

Variable input parameter influence on river corridor prediction

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This paper considers the erodible river corridor, which is the area in which the main river channel is free to migrate over a period of time. Due to growing anthropogenic pressure, predicting the corridor width has become increasingly important for the planning of development along rivers. Several approaches can be used to predict the future erodible corridor width but the results possess a large degree of uncertainty in all cases. The work presented here addresses prediction of the erodible corridor width of a reach of the River Irwell, UK, taking into account the uncertainty that arises from input parameters such as representative discharge, channel width, sediment and so on. The work adopts a probabilistic framework for assessment using Monte Carlo type simulations. Future river corridor width predictions, based on a model calibrated on past observations, are presented in a probabilistic manner using confidence levels. The results indicate the necessity of capturing input variability in the modelling process. Furthermore, the understanding gained from a relatively simple model used in a probabilistic framework is greater than a more complex one where only a few runs are feasible.

Notation

B	bankfull width (m)
C	Chézy coefficient ($\text{m}^{1/2}/\text{s}$)
D_{50}	mean sediment diameter (mm)
E	calibration coefficient
E_h	migration coefficient (s^{-1})
E_u	migration coefficient
g	acceleration due to gravity
H	near-bank excess flow depth (m)
h_0	reach-averaged flow depth (m)
k_B	transverse wave number
n	transverse coordinate
Q	bankfull discharge (m^3/s)
R	local radius of curvature of the channel centreline
s	curvilinear centreline coordinate
t	time
U	near-bank excess flow velocity (m/s)
u_0	reach-averaged flow velocity (m/s)
α_1	calibration coefficient
γ	curvature ratio
θ_0	reach-averaged Shields parameter
κ	von Kármán constant
λ_S	water depth adaptation length
λ_W	flow adaptation length
σ	calibration coefficient

1. Introduction

The location, design and construction of infrastructure that societies rely on often place that infrastructure at risk from a variety of natural phenomena. Such risks are often unavoidable, but can be reduced and mitigated. One key issue is the risk posed to transport infrastructure such as road bridges, railway lines and highways from migrating river channels. Rivers migrate, through the erodible river corridor, as a part of the natural process both within a particular year and across a number of years or even decades.

The erodible river corridor is the area that is occupied by the main river channel during a given timeframe. It includes the main river channel plus the adjacent floodplain area through which the channel migrates or is likely to migrate in the period of time considered (Ellis-Sugai and Godwin, 2001). Predicting the future erodible river corridor width is necessary to calculate the extent of the area that is at risk of erosion due to fluvial processes. This is essential information for designing river restoration works including re-meandering (Piégay *et al.*, 2005; RRC, 2002) and for the planning of developments along rivers with natural banks. Additionally, erodible corridor width delineations can provide guidance for reducing degradation and loss of critical aquatic and riparian habitats, helping to ensure that fluvial processes are accommodated and that the river landscape is not permanently

degraded or disconnected from the river by development. The natural processes governing river movements are complex, and we only have a partial understanding of them and their interactions. This leads to significant uncertainties in the necessary study of these situations for the design of risk reduction and mitigation measures.

Predictions of the erodible river corridor are possible through a number of different methods. Historically, three main groups of approaches have been used to predict the future extent of erodible river corridor widths – simple rules of thumb, historical analyses and modelling (Piégay *et al.*, 2005). Bank erosion and accretion are the processes leading to lateral channel migration. Channel migration modelling integrates river hydrodynamics with sediment transport, bed-level changes, bank erosion and bank accretion, all characterised by natural variability in time and space. Most state-of-the-art two-dimensional (2D) models lack a bank accretion formulation, which makes these models inappropriate for prediction of the channel width evolution (Rüther and Olsen, 2007). This means that these models are only suitable for short-term predictions of the river channel migration. Asahi *et al.* (2013) recently showed the effects of taking into account bank accretion, although in a rough way, for the prediction of the planimetric evolution of meandering rivers. For this, considering the temporal variations of water flow is essential.

Simplified models, applicable only to meandering rivers, assume that the river bed topography can be described by a sequence of alternate bars and/or point bars. In the presence of alternate bars, the transverse variations of flow velocity and water depth can be represented by sinusoids having a wavelength equal to twice the channel width (e.g. Crosato, 1987; Johannesson and Parker, 1989; Zolezzi and Seminara, 2001). In this way, the description of the transverse variation of bed topography and flow velocity follows a 1D approach. Ikeda *et al.* (1981) assumed the transverse shift of the channel centreline to be proportional to the near-bank excess of flow velocity with respect to uniform flow, which, in the presence of alternate bars, is represented by the amplitude of the sinusoid. To take into account the long-term effects of bank instability, Crosato (2008) assumed the transverse shift of the channel centreline to be also proportional to the near-bank water depth excess. Meander migration models further assume that the channel width remains constant in space and time, implying that the lateral channel shift is governed by bank erosion and that opposite bank accretion occurs at the same rate. Zolezzi *et al.* (2012) analysed the effects of channel width variations in phase with the channel curvature and found that width variations enhance river bed dynamics.

Due to assumptions, simplifications and inevitable empirical and numerical aspects, all model approaches possess a large degree of uncertainty, where model uncertainty is defined as ‘any departure from the unachievable ideal of complete determinism’ (Walker *et al.*, 2003). Uncertainty is due to the dynamic, stochastic and uncertain nature of river processes (van Vuren, 2005) and to the

limitations and assumptions of the method. A degree of uncertainty in model estimates is consequently inherent, which has implications on the usefulness of these predictions to decision makers and designers (Warmink *et al.*, 2010).

This paper considers a situation where the migration of a river channel poses a threat to a railway line. In earlier work, this situation was studied using a deterministic approach with a 2D model including bank erosion (Duran *et al.*, 2010); however, the authors found that a much simpler meander migration model (Crosato, 2008) was in fact more suitable for long-term predictions of the river planimetric changes and that, due to a lack of formulations for the bank accretion process, the 2D model resulted in unrealistic river widening. Work with the same meander migration model is presented here. Other advantages of this model are that it requires less data, fewer parameters and, most importantly, less computing resources (in fact, several orders of magnitude lower than in the 2D simulations mentioned earlier). This simpler model is used in a probabilistic framework, allowing us to consider a range of values of key parameters, which is not possible with the more complex model. In this way, the simpler model may in fact give us a greater understanding of future channel migration. This hypothesis – that a simpler model used in a probabilistic framework can be more useful than a more complex deterministic model – is tested for this particular case study.

