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Numerical Modelling of Braided River Morphodynamics: Review and Future Challenges

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Abstract

Numerical morphological modelling of braided rivers is increasingly used to explore controls on river pattern and for applied environmental management. This article reviews and presents a taxonomy of braided river morphodynamic models and discusses the challenges facing model development and use, illustrating these challenges with a case example. The taxonomy is contextualised by an initial discussion of the physical mechanisms of braiding. The taxonomy differentiates between reach-scale and catchment-scale models. Reach-scale models are usually physics-based, which are further divided based upon the mathematical approach used to solve equations (analytical or numerical) and their dimensionality (1D, 2D or 3D). Cellular automata models are one type of numerical model that replace at least some physical processes with expedient rules. A 2D physics-based approach encapsulates sufficient process complexity to provide behavioural predictions. Predictions from catchment-scale landscape evolution models have potential for providing boundary conditions. Future progress in physics-based modelling needs to address three challenges: (i) representation of flow and sediment transport; (ii) temporal and spatial scaling; and (iii) model calibration, sensitivity, uncertainty and validation. The key problem for addressing these is the dearth of laboratory or natural experiment datasets. To show that progress can be made by comparing reach-scale predictions to high-resolution observations, a case study of monitoring and modelling, conducted in the Rees River, New Zealand, is presented. Hydraulic predictions of cellular automata and shallow water equation (Delft3d) models are compared to observed inundation extent. The efficacy of high-resolution, multi-temporal morphological data for assessing 2D physics-based morphodynamic model predictions is also demonstrated.

1. *Introduction*

Numerical simulations of fluvial morphodynamics are used by scientists and river managers to understand and predict the interactions between flow, sediment transport and river form (Figure 1). A number of articles have reviewed existing approaches to numerical modelling in fluvial geomorphology (e.g. Coulthard and Van De Wiel 2012, 2013; Lotsari et al. 2015; Mosselman 2012; Nelson et al. 2005; Nicholas 2013c; Papanicolaou et al. 2008; Spasojevic and Holly 2008; Syvitski et al. 2009; Thomas and Chang 2008; Tucker and Hancock 2010; Van De Wiel et al. 2011; van der Beek 2013; Van Dyke 2013). Of particular note are Van De Wiel et al. (2011), who discuss the application of models to understand and predict evolution in response to environmental change, and Mosselman (2012) who reviews applications in the context of gravel-bed rivers. Further reviews by Thomas and Chang (2008) and Spasojevic and Holly (2008) are especially thorough in their respective description of one- (1D), two- (2D) and three-dimensional (3D) approaches to morphodynamic modelling. To date, however, a review that focuses upon the numerical modelling of braided river morphodynamics has not

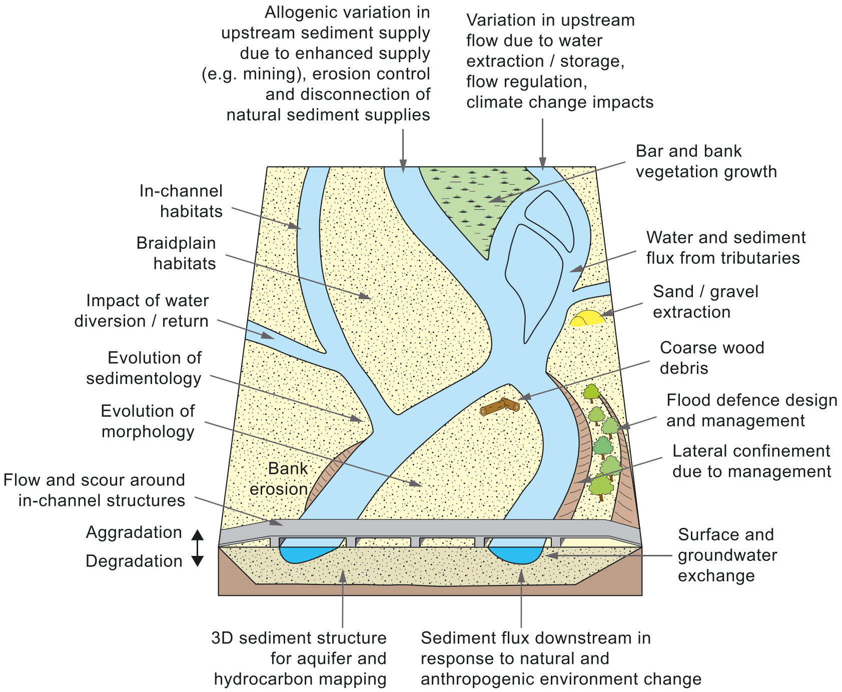

Fig. 1. Problems that are the focus of numerical hydraulic and morphodynamic modelling of braided river systems, from the perspectives of both research and applied environmental management.

been presented. There is considerable interest in using numerical models to investigate the controls on braided river morphology. Also, from an applied perspective, models are being used to inform environmental management decisions. These decisions come in the context of a recognition that the width of braided rivers has decreased as a consequence of in-channel management practices, flow regulation and catchment land-use change (Gurnell et al. 2009; Habersack and Piégay 2008) and the quantity of natural braided river habitat is decreasing (Young 2013). Modelling braided rivers is, however, typically more challenging than simulating single-thread rivers due to the complexities of multiple-pathway and multiple-direction flow and sediment routing and associated morphological change. The objective of this article is, therefore, to evaluate the modelling frameworks suitable for simulating the morphodynamics of river systems with a braided pattern at the reach-scale (Table 1) and to identify the primary challenges associated with such simulations. Whilst some of the issues discussed are generic to modelling in fluvial geomorphology, and environmental modelling in general, the focus is upon how these translate to the specific case of simulating braided river morphodynamics. Since the fraction of sediment transported as bedload is commonly a key control of sand–gravel- and gravel-bed braided river morphology (Leopold 1992), this article focuses upon models that simulate bedload transport mechanisms.

We begin by examining the nature of braided river morphodynamics to provide a context for discussing the numerical modelling of these systems. We then present a novel taxonomy of braided river morphodynamic models. The first level of this taxonomy distinguishes between models that simulate reach- and catchment-scale morphodynamics, and we review different modelling approaches that fall into each of these respective categories. Key challenges for predicting braided river morphodynamics are identified. A case study of the Rees River, New Zealand, is used to illustrate (i) the use of 2D approaches to simulate braided river

Table 1. Definitions of key terms.

Term	Definition
Catchment	A basin, bounded by relatively high topography, through which water and sediment flow within a network of channels that converge to a common outlet.
Reach	A length of river along which discharge and morphological characteristics are approximately uniform. Length is in the order of 10 to 100 river widths (Ferguson 2007). In a numerical model, water and sediment fluxes will be defined at the upstream boundary.
Autogenic	Self-generated or internal behaviour. For a braided river reach, autogenic variation in morphology arises from spatially variable bedload transport, which itself is due to spatially variable morphologies and flow distribution.
Allogenic	Responses to varying boundary conditions. For a braided river reach, examples of allogenic alterations include morphological responses driven by changes to sediment supply (e.g. landslides connected to the upstream channel network), flow change (often driven by climatic variation) and base level change.

hydraulics and morphodynamics; (ii) how high-resolution topographic data can be used to provide data for model boundary conditions and to assess performance; and (iii) an applied context to consider future modelling challenges.

2. Mechanics of Braided Rivers

Braided rivers are found across a range of climatic and physiographic settings (Ashmore 2013). They are associated typically with wide valleys in mountainous regions and their piedmont forelands. Their spatial scale can vary from short reaches in confined valley settings to extensive reaches in laterally unconfined alluvial valleys and fans. Braided river sedimentology encompasses a range of grain sizes, typically from silt to coarse cobbles. Extensive debate exists concerning the controls on the maintenance of braiding (Mueller and Pitlick 2014). Nevertheless, it has been suggested that the transition from a single-thread to a braided channel occurs when one of three conditions is present. These conditions are (i) high bedload flux; (ii) a high width to depth ratio; and (iii) low bank resistance, due to the absence of cohesive sediment or vegetation (Murray and Paola 1994; Paola 2001). Laboratory experiments that produce braided rivers with constant discharge demonstrate that variable discharge is not a prerequisite for braiding (Ashmore 1982). Large floods may, however, be necessary to remove vegetation and thus maintain low bank resistance (Gurnell et al. 2001, 2009; Hicks et al. 2007; Tal et al. 2004). In addition, although aggradation is often observed in alluvial systems that are characterised by braiding, it is not a prerequisite for braiding. For example, New Zealand rivers such as the Rakaia and Waitaki are braided in their coastal reaches, despite degradation trends driven by retreating shorelines. Sediment pulses, however, may result in changes in braiding intensity (Germanoski and Schumm 1993).

The identification of the general conditions for braiding provides a useful initial framework for the mechanisms that need to be included in numerical models of braided river morphodynamics. Representation of these mechanisms is likely to be on a continuum ranging from lumped approximation to near-complete representation for lower-resolution (1D) to higher-resolution (3D) models. Principal mechanisms identified from laboratory experiments (Ashmore 1991; Ferguson 1993) include central bar development, transverse bar conversion, chute cutoff of point bars and lobe dissection. Other mechanisms include bank erosion (Wheaton et al. 2013), bar edge trimming, channel incision, confluence pool scour (Ashmore and

Parker 1983), overbank deposition (Ferguson and Werritty 1983) and lateral bar development. In addition, three avulsion mechanisms have been identified: constriction and overflow, bank erosion and choking (Ferguson 1993). This process-based understanding of braided river morphodynamics from laboratory experimentation contributes to understanding the mechanisms that maintain braiding. Observations of these mechanisms in natural settings are, however, limited. In the absence of these data, synthetic simulation of braided river morphodynamics has considerable potential not only for investigating applied environmental management questions but also to shed light on both the controls on braided river pattern and mechanisms of channel change.

3. Taxonomy

A number of schemes have been proposed to classify morphodynamic models. For example, Paola (2001) distinguishes between reductionist modelling approaches, based upon classical continuum mechanics, and synthesist approaches founded upon highly simplified rules of a system's dynamics. Reductionist approaches are also dubbed "physics-based" (Nicholas 2013c), "process-based" (Hardy 2013) or "computational fluid dynamics" (CFD; Wright and Hargreaves 2013) approaches. Synthesist approaches are also coined as "reduced-complexity" (Brasington and Richards 2007), "cellular" or "exploratory" approaches. Here, a taxonomy is proposed (Figure 2) that first distinguishes between reach- and catchment-scale (Table 1) sediment routing models.

In the taxonomy, reach-scale models are further divided based upon method of solution and then dimensionality. Whilst all the reach-scale models have some form of physical basis, the term "physics-based" is used to refer to classes of models that are based upon fundamental, classical continuum mechanics, in which microscale physio-chemical processes are used to frame the basic component phenomena from which the dynamics of larger-scales are predicted. This approach describes the behaviour of phenomenon using mathematical equations, based on the equations of motion solved either analytically or numerically. The Navier–Stokes equations are the canonical form that describe the three-dimensional motion of fluids (Ingham and Ma 2005). Depth integration of the Navier–Stokes equations results in the derivation of the shallow water equations (SWEs). The shallow water approximation applies where the horizontal extent is much greater than the vertical extent and a vertical hydrostatic pressure distribution is assumed (Jirka and Uijttewaal 2004). These equations can be width-averaged to yield the 1D Saint-Venant equations. The Saint-Venant equations are commonly resolved numerically because analytical solutions are difficult to apply in the natural world. The partial differential equations associated with the principles of mass and conservation are solved by finite element, finite difference or finite volume schemes and then rounded by computer (Bates et al. 2005; Lane 1998), which introduce simplifications, particularly with respect to turbulence closure. Thus, although referred to as "physics-based," the processes that are encapsulated within this category of model are dependent upon the spatial scale being considered. Within the 2D numerical approach category, cellular automata models are a type of numerical model that replace at least some physical processes with expedient rules.

