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BANK RETREAT STUDY OF A MEANDERING RIVER REACH CASE STUDY: RIVER IRWELL

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ABSTRACT

Lack of data is often considered a limitation when undertaking morphological studies. This research deals with morphological studies of small rivers experiencing bank erosion processes when only limited data are available. A reach of the meandering gravel-bed river Irwell (United Kingdom) is taken as a case study in order to analyze the bank retreat process that is endangering the stability of structures located in the area.

Two models of different complexity are applied. The first is a physic-based one-line meander model, computing bed topography, flow field and migration rate of meandering rivers in areas with non-uniform erodibility. The second is a 2D physic-based morphological model with a simplified bank erosion formulation. The model predictions show that the morphological development of the river may endanger the existing structures within the next five years, if no mitigation works are carried out.

The simple meander model produces satisfactory results in much less time using less data. Moreover it allows taking into account the effect of riparian trees and soil heterogeneity on bank erosion. Besides, the simple meander model appears appropriate for probabilistic analysis of future river migration trends. A particular application of this analysis is the study of climate change effects. The probabilistic analysis will be done in a second phase of the study.

KEYWORDS: meandering river, bank erosion, morphodynamics

INTRODUCTION

Unstable meandering rivers are dynamic features of the landscape. Erosion and accretion processes that take place in meandering rivers result in bend growth and channel migration (Luna et al., 1957) [6]. These morphological changes are often source of damage to infrastructure and in general, disturb the human activities. In order to prevent these problems, morphodynamic study based on river modeling is needed. However, the lack of data is often considered a limitation at the moment of undertaking this type of studies because some of the existing computational codes require more data than the available.

The objective of this study is to determine a convenient type of modeling to assess future river migration trends of small meandering rivers with scarce available data. The study will be done by comparing two models of different complexity. The first model is a one-line meander migration model (Crosato, 1990, 2007) [2], and the second model is a 2D morphological model with simplified bank erosion calculation method (Lesser et al., 2004) [6]. For this purpose, a reach of the meandering gravel-bed river Irwell, in the United Kingdom, is taken as a study case in order to analyze the bank retreat process that is endangering the stability of structures located in the area.

MATERIAL AND METHODS

Several models have been developed to describe the interaction between flow, sediment transport, grain-size sorting, and bed topography, most of them achieving undoubted progress. Each of these models approach is founded on certain assumptions that restrict its applicability e.g. models that assume river banks are non-erodible would be expected to over-predict the depth of pools (Thorne, 1992) [11]. On the other hand, many practical options to model bank erosion with a numerical approach have been developed. Simple methods can be used to model bank retreat rate as long as the details of the erosion process are not the main interest of the study.

Two models of different complexity are built for a small meandering river in order to determine which one is more convenient to assess future river migration trends: The first is a physic-based one-line meander model and a complex 2D model. The models are first calibrated on the period 2003-2006 and thereafter, they are used to simulate the future river changes for the period 2006-2010.

One-line meander model

The model combines a steady-state model for water flow and bed topography with a time-dependent river migration model, which computes the bank retreat rates as a function of near-bank hydraulic and morphological properties. Bank advance rate is considered in a simplified way, assuming that it is equal to the bank retreat rate at the other side of the river. To describe the bed topography, the flow equations are coupled to sediment transport and sediment balance equations and consider as well the secondary flow momentum convection in river bends.

The model describing flow and bed topography is a linear version of the more complex non-linear model developed by Koch and Flokstra (1980) [5] and Struiksma et al. (1985)[10] for curved channels valid for small to moderate Froude number.

The bank retreat rate is assumed proportional to the near bank tangential velocity excess and to the near bank water depth excess. The excess velocity term accounts for the effects of fluvial erosion at the toe of the bank and the excess water depth term accounts for geomechanical instability.

2D Model

The 2D morphological model (Lesser et al., 2004) [6] is based on the continuity and momentum equations for water, coupled to the balance and transport equations for sediment, designed for curved channels. In the equations, the sediment transport direction is corrected to take into account the transverse bed slope and the spiral flow in river bends (Struiksma et al., 1985) [10], whereas the spiral flow itself is reproduced in a parameterized way (Blanckaert and Vriend, 2003) [1].

