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Variable input parameter influence on river corridor prediction

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Water Management

Input parameter influence on river corridor predictions

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Variable input parameter influence on river corridor prediction

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Abstract (156 words)

We consider 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 in all cases, the results possess a large degree of uncertainty. The work presented here addresses the 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, etc. The work adopts a probabilistic framework for assessment using Monte Carlo type simulations. The 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. Further 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.

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Notation

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B	is the bankfull width [m]
C	is the Chézy coefficient [$m^{1/2}/s$]
D_{50}	is the mean sediment diameter [mm]
E_u	is the Migration coefficient [-]
E_h	is the Migration coefficient [s^{-1}]
E	is the Calibration coefficient [-]
k_B	is the transverse wave number
H	is the near bank excess flow depth [m]
h_0	is the reach-averaged flow depth [m]
Q	is the bankfull discharge [m^3/s]
U	is the near bank excess flow velocity [m/s]
u_0	is the reach-averaged flow velocity [m/s]
σ	is the Calibration coefficient [-]
α_1	is the 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 (RRC, 2002; Piégay *et al.*, 2005) 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 the erodible river corridor width: 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 characterized 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 the 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 presence of alternate bars, the transverse variations of flow velocity and water depth can be represented by sinusoids having 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

1 variation of bed topography and flow velocity follows a one-dimensional approach. Ikeda et al.
2 (1981) assumed the transverse shift of the channel centreline to be proportional to the near-
3 bank excess of flow velocity with respect to uniform flow, which in presence of alternate bars is
4 represented by the amplitude of the sinusoid. To take into account the long-term effects of bank
5 instability, Crosato (2008) assumed the transverse shift of the channel centreline to be also
6 proportional to the near-bank water depth excess. Meander migration models further assume
7 that the channel width remains constant in space and time, implying that the lateral channel shift
8 is governed by bank erosion and that opposite bank accretion occurs at the same rate. Zolezzi
9 et al. (2012) analysed the effects of channel width variations in phase with the channel
10 curvature and found that width variations enhance the river bed dynamics.
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17 Due to assumptions, simplifications, inevitable empirical and numerical aspects, all model
18 approaches possess a large degree of uncertainty, where model uncertainty is defined as 'any
19 departure from the unachievable ideal of complete determinism' (Walker *et al.*, 2003).
20 Uncertainty is due to the dynamic, stochastic and uncertain nature of river processes (van
21 Vuren, 2005) and to the limitations and assumptions of the method. A degree of uncertainty in
22 model estimates is consequently inherent, which has implications on the usefulness of these
23 predictions to decision makers and designers (Warmink *et al.*, 2010).
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29 In this paper we consider a situation where the migration of a river channel poses a threat to a
30 railway line. In earlier work this situation was studied using a deterministic approach with a two-
31 dimensional model including bank erosion (Duran *et al.* 2009). However, Duran *et al.* found that
32 a much simpler meander migration model (Crosato, 2008) is in fact more suitable for long-term
33 predictions of the river planimetric changes and that due to a lack of formulations for the bank
34 accretion process the 2D model resulted in unrealistic river widening. Here we present work with
35 the same meander migration model. Other advantages of this model are that it requires fewer
36 data, fewer parameters and, most importantly, less computing resource. In fact the latter is
37 several orders of magnitude lower than in the 2D simulations mentioned above. We choose to
38 use this simpler model in a probabilistic framework that allows us to consider a range of values
39 of key parameters that is not possible with the more complex model. In this way the simpler
40 model may in fact give us a greater understanding of the future channel migration. It is this
41 hypothesis that a simpler model used in a probabilistic framework can be more useful than a
42 more complex deterministic model that we seek to test for this particular case study. The work
43 studies the variation in predictions arising from varying the value of the selected parameters
44 within the range of their measured values for future realisations of the river corridor width. The
45 work adopts a probabilistic framework using Monte Carlo type simulations. Both a full Monte
46 Carlo approach using 5000 simulations is presented as well as a shortened version using the
47 Latin hypercube sampling technique of 50 runs. The shortened version is proposed as an
48 alternative method for engineering assessments where time and financial constraints restrict
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1 simulations. We present interesting conclusions, but it is clear that further case studies are
2 required.

3 4 5 **2. Case study: gravel bed meandering River Irwell, UK**

6 The River Irwell has its origin in the Irwell Spring, 427 m above mean sea level (Duran *et al.*,
7 2009). All relevant catchment characteristics are listed in Table 1.

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10 The river reach considered here is located to the east of Rawtenstall, Lancashire (UK) and is
11 about 1.2 km long (Figure 1). Fieldwork undertaken in February 2010 measured the sediment
12 type and river features such as width and depth, while flow data were provided by the
13 Environment Agency. The sampling procedures are explained in Section 4.

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16 In the study area, the river bankfull width varies from 15 to 20.5 m in bends and from 7.5 to 13
17 m in straight reaches (variation through the reach of 7.5-20.5 m). The annual mean discharge,
18 computed from a measured daily discharge time series of 12 years, is 3.17 m³/s and the Q₁₀
19 and Q₉₅ flow values are 7.18 m³/s and 0.68 m³/s, respectively. High flow estimations indicate
20 that the bankfull discharge ranges between 20.5 and 63.3 m³/s. The sediment of the river
21 consists of gravel and sand with median sediment diameter of 7.6 mm.

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

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30 The planimetric changes of this river reach have been previously studied by Duran *et al.* (2009)
31 using the same model, MIANDRAS, which was calibrated and verified on the past river
32 topographic changes. The “optimized” set of parameters and the relative predictions are used
33 as the baseline for the present study (Table 2). The values of calibration coefficients are listed in
34 Table 3. The calibrated migration coefficients are variable along the river course and for the left
35 and right banks, due to the presence of bank protection works and trees (Table 3). The
36 calibration procedure is based on the assumption that the spatially variable channel migration
37 coefficients derived on historical river evolution remain the same in the future. In the traditional
38 deterministic manner, this baseline model would be used to simulate future scenarios, assuming
39 a representative set of environmental variables. This work proposes an extension to standard
40 deterministic techniques, which incorporates the natural variability in environmental variables, in
41 order to predict probable likely locations for river corridor locations in the future.