The work studies the variation in predictions arising from varying the value of the selected parameters within the range of their measured values for future realisations of the river corridor width. The work adopts a probabilistic framework using Monte Carlo (MC) type simulations. A full MC approach using 5000 simulations is presented along with a shortened version using the Latin hypercube sampling technique of 50 runs. The shortened version is proposed as an alternative method for engineering assessments where time and financial constraints restrict simulations. Interesting conclusions are drawn from this work, but it is clear that further case studies are required.

2. Case study: River Irwell gravel bed meandering

The River Irwell has its origin in the Irwell spring, 427 m above the mean sea level (Duran *et al.*, 2010). All relevant catchment characteristics are listed in Table 1. The river reach considered here is located to the east of Rawtenstall, Lancashire, UK, and is about 1.2 km long (Figure 1). Field work undertaken in February 2010 measured the sediment type and river features such as width and depth, while flow data were provided by the UK Environment Agency. The sampling procedures are explained in Section 4.

In the study area, the river bankfull width varies from 15.0 to 20.5 m in bends and from 7.5 to 13.0 m in straight reaches (variation through the reach of 7.5–20.5 m). The annual mean discharge, computed from a measured daily discharge time series of 12 years, is 3.17 m³/s, and the Q_{10} and Q_{95} flow values are 7.18 m³/s and 0.68 m³/s respectively (Table 1). High flow estima-

Catchment attribute	Mean value	Range
Catchment area: km ²	101.0	—
Annual average rainfall: mm	1393.0	—
Mean discharge Q_{mean} : m ³ /s	3.17	—
Q_{95} : m ³ /s ^a	0.68	—
Q_{10} : m ³ /s ^b	7.18	—
Bankfull width: m	12.4	7.5–20.5
Bankfull discharge: m ³ /s	32.5	20.5–63.0
Median grain size D_{50} : mm	7.6	3.0–9.5

^a 95% of recorded flows higher and ^b 10% of recorded flows higher (Environment Agency).

Table 1. River Irwell catchment characteristics in the study area

tions indicate that the bankfull discharge is 20.5–63.3 m³/s. The sediment of the river consists of gravel and sand with a median sediment diameter of 7.6 mm.

In the study area, river bank erosion is threatening key infrastructure. Here, the advance of channel migration may affect the geotechnical stability of a railway embankment, a weir and a bridge. Furthermore, the process of channel migration caused by bank retreat has already resulted in the closure of a popular footpath (Cain, 2007).

The planimetric changes of this river reach were previously studied by Duran *et al.* (2010) using the same model, Miandras, which was calibrated and verified on past river topographic changes. The ‘optimised’ set of parameters and the relative predictions were used as the baseline for the present study (Table 2). The values of calibration coefficients are listed in Table 3. The calibrated migration coefficients are variable along the river course and for the left and right banks, due to the presence of bank protection works and trees (Table 3). The calibration procedure is based on the assumption that the spatially variable channel migration coefficients derived from historical river evolution remain the same in the future. In the traditional deterministic manner, this baseline model would be used to simulate future scenarios, assuming a representative set of environmental variables. This work proposes an extension to standard deterministic

Variable	Value
Channel width: m	11.8
Longitudinal slope: %	0.53
Bankfull discharge: m ³ /s	45
Mean grain size D_{50} : mm	11.2
Grain size D_{90} : mm	30.5

Table 2. Reference characteristics of the study reach (Duran *et al.*, 2010)

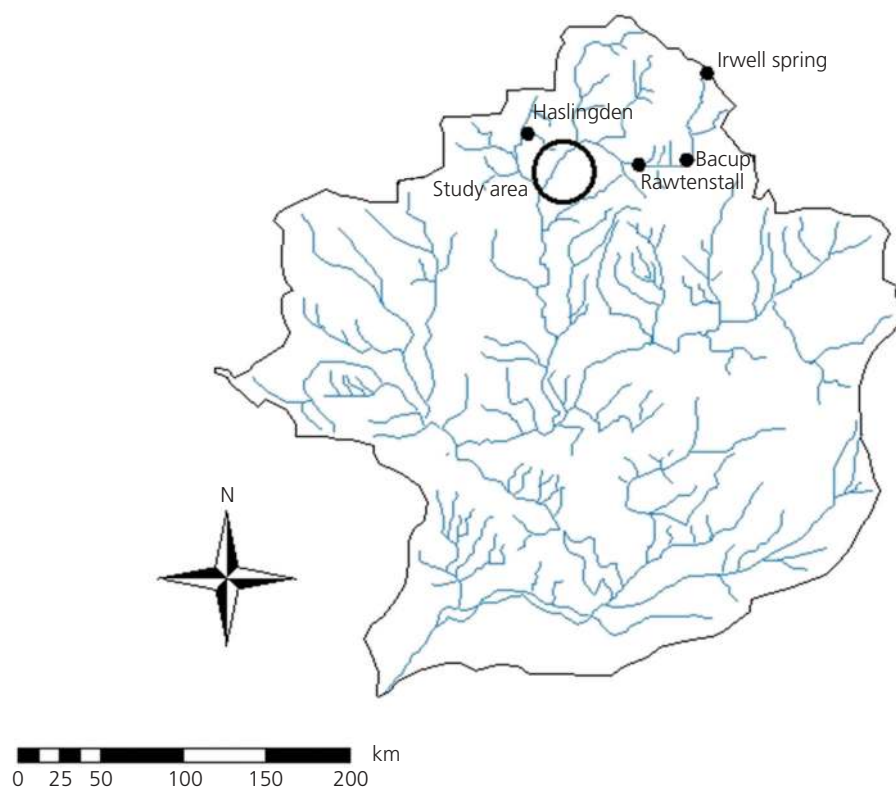


Figure 1. Study area

Calibrated coefficients	Base case	Banks fixed	Vegetated banks	Railway embankment
Migration coefficient E_u	1.0×10^{-5}	0.0	5.0×10^{-6}	5.0×10^{-7}
Migration coefficient E_h	2.0×10^{-5}	0.0	1.0×10^{-5}	1.0×10^{-6}
Coefficient E	1	1	1	1
Coefficient σ	3.5	3.5	3.5	3.5
Coefficient α	0.42	0.42	0.42	0.42

Table 3. Calibrated migration coefficients and other model parameters (Duran, 2008)

techniques, which incorporates natural variability in environmental variables, in order to predict probable likely locations for river corridor locations in the future.

