A SIMPLIFIED MORPHODYNAMIC MODEL FOR GRAVEL-BED RIVERS

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Abstract: The evolution of gravel-bed rivers has major implications for the management and restoration of these streams and their associated aquatic habitat. This is particularly true in braided rivers, where abundant sediment supply and rapid fluctuations in streamflow lead to a high degree of dynamism. Because channel evolution frequently results from decadal to centennial scale forcings such as shifts in water or sediment supply, these timescales of change often preclude field-based measurement of channel morphodynamics. One potential alternative to field-based observation is numerical modeling. However, no morphodynamic model for gravel-bed rivers exists that can predict channel evolution at relevant spatiotemporal scales (e.g. decadal to centennial timescales at bar-scale resolution). Here we present a new event-based morphodynamic model that couples hydraulics driven by computational fluid dynamics with a simplified sediment routing algorithm based on sediment travel distances derived from field and laboratory data. This model efficiently quantifies morphodynamics at spatiotemporal scales coincident with those of channel change. Sediment travel distances, or path lengths, are estimated using morphologic unit spacing in modeled channels. We validate this model using high-resolution laboratory flume and field data collected annually on braided rivers. This morphodynamic model closes a longstanding knowledge gap in our ability to predict channel response at meaningful spatiotemporal scales. When used as a scenario-based exploration tool for predicting channel response to altered hydrologic or sediment regimes, it may provide valuable guidance for the management and restoration of gravel-bed rivers.

INTRODUCTION

Some of the most commonly studied processes in riverine environments occur over time and space scales that render traditional field-based observation impractical or impossible [Gurnell et al., 2009]. These fluvial dynamics include channel migration [Hooke, 1995; Black et al., 2010], shifts in channel form [Landon et al., 1998; Kondolf et al., 2002], and alterations in hydrology and/or sediment delivery [Kondolf, 1997; Montgomery and Buffington, 1998; Grams and Schmidt, 2005]. All of these dynamics occur frequently on timescales ranging from decades to centuries, and channel response to hydrologic and sediment regime shifts may manifest across a variety of spatial scales ranging from individual channel units (e.g. meters) to reaches spanning several kilometers. In such instances where the spatiotemporal scale of channel response renders field-based methods of observation intractable, representation of the fluvial environment using numerical models is invaluable both in terms of disentangling the relative efficacy of competing processes acting to shape channels and predicting future channel response to geomorphic forcings [Nicholas, 2005; Gurnell et al., 2012].

Despite the immense value of numerical models in the explanation and prediction of fluvial processes, the timescales at which channel evolution occurs render most available morphodynamic models (those which predict changes in channel form over time) impractical. Historically, one way of dealing with this problem has been to simplify the physics involved in modeling, giving rise to the so-called ‘reduced complexity’ or 'cellular automata' models [RC/CA; Murray and Paola, 1994; Coulthard et al., 2002; Thomas and Nicholas, 2002]. These models simplify the transport of water and sediment across a cellular network representing the riverscape using a rule set governing each process involved. Because these rule sets are simplified representations of the physics involved in hydrodynamics and sediment transport, RC

models achieve a great deal of computational efficiency, allowing calculations over large spatiotemporal extents (e.g. kilometer-scale, decadal-to-centennial timescales; Nicholas and Quine, 2007; Thomas et al., 2007). Yet this computational efficiency comes at the expense of field realism; because of the simplified nature of the physical processes, particularly the inability to conserve hydraulic momentum leading to inaccurate representation of pool dynamics and meander migration [Nicholas and Quine, 2007], reduced complexity models often fail to reproduce observed channel behavior at the spatial scales of change.

On the other hand, the subset of morphodynamic models driven by computational fluid dynamics (CFD; Bates et al., 2005) involve hydrodynamic components that approximate the solution of the Navier-Stokes Equations and subsequently drive sediment transport. To ensure computational stability, morphodynamics are typically computed by solving a form of the Exner equation (1) of sediment continuity (Paola and Voller, 2005) at fine time steps (seconds-minutes). The Exner equation predicts bed elevation change over time ($\partial z/\partial t$) as a function of sediment porosity γ_p) and the spatio-temporal divergence of sediment flux (∇Qs). This reliance on rapid calculation of morphodynamic evolution comes at the cost of vastly increased computational overhead, making CFD-driven morphodynamic models suitable only over fine spatiotemporal scales for most users (e.g. hours-months at meter-scale resolution; Ferguson, 2007; Coulthard and Van de Wiel, 2012).

$$\frac{\partial z}{\partial t} = \frac{1}{1-\gamma_p}\left(\frac{\partial V_s}{\partial t} + \nabla \cdot Q_s\right) \tag{1}$$

We hypothesize that the fusion of CFD and RC-based morphodynamic modeling may present a novel way forward, in that the high spatial fidelity afforded by CFD-driven models may be coupled with a simplified, empirically-derived rule set for sediment transport and morphodynamic channel evolution (cf. Nicholas and Quine, 2007). As such, this paper presents a new, hybrid morphodynamic model termed the *Model of Riverine PHyiscal form and Ecohydromorphic Dynamics (MoRPHED.)*

THE MODEL

As with previously-developed morphodynamic models, MoRPHED contains routines for simulating hydrodynamics and uses these calculations to drive sediment transport. This section details the methods used in in each of these components, along with ancillary routines such as the parameterization of model boundaries, sediment grain size, and bank erosion. A flowchart of model operation along with required/optional inputs and outputs are shown in Figure 1, and these components are discussed throughout this section. The salient components of the model that directly impact our validation results are discussed here.