Bank retreat is treated in a simplified way using the dry-wet cell method by Van der Wegen et al. (2008) [12] and Roelvink, et al. (2006) [9]. This method assumes that every time step the erosion of a wet cell, which is determined by the speed at which the eroded material is removed, is fully or partially assigned to the adjacent dry cell according to a calibration factor. This bank erosion formulation allows imposing a constant bank slope to the entire model domain.

Study area description

The study area is located east of Rawtenstall, Lancashire, United Kingdom. The River Irwell has its origin in the Irwell spring, 427 m above the mean sea level and the total area of the river basin contributing to the study reach is 120.7 Km^2. At the study reach the Irwell shows a meandering planform with fixed banks at the upstream and downstream boundaries. The migration of the river may endanger the stability of the existing structures: a weir, the A56 motorway bridge and the railway embankment. The main river characteristics are listed in Table 1.

Table 1 Main characteristics of the study reach

Length of the study reach (Km)	1.00
Width (m)	11.80
Slope (%)	0.53
Annual mean discharge year 2006 (m^3/s)	3.50
Higher observed discharge between 1996 and 2006 (m^3/s)	53.00
Sediment type	Gravel
Characteristic grain size D_{50} (mm)	11.20
Grain size D_{90} (mm)	30.50

Field survey

A field survey was carried out in order to obtain more information about the river. This information was later used in the model set up and calibration. Structures such as weirs and areas with river bank protection were identified and included in the model set up. Location of areas with erosion and accretion processes as well as existing bars were mapped and later used to calibrate the model. Also a sediment sample was taken to determine the characteristic grain size which was used in the model set up.

Available data

Topography

Two sources of bed topography data are available: (i) Cross sections extracted from an existing flow model developed within the Strategic Flood Risk Management Framework (SFRMF), and (ii) LiDAR data, both of them property of The Environment Agency.

The data extracted from the SFRMF model consists of ten cross sections along the whole river stretch that is about 800m long. The distance between cross sections is almost 90m which is not sufficient to reconstruct neither the river alignment nor the bed topography. Consequently, this information was not used to build the morphological model. However some of the cross sections were used to check bed levels of the LiDAR topography.

The light detection and ranging (LIDAR) data has a resolution of 2m and the flown date is April 2003, both characteristics make this data set suitable for building the model. Since the LIDAR technology uses pulses of laser light that strike the surfaces of the earth and measure the time of pulse return, a review of the main channel topography is needed because the laser light may strike the water surface instead of the river bed. Some of the SFRMF model cross sections are used to check and correct the main channel topography of the LIDAR data.

Historic river configuration

The historical river configuration data consists of old maps, aerial photographs or satellite images that reveal the changes of the river morphology during the past years. This information is needed to calibrate and validate the model; therefore, it should be subsequent to the topographical information used to build the model. The available information comprises a satellite image, dated to June 2006 (source: Google Earth), and a set of photographs of year 2007. The latter is a good reference to estimate bank erosion rates and identify medium to large morphological changes. However, photographs do not provide precise or quantitative information.

Hydrology

The main source of hydrological data is the Irwell vale gauging station where the data available comprises discharges measured every 15 minutes. The measured discharges correspond to the river Irwell plus inflows from river Ogden that have to be subtracted since it flows into the river Irwell downstream of the study reach. The discharge corresponding to the river Irwell is estimated as 75% of the total discharge at Irwell Vale. A second source of information is the existing flow model developed within the SFRMF which provides water levels at ten cross sections along the study area. This information is used to calibrate the model developed for this study.

From the ten cross sections of the SFRMF model, considering a Chezy roughness coefficient of 22.53 $m^{1/2}/s$ and using a mean slope of 0.0053, the bank-full discharge was calculated to be 45 m^3/s.

Sediment

The particle size of the bed material varies considerably in a lateral direction and along the river. For these reason, it is desirable to have several samples from the main channel and from point bars along the river. However, for the case study only one sediment distribution curve is available, that corresponds to a sample taken at a point bar. This sample only comprises the gravel and sand phases, while, the sediment in the area contains also cobbles and boulders. The sediment characteristic sizes are shown in Table 1. The Meyer-Peter and Muller (1948) [8] formula was used to calculate the sediment transport capacity of the river.