3. Channel migration model

Meander models compute the planimetric evolution of meandering rivers at large spatial and temporal scales. In order to do so, at every computational time step, they determine the lateral shift of the river channel that results from the local bank erosion and accretion rates. A common assumption is that the river width remains constant; this is achieved by assuming that the rate of bank advance on one side of the channel is equal to the rate of bank retreat on the opposite side (Figure 2). This is a major simplification since meandering rivers exhibit width fluctuations in both time and space, varying with the river discharge; however, in the long term, these width variations can be considered less important. It should be noted that, for this reason, meander models are suitable only for long-term predictions.

The mathematical model adopted in this study, Miandras (Crosato, 1987, 2008, 2009), computes the longitudinal profiles of the near-bank excesses of flow velocity and water depth, U and H , respectively, with respect to the reach-averaged values, u_0 and h_0 (Figure 3). These excesses are caused by the local channel curvature and by upstream geometrical discontinuities such as a change of channel

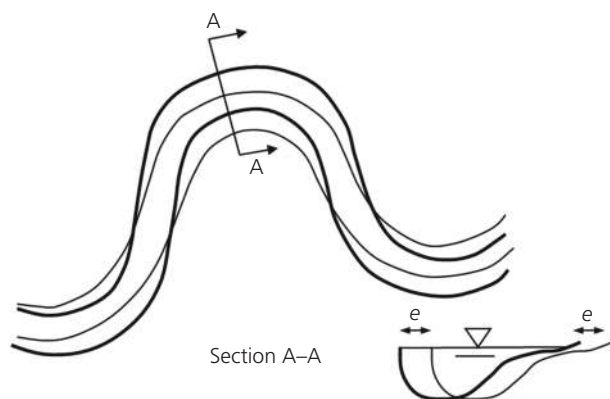


Figure 2. Channel migration scheme (bank advance = bank retreat = e)

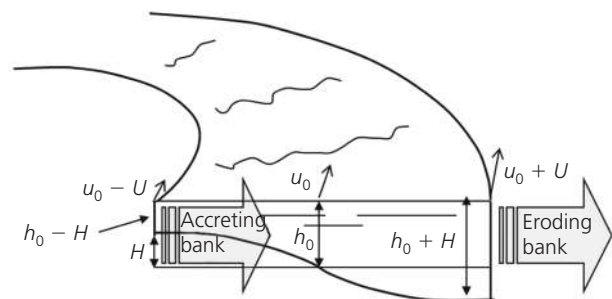


Figure 3. Cross-stream variations of flow velocity and water depth in a curved channel (u_0 and h_0 are the cross-sectionally averaged velocity and water depth, respectively; U and H are the near-bank excesses of the velocity and water depth, respectively)

curvature (bend entrance and exit), which, under certain conditions lead to the formation of steady alternate bars in the river channel (Struiksmas *et al.*, 1985). The long-term local bank erosion rate is assumed to be a function of both U and H . The excess velocity U accounts for the effects of fluvial erosion driven by the local flow velocity (Ikeda *et al.*, 1981). The excess water depth H accounts for geotechnical instability, which is based on the consideration that bank instability increases with erosion at the toe of the bank (higher near-bank water depth). This effect becomes relevant with vertical cohesive banks. The transverse profiles of water depth and velocity are assumed to be perfectly point-symmetrical with respect to the channel centreline (Figures 2 and 3), which implies that the bank accretion rate equals the bank erosion rate on the opposite side and that the river width remains constant.

The basic equations are obtained from the steady-state 2D depth-averaged continuity and momentum equations for water in shallow channel bends (Kalkwijk and Vriend, 1980), coupled to a sediment transport formula and a sediment balance equation (highly simplified model in Struiksmas and Crosato (1989)). The effect of the outer-bend super-elevation of the water free surface is retained in the momentum equations, but neglected with respect to water depth in the continuity equation (assuming a mildly curved channel).

The near-bank excesses U and H correspond to the near-bank

values of the perturbations of flow velocity and water depth, which would be equal to u_0 and h_0 respectively in the case of uniform flow (non-perturbed conditions). Upon linearisation of the equations for small U and H with respect to u_0 and h_0 and after imposing a sinusoidal transverse shape to the perturbations (Figure 3), the equation for the near-bank velocity excess in coordinates s (curvilinear centreline coordinate, positive downstream) and n (transverse coordinate, positive towards the outer bend) becomes

$$1. \quad \frac{\partial U}{\partial s} + \frac{U}{\lambda_W} = \left(\frac{1}{h_0 \lambda_W} \right) \frac{u_0}{2} H - \frac{u_0}{2} \frac{\partial \gamma}{\partial s} - \left(\frac{2 - \sigma}{2} \frac{1}{\lambda_W} \right) \frac{u_0}{2} \gamma$$

where s is the downstream coordinate, u_0 and h_0 are the normal (reach-averaged) values of flow velocity and water depth respectively, λ_W is the flow adaptation length and γ is the curvature ratio. The flow adaptation length is given by

$$2. \quad \lambda_W = \frac{C^2 h_0}{2g}$$

where C is the Chézy coefficient and g is the acceleration due to gravity. The curvature ratio is given by

$$3. \quad \gamma = \frac{B}{R}$$

where R is the local radius of curvature of the channel centreline and B is the channel width.