Morphodynamics at the reach-scale are a function of autogenic behaviour and allogenic alterations. Schematising the location of a braided reach within a catchment's sediment transport zone (Figure 3; Schumm 1977) illustrates that reach-scale morphodynamics will be influenced by allogenic alterations, such as sediment and water fluxes from upstream and changes to base level downstream. Thus, to simulate reach-scale morphodynamics at timescales of 1 to 100 years, when allogenic alterations are likely to be unsteady, external boundary conditions are required for reach-scale modelling. In the absence of empirical data, one source of external boundary conditions is to generate these from predictions from coarser models. Two model

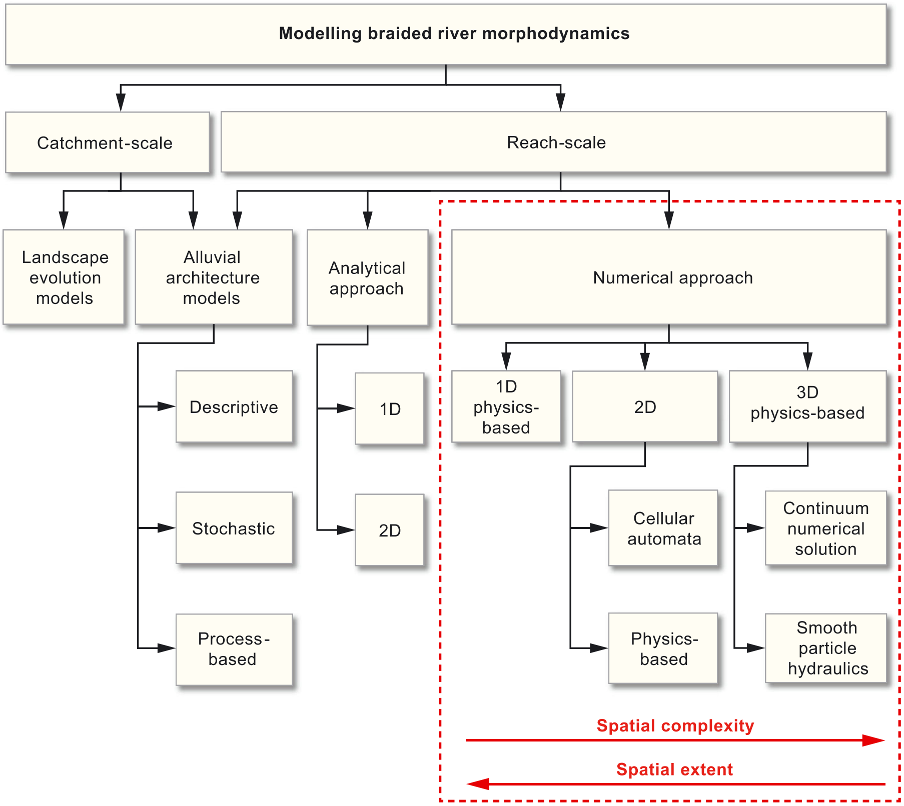

Fig. 2. Taxonomy of braided river morphodynamic models. The hashed box around models with a numerical approach is used to identify trends in spatial complexity and extent between 1D, 2D and 3D models.

classes are potentially useful in this respect and are listed in the taxonomy: landscape evolution models (LEMs) and alluvial architecture models. These models have been extensively reviewed elsewhere; the focus of Section 13 is upon assessing their value for providing external boundary conditions. Analysis of alluvial architecture models focuses upon evaluating their potential for providing external boundary conditions. However, since they are also used by geomorphologists to understand bar development, they are classified as both catchment- and reach-scale models in the taxonomy.

4. Reach-scale Modelling

4.1. Analytical Models

Analytical models provide closed-form approximate solutions to model process (i.e. differential water and sediment flow) equations (Odoni and Lane 2011; Zolezzi et al. 2012). They are purely mathematical and thus have minimal or no data needs. Models typically make a set of simplifying assumptions, such as uniform grain size, steady discharge, fixed banks and that bedload transport is in equilibrium with flow, to predict bar morphology and amplitude. A variety of models have been developed, however, that contain fewer simplifications. Recent examples include investigating river response to changing width (Zen et al. 2014) and sediment input (Di Silvio and Nones 2014). The primary limitation associated with transferring analytical

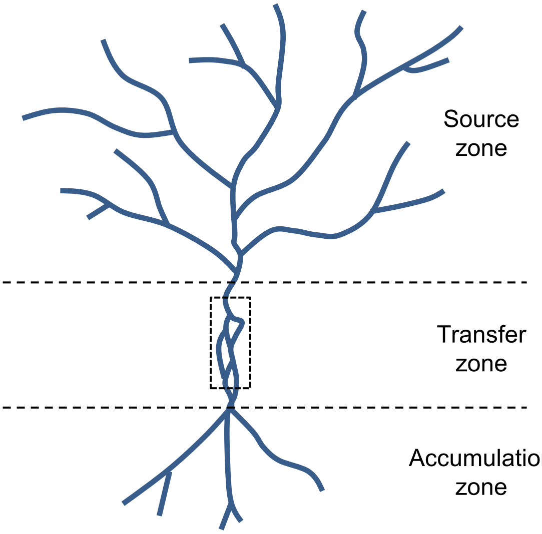

Fig. 3. Conceptual model of a fluvial system. Based on Schumm (1977). The dashed box in the transfer zone indicates a braided reach. The upper region is the sediment source zone and is the primary area where water and sediment are produced. It is typically characterised by confined valleys, with strong connections between hillslopes and river channels. The middle region is the transfer zone; valleys are typically partly confined, and for stable channel morphology, there must be a balance between sediment supply and sediment output. The lower region is the accumulation zone, where sediment is deposited.

models for single-thread rivers to multiple-thread rivers is that compared to narrower single-thread rivers, braided rivers have significant variation in depth and local slope. This results in localised bedload transport, which is poorly represented by reach-averaged predictions of depth and bed shear stress. This limitation also affects numerical 1D models and is discussed further in Section 6. Thus, whilst analytical models have been used to predict the occurrence of braiding (Crosato and Mosselman 2009; Hall 2005; Parker 1976) using reach-averaged conditions, Zolezzi et al. (2012) suggest that assuming the morphologically active width (Ashmore et al. 2011) of a braided river, rather than the total width, is necessary to apply single-thread analytical models to predict the morphodynamics of natural braided rivers. The quality of predictions was, however, not equal between all three natural rivers that Zolezzi et al. (2012) considered. Moreover, the necessity for empirical data on the active width geometry may require substantial observational campaigns. Further limitations to applying analytical models to natural rivers are associated with the assumption of equilibrium bar shape and length; in natural settings, bar morphology is usually a function of a range of different magnitude flow and sediment pulse events, some of which occur below formative discharge. Overall, analytical models can be used to contribute to an understanding of the primary controls on river morphodynamics, but since the models require considerable simplification of processes and boundary conditions, they are not suitable for reach-scale simulation of natural morphodynamics.

4.2. NUMERICAL 1D MODELS

One-dimensional models simplify flow and sediment transport processes by assuming width-averaged variations in bed level and grain size distribution. One-dimensional models are thus suitable for cases where a reach is sufficiently straight and uniform to be represented by a transversely aligned cross-section. For the case of braided rivers, the branching network is therefore assumed to behave as one channel, negating the network's natural curved geometry with significant topographic steering, flow expansion and contraction. One-dimensional morphodynamic models consist of two primary computational components (Wu 2008). First, a flow model predicts water level and velocity. The type of flow model used will depend upon flow conditions and available topographic data. A dynamic wave model, which solves the differential conservation equations of mass and momentum for gradually varied unsteady flow (the 1D Saint-Venant equations), is applicable across a range of flow conditions. A diffusion wave model assumes local and convective accelerations in the momentum equation are negligible and is thus a more stable model than the dynamic wave model. A kinematic wave model simplifies the momentum equation to the longitudinal channel slope and is suitable if detail in topographic surveys is coarse. Second, the sediment mass continuity equation (Exner equation) is solved.

A plethora of 1D morphological models have been developed, a number of which are summarised by Papanicolaou et al. (2008), Thomas and Chang (2008) and Thorne et al. (2010). Multi-grain size models have been used for a range of investigations including those that have focused upon armouring, downstream fining, sediment pulses from landslide and tributary inputs, dam removal and base level change (Hardy 2013). One-dimensional models have also been used to simulate variations in flow due to projected climate change (Gomez et al. 2009; Verhaar et al. 2008). One-dimensional models are characterised by three limitations that are relevant for cases of single-thread river systems but are particularly constraining for multi-channel applications. First, and most importantly, 1D models must be parameterised to represent the lateral variation in bed shear stresses that are characteristic of braided rivers. Compared to single-thread rivers, braided rivers have significant variation in depth and local slope. This results in extreme variations in shear stress across individual sections, which is not represented in traditional 1D models that assume uniform channel geometry. Given the non-linear relationship between excess shear stress and bedload transport, reducing the shear stress to a uniform mean gives rise to a dimensioning problem where mean shear stress estimates may be below transport thresholds but natural local shear stresses may be well above the threshold. Second, secondary circulation is not directly incorporated in the 1D Saint-Venant equations, although it has important consequences for bedload transport and sedimentology. For the case of single-thread (Ferguson 2003) and braided (Bertoldi et al. 2009; Nicholas 2000; Paola 1996) rivers, empirical equations have been developed to represent spatial variations in bed shear stress. To date, Bertoldi et al.'s (2009) formulation has the most sophisticated approach to adjusting for lateral variation in bed shear stress through its use of topographic cross-sections. Third, lateral movement of sediment is often not represented. Whilst this is inherent to the 1D framework, poor or absent representations of bank erosion result in morphological evolution being confined to long profile and sediment is not transferred between the channel and floodplain and vice-versa. When floodplain sediment storage is, however, represented in a 1D model, a slower, more realistic long profile evolution is predicted (Lauer 2012; Parker et al. 2008). In summary, appropriately parameterised 1D models are able to predict longitudinal morphological properties, average transport rates and sorting patterns. They cannot, however, be applied to predict bar-scale dynamics.

4.3. NUMERICAL 2D MODELS

4.3.1. Cellular automata

Two-dimensional cellular automata models aim to provide plausible explanations of observed phenomenon by capturing the essence of system behaviour with a minimal set of rules (Murray 2003; Wolfram 2002). For example, Jerolmack and Paola's (2007) model of river avulsion characterises the abandonment and reoccupation of a small number of flowpaths using a cell size that is greater than channel width; in-channel processes are therefore negated. The foundations of cellular automata modelling are strongly based upon the notion that system behaviour at a particular scale emerges from pertinent interactions between dynamic variables at one scale below that which is of interest (Werner 1999). Model building is thus parsimonious by design. Cellular automata models sit within an Eulerian (grid-based) frame of reference and use a set of transition rules to define local fluxes. They are distinct from physics-based numerical schemes for the solution of more complicated mass and energy conservation equations (Section 4.3.2) because they use rules to simulate the interaction between only adjacent cells. Such rules can be statistical, heuristic, empirical or be based upon simplifications of continuum mechanics (Fonstad 2013).

Murray and Paola's (1994, 1997) seminal work on braided river formation exemplifies the cellular automata approach. Flow is routed based on an algebraic rule that assumes conservation of mass and directs water to up to three immediately downstream cells, based upon local bed slope. Sediment transport is calculated from a non-linear rule that computes erosion as a function of discharge, local bedslope and lateral erosion. Braiding emerges due to the expansion of flow around bars, flow diversion along the steepest pathway and subsequent flow contraction, which generates erosion. The model predicts the generic dynamics of braiding including channel shifting, avulsion and migration. In doing so, the model demonstrates that braiding is the emergent river style under conditions of non-linear sediment transport, topographically driven flow expansion and contraction and unimpeded lateral erosion. The utility of the model is in this explanation of emergent properties (Murray 2007). Nevertheless, a number of investigations have scrutinised the model's predictions and further developed the abstracted flow and sediment transport rules in an attempt to generate more natural braided morphology.

Thomas and Nicholas (2002) extended Murray and Paola's (1994, 1997) flow routing scheme to five downstream cells and developed the scheme to discriminate between sub-critical and critical flows. This routing scheme was then applied by Thomas et al. (2007) to drive a cellular automata model with an enhanced sediment transport algorithm. The model was applied to simulate morphological evolution for a period of 200 years, using a domain which was similar to that of a 450 m long reach of the Avoca River, New Zealand. Nicholas (2009) further developed the Thomas and Nicholas (2002) scheme with the introduction of two calculation steps, first to estimate water surface elevation and then to distribute flow. The scheme yielded flow predictions similar to those from a model based upon the SWEs and was more computationally efficient than the original scheme. The routing scheme was applied by Nicholas et al. (2012) to simulate flow along a 30 km reach of the Rio Paraná, Argentina. Model predictions of flow depth and velocity were compared to transect measurements. Overall, the predictions of the cellular automata model were comparable to results from a 3D CFD model and an SWE model. Whilst this study reach did feature several islands, flow partitioning was relatively simple. Moreover, the gradient of 4.4×10^{-5} is very low compared to many piedmont braided gravel bed rivers. The original Murray and Paola (1994, 1997) model has also been developed by Parsons and Fonstad (2007), who used a form of Manning's equation to calculate suitable flow rates between model grid cells to predict realistic unsteady flow. The reach-scale component of CAESAR (Coulthard et al. 2007) also develops Murray and Paola's model to include flow routing in any of four cardinal directions.

