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Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river

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[1] Previous flume-based research on braided channels has revealed four classic mechanisms that produce braiding: central bar development, chute cutoff, lobe dissection, and transverse bar conversion. The importance of these braiding mechanisms relative to other morphodynamic mechanisms in shaping braided rivers has not yet been investigated in the field. Here we exploit repeat topographic surveys of the braided River Feshie (UK) to explore the morphodynamic signatures of different mechanisms of change in sediment storage. Our results indicate that, when combined, the four classic braiding mechanisms do indeed account for the majority of volumetric change in storage in the study reach (61% total). Chute cutoff, traditionally thought of as an erosional braiding mechanism, appears to be the most common braiding mechanism in the study river, but was more the result of deposition during the construction of diagonal bars than it was the erosion of the chute. Three of the four classic mechanisms appeared to be largely net aggradational in nature, whereas secondary mechanisms (including bank erosion, channel incision, and bar sculpting) were primarily net erosional. Although the role of readily erodible banks in facilitating braiding is often conceptualized, we show that bank erosion is as or more important a mechanism in changes in sediment storage than most of the braiding mechanisms, and is the most important “secondary” mechanism (17% of total change). The results of this study provide one of the first field tests of the relative importance of braiding mechanisms observed in flume settings.

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1. Introduction

[2] Of all the planforms and river styles alluvial rivers may exhibit, braided rivers are the most dynamic [Brierley and Fryirs, 2005]. They owe this dynamism to their abundant bedload and readily erodible banks, which results in a high frequency of avulsions and complex flow patterns converging and diverging around active central bars [Ashmore, 1982; Charlton, 2007; Chew and Ashmore, 2001; Jerolmack and Mohrig, 2007; Miall, 1977]. Indeed, the maintenance of braiding is partly dependent on this very dynamism, as high rates of channel turnover inhibit the growth of bar-top vege-

tation which may otherwise stabilize the bed and banks through root reinforcement and increased flow resistance [Hicks *et al.*, 2007; Paola, 2001; Tal and Paola, 2007].

[3] The continuously shifting network of channels, splitting at diffluences, and converging at confluences, give rise to a distinctive set of three-dimensional morphologies. Characteristic forms include a range of active bars, including mid-channel, bank-attached, and compound bars, with locally deep scour holes formed by high rates of sediment transport at confluences [Ashmore, 1982; Bridge, 1993]. The formation of multiple mid-channel bars (i.e., braiding) requires large width-to-depth ratios, which can only be accommodated by readily erodible banks [Ferguson, 1987; Millar, 2000; Zubik and Fraley, 1988].

[4] Existing conceptual models of braiding emphasize that there is no single process that leads to the division of flow and the evolution of mid-channel bars [Bridge, 1993; Ferguson, 1993; Leddy *et al.*, 1993]. Rather, there are a suite of depositional (e.g., bar building) and erosional (e.g., channel cutting and bar dissection) processes that operate over time to develop and maintain the multi-thread character of these systems [Bridge, 1993; Ferguson, 1993; Kleinhans, 2010]. Much of our understanding of braided river dynamics comes from flume [e.g., Ashmore, 1982, 1991; Ashworth, 1996; Germanoski and Schumm, 1993] and, to a lesser extent,

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numerical modeling studies [Hicks *et al.*, 2009; Murray and Paola, 1994; Nicholas *et al.*, 2006]. In Ashmore's [1991] seminal work on "how do gravel-bed rivers braid?" and Ferguson's [1993] review of "understanding braiding processes in gravel-bed rivers", four principal mechanisms of channel change and evolution emerge: central bar development, transverse bar conversion, chute cutoff of point bars, and lobe dissection. In addition, there is a large body of research that has articulated conceptually and documented qualitatively, the mechanisms that underpin braided river morphodynamics [Best and Bristow, 1993; Bridge, 1993; Sambrook-Smith *et al.*, 2006].

[5] Despite the collective significance of this body of literature, little has been done to quantify the relative importance of specific braiding mechanisms in terms of change in sediment storage and their contribution to the dynamics of the river. Recent advances in repeat topographic surveying techniques and geomorphic change detection [Hicks *et al.*, 2007; Milan *et al.*, 2011; Williams *et al.*, 2011] now permit such a quantitative analysis of braided river morphodynamics, but to date, have not yet been adequately exploited for this purpose.

[6] The goals of this paper are to (a) classify the morphodynamic signature of observed channel changes in a braided river, and (b) test the perceived dominance of the "classic braiding mechanisms" (as defined by Ashmore [1991] and Ferguson [1993]) to the overall volumetric changes in sediment storage in an actively braided, gravel-bed river. To accomplish this, we use high-resolution digital elevation models (DEMs) derived from repeat topographic surveys of a braided system over a 5-year period. We take the "dynamism" of the channel to be expressed geomorphically by turnover due to erosion and deposition, which is manifested topographically by changes in sediment storage. Specifically, we seek to quantify, for potentially the first time in the field, the relative contribution of different braiding mechanisms to the storage dynamics of sediment within a braided gravel-bed river. Further, we explain ways in which the relative importance of different braiding mechanisms are controlled by variations in discharge. The significance of this contribution is partly conceptual and partly methodological. We provide empirical insight into how much work (i.e., net displacement of sediment in storage due to fluvial forces) is done by these key braiding mechanisms and how complete current conceptual models of braiding actually are. Methodologically, we lay out a pragmatic form of empirical analysis others can apply to the expanding collection of repeat topographic time series data on their own study rivers.

2. The Glen Feshie Study Site

2.1. Physical Setting

[7] The River Feshie is a braided gravel-bed river well known for its extensive gravel bar deposits [Ferguson and Werritty, 1983]. The Feshie has been the focus of numerous studies of bar development [Ferguson and Werritty, 1983], sediment transport [Ferguson and Ashworth, 1992], geomorphic change detection [Brasington *et al.*, 2000, 2003], historical planform change [Werritty and Ferguson, 1980; Werritty and McEwen, 1993], and hydrology [Soulsby *et al.*, 2006]. Situated in the heart of the Scottish Highlands, the Feshie has three actively braided reaches: one at its confluence with

the River Spey and two reaches upstream, the most active of which is a 3 km long reach near Glenfeshie Lodge that encompasses the ~1 km study reach in this paper (Figure 1).

[8] Glen Feshie itself is a glacial trough, which was deglaciated roughly 13,000 years B.P. [Gilvear *et al.*, 2000] and is now flanked by fluvio-glacial outwash terraces [Robertson-Rintoul, 1986]. The flow-regime is unregulated and flashy, reflecting the steep and rugged terrain of the catchment [Soulsby *et al.*, 2006]. This catchment is underlain by Moinian schist, which dominates the coarse bedload, and a small proportion of granite of the Cairngorm batholith. Average valley gradient is ~0.01 and the median surface grain size declines downstream through this braided reach from 110 to 35 mm, with significant grain size variability between wetted channels and bar tops. In this paper, we focus on a ~700 m long sub-reach at Glen Feshie, which was topographically surveyed annually during summer low flows between 2000–2007 [Rumsby *et al.*, 2008; Wheaton, 2008]. Data are presented for a 5 year period from 2003 to 2007, from which four analysis periods (epochs of change) are derived.

[9] Since at least the mid 1800s, this reach of the Feshie has maintained a persistent braided character [Figure 2f; see also Rumsby *et al.*, 2001; Werritty and Ferguson, 1980; Werritty and Brazier, 1991]. As documented by aerial photos dating back to 1946 and UK Ordnance Survey maps dating back to 1869, the Feshie has maintained a braiding index [Robertson-Rintoul and Richards, 1993] between 2 and 4 and a braiding intensity between 2 and 5 [Egozi and Ashmore, 2009]. The braiding index was calculated by counting the number of active channels in each of five cross sections and averaging them, whereas the braiding intensity was calculated by dividing the length of all braid channels by the length of the reach as per Mosley [1981].

2.2. Hydrologic Record

[10] A long-term flow record does not exist at the study reach, but Brasington and Cox (personal communication) and Ferguson and Werritty [1983] have gauged the study reach for short periods. A more robust record of continuous, 15 min resolution discharge dating back to 1992 is available from the Scottish Environmental Protection Agency (SEPA) at Feshie Bridge, 11 km downstream of the Glen Feshie study site. The maximum recorded daily discharge at Feshie Bridge was measured on 24 December 1999 at $121.5 \text{ m}^3 \text{ s}^{-1}$ with an instantaneous peak of $222.5 \text{ m}^3 \text{ s}^{-1}$ from the same day. Ferguson and Werritty [1983] reported that the same gauging station was also maintained by the Department of Agriculture and Fisheries for Scotland from 1951 to 1974. The summary statistics for peak flows and mean discharge [Ferguson and Werritty, 1983] are very similar to the 1992–present record (Figure 2d).

[11] In all epochs, some portion of the braidplain in the study reach was likely inundated, but both the frequency and severity of those floods is significantly less in the 2004–2003 and 2006–2005 epochs than during either the 2005–2004 or 2007–2006 epochs. Ferguson and Werritty [1983] reported that "bankfull flows" in the study reach are somewhere in the $20\text{--}30 \text{ m}^3 \text{ s}^{-1}$ range, which corresponds to a discharge of $28\text{--}42 \text{ m}^3 \text{ s}^{-1}$ at Feshie Bridge using a downscaling coefficient we developed empirically of 0.71. For this short duration record, there are essentially two drier epochs (2004–2003 and 2007–2006) and two wetter epochs

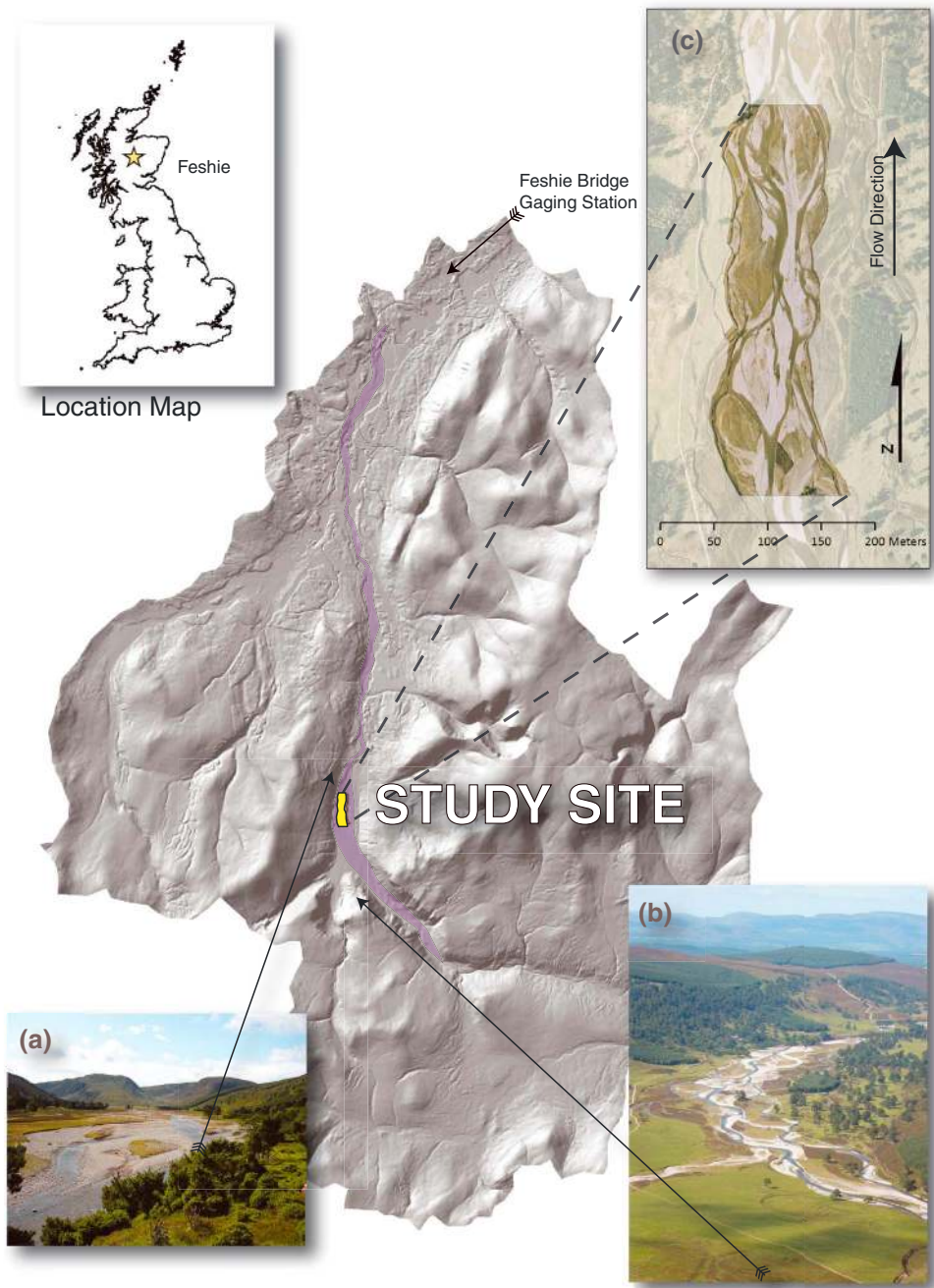


Figure 1. Location, vicinity and site maps for River Feshie study reach. The vicinity base map is from the Ordnance Survey 1:25,000 series and shows the Feshie flowing generally north through its catchment to its confluence with the River Spey downstream of Loch Insh. The weakly braiding/wandering portion of the Feshie has been delineated with a light purple shading and the 1 km long study reach is shown inside a yellow box. (a) Oblique images of the reach are shown looking upstream from the bottom of the reach and (b) down valley from a ridge upstream of the reach. (c) The inset site map shows the survey boundaries of the reach overlaid on 2005 aerial imagery.