The coefficient σ is added to the bed friction term in order to reproduce the effects of secondary flow momentum convection (Struiksmas and Crosato, 1989), and is used as a calibration coefficient. Its value falls between 2 and 4. For $\sigma > 2$, the bed friction is lower near the eroding bank, which has an effect similar to the secondary flow momentum convection: a transverse shift of the position of the maximum flow velocity towards the outer bank, resulting in higher values of U and H . The equation for the water depth excess is derived from the linearised sediment transport and sediment balance equations

$$4. \quad \frac{\partial H}{\partial s} + \frac{H}{\lambda_S} = \frac{h_0}{u_0} (b - 1) \frac{\partial U}{\partial s} + \frac{A}{2} h_0^2 k_B^2 \gamma$$

in which b represents the degree of non-linearity in the dependence of sediment transport on the flow velocity and k_B is the transverse wave number of the velocity and water depth perturbations, given by

$$5. \quad k_B = \frac{m\pi}{B}$$

with m being the bar mode, which is a function of the number of bars in the channel cross-section (for meandering rivers $m = 1$). The parameter λ_S is the water depth adaptation length, given by

$$6. \quad \lambda_S = \frac{f(\theta_0)}{k_B^2 h_0}$$

λ_S corresponds to the adaptation length of the bed topography to upstream flow disturbances (i.e. imposed on the flowing water and sediment, such as a change of channel curvature). The function $f(\theta_0)$ is given by

$$7. \quad f(\theta_0) = \frac{0.85}{E} (\theta_0)^{0.5}$$

Equation 7 is an empirical relation for the effects of the transverse bed slope (see Talmon *et al.*, 1995), in which E is a calibration coefficient and θ_0 is the cross-sectionally averaged Shields parameter. Talmon *et al.* (1995) suggest using $E = 0.5$.

A is a coefficient accounting for the effects of curvature-induced spiral flow on the bed shear stress direction, given by Olesen (1987) as

$$8. \quad A = \frac{2\alpha_1}{\kappa^2} \left(1 - \frac{g^{0.5}}{\kappa C} \right)$$

where κ is the von Kármán constant and α_1 is a calibration coefficient. Increasing α_1 leads to a generalised increase of the effects of curvature on the flow field. Practical experience by Struiksmas (personal communication) indicates that α_1 should have a value between 0.4 and 1.2 (the standard value for small-scale rivers is 0.5).

The general equation that is used to compute the rate of lateral shift of the main channel axis is

$$9. \quad \frac{\partial n}{\partial t} = E_u U + E_h H$$

where n denotes the transverse coordinate, which is equal to zero at the channel centreline, t is time, and E_u and E_h are migration coefficients representing the effects of erosion and accretion of opposite banks. U and H are the excess near-bank flow velocity and water depth with respect to their respective reach-averaged values u_0 and h_0 , so that these represent the threshold values below which banks do not erode but accrete. The model

incorporates the effects on U and H of the downstream part of the channel in two ways: in the number of points along the channel axis that are used to compute the local curvature (Crosato, 2008) and in the numerical discretisation of the equations, which is done by using the explicit Runge–Kutta method for first- and second-order differential equations. A full model description is given by Crosato (1987, 2007, 2008, 2009).

The long-term simulations undertaken in this paper use approximations using the bankfull, or bank-forming discharge, following the method first proposed by Ikeda *et al.* (1981).

4. Methodology

This work applies the described meander migration model Miandras within a probabilistic framework with the purpose of providing a greater understanding of future channel migration. A range of values of key parameters is considered in order to understand the influence of the uncertainty of these parameters on river corridor width predictions to assess the possible future channel locations of the River Irwell in the UK.

The key parameters varied within the framework represent the initial environmental conditions, and tend to be sampled from the studied reach. Consequently, the variability captured during the sampling process can influence both the input and the output of the modelling process. The selected parameters define the general characteristics of the river reach (e.g. reach-averaged main channel width, sediment median diameter, bankfull discharge and roughness coefficient), and are represented by a single (reach-averaged) value in meander migration models such as that presented by Johannesson and Parker (1989) and Miandras. These parameters are often derived from field measurements and then adjusted during model calibration. For this, it is usually assumed that the calibrated model already includes the effects of their uncertain values. However, since morphodynamic models are calibrated on past conditions, their predictions still remain uncertain. Consequently, model performance is usually validated by simulating another historical period for which data are available, without changing the values of the parameters. A comparison of measured and predicted conditions provides insight into the uncertainty associated with the model predictions, but this is strictly only applicable for the validation period. It is impossible to do the same for future predictions, which remain inherently uncertain.

Along with the initial channel alignment and valley slope, the input variables and model parameters required by the adopted model are

- bankfull discharge Q , bankfull width B , bankfull Chézy coefficient C and median sediment grain size D_{50}
- migration coefficients E_b and E_u
- calibration parameters σ , E and α_1 .

The spatially variable migration coefficients are derived from calibration on past planimetric changes. These are bulk param-

eters that include the effects of bank material, riparian vegetation (Wynn *et al.*, 2004), pore water pressure (Dapporto *et al.*, 2003; Rinaldi and Casagli, 1999), groundwater flow (van Balen *et al.*, 2008) and numerical aspects such as the choice of how to compute the local channel curvature, numerical smoothing filters, and time and spatial steps (Crosato, 2007). For this reason, the migration coefficients can only be derived by means of model calibration based on the best fit of model predictions to historical channel centreline alignments. For this study, we assume that they remain constant with time, which corresponds to assuming that the physical situation of the river banks remains unchanged. The values adopted for these parameters are those derived from previous calibration by Duran *et al.* (2010), which was carried out on the channel alignments 2003, 2006 and 2007. The same applies for the other calibration parameters, σ , E and α_1 .

Varying the values of the migration coefficients has direct effects on the computed lateral channel shifts. Increasing the value of E_u leads to higher bank erosion rates, which is especially evident where the near-bank velocity excess U is the highest. For the River Irwell, this occurs downstream of river bends. Increasing the value of E_b leads to higher bank erosion rates where the near-bank water depth excess H is the highest, at the location of the pools opposite the point bars. This work does not assess the uncertainties related to these parameters, which are not spatially uniform but vary along the river, since their local values are affected by the presence of bank protection works, trees planted on the river banks, local structures and so on. Moreover, the effects of uncertainties related to randomly varying bank erodibility have already been investigated in previous studies (e.g. Posner and Duan, 2011). Variation of the values of the migration coefficients (in a reasonable range for this river) and the other calibration coefficients does not change the main outcomes of the analysis, focusing on the effects of varying the values of those input parameters that are often considered as known, because they are measurable: discharge, width, sediment characteristics and bed roughness. These variables were used to define the data collection and design the probabilistic framework for analysis.