42 43 44 **3. Channel Migration Model**

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

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12 The mathematical model that is adopted in this study, MIANDRAS (Crosato 1987, 2008 and
13 2009), computes the longitudinal profiles of the near-bank excesses of flow velocity and water
14 depth, named U and H respectively, with respect to the reach-averaged values, u_0 and h_0
15 (Figure 4). These excesses are caused by the local channel curvature and by upstream
16 geometrical discontinuities, such as a change of channel curvature (bend entrance and exit),
17 which, under certain conditions lead to the formation of steady alternate bars in the river
18 channel (Struiksma *et al.* 1985). The long-term local bank erosion rate is assumed to be a
19 function of both U and H . The excess velocity, U , accounts for the effects of fluvial erosion,
20 driven by the local flow velocity (Ikeda *et al.* 1981). The excess water depth, H , accounts for
21 geotechnical instability, which is based on the consideration that bank instability increases with
22 erosion at the toe of the bank (higher near-bank water depth). This effect becomes relevant with
23 vertical cohesive banks. The transverse profiles of water depth and velocity are assumed to be
24 perfectly point-symmetrical with respect to the channel centreline (Figures 2 and 3), which
25 implies that the bank accretion rate equals the bank erosion rate at the opposite side and that
26 the river width remains constant.

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

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

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

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:

$$\lambda_w = \frac{C^2 h_0}{2g} \quad (2)$$

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

$$\gamma = \frac{B}{R} \quad (3)$$

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 the secondary flow momentum convection (Struiksmá 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 linearized sediment transport and sediment balance equations:

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

Where the parameter k_B is the transverse wave number of the velocity and water depth perturbations, given by the expression:

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

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:

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

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

$$f(\theta_0) = \frac{0.85}{E} \sqrt{\theta_0} \quad (7)$$

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

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

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

In Equation 4, b represents the degree of non linearity in the dependence of sediment transport on the flow velocity, whereas A is the coefficient accounting for the effects of the curvature-induced spiral flow on the bed shear stress direction, given by Olesen (1987).

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

$$\frac{\partial n}{\partial t} = E_u U + E_h H \quad (8)$$

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 the 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

1 effects on U and H of the downstream part of the channel in two ways: in the number of points
2 along the channel axis that are used to compute the local curvature (Crosato, 2008) and in the
3 numerical discretization of the equations, which is done by using the explicit Runge-Kutta
4 method for 1st and 2nd order differential equations. A full model description can be found in
5 Crosato (1987, 2007, 2008 and 2009).
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9 For long-term simulations undertaken in this paper, approximations using the bankfull, or bank-
10 forming discharge, following the method first proposed by Ikeda *et al.* (1981), are used.
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13 **4. Methodology**

14 The current work applies the described meander migration model MIANDRAS, within a
15 probabilistic framework with the purpose of providing a greater understanding of the future
16 channel migration. We consider a range of values of key parameters to understand the
17 influence of the uncertainty of these parameters on river corridor width predictions to assess the
18 possible future channel locations of the River Irwell (UK).
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24 The key parameters varied within the framework represent the initial environmental conditions,
25 and tend to be sampled from the studied reach. Consequently, the variability captured during
26 the sampling process can influence both the input and the output of the modelling process. The
27 selected parameters define the general characteristics of the river reach, such as the reach-
28 averaged main channel width, the sediment median diameter, the bankfull discharge and the
29 roughness coefficient and are represented by a single (reach-averaged) value in meander
30 migration models, such as Johannesson and Parker's (1989) and MIANDRAS. These
31 parameters are often derived from field measurements and then adjusted during model
32 calibration. For this, it is usually assumed that the calibrated model already includes the effects
33 of their uncertain values. However, since morphodynamic models are calibrated on past
34 conditions, their predictions still remain uncertain. Consequently, model performance is usually
35 validated by simulating another historical period for which data are available, without changing
36 the values of the parameters. The comparison between measured and predicted conditions
37 provides insight into the uncertainty associated with the model predictions, but this is strictly
38 only applicable for the validation period. It is impossible to do the same for future predictions,
39 which remain inherently uncertain.
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50 The input variables and model parameters that are required by the adopted model, apart from
51 the initial channel alignment and valley slope, are:
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- 54 • bankfull discharge (Q), bankfull width (B), bankfull Chézy coefficient (C), median
55 sediment grain size (D_{50}),
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- 58 • migration coefficients E_h and E_u and
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- calibration parameters σ , E and α_I .

The spatially variable migration coefficients are derived from calibration on past planimetric changes. These are bulk parameters that include the effects of bank material, riparian vegetation (Wynn *et al.*, 2004), pore water pressure (Dapporto *et al.*, 2003; Rinaldi and Casagli, 1999), ground water flow (van Balen *et al.* 2008), and numerical aspects, such as the choice of how to compute the local channel curvature, numerical smoothing filters, 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.* (2009), which was carried out on the channel alignments 2003, 2006 and 2007. The same applies for the other calibration parameters, σ , E , 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 Irwell River, this occurs downstream of river bends. Increasing the value of E_h leads to higher bank erosion rates where the near-bank water depth excess, H , is the highest, at the location of the pools opposite of 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, etc. Moreover, the effects of uncertainties related to randomly varying bank erodibility have been already investigated in previous studies (e.g. Posner and Duan, 2011). The variation of the value of the migration coefficients (in a reasonable range for this river), as well as of the other calibration coefficients does not change the main outcomes of the analysis, focusing on the effects of varying the value 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 sets out the experimental methodology undertaken. To understand and capture the variability in the environmental conditions in the study reach required by the model a period of fieldwork was undertaken in February 2010. The sampled data was gathered and represented as probability distribution functions (PDF) for the basis for the probabilistic assessment, where both standard Monte Carlo (full analysis) and Latin Hypercube sampling 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 spans 12 years (21/01/1996 to 14/02/2007, source: Environment Agency, UK) and consists of 15 minute time series. The bankfull discharge, Q , was estimated on flow recurrence. It is generally accepted that the 1.5, 2 or 5 year recurrence flood represents the bankfull discharge of a river (Williams, 1978; Johnson and Heil, 1997, Parker *et al.* 2007). Site observations on maximum bar height, active flood plain, height of valley flat, 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 and 5 year recurrence interval were used to establish the Probability Density Function (PDF) (Figure 4). The 1.5 year and the 5 year recurrence flow estimated for the Irwell Vale station are 21 m³/s and 57 m³/s, respectively.