Compared to the number of studies that have examined the hydraulic performance of cellular routing schemes, there have been far fewer attempts to review their morphodynamic predictions. In part, this has been justified by the need for robust flow distribution rules that are a precursor to estimating bedload transport flux. Dynamical systems analysis, using state space plots of braided reach evolution, indicates that spatial patterns of wetted width are similar in both natural braided rivers and those simulated using the Murray and Paola model (Murray and Paola 1996; Sapozhnikov et al. 1998). When the model is initialised with topography from either laboratory experiments (Doeschl-Wilson and Ashmore 2005) or natural braidplains (Nicholas and Quine 2007), however, there is little resemblance between subsequent predicted and observed morphological change. This has been attributed both to errors in flow routing and the sensitivity of the sediment routing calculations to local bed slope. Fundamentally, however, the sensitivity of avulsion mechanisms to small vertical variations in braidplain topography will always challenge direct comparison of modelled and observed morphological change.

The development of the hydrodynamic and sediment transport components of cellular automata models of braiding encapsulates the tension between constructing models for explanation and prediction (Murray 2007). The continual enhancement of cellular automata models with ever more detailed sets of rules to produce predictions that mimic observed dynamics is in stark contrast to Murray and Paola's (1994, 1997) original objective of building a model with essential physics to explain emergent behaviour. Whilst cellular automata models offer a flexible modelling platform, where the level of reality can be chosen and results can be plotted in a spatially elegant manner (Fonstad 2006; Murray and Fonstad 2007), they are best suited to qualitative rather than quantitative predictions of landform morphologies and dynamics (Coulthard and Van De Wiel 2013; Fonstad 2013). This arises because cellular automata models are convincing in their prediction of kinematics, or motion. Driving force distribution, however, is not represented physically so the temporal dynamics are not effectively constrained. The application of cellular automata models to predict natural braided river morphodynamics is therefore likely to be limited because their simple flow routing algorithms do not redistribute momentum. These limitations result in predictions that are overly sensitive to local bed slope. Moreover, Nicholas et al. (2012) indicate that the computational time for unsteady, 2D cellular automata models to iterate to a solution is similar to that of running an SWE model. For the purpose of predicting landforms, this therefore diminishes the utility of applying hydraulic cellular automata models.

4.3.2. Physics-based

Most physics-based models simplify the morphodynamics problem by decoupling the processes of flow and sediment transport, although it is not axiomatic that flow and transport could not be solved simultaneously (see, for example Siviglia et al. (2013) for a fully coupled morphodynamic model). The decoupled approach typically involves three computational steps: (i) predicting flow; (ii) predicting sediment entrainment, transport and deposition; and (iii) updating the bathymetric grid (Spasojevic and Holly 2008). The second of these steps is the most complex (Mosselman 2012) and particularly prone to uncertainty because sediment entrainment and transport are non-linearly related to bed shear stress. For non-uniform sediment, the classic approach to this second step is to divide the sediment into fractions, partition bed shear stress, calculate the transport and mass conservation for each fraction whilst allowing for hiding and exposure effects and then update the active sediment layer with a new composition and elevation (Mosselman 2005). Compared to a 1D approach, a 2D approach results in spatially explicit predictions of depth, velocity and bed shear stress, incorporating the influence of topography in steering flow and allowing lateral variation in water surface elevation (Nelson et al. 2005; Spasojevic and Holly 2008). With appropriate parameterisation, the effects of secondary flow (Lane 1998) and transverse and longitudinal bed slopes on bedload transport can be also incorporated into 2D models.

Shallow water equation models are widely accepted as being fit for a range of flood modelling purposes (Néelz and Pender 2010), assuming suitably accurate topographic data are available, roughness is suitably parameterised and appropriate turbulence closure is used. In the context of predicting the flow dynamics of braided rivers, SWE models have been applied to both gravel-bed (Hicks et al. 2006; Jowett and Duncan 2012; Thomas and Nicholas 2002) and sand-bed rivers (Nicholas et al. 2012). Two-dimensional models, however, are often calibrated and validated with relatively sparse observational data resulting in uncertain assessments of their predictive power.

An early approach to assessing SWE morphodynamic models was to compare their predictions qualitatively to experimental (laboratory) flume experiments. Both the numerical and experimental models often start with a longitudinal slope, with constant gradient and random perturbations, and are run until a relatively stable braided planform emerges. Shimizu and Itakura (1989) simulated the formation of alternate bars. Their results suggest that so long as secondary circulation is parameterised in the 2D model, numerical predictions of bar amplitude and wavelength have a close correspondence to experimental results. McArdell and Faeh (2001) utilise an SWE model to simulate experimental braided rivers reported by Fujita (1989). They report, however, that although the numerical model can output physically realistic features, there are differences, such as the range of transverse vertical topographic relief. The potential of the SWE approach for simulating braided rivers has also been demonstrated by Jang and Shimizu (2005).

The demonstration that SWE models have some, albeit not fully assessed, predictive capability for generating braided planforms has instigated a number of numerical modelling investigations that consider the controls on river pattern by creating "synthetic" experiments, where processes and associated parameterisations can be adjusted. Such an approach has been used by Takebayashi and Okabe (2009) to simulate braided rivers with a uniform grain size of 1 mm, using an SWE model with a shock-capturing Total Variation Diminishing (TVD) numerical scheme. These experiments demonstrate that the number of channels decreases when vegetation is represented in the model and that wavelength of submerged bars is shorter for simulations with steady rather than unsteady flow. The importance of vegetation in controlling a braided to meandering river style has also been shown by Li and Millar (2011).

Nicholas's (2013a, 2013b) experiments with the Hydrodynamics and Sediment Transport in Alluvial Rivers model (HSTAR) demonstrate the potential of a SWE framework to investigate controls on river pattern (Figure 4). Focusing upon large sand-bed rivers, Nicholas investigates controls by varying sediment diameter, river gradient, Chezy bed roughness, bank erodibility and vegetation establishment. The results indicate, for the first time, that a single SWE model, with appropriate parameterisation, can be used to generate meandering, braided and anabranching river styles. Overall, synthetic experiments with SWE models have contributed to defining the process complexity that is needed to predict braided morphology, for example, the importance of secondary circulation for the prediction of near bank bed shear stress, the need for a suitable bank erosion algorithm and appropriate representation of vegetation dynamics.

An alternative framework for investigation, in addition to modelling experimental and synthetic rivers, is to base numerical experiments on natural rivers. Braided river models have been demonstrated using Delft3d (Lesser et al. 2004) for the Lower Yellow River, China (Xia et al. 2013); Allier River, France (Crosato and Saleh 2011); and River Rhone, Germany (Kleinhans 2010), and the MIKE21C hydrodynamic model (DHI 1999) with bedload transport and morphological change components (Li and Millar 2007) to simulate multi-fraction bedload transport for the braided Fraser River, Canada. Nicholas (2013a) uses HSTAR to simulate the gravel-bed Waimakariri River, New Zealand, although a uniform grain size is used (Figure 4). Detailed assessments of hydraulic and morphodynamic model predictions in a sand-bed braided river setting are presented by Lotsari et al. (2013) who utilise the TUFLOW (Syme 1991)

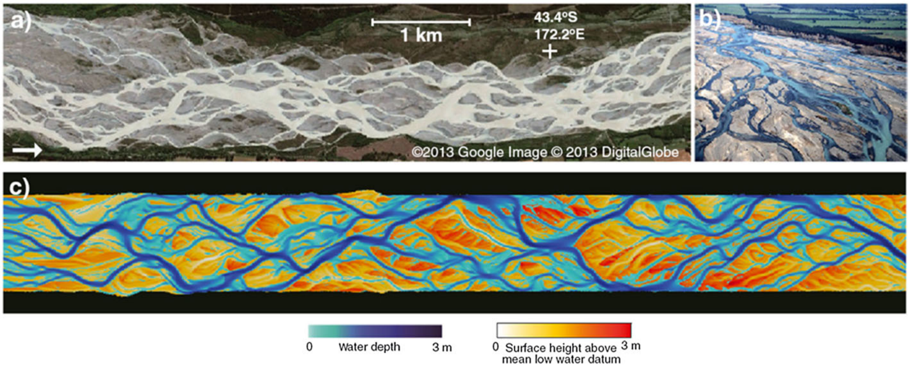

Fig. 4. HSTAR morphological predictions for a simulation based on the characteristics of the Waimakariri River, New Zealand (Nicholas 2013a). The model incorporates secondary circulation and the influence of gravity in deflecting sediment transport direction. Bank erosion is a function of (i) a bank erodibility parameter; (ii) transport rate parallel to the bank; and (iii) bank slope. Vegetation is represented by a simple rule that relates vegetation growth to the time that topography has not been inundated above a critical threshold depth. The model uses a single grain size of 35 mm and the Meyer-Peter and Müller (1948) bedload transport formula. Predicted braidplain morphologies with two or three main channels across each braidplain width and multiple minor channels compare well to the observed braidplain morphology.

MORPH model. When simulating real rivers, the primary challenge in assessing model performance is the availability of natural experiment datasets that quantify topographic change, at a suitable frequency, and quantify bedload transport rates at model boundaries.

An emerging approach to addressing the considerable computation run times that are encountered in physics-based simulation is to integrate a cellular automata sediment transport approach with physics-based flow algorithms. This approach is demonstrated by Coulthard et al. (2013), albeit for a meandering river. CAESAR is integrated with LISFLOOD-FP, which assumes conservation of mass with a dynamic wave approximation. Application of the integrated model to simulate sediment yields from a 150 km^2 upland catchment during a 40 year period, and the morphological evolution of meander bends along a 7 km long reach for a 10 year period, results in dynamics that are substantially different to those predicted by the original cellular automata model. The calibration and validation of such models remain, however, at an early stage.

4.4. NUMERICAL 3D MODELS

4.4.1. Flow: continuum numerical solution

Three-dimensional flow models are utilised in morphological modelling to predict naturally heterogeneous flow fields, including turbulent phenomenon, to estimate the forces that influence the entrainment and deposition of individual particles (Hardy 2013). Three main approaches have been developed to model turbulence in 3D CFD models. First, the Reynolds Averaged Navier–Stokes (RANS) semi-empirical approach uses temporal averaging to estimate the effects of turbulence on mean flow (Lane et al. 1999). Second, the Large Eddy Simulation (LES) approach uses filters to remove the smallest scales of turbulence, which are then estimated at a sub-grid scale, and focuses modelling effort at resolving the largest scales of turbulence (Bates et al. 2005; Keylock et al. 2005). Finally, Detached Eddy Simulation (DES) is a hybrid approach that switches between RANS and LES approaches depending upon flow conditions and mesh resolution (Keylock et al. 2012). A wide variety of research and commercial 3D morphological models are available (Papanicolaou et al. 2008). The accuracy of 3D RANS water surface elevation, bed shear stress and velocity direction and magnitude predictions have been shown to be more accurate than 2D predictions for natural confluence (Bradbrook et al. 1998; Lane et al. 1999) and natural braided river (Nicholas and Sambrook Smith 1999) settings.

Three-dimensional CFD models have been applied primarily in morphological modelling to calculate the stresses exerted on a grain by fluid flow and interactions with other particles (Cleary and Prakash 2004; Hardy 2005; Richards et al. 2004). At this scale, the saltating trajectories of individual grains are modelled. Both the origin (Cundall and Strack 1979) and development of Discrete Element Modelling techniques have been in the field of granular physics (Frey and Church 2011). Hardy (2012) categorises Discrete Element Modelling bedload transport models into two approaches. The first approach uses CFD to drive grain entrainment. Examples include the consideration of both uniform (Bozzi and Passoni 2012; McEwan and Heald 2001; Nabi et al. 2013) and mixed grain particles (Schmeeckle and Nelson 2003). The second approach uses Discrete Element Modelling to derive a probabilistic distribution of sediment entrainment and transport, based upon Einstein's (1950) model of episodically moving particles with random step lengths and rests (Hodge et al. 2007; MacVicar et al. 2006; Niño et al. 2002). Whilst Discrete Element Modelling is not yet practical at the reach-scale (Coulthard and Van De Wiel 2013) due to computational limitations, probabilistic models with relatively simple lateral bank erosion algorithms have been demonstrated to generate synthetic braided river patterns (Davy and Lague 2009; Figure 5). At present, therefore, Discrete Element Modelling has potential for exploratory modelling and for providing parameterisations, such as particle step-lengths, for coarser resolution morphological models.