Figure 4 illustrates the experimental methodology undertaken. To understand and capture variability in the environmental conditions in the study reach required by the model, field work was undertaken in February 2010. The sampled data were gathered and represented as probability distribution functions (PDFs) for the basis of the probabilistic assessment, where both standard MC (full analysis) and Latin hypercube sampling (LHS) techniques (shortened analysis) were employed. The following sections describe the data collection and PDF generation for the four chosen parameters, and how the issue of interdependency between parameters was addressed.

4.1 Bankfull discharge

The discharge time series collected at Irwell Vale gauging station, located 1–2 km downstream of the study area, was used to estimate the bankfull discharge. The flow data available from the

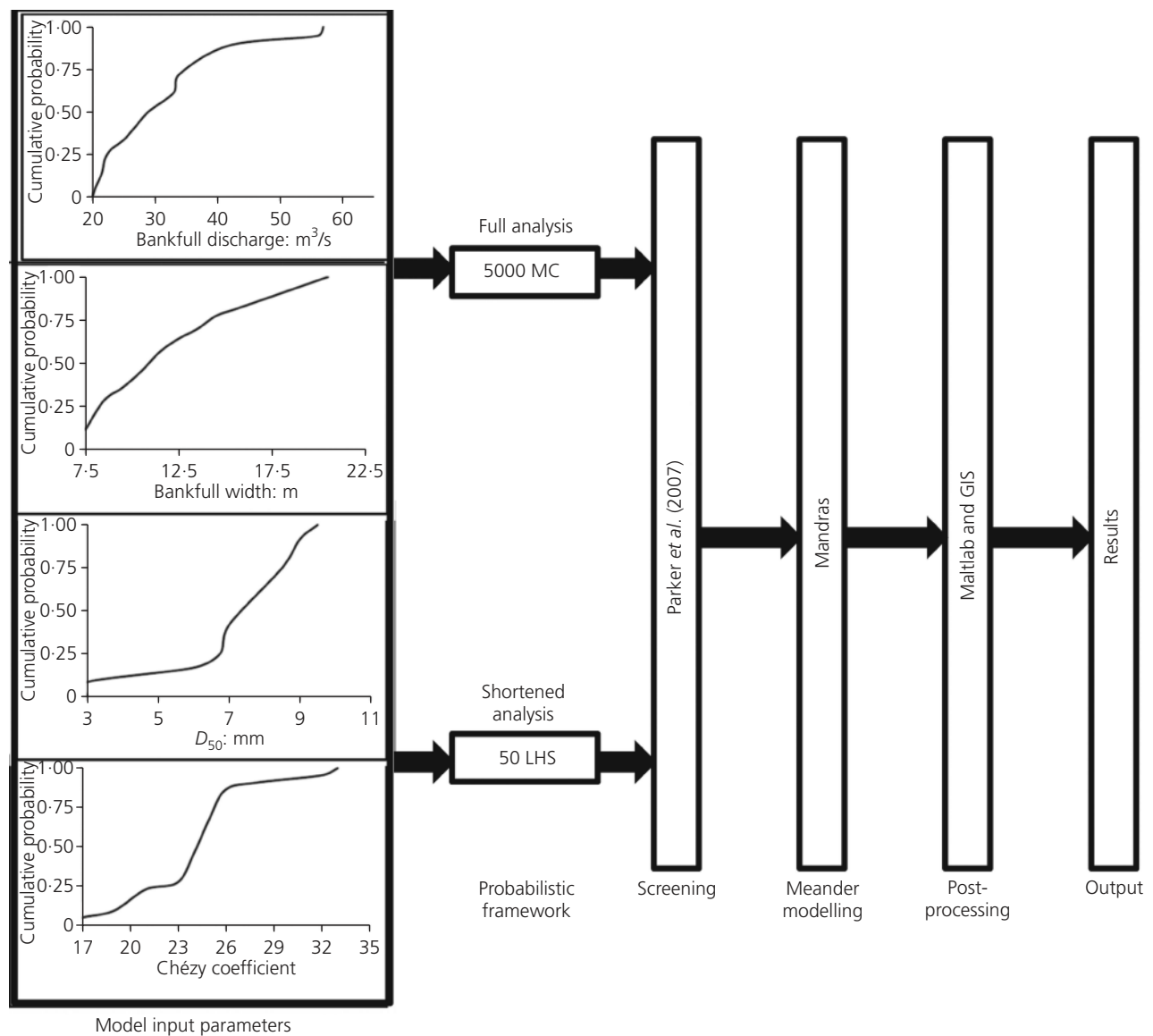


Figure 4. Research methodology

UK Environment Agency spans 12 years (21 January 1996 to 14 February 2007), and consists of 15 min time series. The bankfull discharge Q was estimated on flow recurrence. It is generally accepted that a 1.5-year, 2-year or 5-year recurrence flood represents the bankfull discharge of a river (Johnson and Heil, 1997; Parker *et al.*, 2007; Williams, 1978). Site observations on the maximum bar height, active flood plain, height of the valley flat and height of the lower limit of perennial vegetation showed different elevation levels for the bankfull depth and width of the river, and indicated that it is sensible to consider a wide range of bankfull discharges. To include or overcome this variability, all discharges in the range between the 1.5-year and 5-year recurrence interval were used to establish the PDF (Figure 4). The 1.5-year and the 5-year recurrence flow estimated for the Irwell Vale station are 21 and $57 m^3/s$ respectively.

4.2 Median sediment size

Sediment samples were collected from the study area during the field campaign conducted in February 2010. Three samples were taken on point bars, while a further nine samples were taken from the river bed and banks using a structured grid approach with a spacing of 100 m. The resulting median sediment size D_{50} ranged between 3.5 and 11 mm (gravel). The collected data formed the basis of the PDF (Figure 4).

4.3 Bankfull width

The bankfull channel width B was measured onsite using the same structured sampling grid, this time at intervals of 25 m. The river width in the study reach was 7.5–20.5 m, with a mean value of 12.2 m (Figure 4).