Hydraulic Model: The hydraulic component of MoRPHED is driven using the freely-available, open-source Delft3D software (Version 4.00.01, Deltares, Delft, Netherlands). Delft3D solves the shallow-water form of the Navier-Stokes equations, and herein we employed the model in two-dimensional (depth-averaged) form, as this provided an ideal compromise between computational efficiency and the ability to resolve hydraulics at the scale of our DEMs [Lane et al., 1999]. For all modeling, we employed Cartesian orthogonal grids generated using the RGFGRID module of the Delft3D suite and kept constant throughout a modeled event series, and adjusted the model time step to satisfy the Courant-Friedrichs-Levy condition. Models were run at a steady upstream discharge and were allowed to run to steady state (no observed change in depth, velocity, or inundation extent in QUICKPLOT model postprocessor).

For all simulations, discharge was specified at the upstream boundary and a corresponding water surface elevation was set at the downstream boundary. Delft3D requires an input DEM, along with simulated water discharge and boundary conditions. The downstream water surface elevation for each modeled

discharge was used to parameterize the hydraulic model boundary, and was calculated by determining reach-scale conveyance associated with reach-average slope and roughness [cf. USACE, 2010]. Although numerous hydraulic variables can be computed and exported from Delft3D, here we used (a) water depth, (b) flow velocity resolved into streamwise and lateral components, and (c) bed shear stress.

MoRPHED is an event-scale model, predicting channel evolution at the scale of individual floods. We do this for two reasons, (a) because the calculation of morphodynamics at coarser intervals allows for greatly reduced computational overhead associated with the model, and (b) because we argue that modeling at finer intervals, while allowing the ability to capture rapid transient events such as prograding bedload sheets and bank retreat during the course of a single flood, is difficult if not impossible to validate since the most common data geomorphologists have describe channel form only before and after a single event [Bertoldi et al., 2010; Williams et al., 2013; Mueller et al., 2014] along with sediment transport resulting from that event [Pyrce and Ashmore, 2003a, 2003b; Snyder et al., 2009; Kasprak et al., 2015].

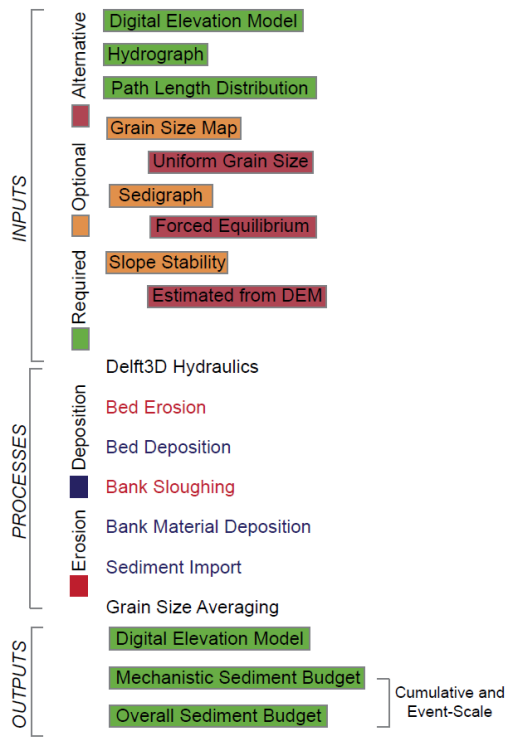

Figure 1 Flowchart of modules included in MoRPHED and their operation

<u>Sediment Entrainment:</u> MoRPHED employs a critical nondimensional value of the bed shear stress (Shields stress) to determine whether sediment can be entrained at a particular location. As our model is developed and used on gravel-bed rivers, the theory and threshold values of Shields stress for entrainment have been well studied in these settings. Incipient motion for gravel occurs when the Shields stress (τ^*) exceeds 0.03-0.07 [Buffington and Montgomery, 1997; Snyder et al., 2009]:

$$\tau^* = \frac{\tau_B}{(\rho_s - \rho)gD} \tag{2}$$

where ρ_s is sediment density (2650 kg/m^3), g is acceleration due to gravity, and D is the median particle size (see Section 2.4). The bed shear stress (τ_B) was computed using the output from Delft3D.

[Montgomery et al., 1996] proposed an event-scale model to predict sediment scour depth (D_s):

$$D_s = \frac{Q_b}{u_b \rho_s (1-\gamma)} \tag{3}$$

where Q_b is the average bedload transport rate during the event, u_b is the bedload velocity, and γ is the bed sediment porosity. Estimating Q_b, while straightforward, is often inaccurate as it is a strongly nonlinear process; however, most transport relations take a power-law form (e.g. Meyer-Peter Müeller equation):

$$Q_b = (\tau_b - \tau_{bC})^{1.5} \tag{4}$$

where the critical bed shear stress is given for a particular grain size by rearrangement of Equation 2. Bedload velocity is calculated via an equation of the form:

$$U_b = a(u_* - u_{*C}) \tag{5}$$

where u_*, the shear velocity, is computed as

$$u_* = \sqrt{\frac{\tau}{\rho}} \tag{6}$$

Which can be estimated directly from the bed shear stress obtained from Delft3D. The constant a in Equation 6 has been studied by many researchers [Garcia, 2008], and is generally around 9.

Sediment Transport and Deposition: Once entrained, sediment is mobilized downstream along flowlines which are delineated using velocity components from Delft3D to calculate velocity vectors.