4.4.2. Coupled flow and sediment: smooth particle hydrodynamics

Smooth particle hydraulics (SPH) has its origin in 1970s astrophysics (Cleary and Prakash 2004). It is a useful Lagrangian solver for coupled, fluid–solid interaction models. Smooth particle hydraulics involves discretising a fluid or solid as a particle, or "blob" (Gingold and Monaghan 1977). The centre of each blob is attributed with physical properties, and during simulation, the blobs move in response to forcing by other particles. For fluid flow, the Navier–Stokes

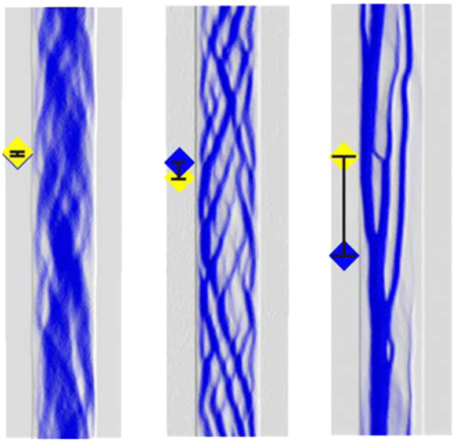

Fig. 5. Predictions from the Eros Discrete Element Model for different particle step lengths, as indicated by the yellow and blue diamonds to the left of each image. A braided pattern emerges for the intermediate step length (Davy and Lague 2009).

equations are solved using Lagrangian continuum methods for solving partial differential equations. An interpolation kernel is used to smooth the information contained at the centre of each particle when spatially distributed model predictions are required, such as water surface elevation. Compared to continuum mechanical approaches, SPH has a number of advantages (Cleary and Prakash 2004; Liu and Liu 2010). First, complex topography can be accommodated, and since the approach is meshless, grids do not have to be defined *a priori*. Second, there is no mass loss or numerical diffusion. Third, there is no non-linear convective term in the momentum equation. Fourth, additional properties, such as sediment transport, can be included in the particles and their histories can be traced. The SPHysics fluid solver and associated test cases are available open source (Gomez-Gesteira et al. 2012a, 2012b).

In the field of fluvial geomorphology, SPH has been applied to simulate dam break flow (Cleary and Prakash 2004; Gomez-Gesteira et al. 2010) and fluvial erosion (Bursik et al. 2003; Cleary et al. 2010; Monaghan 1994), although many demonstrations use synthetic rather than natural grids. An SPH approach to modelling shallow water flood hydraulics has also been validated for a hypothetical breach flood (Krištof et al. 2009). Depth predictions were found to be similar to those estimated by an established, commercial 2D SWE model (Vacondio et al. 2013), but predictions from the SPH splitting-coalescing model had a computational time that was 15 times faster than a 2D SWE TUFLOW model. The potential of utilising SPH for rapid shallow water simulation has thus been demonstrated, but flow velocities have not yet been validated. This is required before SPH approaches are used to estimate morphological change, since realistic bed shear stresses must be estimated if they are to be used to estimate sediment flux from empirically derived bedload transport equations.

5. *Catchment-scale Modelling*

5.1. LANDSCAPE EVOLUTION MODELS

Landscape evolution models couple two or more processes (e.g. hydrological, hillslope, fluvial, climatic, lithological and tectonic) to simulate long-term drainage basin evolution. LEMs therefore take a holistic (Coulthard and Van De Wiel 2013) view of how drainage density and catchment form evolve over a relatively large spatial extent (typically 10^1 to $10^3\,km^2$) and temporal duration (typically 10^1 to 10^6 years). As discussed in Section 3, they have potential for providing external boundaries for reach-scale models. Pertinent reviews of LEMs focus upon computational code (Coulthard 2001), the conceptual basis of process laws and methods (Tucker and Hancock 2010) and hillslope and channel geomorphic laws (Dietrich et al. 2003). Early LEMs were presented by Ahnert (1976) and Kirkby (1987). A plethora of models are now available including SIBERIA (Willgoose et al. 1991a,1991b), GOLEM (Tucker and Slingerland 1994), CAESAR (Coulthard et al. 1998) and CHILD (Tucker and Bras 2000). Model development is increasingly a community activity, and many models are now available through the open-access Community Surface Dynamics Modelling System (CSDMS) (Slingerland and Syvitski 2013).

Landscape evolution models are applied to investigate generic drainage basin evolution questions, often using artificial landscapes, and also to consider specific catchment case studies (Istanbulluoglu 2009). For example, CAESAR has been used to both investigate the production of sediment pulses from autogenic system dynamics (Van De Wiel and Coulthard 2010) and to simulate the sedimentary record (Coulthard and Macklin 2003). Computational restrictions have tended to limit the spatial resolution of LEMs since the demand to solve mass and energy continuity equations accurately requires short model timesteps and thus leads to long simulation times when models are iterated over long timescales. The representation of channel dynamics (e.g. bar evolution and bank erosion) has therefore tended to be relatively coarse, and LEMs have not been suitable for simulating change at the river planform scale. LEMs are, however, becoming increasingly sophisticated, and a range of developments are enriching the physical detail of simulations including multiple direction flow routing (Coulthard et al. 2002; Pelletier 2004), vegetation (Istanbulluoglu and Bras 2005), lateral erosion (Coulthard and Macklin 2003) and multiple grain size sediment transport (Coulthard and Van De Wiel 2007). At this scale of investigation, CAESAR has been applied to simulate the evolution of braided rivers for periods of 8 (Ziliani et al. 2013) and 20 years (Coulthard et al. 2007). However, comparisons with natural planform change indicate disparities between model predictions and natural change. One source of these disparities is likely to be associated with spatial resolution. For example, Ziliani et al.'s (2013) application of CAESAR to the braided Tagliamento River, Italy, required a 25 m resolution grid to achieve realistic computation run times, even though the average width of secondary channels was equal to this dimension. More fundamentally, it may be that the abstract physical rules associated with these applications hinder calibration efforts to generate realistic process rates. Thus, the results from these models may be suitable for defining the external boundaries of higher-resolution, reach-scale models, assuming suitable calibration data are available, but by themselves, their predictions are not of a sufficiently high quality to characterise morphodynamics with a reach.

5.2. ALLUVIAL ARCHITECTURE MODELS

Alluvial architecture models (Allen 1978) aim to describe the accumulation of channel and floodplain deposits in sedimentary basins. Investigations commonly seek to explain how climate and tectonics influence variations in sedimentary unit geometry and spatial distribution, the proportion of channel and floodplain deposits, and grain size characteristics (Bridge and Demicco 2008). Alluvial architecture models are thus typically focused upon greater spatial scales and longer timescales than LEMs. The development of alluvial architecture models has primarily been driven by the need to map the properties of sedimentary basins to exploit petroleum resources and extract groundwater. These models warrant examination here, however, to evaluate their potential for providing boundary condition data for simulations of reach-scale braided river morphodynamics.

Alluvial architecture models can be classified into those that are (i) descriptive; (ii) stochastic; or (iii) process-based (Bridge 2008; Koltermann and Gorelick 1996). Descriptive models of alluvial architecture aim to model the geometry, grain size and sedimentary structure of deposits by considering the interaction of flow, sediment transport, grain size, bedforms and morphology. Models (e.g. Bridge 1993, for sandy deposits) assume simple braid bar geometry, steady flow and do not consider flow structure in detail. Descriptive models are thus overly simplified (Bridge 2008) and are therefore unsuitable for providing boundary conditions for reach-scale morphodynamic simulations. Indeed, they are more typically used by geomorphologists to conceptualise morphological development at the reach-scale. Stochastic, or structure-imitating, models include a random component that is utilised to explain unpredictable variations in observed dynamics (Chorley et al. 1984). In the context of braided river modelling, two types of models are of interest: random walk and sedimentary unit-based geometric models. The computational procedure for random walk models is to move, join and split channels (Howard et al. 1970; Krumbein and Orme 1972; Webb 1994, 1995). Three-dimensional architecture can be simulated by stacking braidplain layers (Webb and Anderson 1996). Whilst this approach enables the estimation of distributed hydraulic properties, random walk models are of limited value in explaining and predicting the 3D form of natural braided rivers. Geometric models of alluvial architecture use available observations, outcrop analogues and random positioning of sedimentary units to generate 3D sedimentary fill (Bridge and Demicco 2008). Most stochastic models have focused upon simulating single-thread, channel-floodplain systems. Ramanathan et al. (2010) and Huggenberger and Regli (2006), however, provide examples of stochastic models of braided river architecture. Models are dependent upon incomplete observations and associated assumptions of the geometry and location of sedimentary units that are used to build the model. Moreover, the distribution of these units is not, in practice, random (Bridge 2008). Process-based models simulate simplified physical processes to build sedimentary fill through channel avulsion and deposition (see Bridge 2008 and Hajek and Wolinsky 2012 for reviews). From the perspective of simulating multi-thread rivers, a number of models have simulated sedimentation associated with braiding (e.g. Paola et al. 1992, 1999; Tetzlaff 1991; Tetzlaff and Harbaugh 1989). Process-based models have the potential to investigate exploratory questions associated with controls on sedimentation (Coulthard and Van De Wiel 2013), but they lack links between different scales of process and remain underdeveloped (Bridge 2008).

Overall, there is considerable mismatch between the space and timescales of alluvial architecture models and those associated with reach-scale models. In particular, process-based models are limited by the incomplete physical descriptions of processes that are necessary to achieve computational run times that are commensurate with simulating up to sedimentary basin filling over timescales of 10^3–10^6 years. Predictions of transport rates for external model boundaries are thus likely to be too coarse for useful implementation in reach-scale models. Whilst alluvial architecture models may have some value in deriving average characteristics of sedimentary fill, such grain size information could also be acquired from empirical assessment.

6. Challenges for Reach-scale Prediction

The above review indicates that a 2D physics-based approach encapsulates sufficient process complexity to provide behavioural, reach-scale morphodynamic predictions. This approach implements SWEs to estimate spatially distributed bed shear stresses, thus accounting for the significant variation in depth and local slope that is characteristic of braided rivers. Two-dimensional flow predictions are then used as inputs to empirical bedload transport equations to estimate sediment flux. There are three challenges associated with applying 2D physics-based models to make morphological predictions.

The first challenge is the representation of flow processes and sediment transport. The accuracy of hydraulic predictions is paramount as they combine non-linearly in sediment transport algorithms to determine morphological evolution. There is, therefore, a need to assess the components of flow routing models to ensure reliable estimates of bed shear stress. Also, estimating bedload transport rates in gravel-bed rivers is not straightforward (Gomez 1991; Wilcock et al. 2009), with non-linearities and uncertainties in bedload transport predictions necessitating rigorous calibration of appropriate transport formulae.

The second challenge is temporal and spatial scaling. Scaling problems are pertinent in all disciplines of environmental modelling due to natural spatial heterogeneity and process non-linearities, the dominance of particular processes at particular scales and feedback between processes (Zhang et al. 2013). In particular, the sensitivity of morphological predictions to grid resolution has received relatively little attention. Larger grid cells result in more diffuse patterns of flow and, with respect to morphological modelling, more diffuse morphological adjustment. This can result in sharp gradients, such as bank lines, being attenuated and a need for a secondary set of parameterisations to maintain these gradients – at least where gravity is a significant driver of processes. Attention to scale is thus particularly important for modelling bank erosion. With respect to temporal scaling, physics-based morphological models that apply finite difference methods to solve partial differential equations must satisfy the Courant–Friedrichs–Levy criterion (Lane 1998) to ensure accurate and stable predictions. Such a criterion is relatively restrictive in terms of computational power. However, the use of parallelisation techniques, particularly through High Performance Computing (HPC), means that new opportunities for smaller grid sizes and larger model domains are emerging.

The third challenge combines issues associated with model calibration, sensitivity, uncertainty and validation. Many of these issues have previously been reviewed from the perspective of environmental modelling (Mulligan and Wainwright 2013), modelling river morphodynamics and environmental change (Coulthard and Van De Wiel 2012), hydrological modelling (Beven 2012) and ecohydraulics (Maddock et al. 2013). With respect to braided river morphodynamics, the key problem associated with addressing model development and assessment issues is the dearth of laboratory or natural experiment datasets that are available for model development. Techniques to acquire high-resolution, spatially and temporally distributed direct measurements of morphological change during forcing events in braided river environments remain elusive. Acoustic Doppler Current Profiler surveys show potential (Rennie 2012; Williams et al. 2015), but data acquisition remains relatively slow and access at high flows is problematic. An alternative technique for mapping morphological change is through the use of DEMs of Difference (DoDs; Brasington et al. 2000, 2003; Williams 2012). With appropriate measurement or assumptions about sediment supply, DoDs can then be used to infer bedload transport rates between connected zones of erosion and deposition. However, since DoDs only offer snapshots of morphological evolution and do not provide temporal data on morphodynamics during high flows, there is a need for survey frequencies to be commensurate with characteristic rates of change.

7. *Case Study: Modelling the Rees River*

The aim of the following case study is to demonstrate how high-resolution survey data, acquired in a natural braided river setting, can be used to assess numerical model predictions. The first objective of this case study is to compare hydraulic predictions of cellular automata and SWE models with observations of inundation extent. The second objective is to compare observed and modelled morphological predictions for a single high-flow event using a physics-based approach. This article's supplementary material provides further information on the study area's grain size distribution, topographic data acquisition, and modelling assumptions.