4.2 Median Sediment Size

Sediment samples were collected from the study area during a 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} , ranges 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 ranged between 7.5 and 20.5 m with a mean value of 12.2 m (Figure 4).

4.4 Chézy Coefficient

The hydraulic roughness of the River Irwell reach under study was estimated by matching 24 recent photos of the 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. The results gave a mean Chézy coefficient of 24.6 m^{1/2}/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 bankfull hydraulic geometry of single-

1 thread gravel-bed rivers (like the Irwell) developed by Parker *et al.* (2007). This relation relates
2 the three parameters B , Q and D_{50} to each-other:
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$$5 \quad B = \frac{4.63}{g^{1/5}} Q^{0.4} \left(\frac{Q}{\sqrt{gD_{50}^2}} \right)^{0.0667} \quad (9)$$

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10 The check whether a set of parameters could be considered a realistic combination for a river
11 like the Irwell was based on the application of Eq. 9. If the randomly generated value of bankfull
12 width, B , deviated more than 65 %, from the result of Equation 9, the parameter set was
13 assumed to be unrealistic and was not used to run the meander migration model.
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18 It should be noted that whilst some uncertainty is estimated from temporal variations (i.e.
19 discharge) for others a longitudinal variation is used (i.e. width). These estimates have to be
20 made from the data that are available. The temporal variation in average width would be a
21 good estimate, but as this was not available the longitudinal variation was an acceptable
22 alternative. This issue is encountered whether we use a simple model in a probabilistic
23 framework or a few runs of a more complex model.
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29 **4.6 Prediction of future planimetric evolution and representation of probabilistic outputs**

30 The model was used to simulate the future planimetric evolution of the Irwell River over the next
31 50 years, starting from the 2007 channel alignment (Figure 5). The duration of the simulation
32 period was chosen to establish the uncertainty extent of river corridor width estimates over an
33 indicative period of time considered to be useful for engineering interventions.
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38 For the standard Monte Carlo analysis 5000 model simulations were undertaken. A second
39 shortened analysis used Latin hypercube sampling. The probability distributions were divided
40 into 50 non-overlapping equal-probability intervals, which were then sampled. The subsequent
41 parameters were then combined to create complete sets.
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46 The model outputs take the form of future bank lines and centre line coordinates as well as
47 longitudinal and transverse bed level profiles. A raster-based analysis was devised to map all
48 river alignments and derive useful and applicable information from the outputs.
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52 **5. Results and discussion**

53 The results of the probabilistic modelling for future river corridor positions are shown in Figures
54 6 and 7 and Table 4. Variations in predicted river corridor width vary along the study reach for
55 each given confidence level. For the full assessment the river corridor width at 95% confidence
56 level averaged over the study reach is 50.8 m with minimum and maximum predictions of 22.4
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1 and 75.5 m, respectively. For the shortened assessment the reach averaged values were 33.3
2 m with maximum and minimums of 42.2 m and 19.2 m, respectively.
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5 Figure 6 and 7 shows the area in which the future river corridor may be located, using both the
6 full and shortened probabilistic framework proposed. A deterministic run of the model using a
7 representative set of environmental variables is captured within the result set presented under
8 the 76-95%ile corridor. Standard 25% changes to parameters within a sensitivity study
9 approach results in variations of results of up to 24 m in particular locations around the meander
10 bends. In comparison it is clear that using the probabilistic framework adds information to these
11 results and provides a reasonably wide erodible corridor at some locations. The variation in
12 predictions provided by the probabilistic framework adds information to those interested in
13 managing the river corridor and any associated infrastructure, by indicating zones of river
14 migration. This is a departure from the deterministic approach which provides only single
15 realisations for a future river position, and provides more information than a straight sensitivity
16 study as zones of potential erosion can be determined. These predicted zones could be used
17 to inform land use plans and infrastructure design in the river corridor.
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26 Looking at the results in more detail and focusing first on the full analyses, if local differences in
27 migration coefficients are accounted for, and in particular if some bank stretches are protected
28 or naturally non-erodible, smaller differences between the confidence levels are expected.
29 Special attention should be paid, however, to river banks close to bank protected areas, since
30 these areas are often characterized by higher bank erosion rates (Crosato, 2008; Duran *et al.*,
31 2009). In the study area the lateral extension of river meanders is relatively small, as is the river
32 sinuosity. For river reaches with higher sinuosity higher bank erosion rates, and hence larger
33 differences between confidence levels, are expected. Further case studies would substantiate
34 these hypotheses.
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41 Figure 6 demonstrates the spatial variation of the erodible river corridor width which increases
42 depending on the confidence interval required, and varies along the study reach depending
43 upon the morphological conditions and specific location. It is clear that the variation in model
44 inputs based on the natural variability in the study reach significantly impacts the outcome of the
45 meander model simulations and hence the prediction of the erodible corridor width. The results
46 of the analysis indicate the need to incorporate an estimate of environmental variability into
47 erodible corridor predictions within a probabilistic framework, to capture the true potential extent
48 of the erodible corridor width. Presenting the results in this format would allow river managers a
49 greater insight into probable river corridor widths and inform decisions on development within
50 likely erosion areas as well as potential river restoration designs.
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58 The error in terms of new channel alignment given by the application of meander migration
59 models, increases with the time span of the prediction or simulation. This should be taken into
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1 account when applying meander migration models in particular and any morphodynamic models
2 in general.
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5 If Figures and 6 and 7 are compared, it is clear that the shortened analysis using the Latin
6 hypercube sampling technique does not capture the full extent of the potential river corridor. In
7 some areas the results of the analysis are similar, where the meander potential is less, however
8 at the bend locations significant discrepancies can be observed between methods. The
9 shortened method, despite underestimating variability, does provide a useful insight into the
10 potential corridor migration, which is a considerable improvement over deterministic
11 assessments. In situations where simulations are constrained by time or finance then this
12 method does offer a feasible option for incorporating probabilistic methods into analyses, but
13 users should be realise that for projects with higher risk the full method may be more advisable.
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20 Capturing external variability and uncertainty, such as the influence of climate variability would
21 add a further dimension to this work. In this case, this would be undertaken by estimating the
22 influence of potential climate variability upon the bankfull discharge prediction. Then further
23 probabilistic modelling would be undertaken to investigate the influence these changes may
24 have.
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29 These results indicate that there is a need to understand the influence of the variability of input
30 parameters on morphological simulation modelling. Further, there may be a need to expand
31 this framework to understand other forms of uncertainty on model prediction such as model
32 structure, numerical methodology, or numerical parameters. Expanding the framework in such
33 a way would allow for a fuller uncertainty analysis.
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38 **6. Conclusions**