At each cell along the flowpath, the volume of sediment to be deposited is given by a path length distribution (Figure 2). In the simplest sense, this distribution details the proportion of all eroded sediment which is deposited at a particular distance downstream. These distributions have been studied by numerous researchers and found to take several forms in braided rivers. Exponential decay, or heavy-tailed distributions (Figure 2A) are marked by a large number of particles that are mobilized short distances downstream, and may result from floods that do not generate sufficient shear stress for particle transport across the braidplain [Pyrce and Ashmore, 2003a, 2003b]. During floods which are competent across large areas of the braidplain, typical path length distributions exhibit peaks which correspond to the location of likely depositional sites downstream (Figures 2B, 2C). Kasprak et al. [2015] and Pyrce and Ashmore [2003a, 2003b] both noted that these depositional sites were most frequently the location of bar heads (e.g. flow diffluences; those places where one anabranch splits into multiple channels). As such particle path length distributions could be readily constructed using morphometric indices which described the characteristic diffluence spacing in braided channels. MoRPHED deposits sediment in cells along delineated flowpaths in a volume given by the path length distribution, which is specified by the user and can take a variety of forms in the model with chosen moment statistics (Gaussian, Exponential Decay, or any user-defined shape input using a text file).

Sediment Import and Export: For each simulated event, MoRPHED tracks the volume of sediment passing the downstream or lateral reach boundaries. In effect, export of sediment occurs when the user-specified path length distribution is longer than the flowpath delineated from a particular erosion cell. When this occurs, the remaining volume of sediment is recorded by MoRPHED as having been exported from the reach. Sediment import is user-specified and can be (a) set equal to the volume of sediment export during the preceding event (e.g. sediment equilibrium; Grams and Schmidt, 2005; Mueller et al.,

2014), (b) specified as a percent of sediment export during the preceding event, or (c) specified via a text file detailing volumetric sediment import during each event (e.g. sedigraph timeseries). Algorithmically, MoRPHED computes flowpaths from each wetted cell at the upstream reach boundary and distributes the total volume of imported sediment to each cell of each flowpath as specified in the user-input path length distribution.

MODELING SITE

The wandering gravel bedded River Feshie (Figure 3) is a tributary of the River Spey and drains 231 km^2 of mountainous, postglacial terrain. Underlain by metamorphic and igneous rocks, the basin ranges from around 230 m to 1260 m in elevation. The mean flow near the river's outlet was reported by Ferguson and Werritty [1983] as 8 m^3/s with Q_5 = 80 m3 sec^{-1}. Topographic data for the 1 km study reach of the Feshie consist of nine years of resurveys (2000, 2002-2008, 2013) comprising more than a decade of channel change using RTK-GPS (2000-2006) along with TLS and RTK-GPS fusion scans performed for three years (2007-8, 2013). Additionally, the Feshie dataset contains continuous hydrograph data (~55 years) and aerial photo records (~60 years), along with UK Ordnance Survey channel planform maps dating to 1869. The Feshie has been the site of a great deal of previous research ranging from bar morphodynamics [Ferguson and Werritty, 1983; Wheaton et al., 2013], development of riverine survey and DEM-differencing/change detection methodologies [Brasington et al., 2000; Hodge et al., 2009; Wheaton et al., 2009, 2013] and ongoing morphodynamic modeling efforts [Raj Baral et al., In Prep.]. The combination of annual resurveys capturing over a decade of channel change in combination with mapping and aerial photographs dating back over a century make the Feshie an ideal candidate with which to examine the performance of MoRPHED at annual and decadal scales.

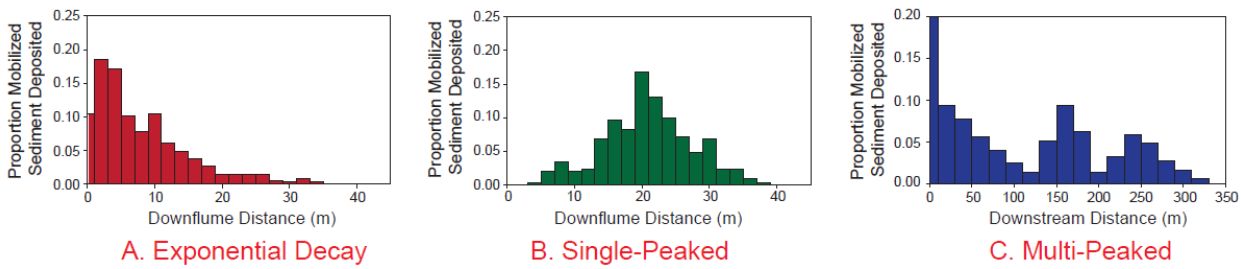

Figure 2 Example path length distributions

RESULTS AND ANALYSIS

Hydraulic Modeling and Validation: The use of Delft3D to model two-dimensional hydraulics in braided, gravel-bed rivers is discussed extensively by Williams et al., [2013], who specifically applied the model to the braided River Rees in new Zealand. As with Williams et al. [2013], the inundation extent outputs of Delft3D on the Feshie were compared with field-surveyed values and used to calibrate the model parameters (Colebrook-White roughness and horizontal eddy viscosity) until good agreement was reached.