7.1. STUDY REACH

The case study uses observations from the ReesScan dataset, which records morphological change across a 2.5 km long by 0.7 km wide braided reach of the Rees River, New Zealand, through a sequence of high-flow events that occurred between October 2009 and May 2010. Rates of morphological change within the study area are high due to the Rees catchment's active tectonic setting, easily erodible schist geology and frequent high-flow events. A detailed description of the Rees catchment and study reach is available in Cook et al. (2014) and Williams et al. (2011), respectively. For the study reach, D_{50} surface and subsurface grain size, with associated standard deviations, were 19.9 ± 10.4 mm and 7.5 ± 1.6 mm, respectively.

7.2. METHODS

Digital Elevation Models (DEMs) of the study reach were constructed using a fusion of mobile Terrestrial Laser Scanning (TLS) and optical-empirical bathymetric mapping, as described by Williams et al. (2014). Vertical errors in the DEMs were between 0.03 and 0.12 m in exposed and inundated areas of the models, respectively.

The comparison of flow predictions from cellular automata and SWE models focused upon comparing steady-state discharges of 7.3 and 54.7 m^3s^{-1}. Predictions were compared to aerial imagery that recorded inundation extent at each of these flows. The cellular automata scheme was similar to Murray and Paola's (1994, 1997) model (as described in Section 8). The SWE model used Delft3d software (Lesser et al. 2004), with setup and calibration guided by Williams et al. (2013). Delft3d software was also used to simulate morphological change, for a 44 h event that peaked at 227 m^3s^{-1}.

7.3. Results

7.3.1. Comparison between 2D cellular automata and physics-based flow routing

Figure 6 compares observed and predicted inundation extents. At low flow, the cellular automata model predicts an inundation pattern that has a higher braiding intensity than that observed. The low-flow SWE model inundation predictions (Figure 6b) show greater affinity to the observed inundation extents, with comparable flow routing, although there are differences in observed and predicted channel widths. The cellular automata model predictions for high flow (Figure 6c) have a similar routing pattern to the low-flow simulation (Figure 6a), although channel depth (not shown here) was greater. The low-flow SWE model inundation predictions (Figure 6d) predict a similar braiding intensity to the observed inundation pattern, albeit with minor variations in inundation extent.

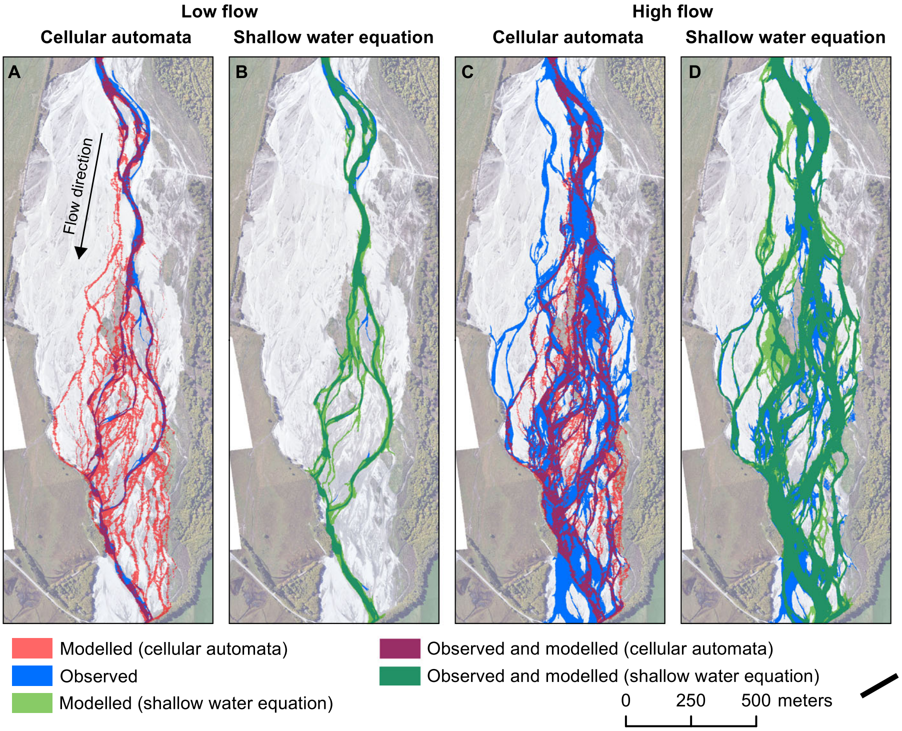

Fig. 6. Comparison of flow predictions using a cellular automata model (Murray and Paola 1994, 1997) and shallow water equation model (Delft3d) for a 2.5 km long reach of the Rees River, New Zealand. Flow is simulated across a 2 m resolution grid, for a low flow of 7.3 m^3s^{-1} (A and B) and a high flow of 54.7 m^3s^{-1} (C and D). Predictions are compared against observed inundation extents, which were digitised from aerial photos.

7.3.2. 2D physics-based morphodynamic modelling

Figure 7 compares observed and predicted DoDs and volumetric sediment budget. There is strong spatial coherence between units of observed and predicted morphological change. From the perspective of the reach sediment budget, the total volume of predicted erosion ($-40{,}459\,m^3$) is within the observed volume of erosion 87% (1.5 standard deviation) confidence interval ($-37{,}024 \pm 10{,}551\,m^3$). The total volume of predicted deposition ($40{,}297\,m^3$) is greater than the 87% confidence interval of observed deposition ($27{,}692 \pm 9{,}842\,m^3$).

7.4. DISCUSSION: ILLUSTRATION OF MODELLING CHALLENGES

This case study demonstrates that high-resolution survey data, acquired in a natural braided river setting, can be used to assess numerical model predictions. The SWE equation hydraulic model yields sufficient process complexity to predict low- and high-flow inundation extents that are comparable to observed inundation extents. In contrast, predictions from the cellular automata scheme perform poorly because the abstracted flow routing formula is hyper-sensitive to bed

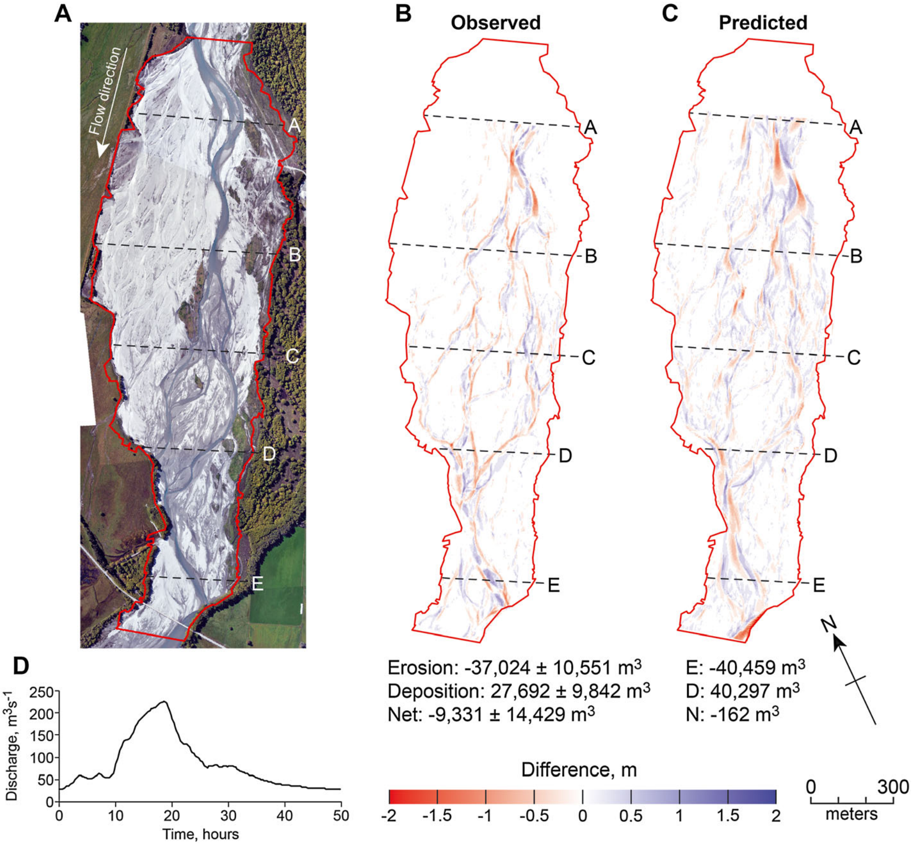

Fig. 7. Observed and predicted morphological change during a 227 m^3s^{-1} high-flow event on the Rees River, New Zealand. The observed DEM of Difference is produced by using probabilistic thresholding at the 87% confidence interval; the volumetric uncertainties are calculated by multiplying the estimated probabilistic error thickness by cell area and then summing all cells, as described by Erwin et al. (2012). Observed and predicted changes are not compared north of cross-section A. The predicted morphological change is based upon a Delft3d simulation, assuming shallow water flow and bedload transport predicted by the Gaeuman et al. (2009) formula.

topography, which is the only gradient used to drive flow routing. By neglecting the higher-order terms of Navier–Stokes equations present in the SWE model, the bed topography sensitivity of the kinematic routing scheme drives flow out of the main anabranches, leading to highly dispersive routing patterns. It should be noted that cellular automata schemes that include higher-order terms, and route flow in more than the downstream direction, are available (see Section 8), but it is beyond the scope of this case study to assess more than one scheme. The comparison between predicted and observed volumes of erosion and deposition from the Delf3d morphologic modelling indicates that a 2D physics-based approach is capable of behavioural simulations. This approach thus demonstrates the potential of comparing model predictions using DoDs that record morphological change during single high-flow events.

8. Conclusion

This article has presented a taxonomy of braided river morphodynamic models and evaluated them, in the context of the mechanics of braided rivers, to identify the modelling approach that encapsulates sufficient process complexity to provide behavioural reach-scale morphodynamic predictions. Of the reach-scale sediment routing models, it is a 2D physics-based approach that offers the most potential for simulating braided river morphodynamics at the temporal and spatial scales that are of interest to investigations that focus upon applied river management and understanding morphodynamics at the scale of multiple bars. At the catchment-scale, LEMs have considerably more potential than alluvial architecture models for providing external boundary conditions for reach-scale models. Progress in 2D physics-based modelling of braided river morphodynamics is dependent upon work addressing three primary modelling challenges: (i) the representation of flow processes and sediment transport; (ii) temporal and spatial scaling; and (iii) model calibration, sensitivity, uncertainty and validation. Progress towards eliminating these challenges, however, will only be made if new, high-resolution observation datasets of laboratory and natural braided river morphodynamics are acquired. The Rees River case study that is presented at the end of this article not only demonstrates the efficacy of a 2D physics-based hydraulic approach relative to a cellular automata approach but also demonstrates how multi-temporal DEMs can be used to calibrate morphodynamic simulations.

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Note

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References

Ahnert, F. (1976). Brief description of a comprehensive three-dimensional process-response model of landform development. *Zietschrift für Geomorphologie* 25(Supplementband), pp. 29–49.

Allen, J. R. L. (1978). Studies in fluviatile sedimentation: an exploratory quantitative model for architecture of avulsion-controlled alluvial suites. *Sedimentary Geology* 21, pp. 129–147.

Ashmore, P. E. (1982). Laboratory modelling of gravel braided stream morphology. *Earth Surface Processes and Landforms* 7(3), pp. 201–225.

Ashmore, P. E. (1991). How do gravel-bed rivers braid. *Canadian Journal of Earth Sciences* 28(3), pp. 326–341.

Ashmore, P. E. (2013). Morphology and dynamics of braided rivers. In: Shroder, J. F. (ed-in-chief) *Treatise on geomorphology*, Wohl, E. (ed.) Fluvial geomorphology, vol. 9. San Diego: Academic Press, pp. 289–312.

Ashmore, P. E., Bertoldi, W. and Gardner, J. T. (2011). Active width of gravel-bed braided rivers. *Earth Surface Processes and Landforms* 36(11), pp. 1510–1521.

Ashmore, P. E. and Parker, G. (1983). Confluence scour in course braided streams. *Water Resources Research* 19(2), pp. 392–402.

Bates, P. D., Lane, S. N. and Ferguson, R. I. (2005). Computational fluid dynamics modelling for environmental hydraulics. In: Bates, P. D., Lane, S. N. and Ferguson, R. I. (eds) *Computational fluid dynamics: applications in environmental hydraulics*. Chichester: Wiley, pp.1–15.

Bertoldi, W., Ashmore, P. and Tubino, M. (2009). A method for estimating the mean bed load flux in braided rivers. *Geomorphology* 103(3), pp. 330–340.

Beven, K. (2012). *Rainfall–runoff modelling: the primer*. 2nd ed. Oxford: Wiley.

Bozzi, S. and Passoni, G. (2012). Mathematical modelling of bottom evolution by particle deposition and resuspension. *Applied Mathematical Modelling* 36(9), pp. 4186–4196.