(2005–2004 and 2006–2005) with 2007–2006 significantly wetter. Note, that we report all epochs as “new” minus (–) “old” (e.g., 2004–2003), as this is consistent with the order the elevations in each survey has to be subtracted from each other for erosion to be negative and deposition to be positive. Interestingly, none of these floods even exceed the 2 year recurrence interval (peak on 1 December 2006 is

$125.3 \text{ m}^3 \text{ s}^{-1}$ at Feshie Bridge) and our study period does not capture any rarer high magnitude floods. For comparison, flows exceeded c. $140 \text{ m}^3 \text{ s}^{-1}$ at Feshie Bridge during our study period once versus the three times during the 1976–1981 *Ferguson and Werritty* [1983] study period. *Ferguson and Werritty* [1983] estimated that overbank flooding in the study reach during the first 3 years of their

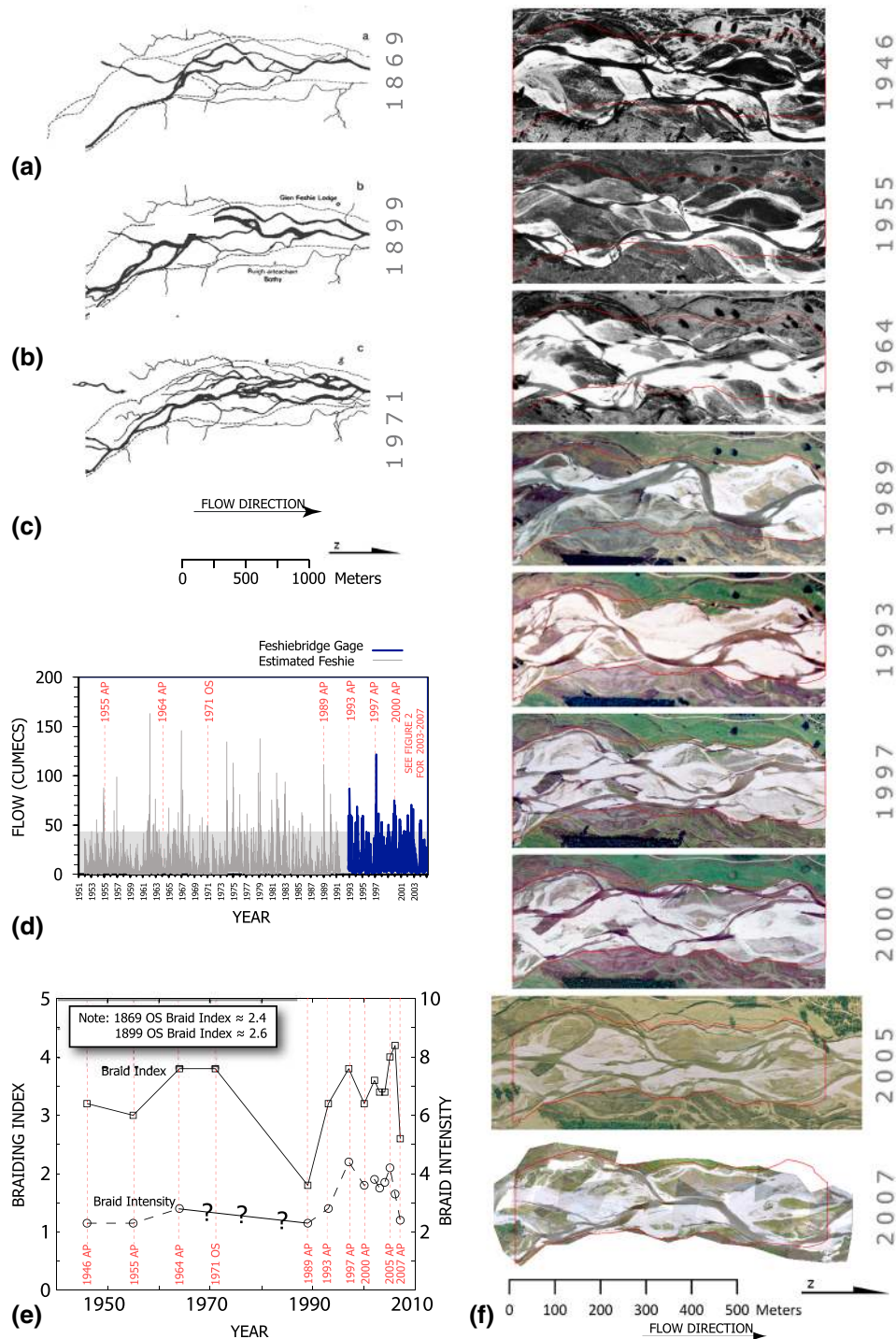


Figure 2. Historical patterns of channel change on the Feshie between 1869 and 2007, illustrating persistence of braided platform. Six-inch County series Ordnance Survey (OS) maps from the (a) first edition survey in 1869, (b) the second edition survey in 1899, and (c) 1:10,000 National Grid Series in 1971, modified from *Werritty and Brazier* [1991] and *Werritty and Ferguson* [1980]. (d) Hydrograph for the period 1952-2007, with dates of Ordnance Survey maps and air photos denoted by red vertical dashed lines. (e) The braiding index and braid intensity from 1946 to 2007. (f) All known available aerial photography for the reach prior to 2008 [see *Wheaton*, 2008, various sources].

study period occurred sometime between 16 and 51 times (depending on the threshold assumed), and a similar analysis we performed shows that overbank flooding occurred in the study reach between 38 and 79 times in our study (Table 1).

[12] For inferring the relative number and magnitude of floods during our study epochs, instantaneous peak flows were used. The top part of Table 1 includes mean flows, ranked peak flows for each epoch as well as peaks over

Table 1. Flow Statistics From Feshie Bridge

Epoch:	Flow Statistics for Study Period			
	2004–2003	2005–2004	2006–2005	2007–2006
Mean Flow (m^3s^{-1})	6.3	8.8	5.6	9.3
Peak Mean Daily flow (m^3s^{-1})	55.2	63.0	46.4	76.3
Peak Instantaneous Flow (m^3s^{-1})	106.1	107.4	75.1	125.3
2nd high flow (m^3s^{-1})	92.0	101.1	70.4	115.2
3rd high flow (m^3s^{-1})	84.5	85.6	69.8	83.8
4th high flow (m^3s^{-1})	72.9	85.1	59.9	82.6
POT (28 m^3s^{-1}) Low Bankfull	7	22	9	41
POT (42 m^3s^{-1}) High Bankfull	5	12	5	16
POT (127 m^3s^{-1}) 2 year RI	0	0	0	0
Total Flow > Bankfull (m^3)	154,291	229,405	71,468	266,097
	Flow Recurrence Intervals			
Return Period (years)	2	5	10	50
Flow (m^3s^{-1})	127.0	161.9	187.3	222.1

threshold that counted the number of storms in each year over 28 m^3s^{-1} (a low bankfull estimate), 42 m^3s^{-1} (a high bankfull estimate) and 127 m^3s^{-1} (the 2 year recurrence interval flow). The bottom row of Table 1 shows the standard flow recurrence intervals (using a Log-Pearson Type III analysis of maximum daily flows). For context, the average instantaneous peak annual discharge is 135.8 m^3s^{-1} , and the 2 year recurrence interval flood is 127.0 m^3s^{-1} over 19 years of record. As our survey frequency is annual, the changes captured between topographic surveys integrate the effects of a range of competent flow events with varying magnitudes and frequencies. From Figure 3, it is clear that the 2007–2006 and 2005–2004 epochs boasted significantly more potentially competent floods as well as notably higher peak flows. Based on peak instantaneous discharges, all four epochs were less than the long-term average, with the 2004–2003 and 2005–2004 epochs experiencing a nearly identical range of flows.

3. Methods

[13] To explore how braiding mechanisms are expressed through changes in sediment storage over a geomorphically active (but by no means extreme) 5 year period in the braided river Feshie, we relied on high-resolution repeat topography to produce DEMs of difference (DoDs). Here we first review the acquisition of topographic data and DEM construction. We then describe a simple topology applied to those DEMs to record an expression of braiding behavior. To infer the braiding mechanisms from DoDs, we needed to distinguish those changes resulting from geomorphic processes from those changes arising simply due to noise in our DEM data. Therefore, we also briefly review a methodology outlined by *Wheaton et al.* [2010a] that robustly addresses this geomorphic change detection problem. Finally, we describe the analysis and interpretation of DoDs used to track braiding mechanisms as expressed through changes in sediment storage with spatial segregation or masking [*Wheaton*, 2008; *Wheaton et al.*, 2010b].

3.1. Topographic Surveys, DEMs and Channel Node Topology

[14] Repeat topographic surveys were conducted with between two and five Leica System 1200 rtkGPS rovers

operating simultaneously and a base station occupying a benchmark set on a control network we established using the British National Grid projection. Raw topographic data were filtered and points with positional errors > 5 cm were removed. Concurrent 1 m resolution DEMs were derived from triangulated irregular networks (TINs) of the processed rtkGPS topographic surveys of each site (between 30,000 and 50,000 points per survey; average density 0.3 points/ m^2). The DEMs used here are the same reported in *Wheaton et al.* [2010a], and they provide a record of geomorphic change (behavior) in a series of individual DEMs. Detrended DEMs were used to help differentiate areas accessed by various stage flows, and were derived by normalizing raw elevation data with respect to a smoothly sloping plane set to the surrounding valley slope and elevated to the mean valley elevation.

[15] From the detrended DEMs, we derived an inventory of braid channel nodes using *Ferguson's* [1993, pp. 75–76, Figure 2] topology. Nodes inventoried included (i) confluence junctions between two braid channels, (ii) diffluences or bifurcations where a single channel splits into two, and (iii) channel heads. *Ferguson* [1993] showed that channel heads can form either by head-cutting/incision from flows over a bar top or braid plain, or from partial choking of an anabranch. We independently identified and digitized (as points) all braid nodes for each of the five DEMs. In simple terms, braiding is maintained when the number of confluences is roughly matched by the number of channel heads and/or bifurcations [*Kleinhans et al.*, 2012]. For example, a channel that only has confluences from tributaries is not braided; a channel that has more bifurcations than confluences is a distributary system, like a delta or fan [*Jerolmack and Mohrig*, 2007; *Kleinhans et al.*, 2012]. We classified all channel heads, diffluences and confluences (high and low stage) that were resolved within a 1 m resolution DEM (i.e., generally > 2 m in width). We used this topology to assess the persistence of braiding conditions and inform our later classification of braiding mechanisms.