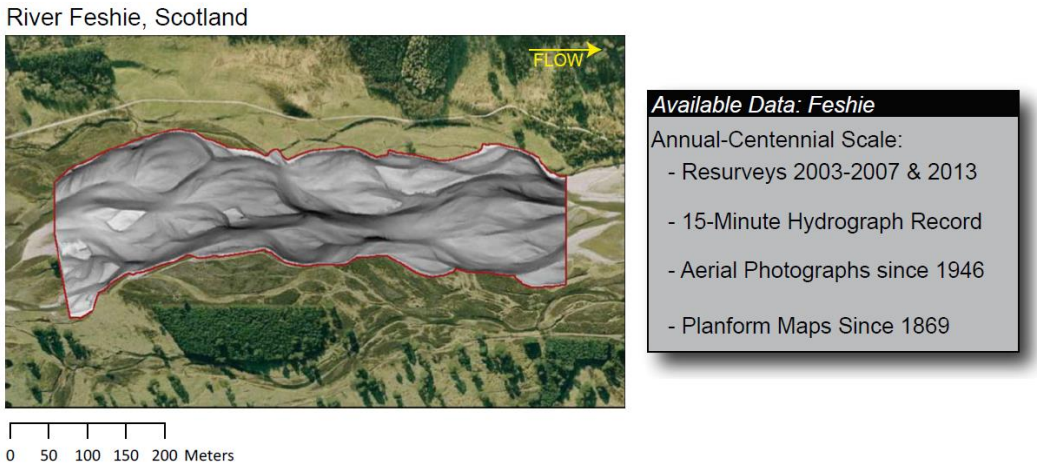

Figure 3 River Feshie modeling reach; base is a 2014 aerial photo with 1 m hillshade overlay

We leveraged existing surveys of wetted areas from 2003-2007 in concert with surveyed water depth in those years to examine the performance of Delft3D with regard to inundation extent and flow depth at randomly selected points across the braidplain. Because field surveys were conducted at low flows to facilitate rapid measurement of braidplain topography, here we are only able to validate the results of Delft3D at these low flows. However, Delft3D has been employed and validated on gravel-bed braided rivers at flood stage [Javernick, 2014], demonstrating that the model can accurately reproduce flood-stage hydraulic features and can be used to drive morphodynamic evolution at the event-scale. For modeling on the Feshie, we estimated discharge by downscaling the average observed flow for the relevant survey period at the nearest gauging station (SEPA # 8013, Feshie at Feshiebridge) located approximately 11 km downstream, using a coefficient of 0.71 [Wheaton et al., 2013]. We estimated the downstream water surface elevation using surveyed inundation extent in combination with the DEM for each year modeled. Downstream water surface elevations estimated from the spatial data were cross-checked using a reach-scale conveyance calculation [Williams et al., 2013].

Results of our validation of Delft3D on the Feshie at low flow are shown in Figure 4. Here we report (a) the mean of depth differences between modeled and observed values (D_{diff}), along with (b) the congruence of the modeled and measured inundation extents (F_c; cf. Bates and Roo, 2000) as described by the ratio of intersection and union areal extents. These two metrics are described by equations 12 and 13, respectively.

$$D_{diff} = \frac{\sum_i^n x_{mod} - x_{obs}}{n} \tag{7}$$

$$F_c = \frac{IA_{obs} \cap IA_{mod}}{IA_{obs} \cup IA_{mod}} * 100 \tag{8}$$

The validation metrics indicate that at low flow, Delft3D accurately predicted both depth and inundation extent across the Feshie study reach. Both D_{diff} and Fc are consistent with validation work performed by Williams et al., [2013], and are indicative of good agreement between hydraulic model and field-observed flow characteristics.