Bradbrook, K. F., Biron, P. M., Lane, S. N., Richards, K. S. and Roy, A. G. (1998). Investigation of controls on secondary circulation in a simple confluence geometry using a three-dimensional numerical model. *Hydrological Processes* 12(8), pp. 1371–1396.

Brasington, J., Langham, J. and Rumsby, B. (2003). Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. *Geomorphology* 53(3–4), pp. 299–316.

Brasington, J. and Richards, K. (2007). Reduced-complexity, physically-based geomorphological modelling for catchment and river management. *Geomorphology* 90(3–4), pp. 171–177.

Brasington, J., Rumsby, B. T. and McVey, R. A. (2000). Monitoring and modelling morphological change in a braided gravel-bed river using high resolution GPS-based survey. *Earth Surface Processes and Landforms* 25(9), pp. 973–990.

Bridge, J. S. (1993). The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers. In: Best, J. L. and Bristow, C. S. (eds) *Braided rivers*. London: Geological Society, pp.13–72.

Bridge, J. S. (2008). Numerical modelling of alluvial deposits: recent developments. In: de Boer, P., Postma, G., van der Zwan, K., Burgess, P. and Kukla, P. (eds) *Analogue and numerical modelling of sedimentary systems: from understanding to prediction*, Special Publication 40 of the International Association of Sedimentologists. Chichester: Wiley, pp.97–138.

Bridge, J. S. and Demicco, R. V. (2008). *Earth surface processes, landforms and sediment deposits*. Cambridge: Cambridge University Press.

Bursik, M., Martínez-Hackert, B., Delgado, H. and Gonzalez-Huesca, A. (2003). A smoothed-particle hydrodynamic automaton of landform degradation by overland flow. *Geomorphology* 53(1–2), pp. 25–44.

Chorley, R. J., Schumm, S. A. and Sugden, D. E. (1984). *Geomorphology*. London: Metheun.

Cleary, P. W. and Prakash, M. (2004). Discrete–element modelling and smoothed particle hydrodynamics: potential in the environmental sciences. *Philosophical Transactions of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences* 362(1822), pp. 2003–2030.

Cleary, P. W., Prakash, M. and Rothauge, K. (2010). Combining digital terrain and surface textures with large-scale particle-based computational models to predict dam collapse and landslide events. *International Journal of Image and Data Fusion* 1(4), pp. 337–357.

Cook, S. J., Quincey, D. J. and Brasington, J. (2014). Geomorphology of the Rees Valley, Otago, New Zealand. *Journal of Maps* 10(1), pp. 136–150.

Coulthard, T. J. (2001). Landscape evolution models: a software review. *Hydrological Processes* 15(1), pp. 165–173.

Coulthard, T. J., Hicks, D. M. and Van De Wiel, M. J. (2007). Cellular modelling of river catchments and reaches: advantages, limitations and prospects. *Geomorphology* 90(3–4), pp. 192–207.

Coulthard, T. J., Kirkby, M. J. and Macklin, M. G. (1998). Non-linearity and spatial resolution in a cellular automaton model of a small upland basin. *Hydrology and Earth System Sciences* 2(2/3), pp. 257–264.

Coulthard, T. J. and Macklin, M. G. (2003). Modeling long-term contamination in river systems from historical metal mining. *Geology* 31(5), pp. 451–454.

Coulthard, T. J., Macklin, M. G. and Kirkby, M. J. (2002). A cellular model of Holocene upland river basin and alluvial fan evolution. *Earth Surface Processes and Landforms* 27(3), pp. 269–288.

Coulthard, T. J., Neal, J. C., Bates, P. D., Ramirez, J., de Almeida, G. A. M. and Hancock, G. R. (2013). Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: implications for modelling landscape evolution. *Earth Surface Processes and Landforms* 38(15), pp. 1897–1906.

Coulthard, T. J. and Van De Wiel, M. J. (2007). Quantifying fluvial non linearity and finding self organized criticality? Insights from simulations of river basin evolution. *Geomorphology* 91(3–4), pp. 216–235.

Coulthard, T. J. and Van De Wiel, M. J. (2012). Modelling river history and evolution. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 370(1966), pp. 2123–2142.

Coulthard, T. J. and Van De Wiel, M. J. (2013). Numerical modeling in fluvial geomorphology. In: Shroder, J. F. (ed-in-chief) *Treatise on geomorphology*, Wohl, E. (ed.) Fluvial geomorphology, vol. 9. San Diego: Academic Press, pp. 694–710.

Crosato, A. and Mosselman, E. (2009). Simple physics-based predictor for the number of river bars and the transition between meandering and braiding. *Water Resources Research* 45, W03424.

Crosato, A. and Saleh, M. S. (2011). Numerical study on the effects of floodplain vegetation on river planform style. *Earth Surface Processes and Landforms* 36(6), pp. 711–720.

Cundall, P. A. and Strack, O. D. (1979). A discrete numerical model for granular assemblies. *Geotechnique* 29(1), pp. 47–65.

Davy, P. and Lague, D. (2009). Fluvial erosion/transport equation of landscape evolution models revisited. *Journal of Geophysical Research-Earth Surface* 114, F03007.

DHI (1999). *MIKE21C user's guide and scientific documentation*. Horsholm, Denmark: Danish Hydraulic Institute.

Di Silvio, G. and Nones, M. (2014). Morphodynamic reaction of a schematic river to sediment input changes: analytical approaches. *Geomorphology* 215, pp. 74–82.

Dietrich, W. E., Bellugi, D. G., Sklar, L. S., Stock, J. D., Heimsath, A. M. and Roering, J. J. (2003). Geomorphic transport laws for predicting landscape form and dynamics. In: Wilcock, P. R. and Iverson, R. M. (eds) *Prediction in geomorphology*. Washington, DC: AGU, pp.103–132.

Doeschl-Wilson, A. B. and Ashmore, P. E. (2005). Assessing a numerical cellular braided-stream model with a physical model. *Earth Surface Processes and Landforms* 30(5), pp. 519–540.

Einstein, H. A. (1950). The bed-load function for sediment transportation in open channel flows. *Technical Bulletin 1026*. Washington, DC: US Department of the Army, Soil Conservation Service and US Department of Agriculture.

Erwin, S. O., Schmidt, J. C., Wheaton, J. M. and Wilcock, P. R. (2012). Closing a sediment budget for a reconfigured reach of the Provo River, Utah, United States. *Water Resources Research* 48(10, W10512).

Ferguson, R. I. (1993). Understanding braiding processes in gravel-bed rivers: progress and unresolved problems. In: Best, J. L. and Bristow, C. S. (eds) *Braided rivers*. London: Geological Society, pp.73–87.

Ferguson, R. I. (2003). The missing dimension: effects of lateral variation on 1-D calculations of fluvial bedload transport. *Geomorphology* 56(1–2), pp. 1–14.

Ferguson, R. I. (2007). Gravel-bed rivers at the reach scale. In: Habersack, H. M., Piégay, H. and Rinaldi, M. (eds) *Gravel bed rivers VI: from process understanding to river restoration*. Amsterdam: Elsevier, pp.33–53.

Ferguson, R. I. and Werritty, A. (1983). Bar development and channel changes in the gravelly River Fehsie, Scotland. *International Assoication of Sedimentologists Special Publications* 6, pp. 181–193.

Fonstad, M. A. (2006). Cellular automata as analysis and synthesis engines at the geomorphology–ecology interface. *Geomorphology* 77(3–4), pp. 217–234.

Fonstad, M. A. (2013). Cellular automata in geomorphology. In: Shroder, J. F. (ed-in-chief) *Treatise on geomorphology*, Wohl, E. (ed.) Fluvial geomorphology, vol. 9. San Diego: Academic Press, pp. 117–134.

Frey, P. and Church, M. (2011). Bedload: a granular phenomenon. *Earth Surface Processes and Landforms* 36(1), pp. 58–69.

Fujita, Y. (1989). Bar and channel formation in braided streams. In: Ikeda, S. and Parker, G. (eds) *River meandering*, American Geophysical Union Water Resources Monograph, Vol. 12. Washington: AGU, pp.417–462.

Gaeuman, D., Andrews, E. D., Krause, A. and Smith, W. (2009). Predicting fractional bed load transport rates: application of the Wilcock–Crowe equations to a regulated gravel bed river. *Water Resources Research* 45(6, W06409).

Germanoski, D. and Schumm, S. A. (1993). Changes in braided river morphology resulting from aggradation and degradation. *Journal of Geology* 101, pp. 451–466.

Gingold, R. A. and Monaghan, J. J. (1977). Smoothed particle hydrodynamics-theory and application to non-spherical stars. *Monthly Notices of the Royal Astronomical Society* 181, pp. 375–389.

Gomez, B. (1991). Bedload transport. *Earth-Science Reviews* 31(2), pp. 89–132.

Gomez, B., Cui, Y., Kettner, A. J., Peacock, D. H. and Syvitski, J. P. M. (2009). Simulating changes to the sediment transport regime of the Waipaoa River, New Zealand, driven by climate change in the twenty-first century. *Global and Planetary Change* 67(3–4), pp. 153–166.

Gomez-Gesteira, M., Crespo, A. J. C., Rogers, B. D., Dalrymple, R. A., Dominguez, J. M. and Barreiro, A. (2012b). SPHysics – development of a free-surface fluid solver – part 2: efficiency and test cases. *Computers & Geosciences* 48, pp. 300–307.

Gomez-Gesteira, M., Rogers, B. D., Crespo, A. J. C., Dalrymple, R. A., Narayanaswamy, M. and Dominguez, J. M. (2012a). SPHysics – development of a free-surface fluid solver – part 1: theory and formulations. *Computers & Geosciences* 48, pp. 289–299.

Gomez-Gesteira, M., Rogers, B. D., Dalrymple, R. A. and Crespo, A. J. C. (2010). State-of-the-art of classical SPH for free-surface flows. *Journal of Hydraulic Research* 48, pp. 6–27.

Gurnell, A. M., Petts, G. E., Hannah, D. M., Smith, B. P. G., Edwards, P. J., Kollmann, J., Ward, J. V. and Tockner, K. (2001). Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. *Earth Surface Processes and Landforms* 26(1), pp. 31–62.

Gurnell, A. M., Surian, N. and Zanoni, L. (2009). Multi-thread river channels: a perspective on changing European alpine river systems. *Aquatic Sciences* 71(3), pp. 253–265.

Habersack, H. M. and Piégay, H. (2008). River restoration in the Alps and their surroundings: past experience and future challenges. In: Habersack, H. M., Piégay, H. and Rinaldi, M. (eds) *Gravel bed rivers VI: from process understanding to river restoration*. Amsterdam: Elsevier, pp.703–735.

Hajek, E. A. and Wolinsky, M. A. (2012). Simplified process modeling of river avulsion and alluvial architecture: connecting models and field data. *Sedimentary Geology* 257–260, pp. 1–30.

Hall, P. (2005). On the non-parallel instability of sediment-carrying channels of slowly varying width. *Journal of Fluid Mechanics* 529, pp. 1–32.

Hardy, R. J. (2005). Modelling granular sediment transport over water-worked gravels. *Earth Surface Processes and Landforms* 30(8), pp. 1069–1076.

Hardy, R. J. (2012). The potential of using high-resolution process models to inform parameterizations of morphodynamic models. In: Church, M., Biron, P. M. and Roy, A. G. (eds) *Gravel-bed rivers: processes, tools, environments*. Chichester: Wiley, pp.116–122.

Hardy, R. J. (2013). Process-based sediment transport modeling. In: Shroder, J. F. (ed-in-chief) *Treatise on geomorphology*, Baas, A. (ed.) Quantitative modeling of geomorphology. San Diego: Academic Press, pp. 147–159.

Hicks, D. M., Duncan, M. J., Lane, S. N., Tal, M., Westaway, R., Helmut Habersack, H. P. and Massimo, R. (2007). Contemporary morphological change in braided gravel-bed rivers: new developments from field and laboratory studies, with particular reference to the influence of riparian vegetation. In: Habersack, H. M., Piégay, H. and Rinaldi, M. (eds) *Gravel bed rivers VI: from process understanding to river restoration*. Amsterdam: Elsevier, pp.557–584.

Hicks, D. M., Shankar, U., Duncan, M. J., Rebuffé, M. and Aberle, J. (2006). Use of remote-sensing with two-dimensional hydrodynamic models to assess impacts of hydro-operations on a large, braided, gravel-bed river: Waitaki River, New Zealand. In: Sambrook Smith, G. H., Best, J. L., Bristow, C. S. and Petts, G. E. (eds) *Braided rivers: process, deposits, ecology and management*. Oxford: Blackwell, pp.311–326.