39 This work deals with the use of a meandering migration model to assess the erodible corridor
40 width of the meandering River Irwell (UK). It uses this simpler model in a probabilistic
41 framework to investigate whether greater understanding of the future channel migration can be
42 achieved with this method than through deterministic approaches. The work focuses on
43 understanding the influence that the variability in input parameters describing channel
44 geometry, water flow and sediment transport has on model predictions.
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50 Results from both the full Monte Carlo analysis and the shortened analysis indicate that
51 significant spatial variability can be observed in the predicted future erodible river corridor width.
52 This provides a greater insight into the potential extent of the future river corridor width than
53 provided with single deterministic model outputs, and delineates river corridor zones for
54 developers and managers.
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1 The variability predicted is a function of the characteristics of this particular location, and
2 different study areas would demonstrate different degrees of variability, however what is clear is
3 that the natural environmental variation captured through field studies influences the potential
4 location of the future river channel, and this information is not captured through deterministic
5 approaches. Probabilistic approaches can provide this greater understanding, but do require
6 more simplistic migration models to be employed to keep computer resource requirements at a
7 practical level. Despite the full analysis indicating a greater corridor width, the shortened
8 method captures some of the corridor variability predicted, and offers a viable option when
9 constraints prevent full probabilistic analyses.
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15 Results, such as those presented, indicating potential erodible river corridor widths, with
16 confidence limits, would be of use to those responsible for developing or managing river
17 corridors, and report variability in a meaningful way. Understanding the variance in future
18 potential river movements over time are important inputs to river restoration and re-
19 naturalisation projects.
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24
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27 support, Dr. Eric Mosselman for the discussions and Eden Vale Young Associates for obtaining
28 the original data.
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45 **Figure captions (images as individual files separate to your MS Word text file).**

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48 Figure 1 Study area.

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

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

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56 Figure 4 Research methodology

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58 Figure 5 River alignment (2007)

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60 Figure 6 Probability of an area belonging to the erodible river corridor (full analysis).
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Figure 7 Probability of an area belonging to the erodible river corridor (shortened analysis).

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Table 1 River Irwell catchment characteristics in the study area.

Catchment attribute	Unit	Mean value	Range
Catchment area	km^2	101.0	-
Annual average rainfall	mm	1393.0	-
Mean discharge Q_{mean}	m^3/s	3.17	
^{1*} Q_{95}	m^3/s	0.68	
^{2*} Q_{10}	m^3/s	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

* Source: Environment Agency.¹ 95% of recorded flows higher. ²10% of recorded flows higher

Table 2 Reference characteristics of the study reach (Duran et al., 2009).

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

Calibrated coefficients	Base case	Banks fixed	Vegetated banks	Railway embankment
Migration coefficient E_u	1.0E-5	0.0	5.0E-6	5.0E-7
Migration coefficient E_h	2.0E-5	0.0	1.0E-5	1.0E-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 4 Erodible river corridor width (*m*) estimates

Chainage	Probabilistic analysis	50% confidence		75% confidence		95% confidence	
		Full	Short	Full	Short	Full	Short
200*		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

* Sampling grid neglects boundary effect

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Figure 1 Study area.

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 cross-sectionally averaged velocity and water depth; U and H are near-bank excesses of velocity and water depth).

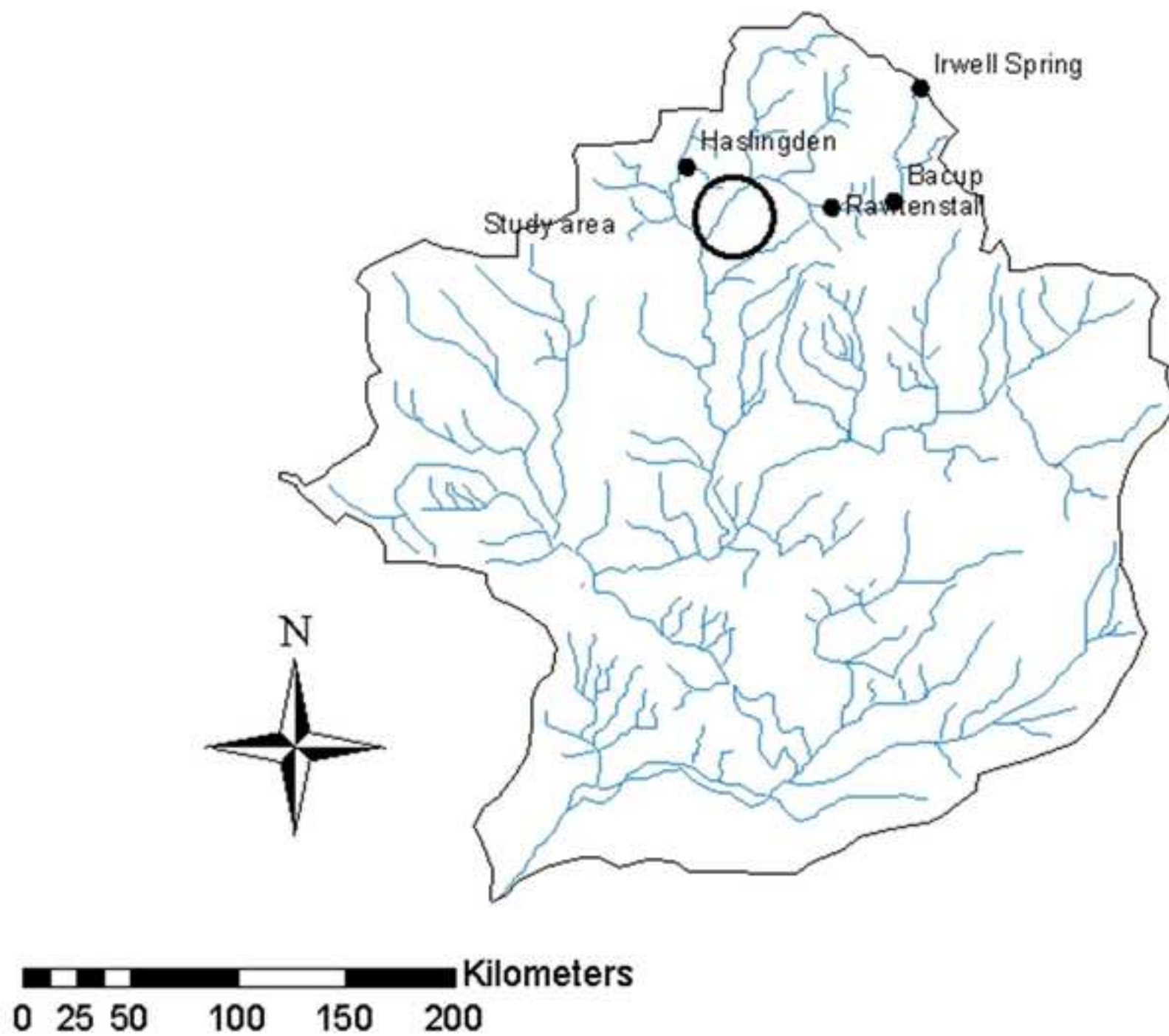
Figure 4 Research methodology.