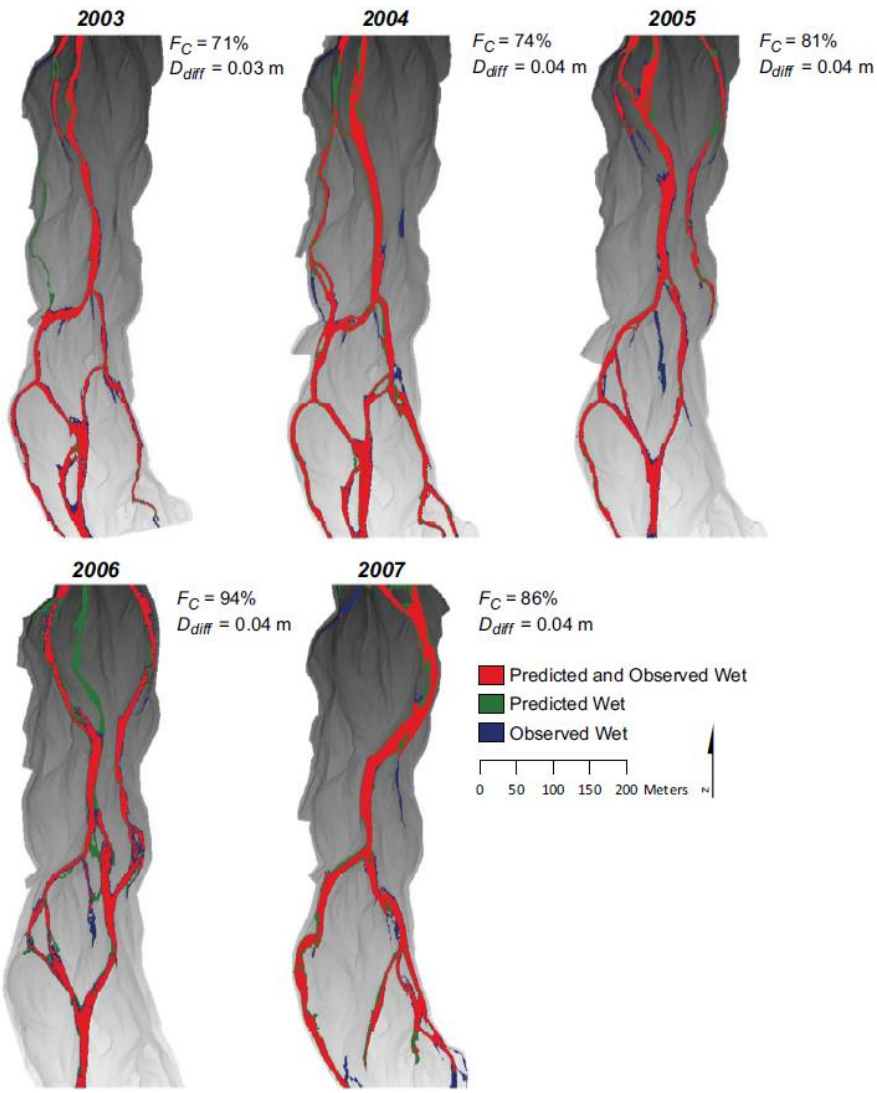

Figure 4 Hydraulic model validation on River Feshie. Mean depth of difference (D_{diff}; Equation 7) and congruence of fit (C_f; Equation 8) are shown for five years of survey data.

Morphodynamic Model Outputs: We modeled two one-year periods using MoRPHED, (a) the period between 2003 and 2004 and (b) the period between 2006 and 2007. We modeled the peak discharge of each flood over 42 m^3/s (high bankfull discharge; Wheaton et al., 2013), for a total of 5 floods in 2003-2004 and 16 floods in 2006-2007. For the hydrologic record and flood peaks over 42 m^3/s, see Wheaton et al., [2013]. We set sediment import equal to sediment export for each model run (reach-scale equilibrium; Figure 1). Though variable grain size is available in MoRPHED, a constant grain size of 0.1 m (representative D_{50} for the Feshie reach; Hodge et al., 2009) was used in these simulations. Bank erosion was not included, as refinement of process representations for lateral channel migration is ongoing. Modeled floods and resultant DEMs-of-Difference (DoDs) from the 2003-2004 and 2006-2007 model periods are shown in Figure 5 and compared with field-surveyed DoDs from the same period.