3.2. Quantifying Geomorphic Changes—DoD

[16] The Geomorphic Change Detection 5.0 (GCD) software (<http://gcd.joewheaton.org>) was used to compute the difference between sequential DEMs and conduct a spatially variable uncertainty analysis to robustly distinguish real

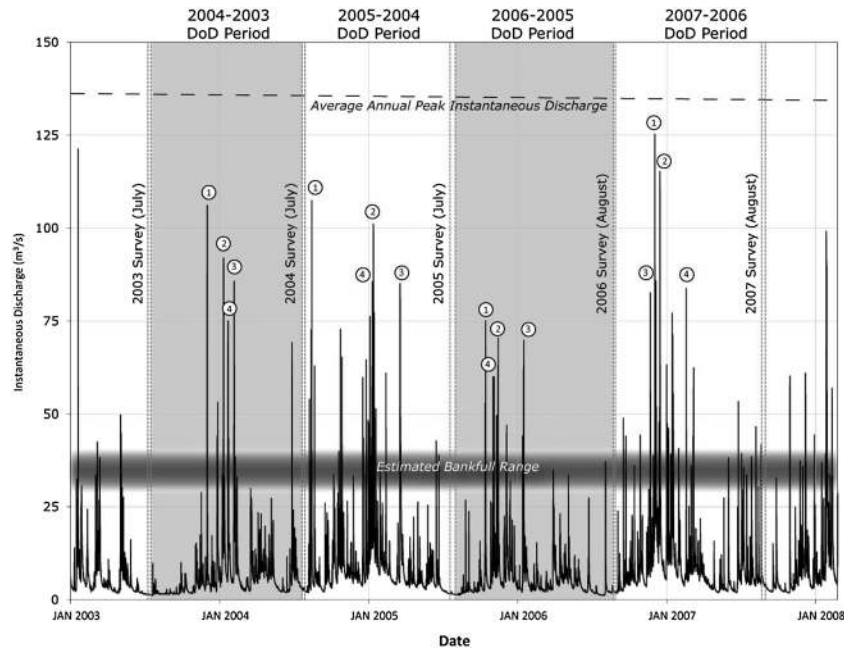


Figure 3. Instantaneous discharge hydrograph for Feshie Bridge during 5 year study period. The dashed vertical lines represent the start and stop dates for the five individual topographic surveys. The shaded periods represent the relatively dry flow years. The numbers in circles represent the top four ranked flows for each epoch. Dashed line represents average peak instantaneous discharge ($135.8 \text{ m}^3 \text{ s}^{-1}$) over 19 year flow record. Shaded interval shows estimated bankfull discharge ($28\text{--}42 \text{ m}^3 \text{ s}^{-1}$) at Glen Feshie study site. Daily flow data are from Scottish Environmental Protection Agency (SEPA).

changes from noise [Wheaton *et al.*, 2010a]. Briefly, this approach employed a spatially variable, probabilistic, and minimum Level of Detection (minLoD) to account for errors propagated from the individual DEMs into the DoD (Figure 4). This was achieved by first estimating errors in each DEM on a cell-by-cell basis with a fuzzy inference system (FIS). The FIS accounts for the tradeoff between the completeness of sampling coverage (point density used as proxy) and topographic complexity (slope used as proxy) while keeping track of instrument-reported 3D GPS point quality. The FIS estimated a spatially distributed metric of surface reliability expressed as a vertical elevation error for each DEM. Basic error propagation was then used to incorporate errors from each concurrent 1 m resolution DEM into the DoD calculations. This propagated error term was used to define the probability that elevation changes measured between two successive DEMs were real by calculating a t score to compare the DoD differences against the minLoD defined by the propagated error [see *Brasington et al.*, 2003; *Lane et al.*, 2003]. An additional probability was estimated based on the spatial coherence of erosion and deposition. This was approximated using a moving window majority-filter determined over a 15 m interval (chosen to reflect average channel width). In essence, the probability of DoD change being real was increased where it was spatially coherent (i.e., if an erosion cell was surrounded by other erosion cells), and decreased where it was fragmented (e.g., a checkerboard of erosion and deposition). These two sets of probabilities of observed change—one reflecting the vertical magnitude (FIS), the other the spatial context (spatial coherence filter)—were combined using Bayes’ Theorem. The DoDs were then thresholded at a

95% confidence interval, so that only changes estimated as having 95% or higher probability of being real were included in the budget.

[17] The volumetric change in storage is calculated by multiplying all elevation changes in the DoD by the cell area and accounting separately for erosion and deposition areas. The quantities described below can all be calculated for any area of interest: for example, the entire reach or just a defined sub-area of the reach. The net change in sediment storage (ΔV_{DoD}) is defined as the sum of all the deposition volumes minus the sum of all the erosion volumes:

$$\Delta V_{\text{DoD}} = \sum V_{\text{Deposition}} - \sum V_{\text{Erosion}} \quad (1)$$

ΔV_{DoD} over some time period Δt (epoch) represents the sediment budget (or expression of conservation of mass, assuming that ΔV_{DoD} , $Q_{b_{\text{in}}}$ and $Q_{b_{\text{out}}}$ all have equal bulk densities):

$$\frac{Q_{b_{\text{in}}} - Q_{b_{\text{out}}}}{\Delta t} = \frac{\Delta V_{\text{DoD}}}{\Delta t} \quad (2)$$

where $Q_{b_{\text{in}}}$ and $Q_{b_{\text{out}}}$ are the volumetric bedload fluxes into and out of the control volume (typically a study reach). By contrast to the net change in sediment storage (ΔV_{DoD}), we also have the total bulk change in sediment storage ($\sum V_{\text{DoD}}$), which is simply the sum of the erosion and deposition change in storage volumes as opposed to the difference. In this study, we do not use bedload flux data and therefore only report net and total changes in sediment storage. However, the summed volumes of erosion ($\sum V_{\text{Erosion}}$) and deposition ($\sum V_{\text{Deposition}}$) both spatially integrate the net changes in sediment storage over the course

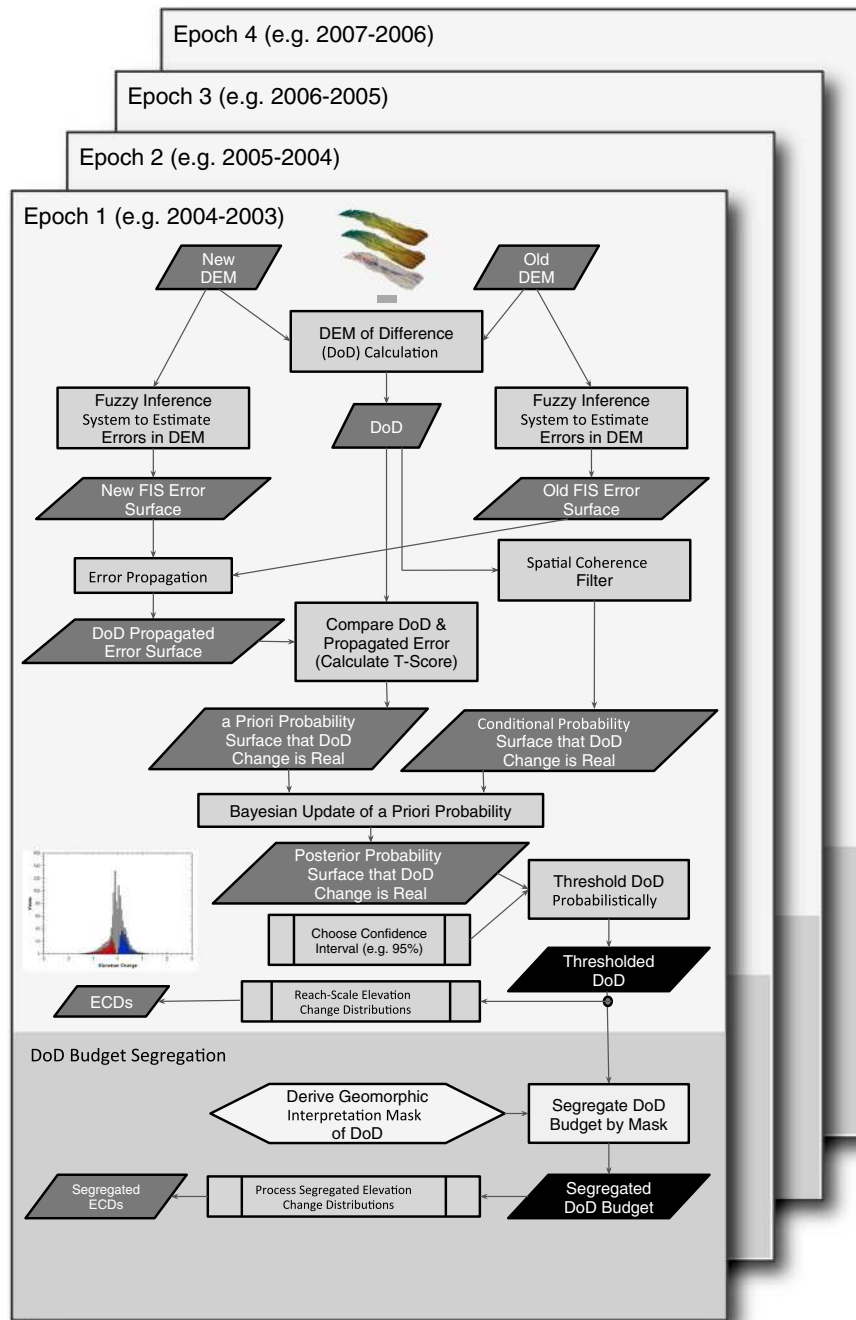


Figure 4. Methodological workflow for geomorphic change detection used in this paper. The rectangles represent calculations performed by the geomorphic change detection software. The parallelograms represent inputs and output.

of the epoch. In terms of the alluvial sediment store that makes up the valley fill, $\sum V_{\text{Erosion}}$ represents withdrawals from storage whereas $\sum V_{\text{Deposition}}$ represents deposits to that storage.

[18] Volumetric percentages of the total bulk change in sediment storage ($\sum V_{\text{DoD}}$), are calculated separately for the erosion or deposition volumes of interest divided by $\sum V_{\text{DoD}}$ (i.e., erosion plus deposition). The net change in sediment storage (ΔV_{DoD}) is the difference of erosion and deposition volumes (negative when erosional, positive when aggradational). The percent imbalance is the departure from a condition of 50-50% split between erosion and

deposition, and is calculated as the volumetric percentage of the bigger of erosion and deposition terms, minus %. For example, an imbalance of -20% indicates that total erosion for a given period represented 70% of the topographic change in the study reach.

[19] The methods described above are useful for establishing confidence that “real changes” were reliably being distinguished from noise. However, here we still report our uncertainty associated with the volumetric estimates of erosion and deposition as \pm one standard deviation of our volumetric error. This is approximated by using the propagated spatially

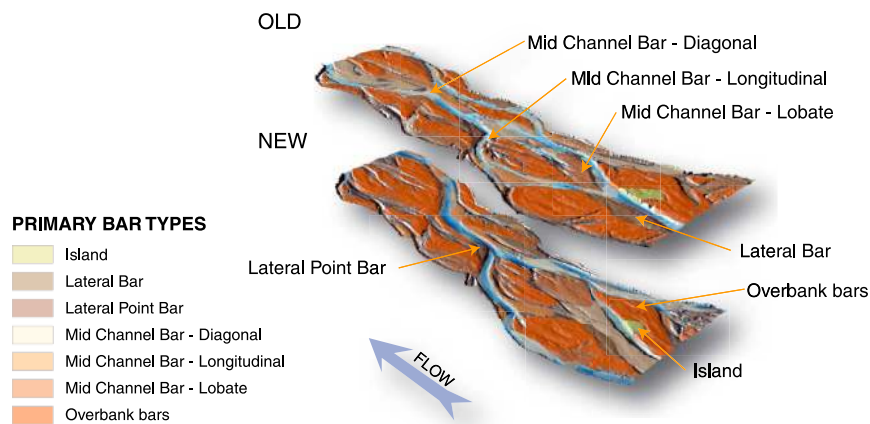


Figure 5. Illustration of primary geomorphic units and bars classified in the reach and how they can change from year to year in response to a combination of braiding mechanisms and other mechanism of change. The bar classifications were used to help infer mechanisms of change and categorize erosion and deposition patterns.

variable error estimates from the FIS error surfaces and converting these to volumetric errors. The thresholded DoD is treated as the mean estimate (as in a probability distribution function), and the propagated errors (sum of squares in quadrature) are an approximation of a standard deviation.