Hodge, R. A., Richards, K. and Brasington, J. (2007). A physically-based bedload transport model developed for 3-D reach-scale cellular modelling. *Geomorphology* 90(3–4), pp. 244–262.

Howard, A. D., Keetch, M. E. and Vincent, C. L. (1970). Topological and geometrical properties of braided streams. *Water Resources Research* 6, pp. 1674–1688.

Huggenberger, P. and Regli, C. (2006). A sedimentological model to characterize braided river deposits for hydrogeological applications. In: Sambrook Smith, G. H., Best, J. L., Bristow, C. S. and Petts, G. E. (eds) *Braided rivers: process, deposits, ecology and management*. Oxford: Blackwell, pp.51–74.

Ingham, D. B. and Ma, L. (2005). Fundamental equations for CFD in river flow simulations. In: Bates, P. D., Lane, S. N. and Ferguson, R. I. (eds) *Computational fluid dynamics: applications in environmental hydraulics*. Chichester: Wiley, pp.19–49.

Istanbulluoglu, E. (2009). Modeling catchment evolution: from decoding geomorphic processes signatures toward predicting impacts of climate change. *Geography Compass* 3(3), pp. 1125–1150.

Istanbulluoglu, E. and Bras, R. L. (2005). Vegetation-modulated landscape evolution: effects of vegetation on landscape processes, drainage density, and topography. *Journal of Geophysical Research, Earth Surface* 110(F2, F02012).

Jang, C. L. and Shimizu, Y. (2005). Numerical simulation of relatively wide, shallow channels with erodible banks. *Journal of Hydraulic Engineering* 131(7), pp. 565–575.

Jerolmack, D. J. and Paola, C. (2007). Complexity in a cellular model of river avulsion. *Geomorphology* 91(3–4), pp. 259–270.

Jirka, G. H. and Uijttewaal, W. S. (2004). Shallow flows: a definition. In: Jirka, G. H. and Uijttewaal, W. S. J. (eds) *Shallow flows*. London: Taylor and Francis, pp.3–14.

Jowett, I. G. and Duncan, M. J. (2012). Effectiveness of 1D and 2D hydraulic models for instream habitat analysis in a braided river. *Ecological Engineering* 48, pp. 92–100.

Keylock, C. J., Constantinescu, G. and Hardy, R. J. (2012). The application of computational fluid dynamics to natural river channels: eddy resolving versus mean flow approaches. *Geomorphology* 179, pp. 1–20.

Keylock, C. J., Hardy, R. J., Parsons, D. R., Ferguson, R. I., Lane, S. N. and Richards, K. S. (2005). The theoretical foundations and potential for large-eddy simulation (LES) in fluvial geomorphic and sedimentological research. *Earth-Science Reviews* 71(3–4), pp. 271–304.

Kirkby, M. J. (1987). Modelling some influences of soil erosion, landslides and valley gradient on drainage density and hollow development. In: Ahnert, F. (ed) *Geomorphological models: theoretical and empirical aspects: Catena Supplement 10*. Cremlingen-Desdelt, Germany: Catena Verlag, pp.1–11.

Kleinhans, M. G. (2010). Sorting out river channel patterns. *Progress in Physical Geography* 34(3), pp. 287–326.

Koltermann, C. E. and Gorelick, S. M. (1996). Heterogeneity in sedimentary deposits: a review of structure-imitating, process-imitating, and descriptive approaches. *Water Resources Research* 32(9), pp. 2617–2658.

Krištof, P., Beneš, B., Křivánek, J. and Šťava, O. (2009). Hydraulic erosion using smoothed particle hydrodynamics. *Computer Graphics Forum* 28(2), pp. 219–228.

Krumbein, W. C. and Orme, A. R. (1972). Field mapping and computer simulation of braided-stream networks. *Geological Society of America Bulletin* 83(11), pp. 3369–3380.

Lane, S. N. (1998). Hydraulic modelling in hydrology and geomorphology: a review of high resolution approaches. *Hydrological Processes* 12(8), pp. 1131–1150.

Lane, S. N., Bradbrook, K. F., Richards, K. S., Biron, P. A. and Roy, A. G. (1999). The application of computational fluid dynamics to natural river channels: three-dimensional versus two-dimensional approaches. *Geomorphology* 29(1–2), pp. 1–20.

Lauer, J. W. (2012). The importance of off-channel sediment storage in 1-D morphodynamic modelling. In: Church, M., Biron, P. M. and Roy, A. G. (eds) *Gravel-bed rivers: processes, tools, environments*. Chichester: Wiley, pp.123–134.

Leopold, L. B. (1992). Sediment size that determines channel geometry. In: Billi, P., Hey, R. D., Thorne, C. R. and Tacconi, P. (eds) *Dynamics of gravel-bed rivers*. Chichester: Wiley, pp.297–311.

Lesser, G. R., Roelvink, J. A., van Kester, J. A. T. M. and Stelling, G. S. (2004). Development and validation of a three-dimensional morphological model. *Coastal Engineering* 51(8–9), pp. 883–915.

Li, S. S. and Millar, R. (2007). Simulating bed-load transport in a complex gravel-bed river. *Journal of Hydraulic Engineering* 133(3), pp. 323–328.

Li, S. S. and Millar, R. G. (2011). A two-dimensional morphodynamic model of gravel-bed river with floodplain vegetation. *Earth Surface Processes and Landforms* 36(2), pp. 190–202.

Liu, M. B. and Liu, G. R. (2010). Smoothed Particle Hydrodynamics (SPH): an overview and recent developments. *Archives of Computational Methods in Engineering* 17(1), pp. 25–76.

Lotsari, E., Thorndycraft, V. and Alho, P. (2015). Prospects and challenges of simulating river channel response to future climate change. *Progress in Physical Geography* 39(4), pp. 483–513.

Lotsari, E., Wainwright, D., Corner, G. D., Alho, P. and Käyhkö, J. (2013). Surveyed and modelled one-year morphodynamics in the braided lower Tana River. *Hydrological Processes* 28(4), pp. 2685–2716.

MacVicar, B. J., Parrott, L. and Roy, A. G. (2006). A two-dimensional discrete particle model of gravel bed river systems. *Journal of Geophysical Research, Earth Surface* 111(F3, F03009).

Maddock, I., Harby, A., Kemp, P. and Wood, P. (2013). Hydraulic modelling approaches for ecohydraulic studies: 3D, 2D, 1D and non-numerical models. In: Tonina, D. and Jorde, K. (eds) *Ecohydraulics*. Chichester: Wiley, pp.31–74.

McArdell, B. W. and Faeh, R. (2001). A computational investigation of river braiding. In: Mosley, M. P. (ed) *Gravel-bed rivers V*. Wellington: New Zealand Hydrological Society, pp.73–86.

McEwan, I. and Heald, J. (2001). Discrete particle modeling of entrainment from flat uniformly sized sediment beds. *Journal of Hydraulic Engineering* 127(7), pp. 588–597.

Meyer-Peter, E. and Müller, R. (1948). Formulas for bedload transport. *Proceedings of the 2nd Meeting of the International Association for Hydraulic Research*, International Association of Hydraulic Engineering and Research, Madrid, Stockholm, Sweden, 6 July 1948, pp. 39–64.

Monaghan, J. J. (1994). Simulating free surface flows with SPH. *Journal of Computational Physics* 110(2), pp. 399–406.

Mosselman, E. (2005). Basic equations for sediment transport in CFD for fluvial morphodynamics. In: Bates, P. D., Lane, S. N. and Ferguson, R. I. (eds) *Computational fluid dynamics: applications in environmental hydraulics*. Chichester: Wiley, pp.71–89.

Mosselman, E. (2012). Modelling sediment transport and morphodynamics of gravel-bed rivers. In: Church, M., Biron, P. M. and Roy, A. G. (eds) *Gravel-bed rivers: processes, tools, environments*. Chichester: Wiley, pp.101–115.

Mueller, E. R. and Pitlick, J. (2014). Sediment supply and channel morphology in mountain river systems: 2. Single thread to braided transitions. *Journal of Geophysical Research, Earth Surface* 119(7), pp. 1516–1541.

Mulligan, M. and Wainwright, D. (2013). Modelling and model building. In: Wainwright, D. and Mulligan, M. (eds) *Environmental modelling: finding simplicity in complexity*. Chichester: Wiley-Blackwell, pp.7–26.

Murray, A. B. (2003). Contrasting the goals, strategies, and predictions associated with simplified numerical models and detailed simulations. In: Wilcock, P. R. and Iverson, R. M. (eds) *Prediction in geomorphology*. Washington, DC: American Geophysical Union, pp.151–165.

Murray, A. B. (2007). Reducing model complexity for explanation and prediction. *Geomorphology* 90(3–4), pp. 178–191.

Murray, A. B. and Fonstad, M. A. (2007). Preface: complexity (and simplicity) in landscapes. *Geomorphology* 91(3–4), pp. 173–177.

Murray, A. B. and Paola, C. (1994). A cellular model of braided rivers. *Nature* 371, pp. 54–57.

Murray, A. B. and Paola, C. (1996). A new quantitative test of geomorphic models, applied to a model of braided streams. *Water Resources Research* 32(8), pp. 2579–2587.

Murray, A. B. and Paola, C. (1997). Properties of a cellular braided-stream model. *Earth Surface Processes and Landforms* 22(11), pp. 1001–1025.

Nabi, M., de Vriend, H. J., Mosselman, E., Sloff, C. J. and Shimizu, Y. (2013). Detailed simulation of morphodynamics: 2. Sediment pick-up, transport and deposition. *Water Resources Research* 49(8), pp. 4775–4791.

Néelz, S. and Pender, G. (2010). *Benchmarking of 2D hydraulic modelling packages*. Bristol: Environment Agency.

Nelson, J. M., Bennett, J. P. and Wiele, S. M. (2005). Flow and sediment-transport modeling. In: Kondolf, G. M. and Piégay, H. (eds) *Tools in fluvial geomorphology*. Chichester: Wiley, pp.539–576.

Nicholas, A. P. (2000). Modelling bedload yield in braided gravel bed rivers. *Geomorphology* 36(1–2), pp. 89–106.

Nicholas, A. P. (2009). Reduced-complexity flow routing models for sinuous single-thread channels: intercomparison with a physically-based shallow-water equation model. *Earth Surface Processes and Landforms* 34(5), pp. 641–653.

Nicholas, A. P. (2013a). Modelling the continuum of river channel patterns. *Earth Surface Processes and Landforms* 38(10), pp. 1187–1196.

Nicholas, A. P. (2013b). Morphodynamic diversity of the world's largest rivers. *Geology* 41(4), pp. 475–478.

Nicholas, A. P. (2013c). Morphodynamic modeling of rivers and floodplains. In: Shroder, J. F. (ed-in-chief) *Treatise on geomorphology*, Wohl, E. (ed.) Fluvial geomorphology, vol. 9. San Diego: Academic Press, pp. 160–179.

Nicholas, A. P. and Quine, T. A. (2007). Crossing the divide: representation of channels and processes in reduced-complexity river models at reach and landscape scales. *Geomorphology* 90(3–4), pp. 318–339.

Nicholas, A. P. and Sambrook Smith, G. H. (1999). Numerical simulation of three-dimensional flow hydraulics in a braided channel. *Hydrological Processes* 13(6), pp. 913–929.

Nicholas, A. P., Sandbach, S. D., Ashworth, P. J., Amsler, M. L., Best, J. L., Hardy, R. J., Lane, S. N., Orfeo, O., Parsons, D. R., Reesink, A. J. H., Sambrook Smith, G. H. and Szupiany, R. N. (2012). Modelling hydrodynamics in the Rio Paraná, Argentina: an evaluation and inter-comparison of reduced-complexity and physics based models applied to a large sand-bed river. *Geomorphology* 169–170, pp. 192–211.

Niño, Y., Atala, A., Barahona, M. and Aracena, D. (2002). Discrete particle model for analyzing bedform development. *Journal of Hydraulic Engineering* 128(4), pp. 381–389.

Odoni, N. A. and Lane, S. (2011). The significance of models in geomorphology: from concepts to experiments. In: Gregory, K. J. and Goudie, A. S. (eds) *The SAGE handbook of geomorphology*. London: SAGE, pp.154–173.

Paola, C. (1996). Incoherent structure: turbulence as a metaphor for stream braiding. In: Ashworth, P. J., Bennett, S. J., Best, J. L. and McLelland, S. J. (eds) *Coherent flow structures in open channels*. Chichester: Wiley, pp.705–723.

Paola, C. (2001). Modelling stream braiding over a range of scales. In: Mosley, M. P. (ed) *Gravel-bed rivers V*. Wellington, New Zealand: New Zealand Hydrological Society, pp.11–38.

Paola, C., Heller, P. L. and Angevine, C. L. (1992). The large-scale dynamics of grain-size variation in alluvial basins, 1: theory. *Basin Research* 4(2), pp. 73–90.