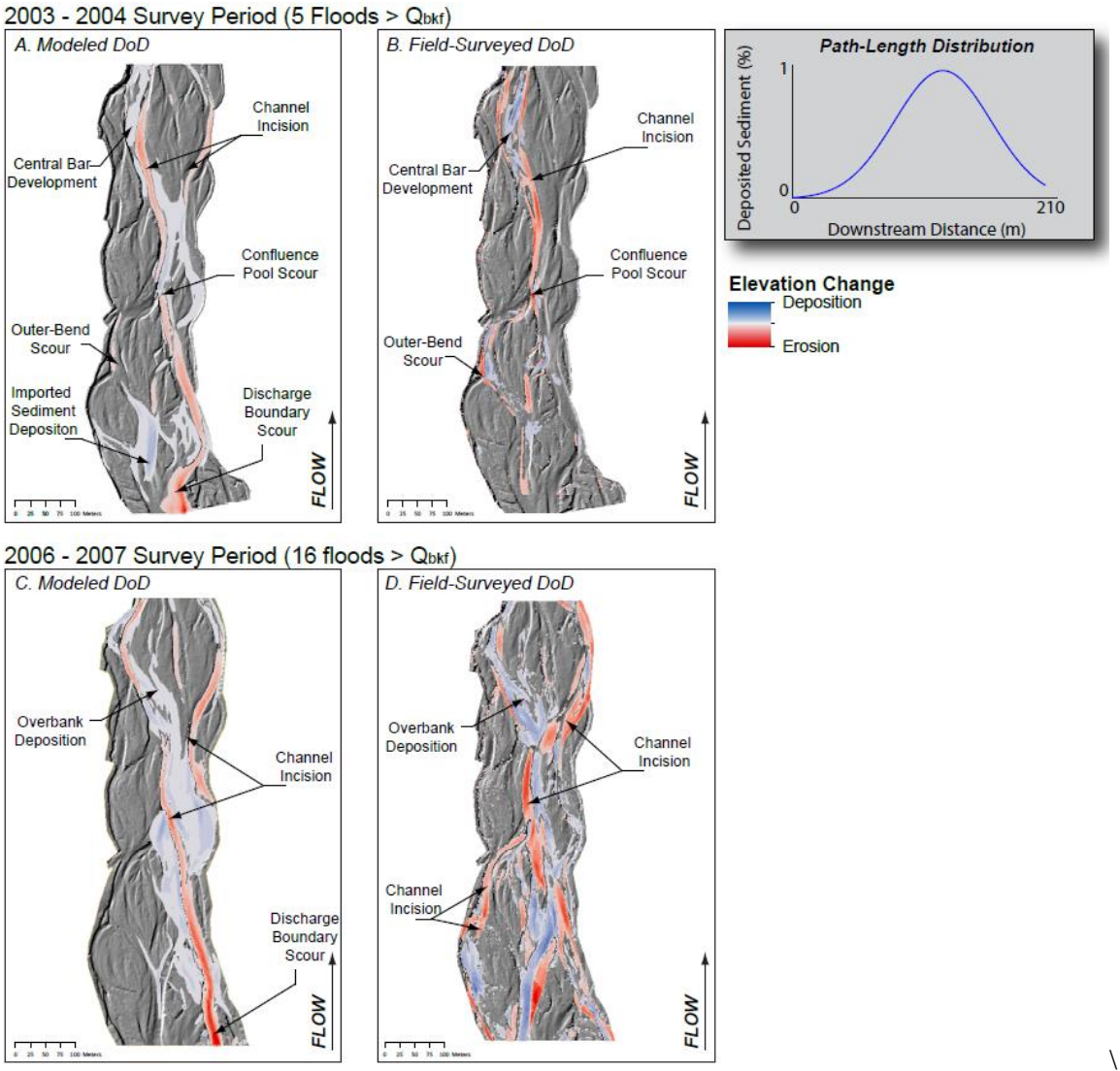

Figure 5 Modeled (A, C) and field-surveyed (B, D) geomorphic change on the River Feshie for 2003-2004 and 2005-2006 periods. DoDs are thresholded to only display geomorphic change greater than 0.1 m in magnitude.

For the 2003-2004 simulation, results of MoRPHED modeling agree reasonably well with geomorphic change observed in field surveys (Figure 6A, 6B). Continuous channel incision along the main anabranch is reproduced, along with bar edge trimming and associated deposition at the downstream end of the study reach. High-magnitude confluence pool scour is observed in both model and field surveys. However, while sediment scoured at the confluence is deposited immediately downstream in the MoRPHED simulation, this sediment appears to have been transferred further downstream (or out of the reach entirely) when examining the results of field surveys (Figure 5B).

In the 2006-2007 simulation, MoRPHED does not reproduce field-surveyed changes as well (Figure 6C, 6D). While certain areas of change are seen in both field and modeled data (e.g. channel incision and overbank deposition near the downstream end of the reach), the model does not appear to reproduce the dynamics of the numerous anabranches that underwent geomorphic change across the braidplain. We believe the simplified planform produced by MoRPHED is largely the result of not explicitly including

bank erosion in the model. As such, focused erosion leads to a largely single-thread channel planform, rather than lateral channel migration forcing avulsions and a dynamic braided channel planform [Ferguson, 2007]. Implementation of a bank erosion algorithm is an ongoing component of MoRPHED model development.

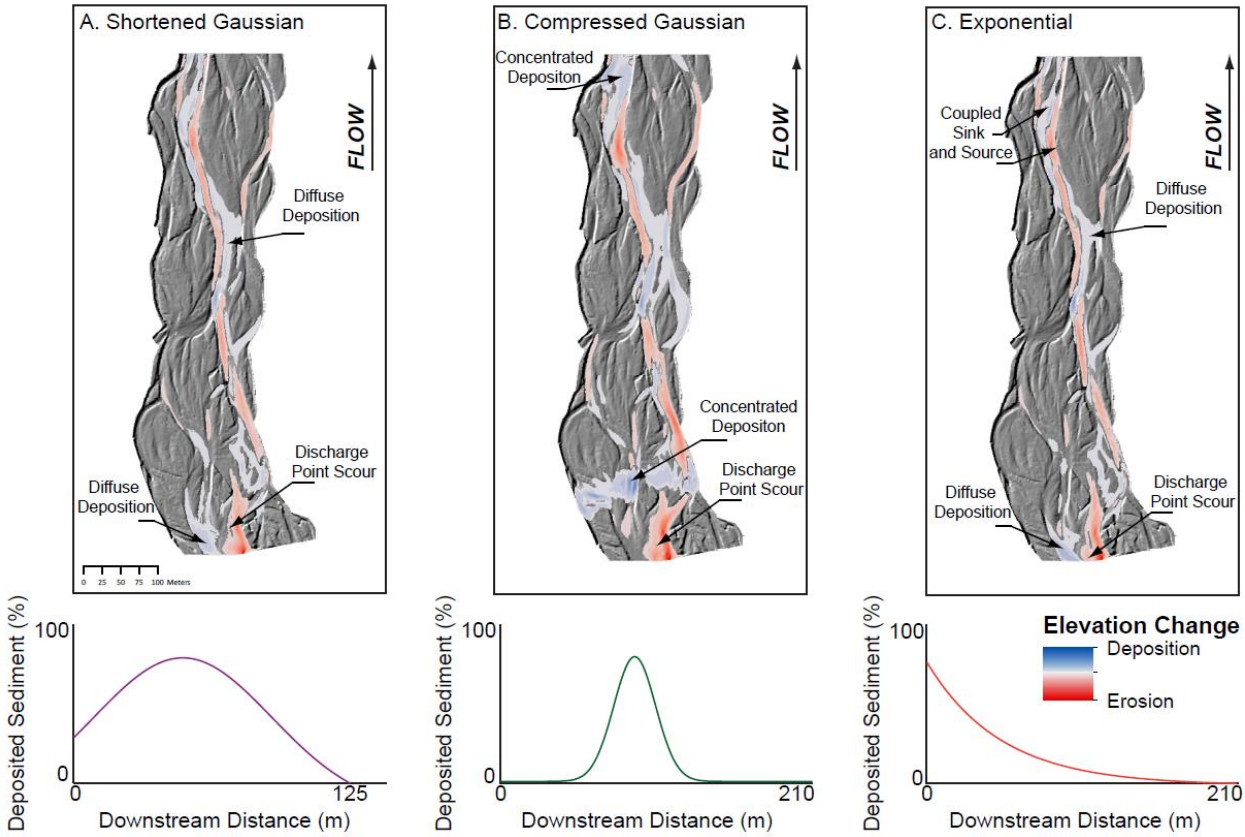

Figure 6 Results of modeling 2003-2004 period using three different path length distributions. DoDs are thresholded to only display geomorphic change greater than 0.1 m in magnitude.