Figure 5 River alignment (2007).

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).

Figure1
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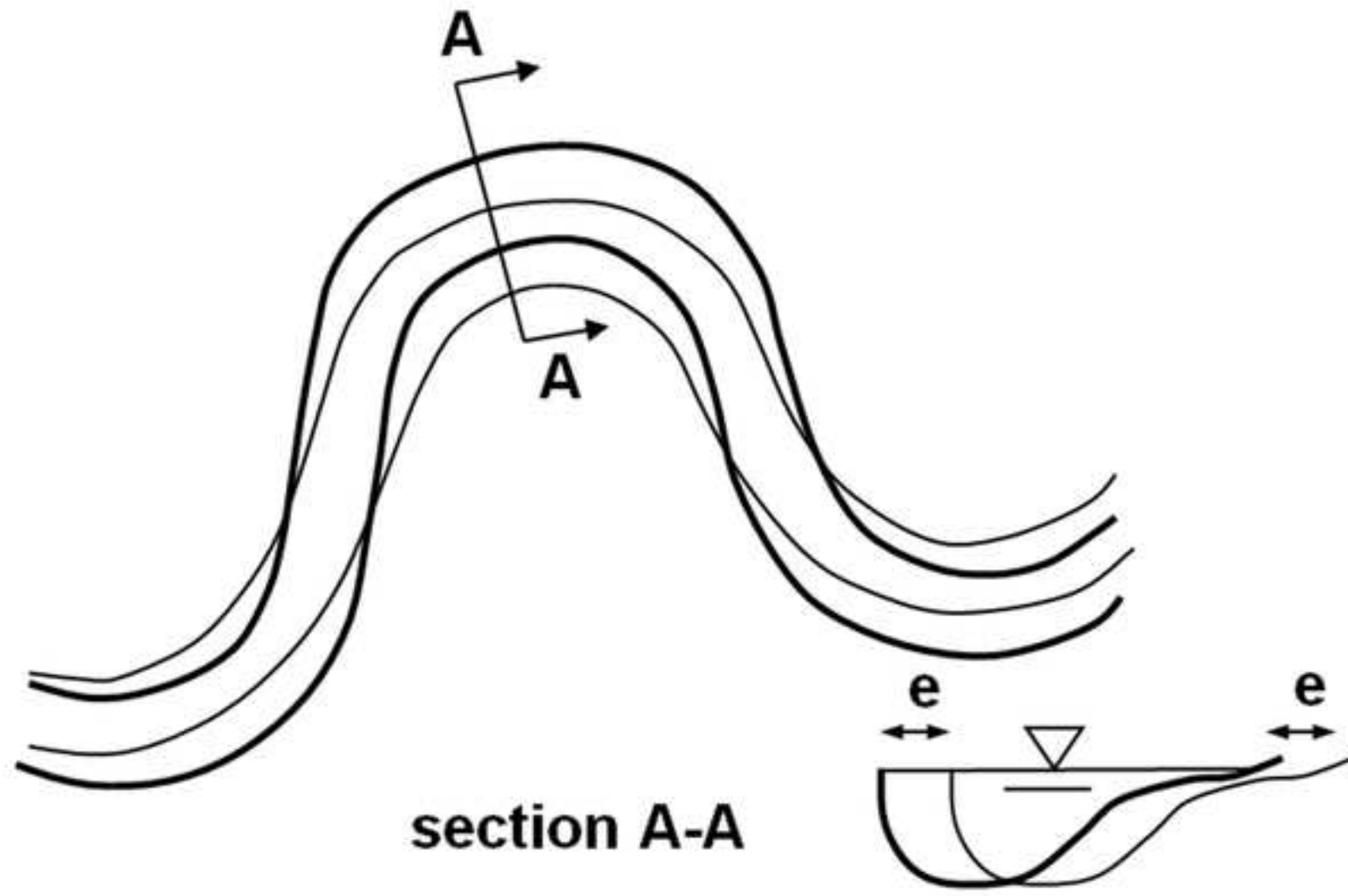