3.3. Classification of Morphodynamic Signatures

[20] Quantitative DoD segregation helps exploit topographic time series in a manner that facilitates a more mechanistic explanation of the signatures resulting from change in sediment storage dynamics [Wheaton *et al.*, 2010b]. Here we consider a morphodynamic signature to be a distinct mechanism of erosion and/or deposition that leads to a consistent morphological response (e.g., creation of a specific geomorphic unit). DoD segregation involves the creation of spatial masks (i.e., polygons) of different categories to segregate the reach-scale DoDs (thresholded at a 95% confidence interval) into separate totals for $\sum V_{\text{DoD}}$, ΔV_{DoD} , $\sum V_{\text{Erosion}}$ and $\sum V_{\text{Deposition}}$ volumes of statistically significant storage changes for each polygon area. Using a mutually exclusive classification of the entire reach ensures that storage changes are not counted multiple times. We were primarily interested in quantifying the contribution of different braiding mechanisms to the dynamism of our study reach, but we also were interested in the importance of other morphodynamic signatures of change in driving the behavior of the Feshie reach over the study period. Mutually exclusive polygons were digitized around individual erosional and depositional units on the thresholded DoDs and then classified manually using a mix of the DEMs, aerial photographs, bar classifications (e.g., Figure 5), and field observations from the beginning and end of each epoch. Below, we describe each morphodynamic signature for which we derived polygons and the process of inferring them from DoDs.

3.3.1. Braiding Mechanisms

[21] All four of the mechanisms identified by Ashmore [1991] and Ferguson [1993] (see section 1.0 above) actually result from a mix of erosion and deposition, but central bar development and transverse bar conversion are predominantly the result of deposition creating mid-channel bars;

whereas chute cutoff and lobe dissection are typically considered primarily the result of erosion converting a bank-attached bar to a mid-channel bar and multiplying the number of mid-channel bars respectively. All four processes involve the formation and/or reshaping of mid-channel bars and as such it was helpful to map all bars on each DEM to help distinguish processes.

[22] Central bar development results in the formation of a roughly symmetrical, elongated medial bar without an avalanche face [Ferguson, 1993]. These were easily identified on the detrended DEMs based on a tear-drop bar shape and position. We examined DoDs for concentrated zones of mid-channel deposition resulting in either new or expanded central bars.

[23] The building blocks of most bar forms are transverse unit bars, or thin sheets of sand, gravel or cobble—one to three grains thick [Rice *et al.*, 2009]. These lobate unit bars combine to create larger bar forms and often are distinguished by their tear-drop and presence of avalanche slip faces at their fronts [Ashmore, 1991]. Transverse bar conversion is a process by which these transverse unit bars accumulate in the middle of the channel and force division of flow around themselves. These lobes were easily identified from the DEMs based on their position downstream of chutes and/or confluence pools and their bulbous shape and steep faced fronts [Ferguson, 1993]. We examined DoDs for expanses of deposition downstream of such features.

[24] Chute cutoff occurs where bank-attached alternate bars or point bars experience headcut incision in the form of a chute as flow takes a short-cut over the bar top, along the channel margin [Ashmore, 1991]. The result is that the detachment of the bar from the bank and a mid-channel diagonal bar forms. We examined sequences of DEMs for bank-attached bars becoming diagonal bars and examined the DoDs for evidence of chute erosion along a channel margin and deposition or expansion of the diagonal bar. This is a common mechanism in the Feshie and was well documented and described by Ferguson and Werritty [1983].

[25] Lobe dissection involves erosion of multiple chutes (as opposed to a single chute) across an existing lobate bar

surface [Ferguson, 1993]. We looked on the DEMs for emergence of chutes across lobate bar surfaces, and multiple, narrow chutes of erosion in the DoDs.

3.3.2. Other Morphodynamic Signatures

[26] In addition to these braiding mechanisms, we also saw evidence of bank erosion, bar edge trimming, channel incision, confluence pool scour, overbank gravel/cobble sheets, and lateral (bank-attached) bar development. The braided rivers literature provides passing mention of each of these mechanisms, but they are not considered primary mechanisms of braiding. As mentioned earlier, readily erodible banks are a prerequisite for the high width-to-depth ratios that facilitate braiding, but of themselves are not a mechanism of braiding. We were interested in the importance of these lesser recognized processes in contributing to the net changes in sediment storage (both ΔV_{DoD} and $\sum V_{\text{DoD}}$). For example, bank erosion and bar edge trimming can produce considerable volumes of locally sourced sediment, which might be a key contributor to the extensive development of mid-channel bars (e.g., central bar development, transverse bar conversion).

[27] Both bank erosion and bar edge trimming appear as narrow, elongated bands of erosion oriented streamwise in the DoD. For bank erosion, these reflect lateral erosion into either the banks of less active surfaces on the braid plain (e.g., islands) or terraces on the edge of the braid plain; whereas for bar edge trimming, these represent lateral erosion along the margins of active bar surfaces. Both tend to be associated with topographic steering of the flow into these features and tend to result in planform convexities on the edges of banks or bars. The relative height of the surface being eroded (reflected in magnitude of erosion) was also used to help distinguish between the two.

[28] Confluence pool scour, where anabranches rejoin and convergent flow forces the scour of a pool, is a hallmark of braided rivers [Ashmore and Parker, 1983]. We looked for discrete zones of scour at confluences resulting in the formation, maintenance or growth of a pool.

[29] We identified channel incision as the down-cutting of an entire existing anabranch, typically from one diffuence to the next confluence. Such channel incision was relatively low magnitude (i.e., < 50 cm) and generally represented an adjustment to a new local base-level being set at the downstream junction, which typically shortened the anabranch length and steepened its profile.

[30] Overbank gravel or cobble sheets delineate areas of overbank deposition onto braidplain surfaces as described by Ferguson and Werritty [1983] characterized by at least decimeter-thick gravel/cobble deposits burying heather, moss and grass vegetation on the braidplain. These bedload sheets are similar to unit bars but only occur in larger braidplain inundating floods, are relegated to the braidplain, and generally produce much larger more aerially extensive deposits. These deposits are differentiated from regular overbank deposition of finer suspended load material (typical floodplain deposits) that are often below minimum levels of detection. We classified potential minor floodplain deposition and micro-topographic scour of the braid plain in a “questionable or unresolved change” category.

[31] In individual anabranches of the braided network, the anabranch channels start off behaving like low-sinuosity single-thread channels and begin to form bank-attached

alternate bars and point bars on inside bends. There, we see lateral (bank-attached) bar development, which is easily differentiated from the other forms of bar development included in the braiding mechanisms and described above. Such lateral bar development is more common in sub-bankfull floods, which are confined to the anabranches and eventually gives way in larger floods to chute cutoff braiding mechanisms and conversion of bank-attached bars to mid-channel bars.

[32] Although not explicitly included as a primary “braiding mechanism”, much of the braided river literature discusses the importance of avulsions in braided rivers [Leddy et al., 1993]. We identified avulsions by the disappearance of a channel diffuence or bifurcation and then used the DoDs to track what mechanisms led up to the avulsion and classify the avulsion type.

4. Results and Interpretations

4.1. DEMs and Topological Classification of Braided Channel Nodes

[33] The five DEMs used for change detection are shown in the top of Figure 6. Overlaid on top of the DEMs are the locations of braid channel nodes including channel heads, bifurcations and confluence junctions. The nodes include both active and relict features preserved in the detrended topography. The number of confluences varies through time between 82 and 124 with an average of 105. However, only 3–5 of these are near-symmetric confluences of sub-equal larger channels with year-round flow. The majority of confluences (75%) are paired with small channel heads leaving only 25% of those associated with bifurcations of channels such as chute cutoffs around diagonal bars. In epochs with a greater duration of braidplain inundating flows (e.g., 2004 and 2007; Table 1) the overall number of channel nodes decreases, potentially reflecting simplification of the braid plain network during larger floods.

4.2. Reach Scale Change in Sediment Storage

[34] The year-to-year changes in sediment storage ($\sum V_{\text{Erosion}}$ and $\sum V_{\text{Deposition}}$) are shown as pie charts in Figures 7a–7d, with the volumetric erosion, deposition, and net change values reported in Table 2. Figures 7a–7d show the thresholded DoDs from which these sediment storage budgets were derived, as well as the raw and thresholded (post uncertainty analysis) volumetric elevation change distributions. The imbalance in the ΔV_{DoD} was consistently calculated as degradational, ranging between –5% in 2004–2005 and –16% in 2003–2004. The total volumetric imbalance was –7%, giving an average annual net loss of $1064 \pm 2767 \text{ m}^3$ of sediment and total net loss of $4640 \pm 11,057 \text{ m}^3$ over the entire 5 year study period.

[35] The large error bars on the net estimate (Figure 8), are the result of rather conservative volumetric estimates for erosion and deposition, which are then propagated into the difference calculation. Over the whole study period, the total erosion volume estimate was $18,612 \pm 9777 \text{ m}^3$ and the total deposition volume was $14,356 \pm 4989 \text{ m}^3$. The $\pm 65\%$ average volumetric error for erosion is notably higher than the $\pm 40\%$ average volumetric error for deposition; due to the fact that much of the erosion took place in steeper areas where lower survey point density may influence the quality

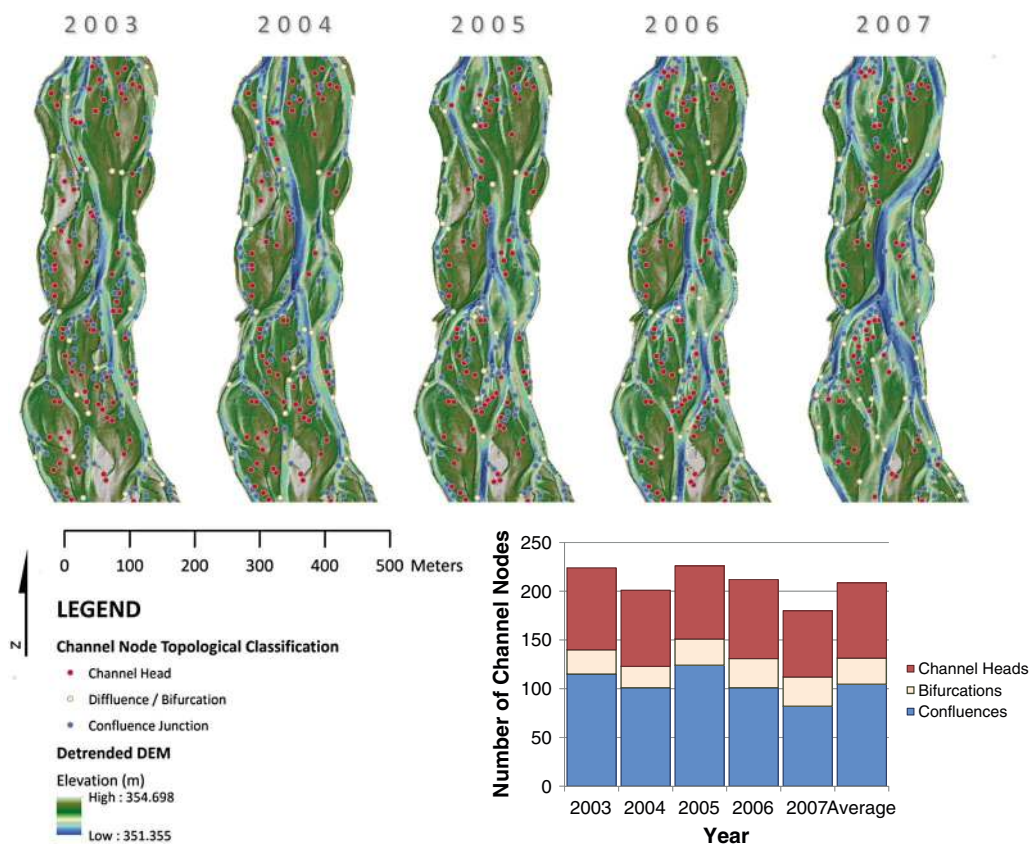


Figure 6. Detrended DEMs from 2003 to 2007 and results of braid channel node topological classification. Through time, some of the channel nodes disappear and many persist—with some staying in the same location and others migrating as the channel evolves. Node topology is based on *Ferguson* [1993].

of topographic survey points (i.e., where there is increased noise in the survey data). Given this uncertainty, we can only conclude that the sign of net change (that is, the balance between erosion and deposition) is indeterminate and that the reach is most likely roughly in equilibrium.