In each model run, inaccuracies due to boundary effects can be observed, with high-magnitude scour at the upstream end of the reach due to channel bed erosion at water discharge points used in the Delft3D model. This scoured sediment (along with imported sediment) creates areas of deposition that were either (a) not observed in field surveys (Figure 6A, 6B), or were observed in a different anabranch than predicted by the model (Figure 6C, 6D).

Morphodynamic Process Representations: Whether or not certain processes are included in any morphodynamic model, along with the algorithms by which those processes are represented, has major implications for the computation efficiency and field-realism of the output solution. To this end, MoRPHED is not only a working morphodynamic model, but perhaps more importantly, provides an interchangeable framework by which users can explore the morphodynamic results of altering process representations. To illustrate this, we conducted three additional simulations using the 2003-2004 discharge record, each of which employs a modified path length distribution (Table 1). The results of these simulations are shown in Figure 6.

Table 1 Path length distribution parameters used in process representation modeling

Name	**Length (m)**	**Coefficient 1**	**Coefficient 2**
Default	210	$\sigma = 40$	$\mu = 125$
Shortened Gaussian	125	$\sigma = 40$	$\mu = 50$
Compressed Gaussian	210	$\sigma = 10$	$\mu = 125$
Exponential	210	$a = 0.1$	$b = 0.2$

While the shortened Gaussian and exponential distributions produced relatively similar model outputs, the compressed Gaussian distribution produced morphologies that reflected the high degree of coupling between erosion and deposition sites. This is particularly visible when observing the high-magnitude deposition resulting from sediment import or the concentrated deposition resulting from central bar trimming in Figure 6B. In Figures 6A and 6C, the deposition resulting from this bar scour is more longitudinally diverse, reflecting that deposition is spread over larger areas in the shortened Gaussian and exponential distributions. The focused nature of deposition in the compressed Gaussian distribution also has implications for erosion, with more high-magnitude erosional areas visible in Figure 6B; these erosional areas were likely not counter-balanced by the extensive depositional sheets seen in Figure 6A and 6C, and occur as more longitudinally-continuous, low-magnitude areas of scour.

CONCLUSIONS

This research seeks to develop a morphodynamic model that combines aspects of computational fluid dynamics with simplified morphologic-sediment transport relations to minimize computational overhead and allow increased simulation time at high spatial resolution. The MoRPHED model developed here has been run over two annual periods along a wandering, gravel bed river. During the 2003-2004 period, which was marked by a small number of peaks over the bankfull discharge (n = 5), the model reproduced field-surveyed geomorphic change reasonably well, although differences in the location of deposited sediment were observed, along with inaccuracies resulting from discharge point locations used in the hydraulic component of MoRPHED. In the 2006-2007 simulation, which was marked by a greater number of flows exceeding bankfull discharge (n = 16), the absence of a bank erosion algorithm in MoRPHED was notable, as the channel tended towards a single-thread planform in model simulations. Ongoing development of MoRPHED seeks to implement bank erosion dynamics and refine model boundary parameterization. MoRPHED is open-source software which is freely available at http://morphed.joewheaton.org, along with user manuals, tutorials, and example datasets.

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REFERENCES

Bates, P., and De Roo, A. (2000). “A simple raster-based model for flood inundation simulation,” Journal of Hydrology, 236(1-2), 54–77, doi:10.1016/S0022-1694(00)00278-X.

Bates, P. D., S. N. Lane, S.N., and Ferguson, R.I. (2005). Computational fluid dynamics, Wiley Online Library.

Bertoldi, W., L. Zanoni, L., and Tubino, M. (2010). “Assessment of morphological changes induced by flow and flood pulses in a gravel bed braided river: The Tagliamento River (Italy),” Geomorphology, 114(3), 348–360, doi:10.1016/j.geomorph.2009.07.017.

Black, E., Renshaw, C. E., Magilligan, F.J., Kaste, J.M., Dade, W.B., and Landis, J.D. (2010). "Determining lateral migration rates of meandering rivers using fallout radionuclides," Geomorphology, 123(3-4), 364–369, doi:10.1016/j.geomorph.2010.08.004.

Buffington, J. M., and Montgomery, D.R. (1997). "A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers," Water Resources Research, 33(8), 1993–2029, doi:10.1029/96WR03190.

Coulthard, T. J., and Van de Wiel, M.J. (2012). "Modelling river history and evolution," Philosophical transactions. Series A, Mathematical, physical, and engineering sciences, 370(1966), 2123–42, doi:10.1098/rsta.2011.0597.

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), 269–288, doi:10.1002/esp.318.

Ferguson, R. (2007). "Gravel bed rivers at the reach scale, in Gravel-Bed Rivers VI: From Process Understanding to River Restoration," vol. 11, pp. 33–53, Elsevier.

Ferguson, R. I., and Werritty, A. (1983). "Bar Development and Channel Changes in the Gravelly River Feshie," Scotland, in Modern and Ancient Fluvial Systems.

Garcia, M. H. (2008). Sediment Transport and Morphodynamics, in Sedimentation Engineering, edited by M. H. Garcia.