Paola, C., Parker, G., Mohrig, D. C. and Whipple, K. X. (1999). The influence of transport fluctuations on spatially averaged topography on a sandy, braided fluvial plain. In: Harbaugh, J. W., Watney, W. L., Rankey, E., Slingerland, R. and Franseen, E. (eds) *Numerical experiments in stratigraphy: recent advances in stratigraphic and sedimentologic computer simulations*. Oklahoma, Tulsa: Society for Sedimentary Geology, pp. 211–218.

Papanicolaou, A. N., Elhakeem, M., Krallis, G., Prakash, S. and Edinger, J. (2008). Sediment transport modeling review – current and future developments. *Journal of Hydraulic Engineering* 134(1), pp. 1–14.

Parker, G. (1976). On the cause and characteristic scales of meandering and braiding in rivers. *Journal of Fluid Mechanics* 76(3), pp. 457–480.

Parker, G., Muto, T., Akamatsu, Y., Dietrich, W. E. and Wesley Lauer, J. (2008). Unravelling the conundrum of river response to rising sea-level from laboratory to field. Part II. The Fly–Strickland River system, Papua New Guinea. *Sedimentology* 55(6), pp. 1657–1686.

Parsons, J. A. and Fonstad, M. A. (2007). A cellular automata model of surface water flow. *Hydrological Processes* 21(16), pp. 2189–2195.

Pelletier, J. D. (2004). Persistent drainage migration in a numerical landscape evolution model. *Geophysical Research Letters* 31(20, L20501).

Ramanathan, R., Guin, A., Ritzi, R. W., Dominic, D. F., Freedman, V. L., Scheibe, T. D. and Lunt, I. A. (2010). Simulating the heterogeneity in braided channel belt deposits: 1. A geometric-based methodology and code. *Water Resources Research* 46(4, W04515).

Rennie, C. D. (2012). Mapping water and sediment flux distributions in gravel-bed rivers using ADCPs. In: Church, M., Biron, P. M. and Roy, A. G. (eds) *Gravel-bed rivers: processes, tools, environments*. Chichester: Wiley, pp.342–350.

Richards, K., Bithell, M., Dove, M. and Hodge, R. (2004). Discrete–element modelling: methods and applications in the environmental sciences. *Philosophical Transactions of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences* 362(1822), pp. 1797–1816.

Sapozhnikov, V. B., Murray, A. B., Paola, C. and Foufoula-Georgiou, E. (1998). Validation of braided-stream models: spatial state–space plots, self-affine scaling, and island shapes. *Water Resources Research* 34(9), pp. 2353–2364.

Schmeeckle, M. W. and Nelson, J. M. (2003). Direct numerical simulation of bedload transport using a local, dynamic boundary condition. *Sedimentology* 50(2), pp. 279–301.

Schumm, S. A. (1977). *The fluvial system*. New York: Wiley.

Shimizu, Y. and Itakura, T. (1989). Calculation of bed variation in alluvial channels. *Journal of Hydraulic Engineering* 115(3), pp. 367–384.

Siviglia, A., Stecca, G., Vanzo, D., Zolezzi, G., Toro, E. F. and Tubino, M. (2013). Numerical modelling of two-dimensional morphodynamics with applications to river bars and bifurcations. *Advances in Water Resources* 52, pp. 243–260.

Slingerland, R. and Syvitski, J. P. M. (2013) A community approach to modeling earth- and seascapes. In: Shroder, J. F. (ed-in-chief) *Treatise on geomorphology*, Baas, A. (ed.) Quantitative modeling of geomorphology. San Diego: Academic Press, pp. 44–49.

Spasojevic, M. and Holly, F. M. (2008). Two- and three-dimensional numerical simulation of mobile-bed hydrodynamics and sedimentation. In: Garcia, J. J. G. (ed) *Sedimentation engineering*. Reston, VA: American Society of Civil Engineers, pp.683–761.

Syme, W. J. (1991). Dynamically linked two-dimensional/one-dimensional hydrodynamic modelling program for rivers, estuaries and coastal waters. Masters of Engineering Science, Department of Civil Engineering, the University of Queensland.

Syvitski, J. P. M., Slingerland, R. L., Burgess, P., Meiburg, E., Murray, A. B., Wiberg, P., Tucker, G. and Voinov, A. A. (2009). Morphodynamic models: an overview. In: Vionnet, C., Garcia, M. H., Latrubess, E. M. and Perillo, G. M. E. (eds) *River, coastal and estuarine morphodynamics*. Santa Fe City, Argentina: Taylor and Francis, pp.3–20.

Takebayashi, H. and Okabe, T. (2009). Numerical modelling of braided streams in unsteady flow. *Proceedings of the Institution of Civil Engineers–Water Management* 162(3), pp. 189–198.

Tal, M., Gran, K., Murray, A. B., Paola, C. and Hicks, D. M. (2004). Riparian vegetation as a primary control on channel characteristics in multi-thread rivers. *Riparian Vegetation and Fluvial Geomorphology* 8, pp. 43–58.

Tetzlaff, D. M. (1991). The combined use of sedimentary process modeling and statistical simulation in reservoir characterization. Paper presented at the *SPE Annual Technical Conference and Exhibition*.

Tetzlaff, D. M. and Harbaugh, J. W. (1989). *Simulating clastic sedimentation*. New York: Van Nostrand Reinhold.

Thomas, W. A. and Chang, H. (2008). Computational modeling of sedimentation processes. In: Garcia, J. J. G. (ed) *Sedimentation engineering*. Reston, VA: American Society of Civil Engineers, pp.649–681.

Thomas, R. and Nicholas, A. P. (2002). Simulation of braided river flow using a new cellular routing scheme. *Geomorphology* 43(3–4), pp. 179–195.

Thomas, R., Nicholas, A. P. and Quine, T. A. (2007). Cellular modelling as a tool for interpreting historic braided river evolution. *Geomorphology* 90(3–4), pp. 302–317.

Thorne, C., Wallerstein, N., Soar, P., Brookes, A., Wishart, D., Biedenharn, D., Gibson, S., Little, C., Mooney, D., Watson, C. C., Green, T. and Coulthard, T. (2010). Accounting for sediment in flood risk management. In: Pender, G. and Faulkner, H. (eds) *Flood risk science and management*. Chichester: Wiley-Blackwell, pp.87–113.

Tucker, G. E. and Bras, R. L. (2000). A stochastic approach to modeling the role of rainfall variability in drainage basin evolution. *Water Resources Research* 36(7), pp. 1953–1964.

Tucker, G. E. and Hancock, G. R. (2010). Modelling landscape evolution. *Earth Surface Processes and Landforms* 35(1), pp. 28–50.

Tucker, G. E. and Slingerland, R. L. (1994). Erosional dynamics, flexural isostasy, and long-lived escarpments: a numerical modeling study. *Journal of Geophysical Research, Solid Earth* 99(B6), pp. 12229–12243.

Vacondio, R., Rogers, B. D., Stansby, P. K., Mignosa, P. and Feldman, J. (2013). Variable resolution for SPH: a dynamic particle coalescing and splitting scheme. *Computer Methods in Applied Mechanics and Engineering* 256, pp. 132–148.

Van De Wiel, M. J. and Coulthard, T. J. (2010). Self-organized criticality in river basins: challenging sedimentary records of environmental change. *Geology* 38(1), pp. 87–90.

Van De Wiel, M. J., Coulthard, T. J., Macklin, M. G. and Lewin, J. (2011). Modelling the response of river systems to environmental change: progress, problems and prospects for palaeo-environmental reconstructions. *Earth-Science Reviews* 104(1–3), pp. 167–185.

van der Beek, P. (2013). Modelling landscape evolution. In: Wainwright, J. and Mulligan, M. (eds) *Environmental modelling: finding simplicity in complexity*. Chichester: Wiley, pp.309–331.

Van Dyke, C. (2013). Channels in the making – an appraisal of channel evolution models. *Geography Compass* 7(11), pp. 759–777.

Verhaar, P. M., Biron, P. M., Ferguson, R. I. and Hoey, T. B. (2008). A modified morphodynamic model for investigating the response of rivers to short-term climate change. *Geomorphology* 101(4), pp. 674–682.

Webb, E. K. (1994). Simulating the 3-dimensional distribution of sediment units in braided-stream deposits. *Journal of Sedimentary Research Section B-Stratigraphy and Global Studies* 64(2), pp. 219–231.

Webb, E. K. (1995). Simulation of braided channel topology and topography. *Water Resources Research* 31(10), pp. 2603–2611.

Webb, E. K. and Anderson, M. P. (1996). Simulation of preferential flow in three-dimensional, heterogeneous conductivity fields with realistic internal architecture. *Water Resources Research* 32(3), pp. 533–545.

Werner, B. T. (1999). Complexity in natural landform patterns. *Science* 284, pp. 102–104.

Wheaton, J. M., Brasington, J., Darby, S. E., Kasprak, A., Sear, D. and Vericat, D. (2013). Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river. *Journal of Geophysical Research, Earth Surface* 118(2), pp. 759–779.

Wilcock, P. R., Pitlick, J. and Cui, Y. (2009). Sediment transport primer: estimating bed-material transport in gravel-bed rivers. *General Technical Report RMRS-GTR-226*. Fort Collins, CO: United States Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Willgoose, G. R., Bras, R. L. and Rodríguez-Iturbe, I. (1991a). A coupled channel network growth and hillslope evolution model: 1. Theory. *Water Resources Research* 27(7), pp. 1671–1684.

Willgoose, G. R., Bras, R. L. and Rodríguez-Iturbe, I. (1991b). Results from a new model of river basin evolution. *Earth Surface Processes and Landforms* 16(3), pp. 237–254.

Williams, R. D. (2012). DEMs of difference. In: Clarke, L. E. (ed) *Geomorphological techniques*. Online ed. London, United Kingdom: British Society for Geomorphology.

Williams, R. D., Brasington, J., Hicks, M., Measures, R., Rennie, C. D. and Vericat, D. (2013). Hydraulic validation of two-dimensional simulations of braided river flow with spatially continuous aDcp data. *Water Resources Research* 49(9), pp. 5183–5205.

Williams, R. D., Brasington, J., Vericat, D. and Hicks, D. M. (2014). Hyperscale terrain modelling of braided rivers: fusing mobile terrestrial laser scanning and optical bathymetric mapping. *Earth Surface Processes and Landforms* 39(2), pp. 167–183.

Williams, R. D., Brasington, J., Vericat, D., Hicks, D. M., Labrosse, F. and Neal, M. (2011). Monitoring braided river change using terrestrial laser scanning and optical bathymetric mapping. In: Smith, M., Paron, P. and Griffiths, J. (eds) *Geomorphological mapping: methods and applications*. Amsterdam: Elsevier, pp.507–532.

Williams, R. D., Rennie, C. R., Brasington, J., Hicks, D. M. and Vericat, D. (2015). Within-event spatially distributed bed material transport: linking apparent bedload velocity to morphological change. *Journal of Geophysical Research, Earth Surface* 120(3), pp. 604–622.

Wolfram, S. (2002). *A new kind of science*. Champaign, IL: Wolfram Media.

Wright, N. G. and Hargreaves, D. M. (2013). Environmental applications of computational fluid dynamics. In: Wainwright, D. and Mulligan, M. (eds) *Environmental modelling: finding simplicity in complexity*. Chichester: Wiley-Blackwell, pp.91–109.

Wu, W. (2008). *Computational river dynamics*. London: Taylor & Francis.

Xia, J. Q., Wang, Z. B., Wang, Y. P. and Yu, X. (2013). Comparison of morphodynamic models for the Lower Yellow River. *Journal of the American Water Resources Association* 49(1), pp. 114–131.

Young, D. (2013). *Rivers: New Zealand's shared legacy*. Auckland: Random House New Zealand.

Zen, S., Zolezzi, G. and Tubino, M. (2014). A theoretical analysis of river bars stability under changing channel width. *Advances in Geosciences* 39, pp. 27–35.

Zhang, X., Drake, N. A. and Wainwright, J. (2013). Spatial modelling and scaling issues. In: Wainwright, J. and Mulligan, M. (eds) *Environmental modelling: finding simplicity in complexity*. Chichester: Wiley, pp.69–90.

Ziliani, L., Surian, N., Coulthard, T. J. and Tarantola, S. (2013). Reduced-complexity modeling of braided rivers: assessing model performance by sensitivity analysis, calibration and validation. *Journal of Geophysical Research, Earth Surface* 118(4), pp. 2243–2262.

Zolezzi, G., Bertoldi, W. and Tubino, M. (2012). Morphodynamics of bars in gravel-bed rivers: bridging analytical models and field observations. In: Church, M., Biron, P. M. and Roy, A. G. (eds) *Gravel-bed rivers: processes, tools, environments*. Chichester: Wiley, pp.69–89.

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