[36] The volumetric elevation change distributions in Figure 7 all have bimodal distributions with the erosional fractions (red left-hand peak) consistently larger the depositional fractions (blue right-hand peak). The grey, original unthresholded distribution shows the magnitude of volume which was thresholded out because it did not meet the 95% confidence criteria (§3.2). This large excluded area conceptually illustrates why the absolute volumetric estimates can be so uncertain despite relatively high spatial confidence (i.e., >95% probability) regarding the location and direction of geomorphic change. However, the percentage erosion and deposition volumes (pie charts) are fairly insensitive in this case to the exclusion/thresholding of that volume [see *Wheaton et al.*, 2010a, Figure 12]. When absolute values are used, both the erosional and depositional distributions are right-skewed and both are long-tailed. Both the erosional and depositional fractions of the elevation change distributions exhibit relatively narrow, low magnitude peaks: typically 20–25 cm for deposition; 35–40 cm for erosion.

4.3. Morphodynamic Signatures of Change in Sediment Storage

[37] Figures 9a–9d shows the maps of the DoD segregation in terms of our classification of morphodynamic

signatures. These include primary braiding mechanisms (central bar development, transverse bar conversion, chute cutoff and lobe dissection) as well as six other mechanisms of change and a questionable or unresolved changes category. The pie charts in Figures 9e–9h show the resulting percentages of total volumetric change in storage for each epoch broken down by each mechanism. Figure 10a uses the same results but plots their absolute magnitudes epoch-by-epoch to highlight both variability, in absolute amounts of work done, as well as consistency in the dominance of specific mechanisms. In the next two subsections, we quantify the relative importance of each signature in contributing to the reach dynamics.

[38] The four main braiding mechanisms accounted for 61% of the total volumetric change in the reach (Figure 10b), but varied between as little as 46% in 2007–2006 and as much as 82% in 2005–2004. Bank erosion was found to be as or more important a mechanism in changes in sediment storage as most of the individual braiding mechanisms, and emerged as the most important “secondary” mechanism (17% of total change). In every epoch, the four primary braiding mechanisms constituted net aggradation with an average ΔV_{DoD} of +1127 m³ and total ΔV_{DoD} of +4506 m³ which equates to average 11% aggradational imbalance. Figure 10a shows that central bar development, transverse bar conversion and chute cutoff were consistently the most important depositional mechanisms of change, but lobe dissection and chute cutoff were not always the most prevalent erosion mechanisms, falling behind bank erosion, channel incision and confluence

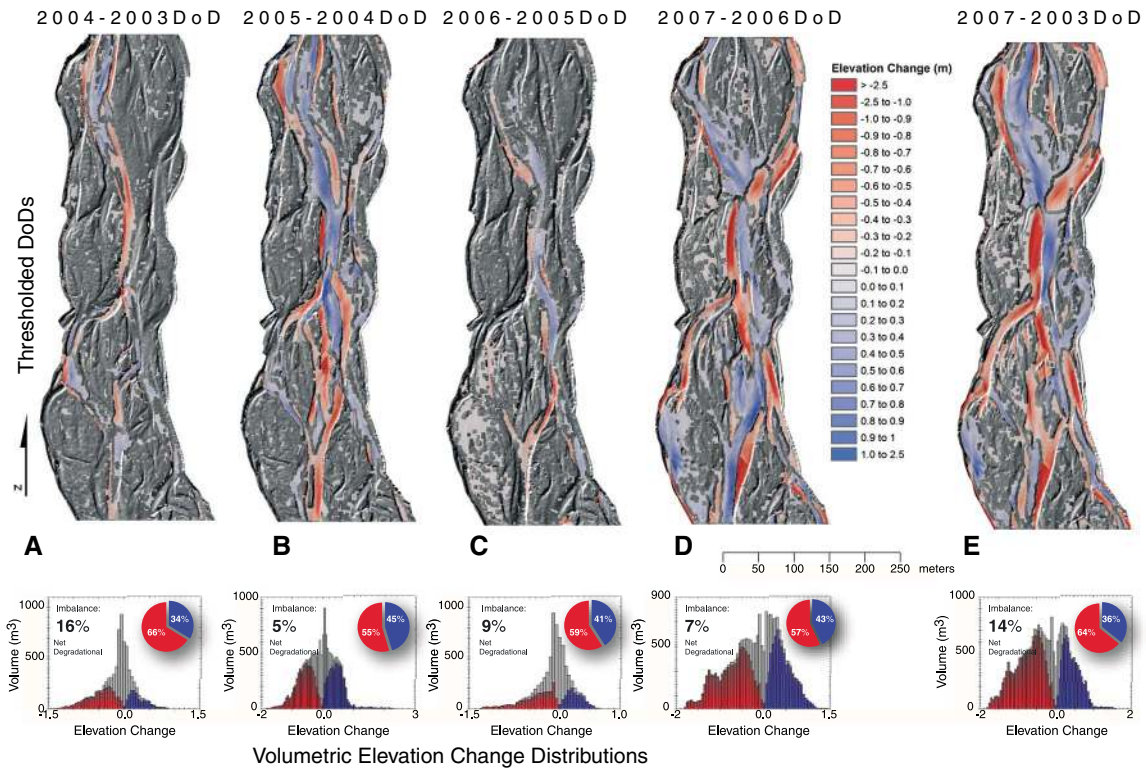


Figure 7. Thresholded DEM of Difference (DoD) maps (top) and their elevation change distributions (bottom) for each epoch. The DoDs shown reflect the changes after an uncertainty analysis (Figure 4) and discarding changes with less than a 95% probability of being real. Hillshades derived from the more recent DEM in each epoch are shown behind the thresholded DoDs for context (i.e., where hillshade is visible, the DoD changes have been determined not to be distinguishable from noise). The volumetric elevation change distributions show the unthresholded DoD in grey, and the thresholded distribution in red and blue for the erosional and depositional fractions respectively. See Table 2 for values.

pool scour in low water years (Figure 9). Figure 11 illustrates the signatures of volumetric elevation changes for each mechanism in a characteristic low-water epoch (2004–2003) and characteristic high-water epoch (2007–2006).

[39] Given that braiding mechanisms constitute a majority (61%) of the sediment dynamics of the reach and are consistently aggradational (11% aggradational imbalance), either upstream external sources of sediment or other erosional mechanisms within the reach must be providing the excess sediment supply. Our best estimate for the overall reach budgets are on average a 9% degradational imbalance (Figure 7). To make up this 20% volumetric discrepancy, the other mechanisms of change must be net degradational. Below, we describe the morphodynamic signatures found in the Feshie for each of the mechanisms of change.

4.3.1. Individual Mechanisms of Change

[40] Chute cutoff was the most prevalent braiding mechanism both on average and in the first three epochs, accounting for 23% of the total volumetric change ($\sum V_{DoD}$) over the study period (more than any other mechanism) and as much as 40% in 2006–2005. *Ferguson* [1993] casts chute cutoff and lobe dissection as a primarily erosional mechanism that leads to the conversion of a bank-attached bar (either point bar or alternate bar) to a mid-channel bar (diagonal bar). We found here that although chute cutoff was a mix of erosion (carving the chute along the bank) and deposition

(building up the new diagonal bar) as described by *Ferguson and Werritty* [1983], in three of the four epochs, the deposition outpaced erosion. Figures 11c and 11g show the shape of elevation change distributions for chute cutoffs in a relatively low water epoch (2004–2003) and relatively high water epoch (2007–2006). These elevation change distributions show the erosional fraction in red with a more dispersed distribution reflecting the range of the bar thicknesses which the chute cutoff channel dissected, whereas the depositional fraction exhibits a more concentrated peak around lower magnitude (c. 25 cm) deposition and growth of the diagonal bar surface.

[41] By contrast, lobe dissection shows a consistently net degradational ECD (Figures 11a and 11e) with a dispersed distribution, again reflecting the range of bar thicknesses of the lobate transverse bars that the chutes carved through. Lobe dissection accounted for 13% of the total volumetric change ($\sum V_{DoD}$) in the reach (Figure 10b), but varied between as little as 5% in 2007–2006 and as much as 24% in both 2005–2004 and 2006–2005 (Figures 9e–9h).

[42] Both central bar development and transverse bar conversion show consistent predominance of deposition (Figure 10a), but in most years, these are not as prevalent forms of deposition as diagonal bar development (i.e., chute cutoff). The notable exception to this was the 2007–2006 epoch (Figure 9h), in which transverse bar conversion

Table 2. Summary of Volumetric and Areal Storage Change by Erosion, Deposition, Net Change (Deposition-Erosion) and Total Change for Each Epoch

Epoch	Erosion			Deposition			Net Change			Total Change	
	$\sum V_{\text{Erosion}}$ (m ³)	Vol Error as %	Area (m ²)	$\sum V_{\text{Deposition}}$ (m ³)	Vol Error as %	Area (m ²)	ΔV_{Net} (m ³)	Volume Percentage Imbalance	Areal Percentage Imbalance	$\sum V_{\text{Total}}$ (m ³)	Areal % of Total Reach
2004–2003	2269 ± 1747	77%	10,249	1156 ± 567	49%	6,298	-1113 ± 1837	-16%	-12%	3425	15%
2005–2004	5681 ± 2549	45%	14,690	5138 ± 1835	36%	19,734	-544 ± 3141	-3%	+7%	10,819	30%
2006–2005	1856 ± 1795	97%	12,297	1288 ± 607	47%	7502	-568 ± 1895	-9%	-12%	3144	17%
2007–2006	8806 ± 3686	42%	22,085	6774 ± 1980	29%	23,607	-2032 ± 4184	-7%	+1%	15,580	40%
2007–2007	12,946 ± 4529	35%	30,491	7222 ± 1778	25%	22,993	-5724 ± 4865	-14%	-7%	20,168	46%
2003	18,612 ± 9777	NA	59,321	4989 ± 1248	NA	57,141	-4640 ± 11,057	NA	NA	32,968	NA
Total	4653 ± 2444	65%	14,830	3589 ± 1248	40%	14,285	-1064 ± 2767	-7%	-4%	8242	26%
Avg.											

Epoch values are totaled and averaged in the bottom rows.

accounted for 27% of total volumetric change ($\sum V_{\text{DoD}}$) for the epoch. Central bar development accounted for 6% of the total volumetric change ($\sum V_{\text{DoD}}$) over the whole study period (Figure 10b), and varied between as little as 0% in 2006–2005 and as much as 9% in 2005–2004 (Figures 9e–9h) with a yearly average of 5%. Change due to transverse bar conversion was consistently larger and accounted for 19% of the total volumetric change ($\sum V_{\text{DoD}}$) in the reach over the entire study (Figure 10b), constituted as little as 9% in 2005–2004 (Figures 9e–9h) and averaged 15% each year.

[43] Bank erosion accounted for 17% of the total volumetric change over the entire study period, ranging from 24% in 2007–2006 to 3% in 2006–2005, with an annual average of 13%. Bank erosion was almost exclusively associated with flow forcing and subsequent channel widening around mid-channel bars, while relatively rare lateral bar development did not produce any detectable bank erosion over the whole study period. These contrast with single-thread channels where lateral bars (e.g., point-bars) are associated with forcing pools and bank erosion on the outer bank of meanders. In the Feshie study reach, bank erosion was forced primarily by lobate bars (i.e., transverse bar conversion) in 2006–2005 and 2007–2006, diagonal bars in 2004–2003 (i.e., chute cutoff), and longitudinal bars in 2004–2005 (i.e., central bar development).