Grams, P. E., and Schmidt, J.C. (2005). "Equilibrium or indeterminate? Where sediment budgets fail: Sediment mass balance and adjustment of channel form," Green River downstream from Flaming Gorge Dam, Utah and Colorado, Geomorphology, 71(1-2), 156–181, doi:10.1016/j.geomorph.2004.10.012.

Gurnell, A., Surian N., and Zanoni L. (2009). "Multi-thread river channels: A perspective on changing European alpine river systems," Aquatic Sciences, 71(3), 253–265, doi:10.1007/s00027-009-9186-2.

Gurnell, A. M., Bertoldi, W., and Corenblit D. (2012). "Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers," Earth-Science Reviews, 111(1-2), 129–141, doi:10.1016/j.earscirev.2011.11.005.

Hodge, R., Brasington, J., and Richards, K. (2009). "Analysing laser-scanned digital terrain models of gravel bed surfaces: linking morphology to sediment transport processes and hydraulics," Sedimentology, 56(7), 2024–2043, doi:10.1111/j.1365-3091.2009.01068.x.

Hooke, J. M. (1995). "River channel adjustment to meander cutoffs on the River Bollin and River Dane, northwest England," Geomorphology, 14(3), 235–253, doi:10.1016/0169-555X(95)00110-Q.

Javernick, L. (2014). "Modeling Flood-induced Processes Causing Russell Lupin Mortality in the Braided Ahuriri River, New Zealand," University of Canterbury.

Kasprak, A., Ashmore, P., Hensleigh, J., Peirce, S., and Wheaton, J.M. (2015). "The Relationship Between Particle Travel Distance and Channel Morphology: Results from Physical Models of Braided Rivers, Journal of Geophysical Research: Earth Surface," doi:10.1002/2014JF003310.

Kondolf, G. (1997). "PROFILE: Hungry Water: Effects of Dams and Gravel Mining on River Channels, Environmental Management," 21(4), 533–51.

Kondolf, G. M., Piégay H., and Landon, N. (2002). "Channel response to increased and decreased bedload supply from land use change: contrasts between two catchments," Geomorphology, 45(1-2), 35–51, doi:10.1016/S0169-555X(01)00188-X.

Landon, N., Piégay, H., and Bravard, J. (1998). "The Drôme River incision (France): from assessment to management," Landscape and Urban Planning, 43.

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), 1–20, doi:10.1016/S0169-555X(99)00003-3.

Montgomery, D., and Buffington J. (1998). “Channel processes, classification, and response, in River Ecology and Management,” edited by R. Naiman and R. Bilby, pp. 13–41, Springer-Verlag.

Montgomery, D. R., Buffington, J.M., Peterson, N.P., Schuett-Hames, D., and Quinn, T.P. (1996). “Stream-bed scour, egg burial depths, and the influence of salmonid spawning on bed surface mobility and embryo survival,” Canadian Journal of Fisheries and Aquatic Sciences, 53(5), 1061–1070, doi:10.1139/f96-028.

Mueller, E. R., Grams, P.E., Schmidt, J.C., Hazel, J.E., Alexander J.S., and Kaplinski, M. (2014). “The influence of controlled floods on fine sediment storage in debris fan-affected canyons of the Colorado River Basin,” Geomorphology, 226, 65–75, doi:10.1016/j.geomorph.2014.07.029.

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

Nicholas, A. P. (2005). “Cellular modelling in fluvial geomorphology,” Earth Surface Processes and Landforms, 30(5), 645–649, doi:10.1002/esp.1231.

Nicholas, A. P., and Quine, T.A. (2007). “Modeling alluvial landform change in the absence of external environmental forcing,” Geology, 35(6), 527, doi:10.1130/G23377A.1.

Paola, C., and Voller, V.A. (2005). “A generalized Exner equation for sediment mass balance, Journal of Geophysical Research,” 110(F4), F04014, doi:10.1029/2004JF000274.

Pyrce, R. S., and Ashmore, P.E. (2003a). “Particle path length distributions in meandering gravel-bed streams: results from physical models,” Earth Surface Processes and Landforms, 28(9), 951–966, doi:10.1002/esp.498.

Pyrce, R. S., and Ashmore, P.E. (2003b). “The relation between particle path length distributions and channel morphology in gravel-bed streams: a synthesis,” Geomorphology, 56(1-2), 167–187, doi:10.1016/S0169-555X(03)00077-1.

Snyder, N. P., Castele, M.R., and Wright, J.R. (2009). “Bedload entrainment in low-gradient paraglacial coastal rivers of Maine, U.S.A.: Implications for habitat restoration,” Geomorphology, 103(3), 430–446, doi:10.1016/j.geomorph.2008.07.013.

Thomas, R., and Nicholas, A.P. (2002). “Simulation of braided river flow using a new cellular routing scheme,” Geomorphology, 43(3-4), 179–195, doi:10.1016/S0169-555X(01)00128-3.

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), 302–317, doi:10.1016/j.geomorph.2006.10.025.

Wheaton, J. M. (2013). “Automated Derivation of Fish Habitat, Geomorphic Units & Transition Zones from Topography, in Eos, Transactions,” American Geophysical Union, San Francisco, California.

Wheaton, J. M., Brasington, J.., Darby, S.E., and Sear, D.A. (2009). “Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets,” Earth Surface Processes and Landforms, 156(December 2009), n/a–n/a, doi:10.1002/esp.1886.

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), 759–779, doi:10.1002/jgrf.20060.

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), 5183–5205, doi:10.1002/wrcr.20391.