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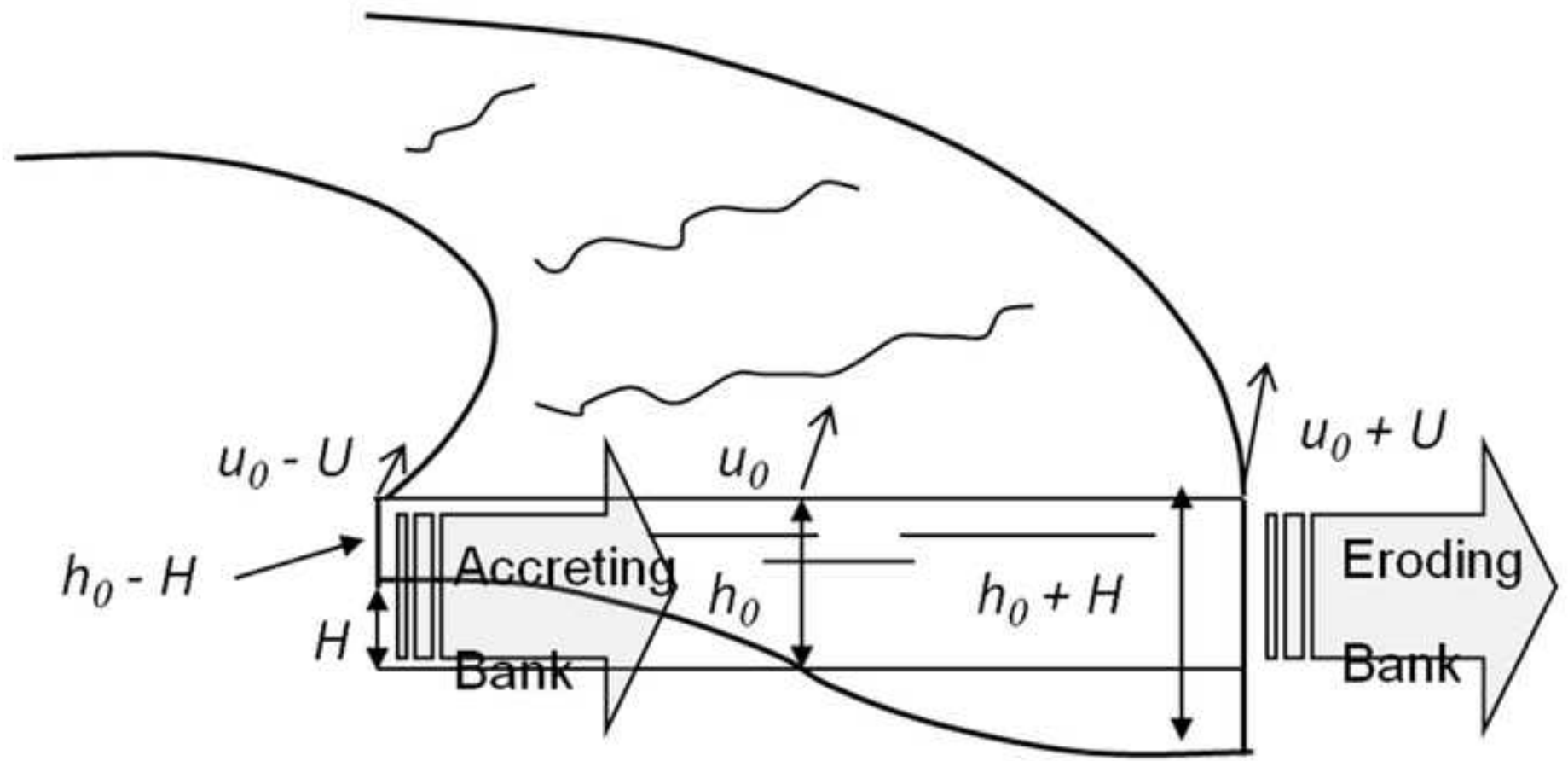


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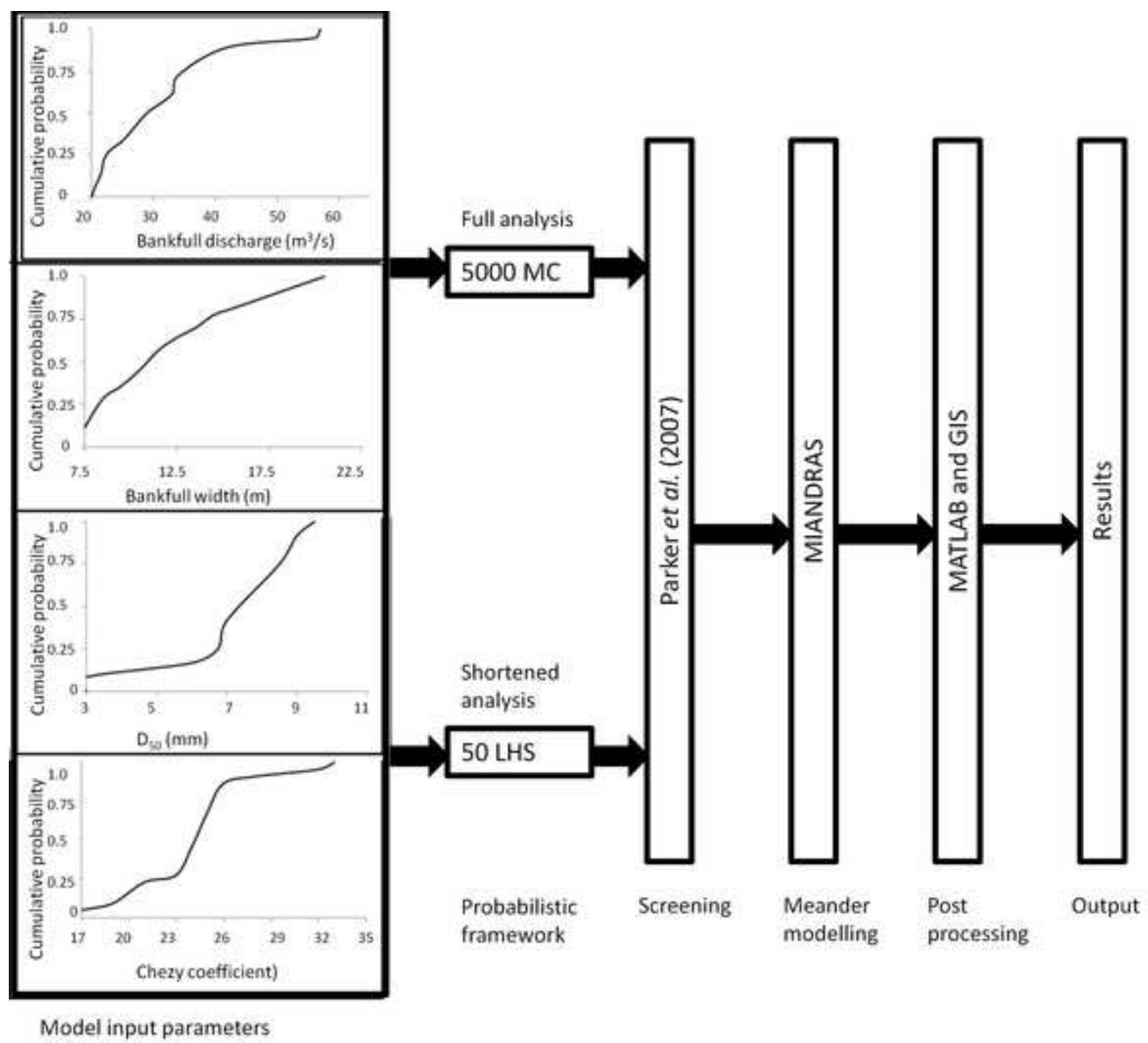