[44] Channel incision was only present in isolated anabranches in 2004–2003 and 2007–2006, with no evidence for systemic downcutting of all the low flow anabranches over the study period. When channel incision did take place, it produced modest quantities of sediment accounting for 5% of the total volumetric change ($\sum V_{\text{DoD}}$) in the reach over the whole study period (Figure 10b), 13% in 2004–2003 and 8% in 2007–2006 (Figures 9e–9h). The

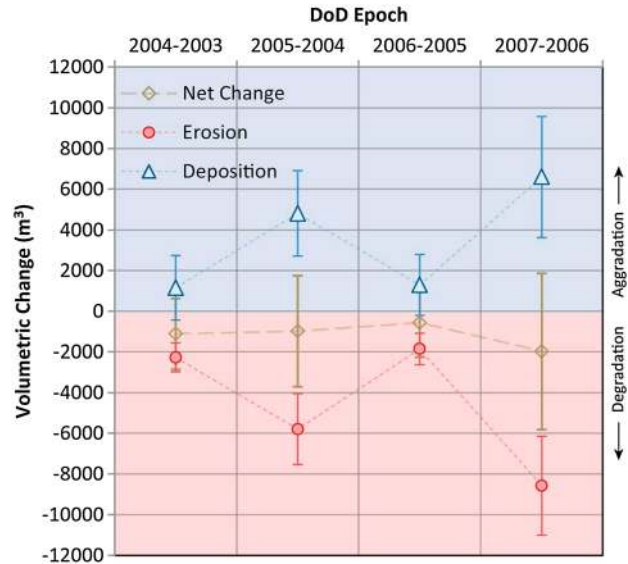


Figure 8. Volumetric change in each epoch, along with resultant net change. Uncertainty in total erosion ($\sum V_{\text{Erosion}}$) and deposition ($\sum V_{\text{Deposition}}$) volume estimates and interpretation of net change (ΔV_{DoD}) shown with error bars. The net change estimate shows consistent minor net degradation, but the uncertainty in this estimate is amplified in large years, such that the net signal may be slightly aggradational.

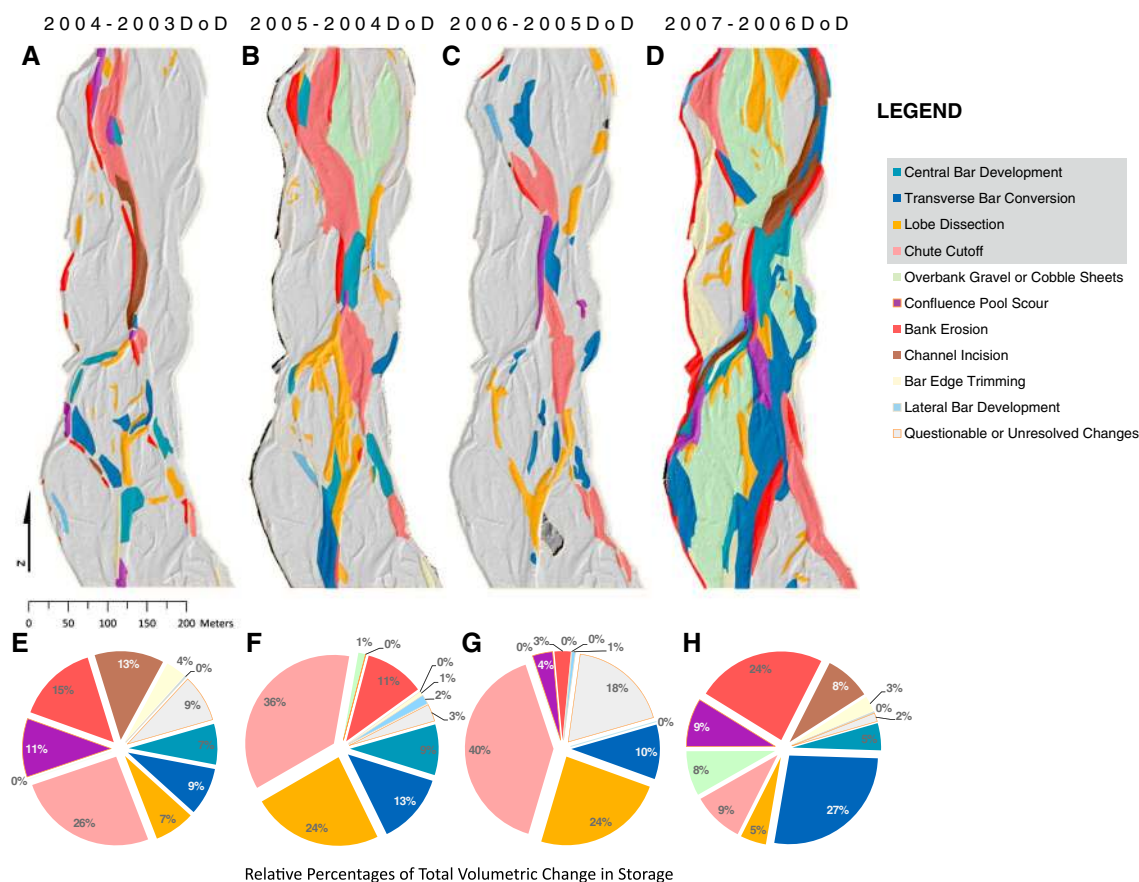


Figure 9. Spatial segregation of change in sediment storage budget by braiding mechanisms and other morphodynamic signatures of change. (a–d) show the geomorphic interpretations spatially for each epoch, whereas (e–h) show pie charts of corresponding relative percentages of volumetric change ($\sum V_{DoD}$).

location of channel incision is consistently located in portions of the main-flow channel that have recently formed from avulsions connecting a higher upstream channel to a lower paleo channel, which then reactivates as the main channel. These newly formed main channels carve new paths that make their way to the paleo-channels along over-steepened routes. Since the path of the new channels is generally shorter in length than the old channel, they are over-steepened, and these channels adjust by incising over their short distances to the new base-level control imposed by the paleo-channel to which they connect. There is no evidence of channel incision persisting in one location for more than a year, suggesting that the adjustment is able to take place rapidly (i.e., on an event or a few event timescales).

[45] Among the defining features of braided rivers are the presence of anabranches with confluences and diffluences [Ashmore, 1991]. The confluences are commonly the locations of scour pools, which Ashmore [1993] and Ashworth [1996] have shown are often the source zone for either central bar development or transverse bar conversion in the bar immediately downstream of the scour pool. Confluence pool scour accounted for 6% of the total volumetric change ($\sum V_{DoD}$) in the reach over the whole study period (Figure 10b), ranging between <1% in 2005–2004 and 11% in 2007–2006 (Figures 9e–9h) with an annual average of 6%. With the notable exception of the most prominent

confluence scour pool in the middle of the reach, most of the volume of confluence pool scour came from either the creation of a new scour pool or discrete episodes of accentuation of an existing pool. Some of the persistent confluence pools (Figure 6) seem to be defined more by their lack of major changes (persistence due to lack of change), as they are zones with adequate convergent flow so as to consistently pass the sediment delivered to them and deposit it downstream at the next bar where flows paths diverge [Ashworth, 1996].

[46] Overbank gravel or cobble sheets on the floodplain/braidplain accounted for 4% of the total volumetric change ($\sum V_{DoD}$) in the reach over the whole study period (Figure 10b). Overbank gravel or cobble sheets only formed in the years with the highest magnitude floods, accounting for only 1% in 2005–2004 and 8% in 2007–2006 of the total epoch volumetric change (Figures 9f and 9h). Despite their relatively minor volumetric contribution to the change in sediment storage, these sheets blanket very large expanses of the reach (Figures 9b and 9d), leaving a disproportionate impression of their significance from an aerial perspective. Ferguson and Werritty [1983] also reported seeing occasional decimeter thick gravel/cobble sheets on the Feshie, but did not quantify their relative importance. These sheets do not occur every year or every flood, but when large floods occur, gravel/cobble sheets are an important sink of sediment

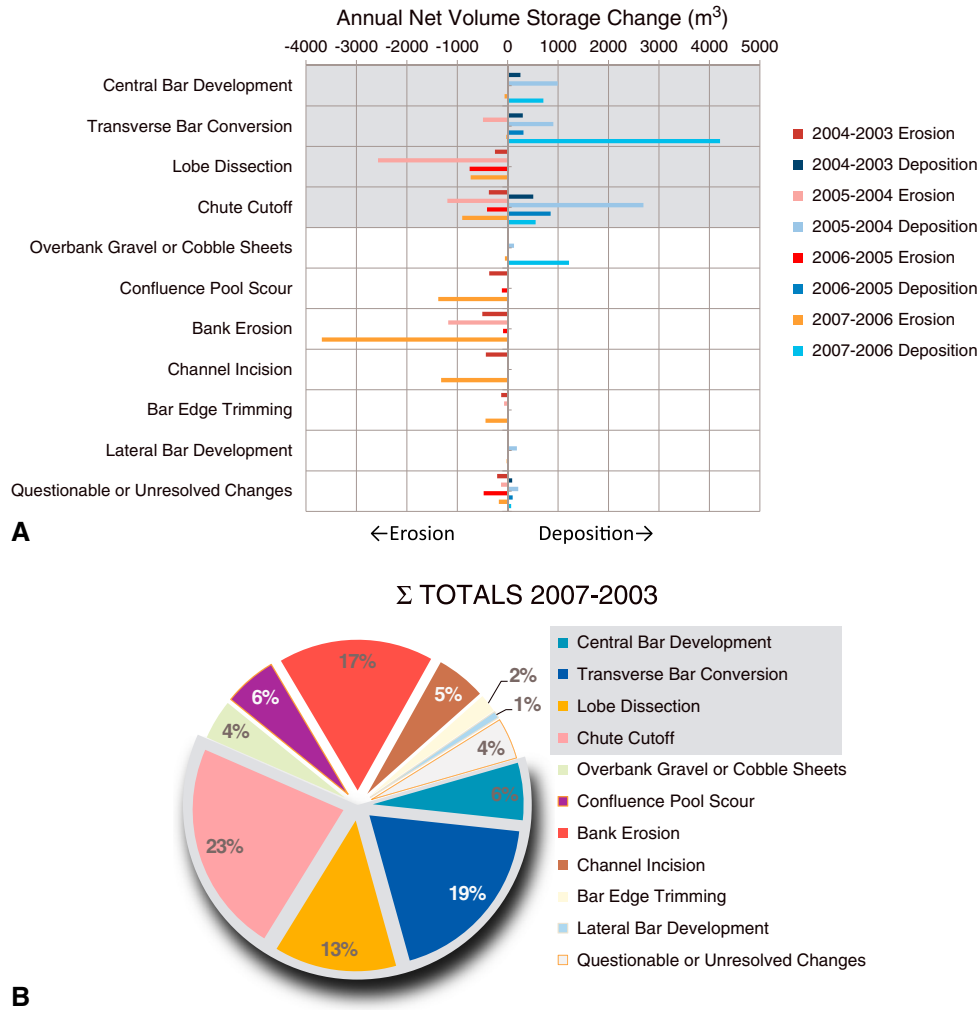


Figure 10. Comparison of primary braiding mechanisms and other morphodynamic signatures of change in sediment storage (ΔV_{DoD}). (a) Bar plot of annual net volume storage change broken down by mechanism and year, separated for total erosion ($\sum V_{Erosion}$) and deposition volumes ($\sum V_{Deposition}$). The top four mechanisms (grey shading in background) represent the primary braiding mechanisms. (b) Cumulative totals of relative percentages of total volumetric change ($\sum V_{DoD}$) for each mechanisms over the entire 2003–2007 study period are shown in the pie chart.

that typically bury the annual grasses, heather shrubs and mosses attempting to colonize the braid plain (see also the expanses of exposed gravels in overbank bars on aerial photos in Figure 2).

[47] The six “other” mechanisms of change accounted for 35% of the total volumetric change in the reach (Figure 10b), but varied between as little as 7% in 2006–2005 and as much as 52% in 2007–2006. The questionable or unresolved changes in the reach made up the other unaccounted 4% of the total over the study period, accounting for on average 8% of the changes each year. More precise survey methods such as ground-based LiDaR [Vericat *et al.*, 2012; Williams *et al.*, 2011] could better constrain the unresolved fraction of the budget.

[48] In every epoch, the six other morphodynamic signatures constituted net degradation with an average ΔV_{DoD} of -2060 m^3 and total ΔV_{DoD} of -8243 m^3 which equates to, on average, a 36% degradational imbalance. This strong tendency towards net degradation amongst the other

mechanisms of change helps explain the missing sediment supply that leads to the net aggradation amongst the primary braiding mechanisms. Given the strength of this discrepancy and previous work in gravel-bed rivers, suggesting sediment travel distances are often on the order of the bar/pool spacing [Pyrcie and Ashmore, 2003], it seems that these other mechanisms may be providing much of the sediment supply locally to facilitate the creation of major mid-channel bars and maintain braiding. Figure 10a shows that other than occasional overbank gravel or cobble sheets in large floods, the confluence pool scour, bank erosion, channel incision, and bar edge trimming mechanisms are indeed comprised of predominantly erosion. Overall, bank erosion contributes the most supply, but different mechanisms dominate year to year (Figure 10b).

