The black and dashed black lines represent the original and Max channel geometries respectively; with the grey and dashed grey lines indicating the corresponding WSE

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

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