4.4 Chézy coefficient

The hydraulic roughness of the river reach under study was estimated by matching 24 recent photos of the River Irwell in the study reach with standard river photographs used as references for hydraulic roughness, following the method developed by Barnes (1967). Thirty experts were asked to estimate the hydraulic roughness of the channel, and the results gave a mean Chézy coefficient of $24.6 \text{ m}^{1/2}/\text{s}$ (Figure 4).

4.5 Interdependency

Not all combinations of parameters can represent a realistic single-thread gravel-bed river such as the Irwell, and indeed some parameter sets formed unrealistic combinations, which meant that these sets had to be discarded. The interdependency between morphodynamic parameters is given by the quasi-universal relation, which describes the bankfull hydraulic geometry of single-thread gravel-bed rivers, developed by Parker *et al.* (2007). This relation relates the three parameters B , Q and D_{50} through

$$10. \quad B = \frac{4.63}{g^{0.5}} Q^{0.4} \left(\frac{Q}{(gD_{50}^2)^{0.5}} \right)^{0.0667}$$

The check whether a set of parameters could be considered a realistic combination for a river such as the Irwell was based on application of Equation 10. If the randomly generated value of bankfull width B deviated by more than 65% from the result of Equation 10, the parameter set was assumed to be unrealistic and was not used to run the meander migration model.

It should be noted that while some uncertainty is estimated from temporal variations (i.e. discharge), for others a longitudinal variation is used (i.e. width). These estimates have to be made from the data that are available. The temporal variation of average width would be a good estimate but, as this was not available, the longitudinal variation was an acceptable alternative. This issue is encountered whether a simple model in a probabilistic framework is used or a few runs of a more complex model.

4.6 Prediction of future planimetric evolution and representation of probabilistic outputs

The model was used to simulate the future planimetric evolution of the River Irwell over the next 50 years, starting from the 2007 channel alignment (Figure 5). The duration of the simulation period was chosen to establish the extent of uncertainty of river corridor width estimates over an indicative period of time considered to be useful for engineering interventions.

For the standard MC analysis, 5000 model simulations were undertaken. A second shortened analysis used LHS. The probability distributions were divided into 50 non-overlapping equal-probability intervals, which were then sampled. The subsequent parameters were then combined to create complete sets.

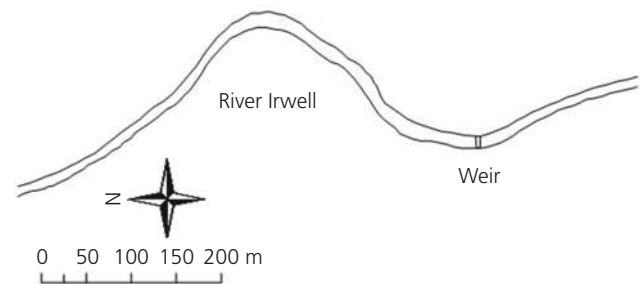


Figure 5. River alignment (2007)

The model outputs take the form of future bank lines and centreline coordinates as well as longitudinal and transverse bed-level profiles. A raster-based analysis was devised to map all river alignments and derive useful and applicable information from the outputs.

5. Results and discussion

The results of the probabilistic modelling for future river corridor positions are shown in Figures 6 and 7 and Table 4. Variations in the predicted river corridor width vary along the study reach for each given confidence level. For the full assessment, the river corridor width at the 95% confidence level averaged over the study reach is 50.8 m, with minimum and maximum predictions of 22.4 and 75.5 m respectively. For the shortened assessment, the reach-averaged value was 33.3 m, with minimum and maximum values of 19.2 and 42.2 m respectively.

Figures 6 and 7 show the area in which the future river corridor may be located, using both the full and shortened probabilistic framework proposed. A deterministic run of the model using a representative set of environmental variables is captured within the result set presented under the 76–95 percentile corridor. Standard 25% changes to parameters within a sensitivity study approach resulted in variations of the results of up to 24 m in particular locations around the meander bends. In comparison, it

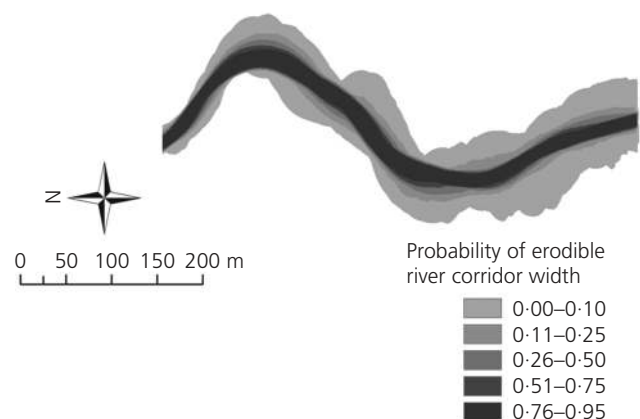


Figure 6. Probability of an area belonging to the erodible river corridor: full analysis

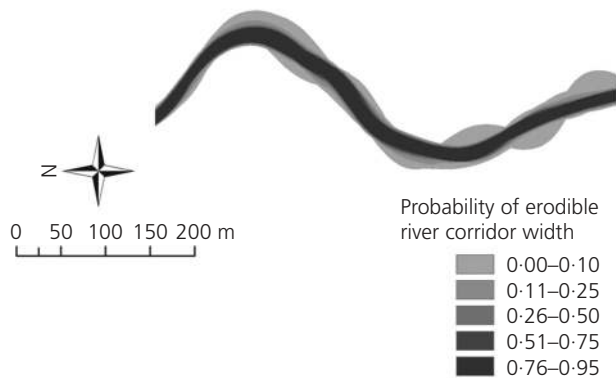


Figure 7. Probability of an area belonging to the erodible river corridor: shortened analysis

is clear that using the probabilistic framework adds information to these results and provides a reasonably wide erodible corridor at some locations. The variation in predictions provided by the probabilistic framework adds information to those interested in managing a river corridor and any associated infrastructure, by indicating zones of river migration. This is a departure from the deterministic approach, which gives only single realisations for a future river position, and provides more information than a straight sensitivity study, as zones of potential erosion can be determined. These predicted zones could be used to inform land use plans and infrastructure design in the river corridor.