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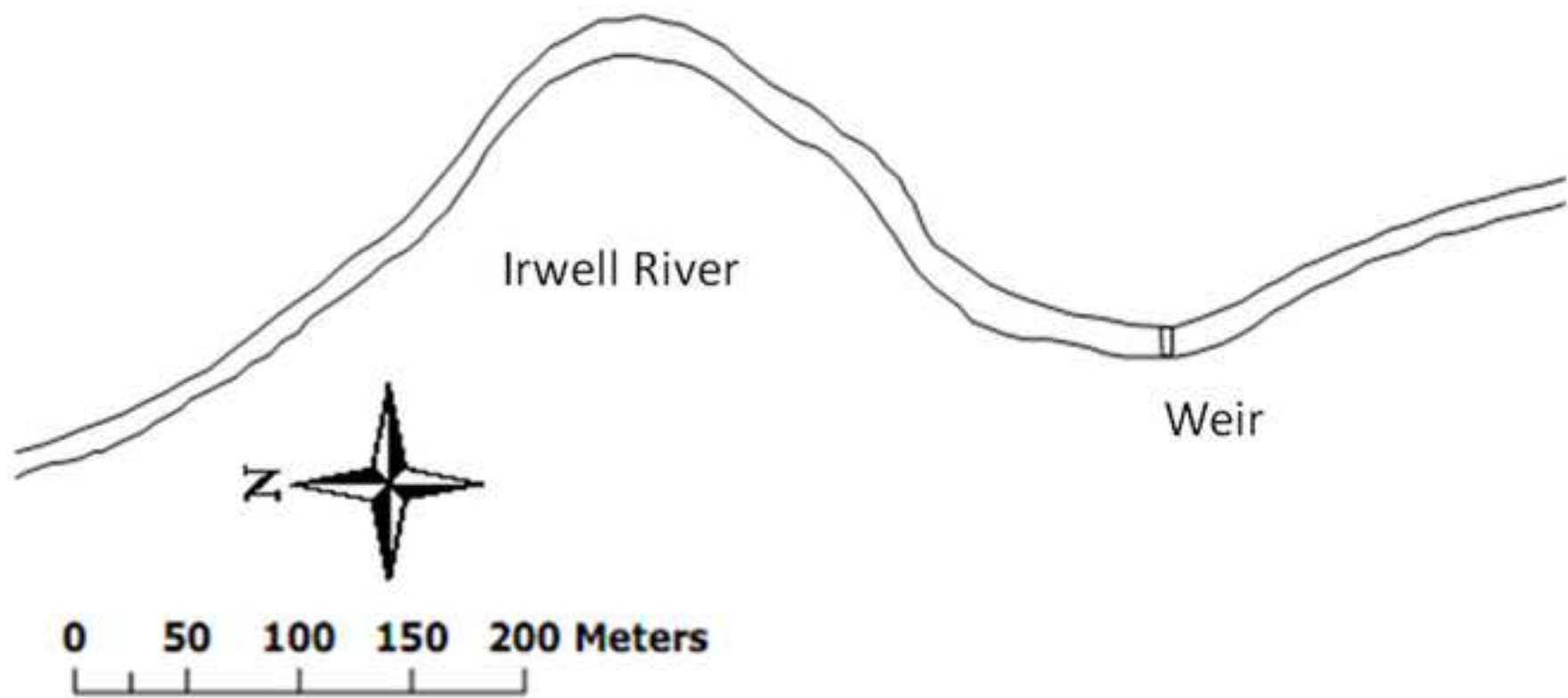