RESULTS

Model calibration

The models have been calibrated on the period 2003 to 2006. The results of calibration describe the predicted river alignment and bed topography in 2006 which are compared with the available river configuration information for the same year. Computed River alignment and bed topography are shown in Figures 1 and 2.

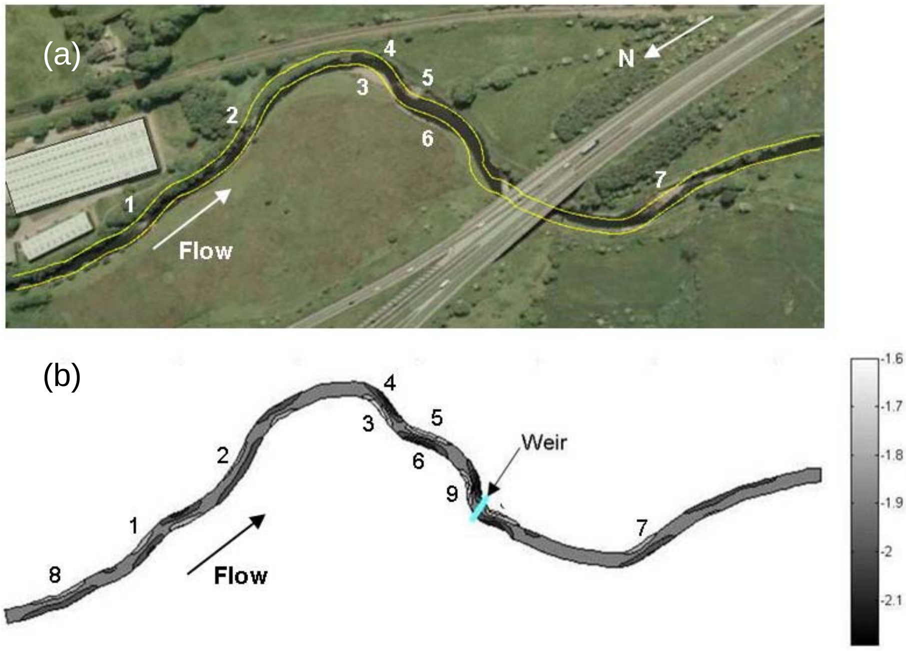

Figure 1. Calibrated one-line meander model. (a) River alignment (b) Bed topography.

River alignment

The results of the one-line meander model are satisfactory (Figure 1) because they match both bed topography, in terms of location of point bars and pools, and river alignment. Use of lower erodibility coefficients in areas with herbaceous vegetation and in the railway embankment contributed to better simulate the river behavior (Gray and Mac Donald, 1989) [4].

The numerical approach that simulates bank erosion in the 2D Model is based on the distribution of the erosion between the source wet cell and the adjacent dry cell. Due to the grid resolution, of about 1m by 1m, the resulting erosion rate is also 1m, where bank erosion rate is estimated to be 0.60 m/year. Therefore, a distortion of the process is introduced. Better results are expected from a finer grid size; however, this would require the reduction of the time step and increase of the cell number, increasing the computational time. Furthermore, in the 2D model the river becomes wider (Figure 2) because the bank advance process is not taken into account and because the dry wet cell method promotes erosion even in straight reaches.

The model has the shortcoming of assuming that the bank erodibility is constant. This assumption may apply when the bank material is homogeneous along the river, the geotechnical properties are uniform and external loads and vegetation are the same along the river banks. However, these conditions are hardly ever met, as for the river Irwell. Therefore, the assumption of constant bank erodibility does not reproduce the natural behavior of the river.

Bed topography

The one-line meander model predicts well the magnitude and location of the bars present in the river except bars 8 and 9 (Figure 2).

The one-line meander model does not have the option to model weirs, therefore the effect caused by the weir upstream of the bridge is not considered in the results. The back water effect of the weir reduces flow velocity and sediment transport capacity so that sedimentation takes place. As a consequence of flow velocity reduction the bar number 5 of Figure 2 is larger than the model prediction and bar number 9 does not exist.