Looking at the results in more detail and focusing first on the full analysis, if local differences in migration coefficients are accounted for, and in particular if some bank stretches are protected or naturally non-erodible, smaller differences between the confidence levels are expected. Special attention should be paid, however, to river banks close to bank protected areas, since these areas are often characterised by higher bank erosion rates (Crosato, 2008; Duran *et al.*, 2010). In the study area, the lateral extension of river meanders is relatively small, as is the river sinuosity. For river reaches with higher sinuosity, higher bank erosion rates – and hence larger differences between confidence levels – are expected. Further case studies would substantiate these hypotheses.

Figure 6 demonstrates the spatial variation of the erodible river corridor width, which increases depending on the confidence interval required and varies along the study reach depending upon the morphological conditions and specific location. It is clear that variation in model inputs based on natural variability in the study reach significantly impacts the outcome of the meander model simulations and hence the prediction of the erodible corridor width. The results of the analysis indicate the need to incorporate an estimate of environmental variability into erodible corridor predictions within a probabilistic framework in order to capture the true potential extent of the erodible corridor width. Presenting the results in this format would allow river managers a greater insight into probable river corridor widths and inform decisions on development within

Chainage	Erodible river corridor width: m					
	50% confidence		75% confidence		95% confidence	
	Full	Short	Full	Short	Full	Short
200 ^a	15.3	14.9	17.4	17.2	23.1	19.2
250	14.7	14.3	17.7	17.8	22.4	21.3
300	19.5	18.2	23.0	21.3	34.9	24.2
350	24.8	23.5	30.1	30.7	52.7	40.6
400	21.8	31.4	27.4	25.4	46.7	41.9
450	23.4	22.3	29.9	31.2	52.3	33.9
500	23.2	22.3	27.5	26.8	43.7	30.7
550	24.6	23.8	29.7	28.6	50.5	36.5
600	19.2	18.0	25.6	22.6	61.9	34.7
650	19.0	19.3	24.1	22.4	65.5	36.3
700	17.4	17.5	22.4	20.7	57.2	42.2
750	19.6	17.6	24.6	23.9	74.6	31.4
800	18.0	16.4	24.2	23.0	75.5	39.8
Reach averaged	20.0	20.0	24.9	24.0	50.8	33.3
Minimum	14.7	14.3	17.4	17.2	22.4	19.2
Maximum	24.8	31.4	30.1	31.2	75.5	42.2

^a Sampling grid neglects the boundary effect.

Table 4. Erodible river corridor width estimates

likely erosion areas as well as potential river restoration designs.

The error in terms of new channel alignment given by the application of meander migration models increases with the time span of the prediction or simulation. This should be taken into account when applying meander migration models in particular and any morphodynamic models in general.

Comparing Figures 6 and 7, it is clear that the shortened analysis (Figure 7) using the LHS technique does not capture the full extent of the potential river corridor. In some areas, the results of the analysis are similar, where the meander potential is less, but significant discrepancies between the methods can be observed at the bend locations. The shortened method, despite underestimating variability, does provide a useful insight into potential corridor migration, which is a considerable improvement over deterministic assessments. In situations where simulations are constrained by time or finance, this method offers a feasible option for incorporating probabilistic methods into analyses, but users should be aware that the full method may be more advisable for projects with higher risk.

Capturing external variability and uncertainty, such as the influence of climate variability, would add a further dimension to this work. This would be undertaken by estimating the influence of potential climate variability on the bankfull discharge prediction. Then, further probabilistic modelling would need to be undertaken to investigate the possible influence of these changes.

The results indicate that there is a need to understand the influence of the variability of input parameters on morphological simulation modelling. Furthermore, there may be a need to expand this framework to understand other forms of uncertainty in model prediction, such as model structure, numerical methodology or numerical parameters. Expanding the framework in such a way would allow for a fuller uncertainty analysis.

6. Conclusions

This work considered the use of a meandering migration model to assess the erodible corridor width of the meandering River Irwell. This simpler model was used in a probabilistic framework to investigate whether greater understanding of future channel migration can be achieved with this method rather than through deterministic approaches. The work focused on understanding the influence of variability in input parameters describing channel geometry, water flow and sediment transport on model predictions.

The results from both a full MC analysis and a shortened analysis indicate significant spatial variability in the predicted future erodible river corridor width. This gives a greater insight into the potential extent of the future river corridor width than is provided by single deterministic model outputs, and delineates river corridor zones for developers and managers.

The variability predicted is a function of the characteristics of this particular location, and different study areas would demonstrate different degrees of variability. However, what is clear is that the natural environmental variation captured through field studies influences the potential location of the future river channel, and this information is not captured through deterministic approaches. Probabilistic approaches can provide this greater understanding, but do require more simplistic migration models to be employed to keep computer resource requirements at a practical level. Despite the full analysis indicating a greater corridor width, the shortened method captures some of the corridor variability predicted and offers a viable option when constraints prevent full probabilistic analyses.

Results indicating potential erodible river corridor widths, with confidence limits, such as those presented here, would be useful to those responsible for developing or managing river corridors, and report variability in a meaningful way. Understanding the variance in future potential river movements over time is an important input to river restoration and re-naturalisation projects.

Acknowledgements

The research results are from a collaboration between Unesco-IHE and Waterpass. The authors thank Dr Ioana Popescu and Dr Solomon Dagachew for their technical support, Dr Eric Mosselman for discussions and Eden Vale Young Associates for obtaining the original data.