4.3.2. Avulsions

[49] During the study period, only one major avulsion was observed (in the 2007–2006 epoch). Ferguson [1993, pp 78–79, Figure 5] described avulsions as a “mechanism

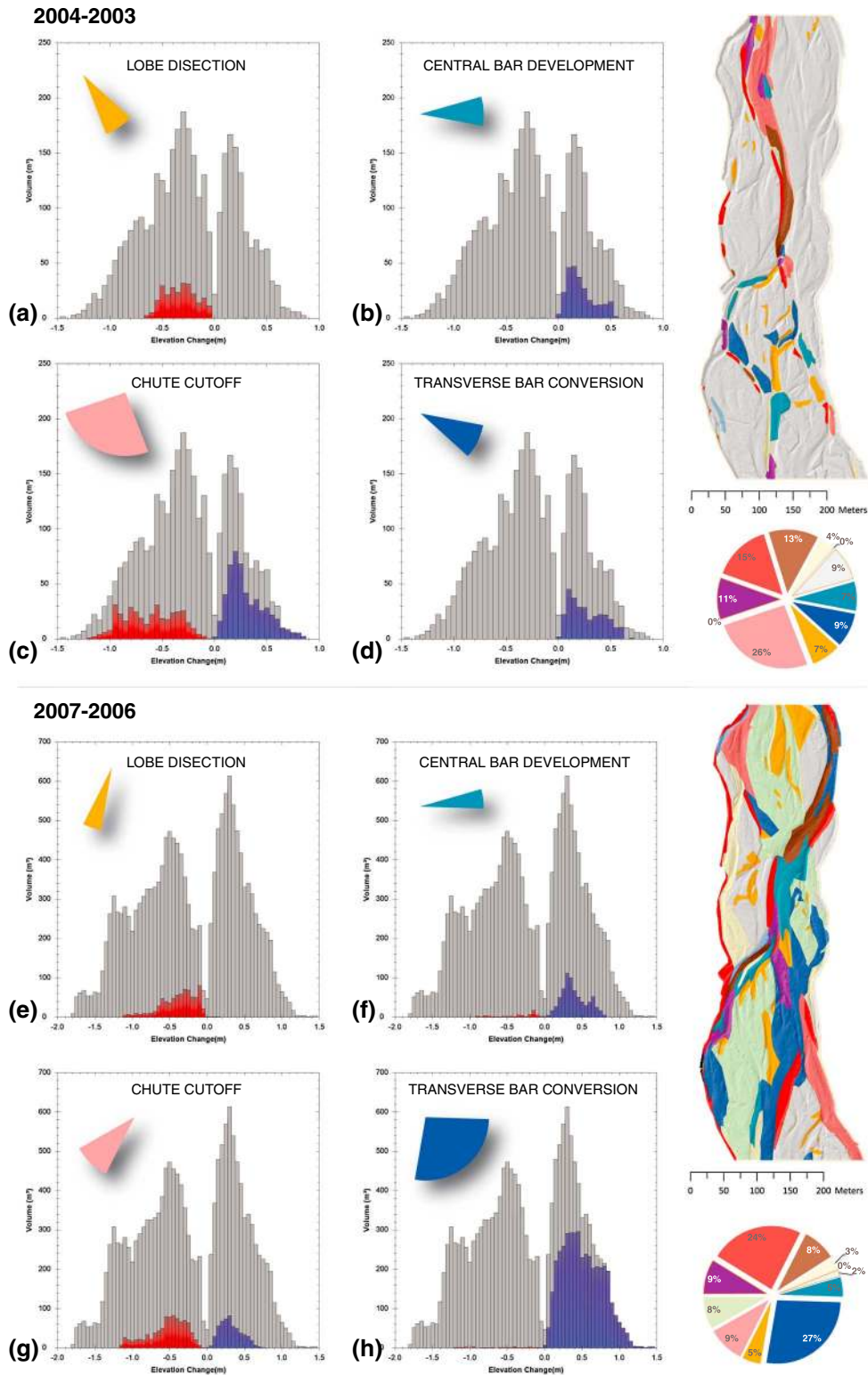


Figure 11. Examples of segregated elevation change distributions from four primary braiding mechanisms during (a–d) a relatively low water epoch (2004–2003) and (e–h) a higher water epoch (2007–2006). Mechanism masks and pie charts from Figure 8 are shown at the right for reference.

characteristic of braiding” and reviewed three primary modes of avulsion. In the first mode (termed constriction and overflow), flow is constricted in a bend promoting overflow on the outside bend, which then connects to a

topographically lower inactive braid channel (Figure 12a). In the second mode (termed bank erosion), flow is again constricted, but bank erosion on the outside bend provides the connection between the active channel and inactive braid

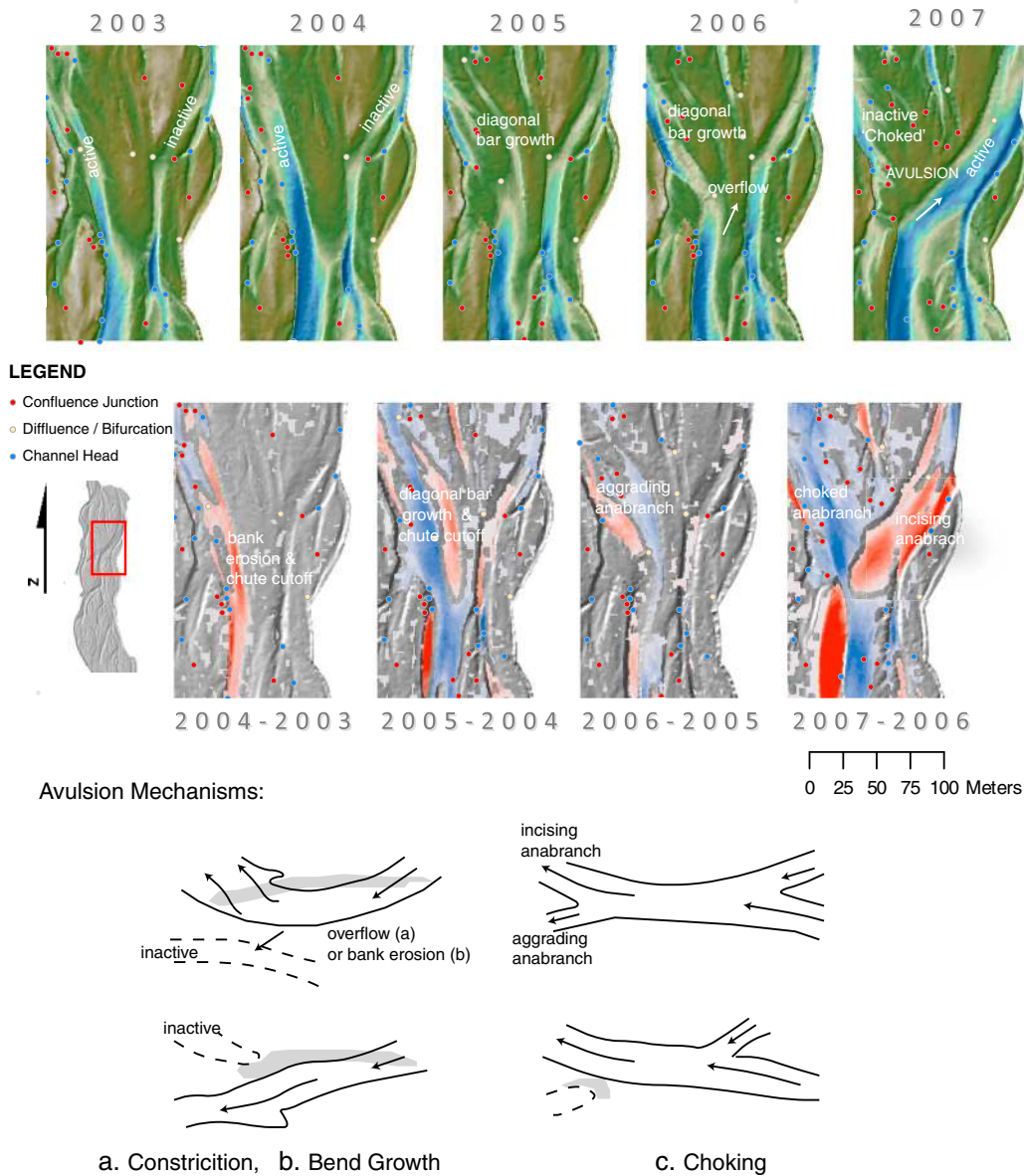


Figure 12. Morphodynamic changes leading up to 2007 avulsion event on Feshie explained in context of *Ferguson’s* [1993; Figure 5] modes of avulsion (bottom). The top row shows a zoomed in view of the detrended DEMs at the location of the avulsion event in 2007 (see Figure 4 reach-wide DEMs and legend). The middle row shows DoDs leading up to (2003–2006) and spanning the avulsion event (2007–2006; see Figure 6 for the DoD legend). Bottom conceptual diagram shows three contrasting avulsion mechanisms adapted from *Ferguson* [1993, Figure 5].

channel (Figure 12b). In the third mode (termed choking), one of the anabranches at a bifurcation is experiencing incision and the other experiencing aggradation, which eventually leads to choking and abandonment of the aggrading anabranch, and the incising anabranch becomes the primary conduit of flow (Figure 12c).

[50] Figure 12 illustrates the mechanisms revealed on the Feshie by our change detection that ultimately led to an avulsion in comparison to the three conceptual models of avulsion summarized by *Ferguson* [1993]. A mix of braiding mechanisms combined and culminated in conditions that facilitated this avulsion event. The avulsion took place on a subtle outside bend of the main anabranch. In 2004–2003,

bank erosion on the outside right bend of an active anabranch and chute cutoff of a point bar began to occur. In 2005–2004, the resulting diagonal bar expanded in the active channel and the channel widened significantly. In 2006–2005, the primary anabranch continued to aggrade as the diagonal bar continued to grow. Finally in 2007, the primary anabranch became so choked with sediment from continued bar development that the active anabranch plugged and the formerly inactive channel, which started to receive overflow in 2006, incised and became the primary anabranch.

[51] It is interesting to note that the choking avulsion mechanism that we witnessed here was also the most common anabranch avulsion mechanism that *Leddy et al.*

[1993] documented (70%–75% of all avulsions). The sequence we documented is also consistent with observations by *Ferguson and Werritty* [1983] of diagonal bar development in the Feshie. *Ferguson and Werritty* [1983] originally termed the choking avulsion an “interruption” of normal diagonal bar development. This “normal development” was later clarified by both *Ashmore* [1991] and *Ferguson* [1993] as chute cutoff—a primary braiding mechanism. So in the Feshie, where normal diagonal bar development (chute cutoff) is prevalent, there are increased opportunities for the process to be “interrupted” by an avulsion.

5. Discussion

[52] We set out to perform one of the first empirical field tests of whether the four classic braiding mechanisms that appear repeatedly in the braided river literature are most responsible for maintaining the dynamism of a braided gravel-bed river. Here we consider the classic braiding mechanisms to be central bar development, transverse bar conversion, chute cutoff, and lobe dissection [*Ashmore*, 1991; *Ferguson*, 1993]. It is plausible that these braiding mechanisms are what are required to initiate braiding, but that some other fluvial processes and morphodynamic signatures are what maintain a reach’s dynamism—i.e., its regular turnover due to erosion and deposition. However, insights from flume observations [*Ashmore*, 1982, 1991; *Ashworth*, 1996] suggest that these braiding mechanisms do occur with regularity over the evolution of braided channel. But what role do morphodynamic signatures like bank erosion and confluence pool scour that are not limited to just braided environments play in the overall dynamics and change in sediment storage of a braided reach?

[53] Analysis using the classification of morphodynamic signatures we identified revealed that in the Feshie, one of the four main braiding mechanisms (chute cutoff) dominated across the monitored flow range, although the volumetrically dominant process does vary between epochs (Figure 9). In three of the four epochs, chute cutoff dominates the volumetric change, followed by lobe dissection (Figure 9). In the highest flow epoch (2007–2006), the dominant braiding mechanism switches to transverse bar conversion, largely in response to channel widening accommodated by bank erosion. This raises the prospect of flow driven sequences of process dominance that ultimately may control braiding and dynamism.