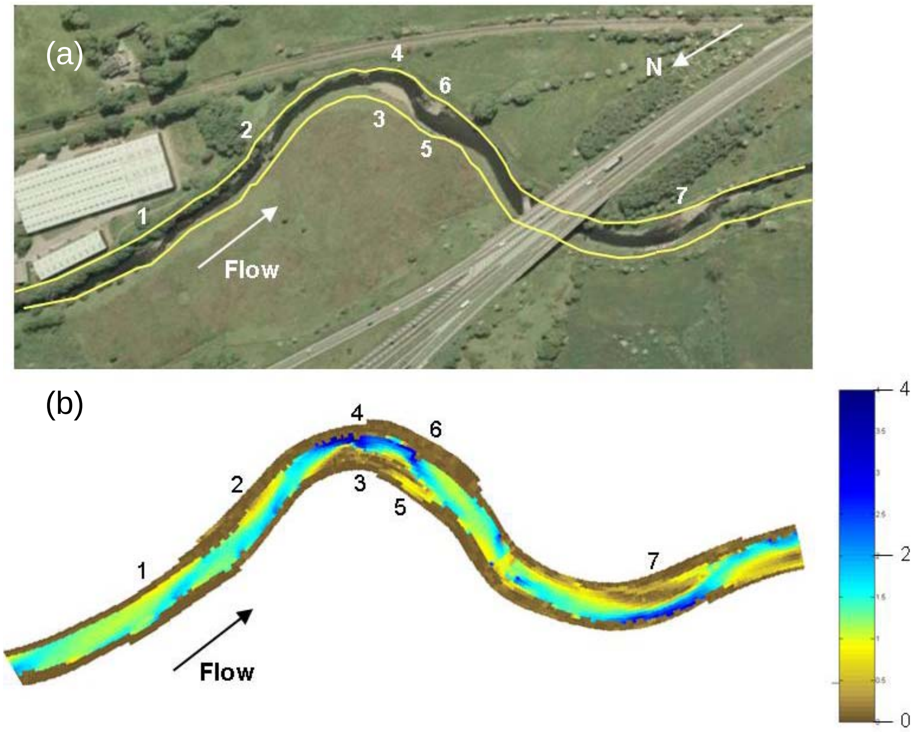

Figure 2. Calibrated 2D model. (a) River banks alignment. (b) Bed topography.

The best fitted calibrated 2D model partially reproduces the morphological development of the river. In the studied bend, the resulting point bar (3) is bigger than the existing one. The erosion of the outer bank is overestimated in (4) which results in washing away the existing bar (6). Additionally, the bank retreat process (5) that takes place downstream of the point bar (3) is not represented by the model and the existing pool is filled with sediment (Figure 2). On the other hand, downstream of the weir, the model reproduces the bar formation and the development of the pool at the outer bend (Figure 2).

Future planimetric changes

The one-line meander model predictions show that in 2010 show the river starts to erode behind the existing channel walls upstream and downstream of the weir. However, the model does not take into account the effect of the weir that lowers the flow velocity upstream, and therefore, the meander growth. With regard to the railway embankment stability, the model indicates that by year 2010 the left river bank might reach the railway embankment toe.