REFERENCES

- Asahi K, Shimizu Y, Nelson J and Parker G (2013) Numerical simulation of river meandering with self-evolving banks. *Journal of Geophysical Research: Earth Surface* **118**(4): 2208–2229, <http://dx.doi.org/10.1002/jgrf.20150>.
- Barnes H (1967) *Roughness Characteristics of Natural Channels*. US Geological Survey, Washington, DC, USA, Water supply paper 1849.
- Cain S (2007) *The Irwell Sculpture Trail*. Cain Bio-Engineering Ltd, Breamore, UK.
- Crosato A (1987) Simulation model of meandering processes of rivers. Extended abstracts. *Proceedings of Euromech 215 – Mechanics of Sediment Transport in Fluvial and Marine Environments, Santa Margherita Ligure-Genoa, Italy*, pp. 158–161.
- Crosato A (2007) Effects of smoothing and regridding in numerical meander migration models. *Water Resources Research* **43**(1): W01401, <http://dx.doi.org/10.1029/2006WR005087>.
- Crosato A (2008) *Analysis and Modelling of River Meandering*. PhD thesis, Delft University of Technology. IOS Press, Amsterdam, the Netherlands.
- Crosato A (2009) Physical explanations of variations in river meander migration rates from model comparison. *Earth Surface Processes and Landforms* **34**(15): 2078–2086.
- Dapporto S, Rinaldi M, Casagli N and Vannocci P (2003) Mechanisms of riverbank failure along the Arno River,

- Central Italy. *Earth Surface Processes and Landforms* **28**(12): 1303–1323.
- Duran R (2008) *Bank Erosion Study of a Meandering River Reach. Case Study: River Irwell*. MSc thesis, UNESCO-IHE, Delft, the Netherlands. See www.unesco-ihe.org/library (accessed 03/11/2014).
- Duran R, Beevers L, Crosato A and Wright N (2010) Bank retreat study of a meandering river reach case study: River Irwell. In *Proceedings of the 7th International Symposium on Ecohydraulics, Concepción, Chile*.
- Ellis-Sugai B and Godwin DC (2001) *Going with the Flow, Understanding effects of Land Management on Rivers. Floods, and Floodplains*. Oregon Sea Grant, Oregon State University, Corvallis, OR, USA.
- Ikeda S, Parker G and Sawai K (1981) Bend theory of river meanders. Part 1: linear development. *Journal of Fluid Mechanics* **112**: 363–377.
- Johannesson H and Parker G (1989) Linear theory of river meanders. In *River Meandering, Water Resources Monograph* (Ikeda S and Parker G (eds)). American Geophysical Union, New York, NY, USA, vol. 12, pp. 181–214.
- Johnson PA and Heil TM (1997) Uncertainty in estimating bankfull conditions. *Journal of American Water Resources Association* **32**(6): 1238–1291.
- Kalkwijk JPT and Vriend H (1980) Computation of flow in the shallow river bends. *Journal of Hydraulic Research* **18**(4): 327–342.
- Olesen KW (1987) *Bed Topography in Shallow River Bends*. PhD thesis, Delft University of Technology, the Netherlands.
- Parker G, Wilcock PR, Dietrich WE and Pitlick J (2007) Physical basis for quasi-universal relations describing bankfull hydraulic geometry of single-thread gravel bed rivers. *Journal of Geophysical Research Earth Surface* **112**(F4): F04005.
- Posner AJ and Duan JG (2011) Simulating river meandering processes using stochastic bank erosion coefficient. *Geomorphology* **163–164**: 26–36, <http://dx.doi.org/10.1016/j.geomorph.2011.05.025>.
- Piégay H, Darby S, Mosselman E and Surian N (2005) A review of techniques available for delimiting the erodible river corridor: a sustainable approach to managing bank erosion. *River Research and Applications* **21**: 773–789, <http://dx.doi.org/10.1002/rra.881>.
- Rinaldi M and Casagli N (1999) Stability of streambanks formed in partially saturated soils and effects of negative pore water pressure: the Sieve River (Italy). *Geomorphology* **26**(4): 253–277.
- RRC (River Restoration Centre) (2002) *Manual of River Restoration Techniques, RRC-Web Edition 2002*. See http://www.therrc.co.uk/rrc_manual.php (accessed 08/10/2013).
- Rüther N and Olsen NRB (2007) Modelling free-forming meander evolution in a laboratory channel using three-dimensional computational fluid dynamics. *Geomorphology* **89**: 308–319, <http://dx.doi.org/10.1016/j.geomorph.2006.12.009>.
- Struiksma N and Crosato A (1989) Analysis of a 2D bed topography model for rivers. In *River Meandering, Water Resources Monograph* (Ikeda S and Parker G (eds)). American Geophysical Union, New York, NY, USA, pp. 153–180.
- Struiksma N, Olesen K, Flokstra C and De Vriend H (1985) Bed deformation in curved alluvial channels. *Journal of Hydraulic Research* **23**(1): 57–79.
- Talmon AM, Struiksma N and van Mierlo M (1995) Laboratory measurements of the direction of sediment transport on transverse alluvial-bed slopes. *Journal of Hydraulic Research* **33**(4): 495–517.
- van Balen RT, Kasse C and De Moor J (2008) Impact of groundwater flow on meandering; example from the Geul River, the Netherlands. *Earth Surface Processes and Landforms* **33**(13): 2010–2028, <http://dx.doi.org/10.1002/esp.1651>.
- van Vuren S (2005) *Stochastic Modelling of River Morphodynamic*. PhD thesis, Delft University of Technology. IOS Press, Amsterdam, the Netherlands.
- Walker W, Harremoës P, Rotmans J et al. (2003) Defining uncertainty – a conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment* **4**(1): 5–17.
- Warmink J, Janssen J, Booij M and Krol M (2010) Identification and classification of uncertainties in the application of environmental models. *Environmental Modelling and Software* **25**(12): 1518–1527.
- Williams GP (1978) Bankfull discharge of rivers. *Water Resources Research* **14**(6): 1141–1154.
- Wynn TM, Mostaghimi S and Alphin EF (2004) The effects of vegetation on stream bank erosion. *Proceedings of the Annual Meeting of the American Society of Agricultural and Biological Engineering, St Joseph, MI, USA*, <http://dx.doi.org/10.13031/2013.16423>.
- Zolezzi G and Seminara G (2001) Downstream and upstream influence in river meandering. Part 1. General theory and application to overdeepening. *Journal of Fluid Mechanics* **438**: 183–211.
- Zolezzi G, Luchi R and Tubino M (2012) Modeling morphodynamic processes in meandering rivers with spatial width variations. *Reviews of Geophysics* **50**: RG4005, <http://dx.doi.org/10.1029/2012RG000392>.

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