5.1. Under-Appreciation of Bank Erosion in Facilitating Braiding

[54] Bank erosion is regarded as a major mechanism of channel change in single-thread channels and much research exists on the topic [*Darby et al.*, 2007], but its role in braided rivers has been overshadowed in the literature by other braiding mechanisms [*Mueller*, 2012]. We found bank erosion to be as or more important of a mechanism than two of the four braiding mechanisms in terms of changes in sediment storage, and it emerged as the most important “secondary” mechanism (accounting for 17% of total change in storage). Indeed recent flume work has emphasized how critical vegetation is in providing bank cohesion to prevent braiding [*Braudrick et al.*, 2009; *Tal and Paola*, 2007]. However, this work stops short of explaining just how

important bank erosion is in braided rivers as a primary geomorphic mechanism of change and an essential local sediment supply source to help feed the deposition required for the function of braiding mechanisms that produce bars (e.g., central bar development, transverse bar conversion and chute cutoff). However, our data provide among the first empirical evidence of the relative importance of bank erosion in a braided river.

5.2. Role of Flow Magnitude and Variability in Braiding Mechanisms

[55] The roles of flow magnitude and variability were not an explicit focus of this study, and such an analysis is easier to untangle with event-based repeat topographic data. Within the braided river literature, the role of flow variability in the maintenance of braiding remains contested [*Bertoldi et al.*, 2010]. Flume studies demonstrate that braiding mechanisms can occur at steady discharges perhaps unintentionally promoting the view that braiding is largely independent of flow variability [*Ashmore*, 1991; *Ferguson*, 1993]. *Lane* [2006] suggested that the role of flow variability was to promote different mechanisms of bar evolution at different high flows as elevated bar surfaces become progressively more inundated and dissected by erosion. *Bertoldi et al.* [2010] demonstrated morphodynamic dependence on discharge from cross-section measurements in a large, braided gravel-bed river. Thus, a greater range of high flows need not necessarily produce a greater volume of geomorphic change than a system with constrained flow variability (e.g., diurnal), but can produce a greater diversity in the mechanisms that bring about those geomorphic changes.

[56] At discharges below bankfull stage, flows are confined to the primary anabranch channels, and channel morphodynamics will be a product of low-flow channel geometry. At flows greater than bankfull, hydraulic patterns and sediment dynamics will be only partially influenced by the low-flow channels, with the flow geometry being controlled by floodplain or braidplain geometry. In order to generate flow division through either dissection of bar surfaces or aggradation of bars within a channel, there must be sufficient flow depth to (a) access the bar surface and generate sufficient shear to entrain and transport bar materials and (b) permit accumulation of unit bars above the general bed level. *Bertoldi et al.* [2010] identify significant differences in sediment volume associated with the transition from flow confinement in primary channel networks below bankfull, and the increase in flow width and activation of secondary channel networks at flows above bankfull.

[57] To provide a simple test of the hypothesis that reach-scale changes in the volume of erosion or deposition were a function of flow variability, we undertook an analysis of total flow volume above a bankfull threshold during the epoch between surveys. *Sear* [2004] explained this response at the event scale in terms of the duration of flow over some critical threshold, and concluded that sediment yields for flood events were best explained in terms of the total event power. In the absence of field measured hydraulic data to estimate total event power for the study reach, we consider flow volumes in excess of bankfull. We calculated the total flow volume greater than bankfull for the reach ($\sum Q - Q_{bf}$). Since flow was sampled at consistent 15 min intervals, this metric is

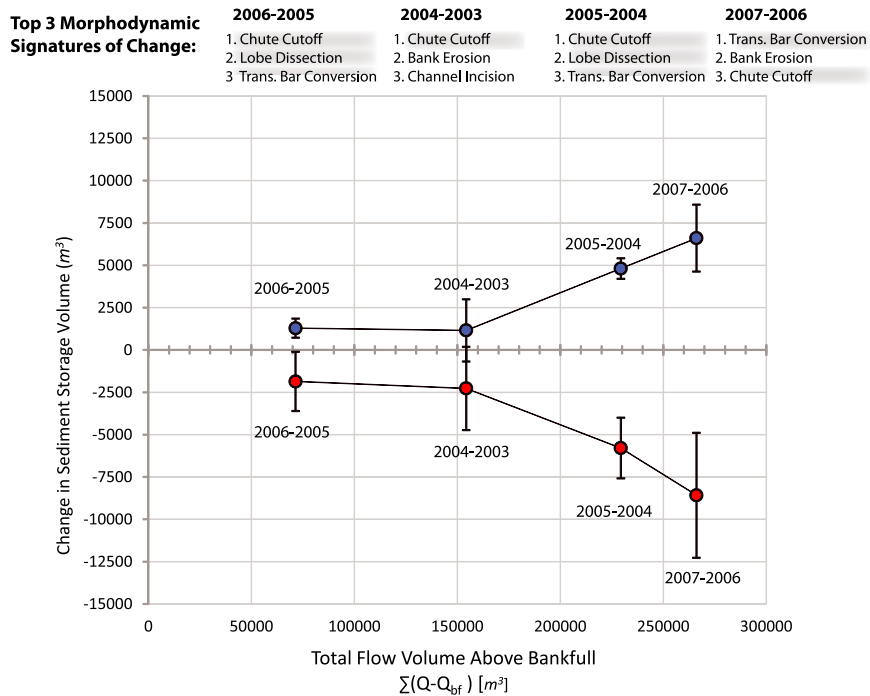


Figure 13. Empirical relationships between change in storage volumes for erosion and deposition and the total water volume in the epoch above bankfull Q_{bf} discharge. Blue is depositional change and red is erosional change in storage. The three dominant morphodynamic signatures of change are shown for each epoch, with braiding mechanisms highlighted in grey.

simply the sum of all 15 min values of $Q > Q_{bf}$ divided by duration above the same Q_{bf} threshold (we chose the median between low and high estimates of Q_{bf} in Table 1). Thus, this metric varies as a function of both the magnitude and duration of flows over Q_{bf} for the period between topographic surveys (Figure 13).

[58] The total number of mechanisms involved in the evolution of the channel pattern and the reach dynamics changes with $\Sigma Q - Q_{bf}$. At the lowest values of $\Sigma Q - Q_{bf}$, six out of the 10 mechanisms operate, of which two contribute 64% of the total volumetric change. As $\Sigma Q - Q_{bf}$ increases, the number of mechanisms rises through eight, to a total of nine out of 10. The range of mechanisms also varies with $\Sigma Q - Q_{bf}$. We had assumed that as duration over bankfull increased, there would be an increase in the processes of bar surface dissection [cf Lane *et al.*, 2008], such as chute cutoff and lobe dissection, and an increase in central bar development and transverse bar conversion as d/d_{50} increased sufficiently for bar formation. In fact, dissection processes remained important throughout our study period, with the exception of the highest $\Sigma Q - Q_{bf}$, when depositional processes of transverse bar conversion, and erosional processes of bank erosion, confluence pool-scour and chute cutoff dominated volumetric changes in storage. We postulate this might be because topographic steering of flows in smaller floods was more effective at “carving up” and sculpting heterogeneity in the braidplain; whereas bigger floods might carry with them higher sediment loads and topographic steering is muted such that they just “paste” big sheets of sediment across the braidplain, which are subsequently reworked by falling-limb flows and smaller floods.

[59] We deduce from this analysis that the total volume of change scales to the magnitude of flow magnitude and variability. Total flow volume above bankfull is also important in switching process dominance towards (in this case) mechanisms of channel widening and transverse bar building. At lower discharges, different braiding mechanisms still dominate, but these are confined to areas immediately surrounding the existing anabranch network, and overall less volumetric change (work) is undertaken.

5.3. Implications for Other Braided Rivers

[60] There are at least four conceptual implications of our findings which can be extended to other braided rivers. First, we have tied the conceptually powerful notion of dynamism, thought to be the hallmark of a braided river, to a measurable metric—change in sediment storage. In so doing, we learned that when combined, classic braiding mechanisms [e.g., Ashmore, 1991; Ferguson, 1993] appear to be responsible for a bulk of the dynamism, a finding that we speculate is likely to be true in most braided rivers where braiding is maintained—regardless of flow regime. Secondly, the importance of bank erosion and other erosional morphodynamic signatures in supplying sediment locally to feed these braiding mechanisms is critical. For gravel-bed braided rivers, we surmise that local changes in storage dynamics due to erosion are the primary supply of sediment for the extensive deposition that takes place regularly to maintain active mid-channel bar surfaces. Third, we found that chute dissection is not only an erosional process, but appears to promote significant deposition with the growth of the resultant mid-channel diagonal bar. This form of bar development has been previously identified [Ferguson and Werritty, 1983], but the

relative roles in dynamism of carving the chute versus building the bar are underappreciated. Finally, we found that the four common braiding mechanisms in combination were net aggradational, despite requiring both significant amounts of erosion and deposition to occur. Since the defining geomorphic units of braided rivers are active mid-channel bars, most persistently braided rivers must have braiding mechanisms with net aggradation change in sediment storage to maintain such bar forms. However, whether or not the entire braided reach is in a state of net aggradation, dynamic equilibrium or net degradation will be explained by the prevalence of the other morphodynamic signatures of change (e.g., bank erosion, bar sculpting, channel incision) in relationship to the upstream supply of sediment to the reach.

[61] From a methodological perspective, this study has demonstrated a tractable and robust workflow for exploiting topographic time series to interrogate the mechanisms responsible for the dynamism of a reach. The DoD segregation techniques are facilitated by the GCD software, and our methods here describe specific techniques for identifying and interpreting geomorphic changes as specific braiding mechanisms and other modes of adjustment. Future studies on other braided rivers may examine whether or not our empirical observations hold of braiding mechanisms (i) dominating, (ii) being primarily depositional and (iii) being fed largely by a locally sourced supply of sediment from (in order of importance) bank erosion, confluence pool scour, channel incision, and bar edge trimming. If these findings hold, they provide a strong basis for testing the validity of morphodynamic simulation models by looking for these morphodynamic signatures as emergent properties in the results.

6. Conclusions

[62] We sought to classify the morphodynamic signatures of change responsible for driving the dynamism of a braided gravel-bed river, and in so doing test presumptions about the relative importance of classic braiding mechanisms versus alternative sediment exchange processes. Recent methodological progress in repeat topographic surveying and geomorphic change detection has opened the door to testing long-standing concepts and theories about how braided rivers function, but we asserted that these data and techniques have not been adequately exploited to progress our understanding of how braided rivers function. We recast the concept of geomorphic dynamism here in terms of erosion and deposition that are manifested topographically by changes in sediment storage. Using geomorphic change detection methods, we examined variability year to year in the morphodynamic signatures that produced that change on a braided reach of the River Feshie via annual resurveys.

[63] Our analyses indicated that the four classic braiding mechanisms frequently described in the literature [Ashmore, 1991; Ferguson, 1993] were in combination responsible for a majority of the dynamism in the reach (61% of total change), and these produced a net aggradational change in storage. However, even though bank erosion is not itself a braiding mechanism, it should be considered a key mechanism in facilitating braiding and, in this study, was the third most important individual mechanism of change. Chute cutoff appeared to be the most common mechanism of the

four which accounted for braiding. We also found that the channel appeared to maintain its braided character in a dynamic equilibrium state over the span of this study, as suggested by topological classification of channel heads, bifurcations, and confluences and braiding indices. In contrast to the four classic braiding mechanisms, other morphodynamic signatures of sediment scour and deposition accounted for 35% of the total topographic change in the reach. While the four classic braiding mechanisms (dominated by chute cutoff) were usually aggradational in nature, these other mechanisms of change were typically erosional. Subsequent analyses indicate that flow magnitude has an impact on the braiding processes that act on the reach, but perhaps more importantly, the time that flows exceeded a bankfull level appear to influence how regularly these processes occur. With an increase in the duration that discharge exceeded bankfull came a corresponding increase in the diversity of braiding processes.

[64] This research marks one of the first cases in which flume-based observations of braided river morphodynamics have been tested empirically in the field via high-resolution data collection techniques. As such, the workflow presented here may be extended to other braided channels. The findings deserve further study, particularly our conclusion that the classic braiding mechanisms described previously in flume work appear to be of critical importance in shaping streams at the reach scale. Furthermore, the relative importance of different suites of morphodynamic signatures could be used as a basis for testing and verifying the performance of morphodynamic models.

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