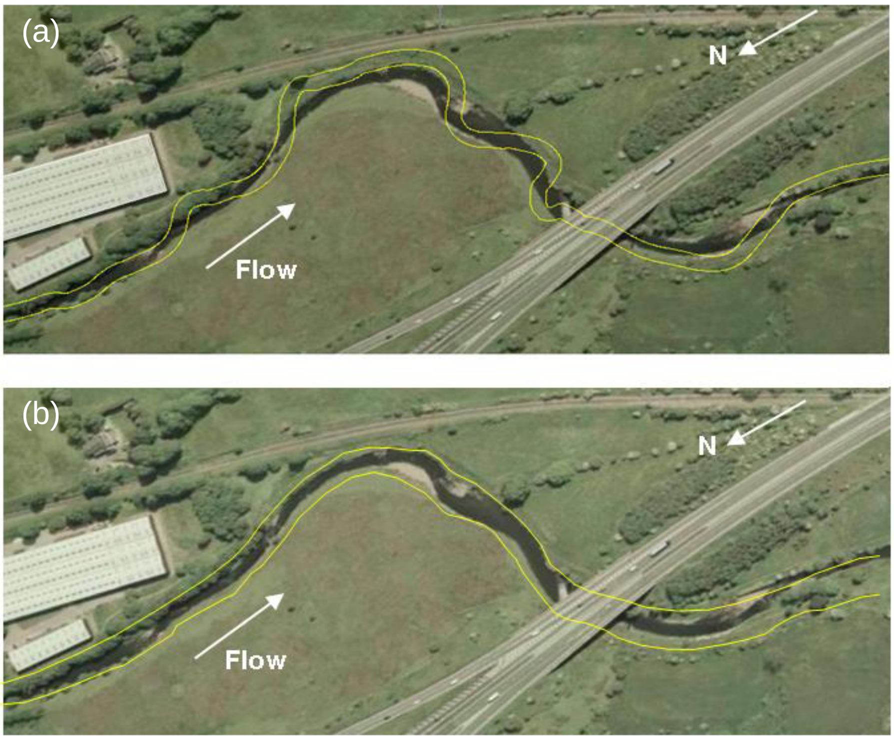

Figure 3. Irwell alignment prediction year 2010. a)One-line meander model. b)2D model

DISCUSSION

From the perspective of the suitability to model small meandering rivers with limited data, it is clear that the one-line meander model offers important advantages because of its simple form and because it allows taking into account factors that reduce the river migration, such as bank protection and vegetation. Even though this model was designed for sand-bed rivers, in this study, the model was successfully calibrated for a gravel bed river.

Meander migration is the result of bank retreat and opposite bank advance. In the case of models that only consider the bank erosion and retreat, like the 2D model used in the research, the river width tends to increase. Better results are expected from the 2D model if bank advance is considered in the computation of the morphological changes, at least in a simplified way.

The one-line meander model uses a few data like a constant channel width, a mean slope and a characteristic grain size. All these parameters are single values that are accompanied with great uncertainty that influences the results. When applying a 2D model, it is possible to use detailed information to describe e.g. topography, sediment and discharge regime, reducing data uncertainties.

On the other hand, the short calculation time in the one-line meander model, makes it possible to carry out a probabilistic analysis of the uncertain parameters to observe their influence on the results. The same type of analysis can be applied to make an assessment of discharge variation due to climate change. The computational time of the 2D model is too large to carry out a large number of calculations as it is necessary for probabilistic analysis.

CONCLUSIONS

This research deals with morphological studies of small rivers experiencing bank erosion processes when only limited data is available. A reach of the meandering gravel-bed river Irwell (United Kingdom) is taken as a case study in order to analyze the bank retreat process that is endangering the stability of structures located in the area. Two models of different complexity have been applied. The first is a physic-based one-line meander model, computing bed topography, flow field and migration rate of meandering rivers in areas with non-uniform erodibility. The second is a 2D physic-based morphological model with a simplified bank erosion formulation.

According to the one-line meander model, the morphological development of the river Irwell will endanger the existing structures within the next five years, if no protection works are undertaken. However, this prediction is accompanied with uncertainty due to the limitations of the available data and, on the other hand, of model assumptions.

In principle, both computational codes, the one-line meander model and the 2D model, require the same type of information. The main difference lies on the fact that the one-line meander model requires simple topographic information: river alignment, characteristic river slope and width, which makes this code suitable to undertake river morphology modeling with limited information.

The one-line meander model appears to be the most appropriate computational code to study the morphological development of the case study river. By approaching the phenomena through the analyses of the physical processes, and by making possible to model the heterogeneity of bank erodibility, a good representation of the natural river development is obtained. This is not achieved with the 2D model where a simplified method for bank erosion calculation and a unique factor for erosion of adjacent dry cells, implicitly assuming constant bank erodibility, are used.

While the 2D model takes days to run, the one-line meander model makes a similar calculation in few seconds what makes it appear appropriate for probabilistic analysis of future river migration trends. This probabilistic analysis will consider the uncertainties linked to river geometry and sediment size. A particular application of this analysis can be the study of climate change effects which involves changes in the discharge regime. The probabilistic analysis will be done in a second phase of the study.

The effects of changing the river width and the sediment grain size will be further studied. Additionally the effect of climate change on the river morphology will be studied by considering possible changes on discharge regime.

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