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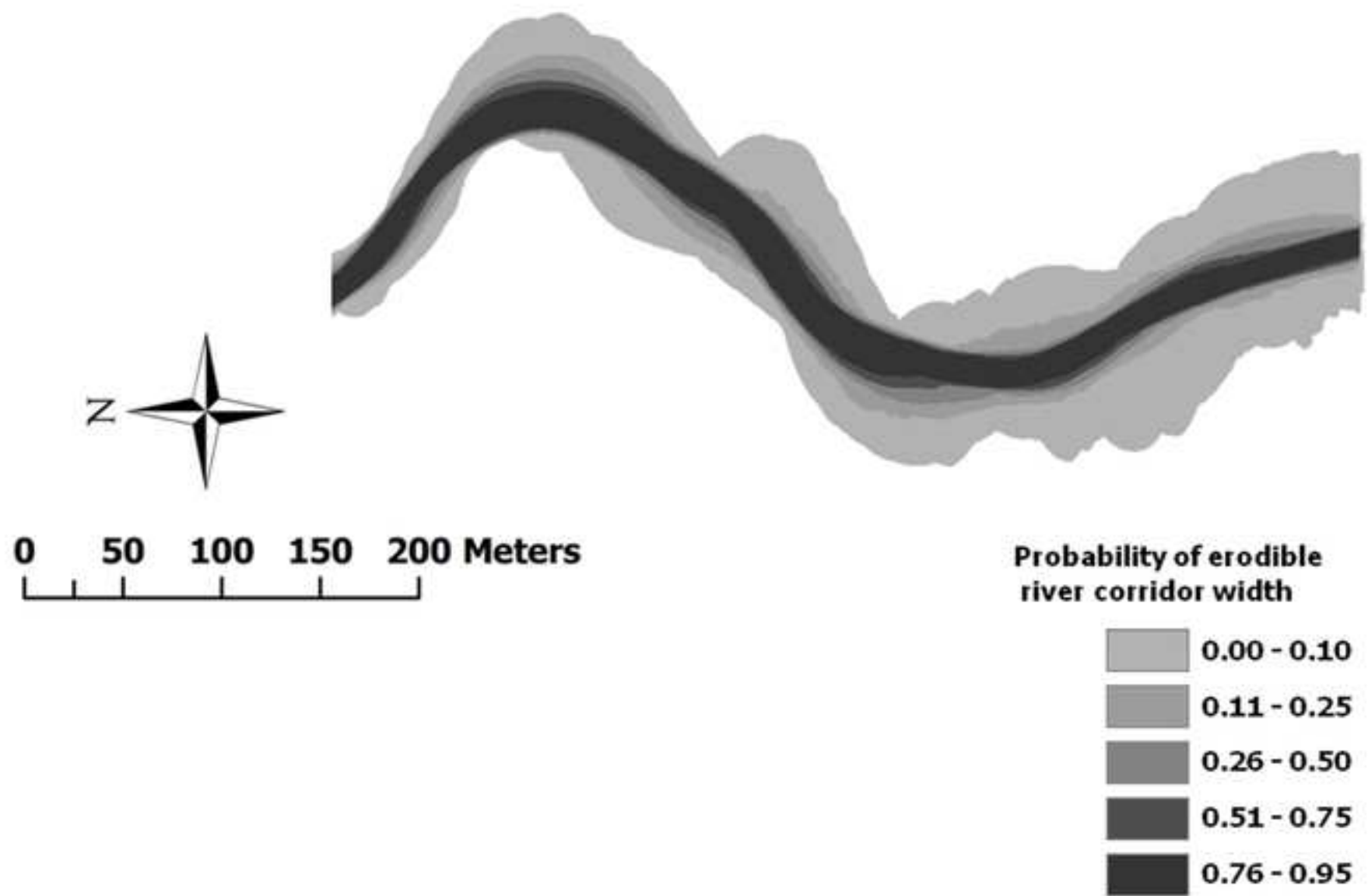
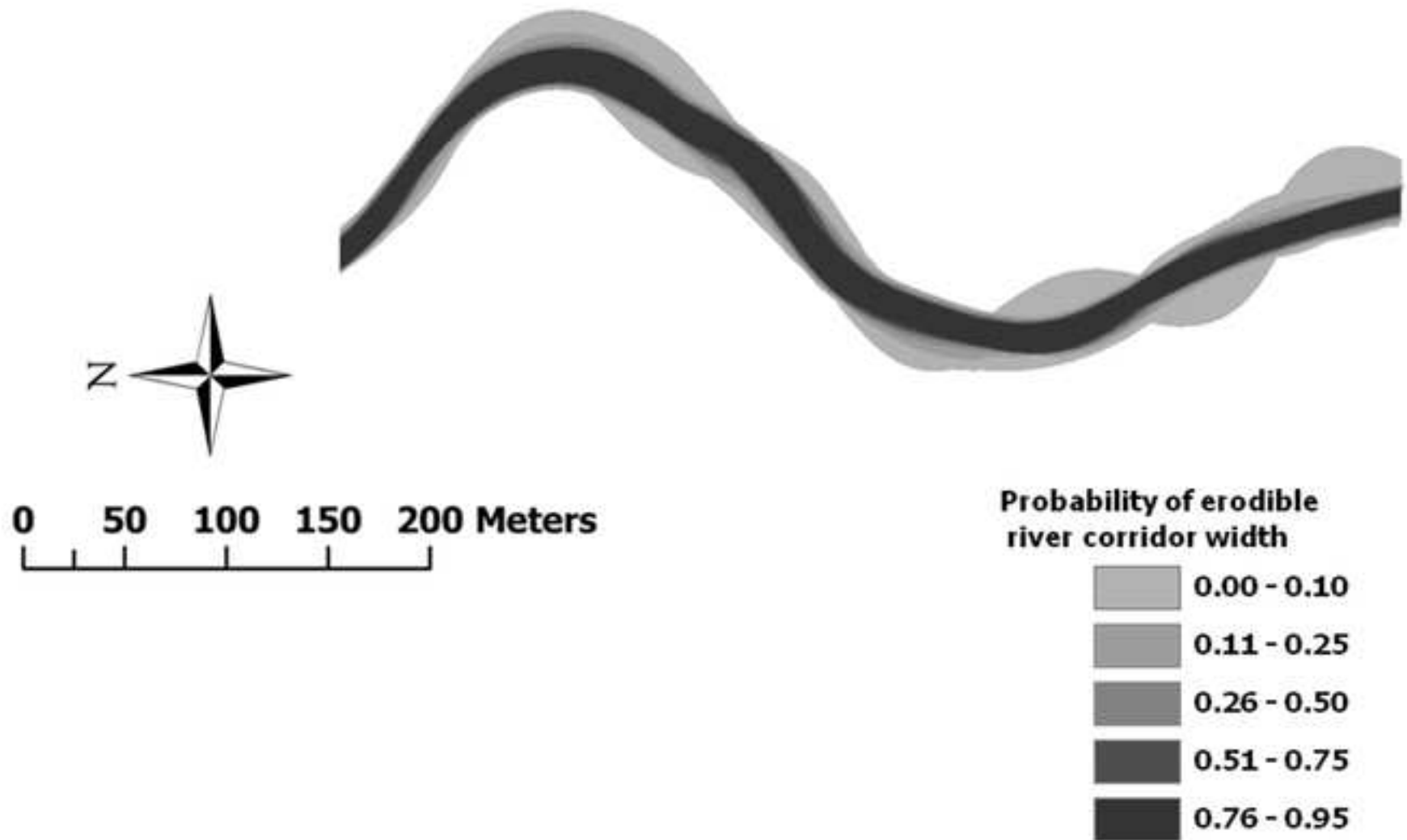


Figure7

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Heriot Watt University
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Riccarton
Edinburgh
EH14 4AS

23rd September 2014

Water Management

To whom it may concern:

Subject: Post review: Research paper - Influence of variable input parameters on river corridor width predictions

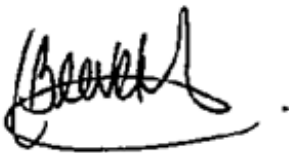
Dear Editor:

We are pleased to submit the following research paper with the necessary minor revisions following review "*Influence of variable input parameters on river corridor predictions*" (short title '*Input parameter influence on river corridor predictions*') to Water Management for your consideration for publication.

We would like to thank the reviewers and the Editor for their constructive comments which we have now responded to. Details of the manuscript revision can be found in Appendix A to this letter where each update has been described and justified. We believe that this has resulted in an improvement to the submitted manuscript.

Thank you in advance for your consideration and we look forward to hearing from you.

Yours faithfully,

A handwritten signature in black ink, appearing to read 'Lindsay Beevers', followed by a period.

Lindsay Beevers (on behalf of all authors)

Appendix A

Title: Input parameter influence on river corridor predictions

Article number: WATER-D-13-00114

Minor comments as indicated below ie:

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