# Chapter 8

# River Feshie - Investigating the Dynamics of a Braided River in the Scottish Highlands

## 8.1 Introduction

The River Feshie, in the heart of the Scottish Highlands, is an anomaly in the contemporary British Isles landscape. It boasts an unconfined 3 km-long braided reach and active braidplain, set within a longer, actively wandering 8 km reach called Glen Feshie. The Glen itself is a glacial trough, which was deglaciated roughly 13,000 BP (Gilvear *et al.* 2000) and is flanked by impressive fluvio-glacial terraces on the valley sides (Robertson-Rintoul 1986). The river has an abundant supply of fluvial and fluvio-glacial sediments to rework from its own valley floor (Figure 8.1). Combine this with the unregulated and flashy flow-regime of the Feshie (Soulsby *et al.* 2006), its credence as a classic Scottish salmon stream (Gardiner & Mackay 2002, Grant *et al.* 2006), and an upper catchment that drains 'some of the steepest, most mountainous terrain in the United Kingdom' (Soulsby *et al.* 2006) it is no wonder the Feshie has been the subject of so much geomorphological[1], hydrological[2], and geological[3] research for so long. Gilvear *et al.* (2000) called the Feshie 'the best example of a relatively natural highly active gravel-bed river in the UK...' and credited the rich vegetation diversity on its alluvial fan to this dynamism. For these impressive fluvial traits, the Feshie is designated as a Site of Special Scientific Interest by the Joint Nature Conservation Commission under the Wildlife and Countryside Act of 1981 (Werritty & Brazier 1991, Werritty & McEwen 1993).

For five years from the late 1970's, two sub-reaches of this braided[4] reach in the Feshie were

[1] For example, Gilvear *et al.* (2000), Ferguson & Ashworth (1992), Ferguson & Werritty (1983), Rumsby *et al.* (2001), Werritty & Ferguson (1980), Brasington *et al.* (2000), Brasington *et al.* (2003) and Robertson-Rintoul (1986).

[2] For example, Soulsby *et al.* (2006), Rodgers *et al.* (2005), Soulsby *et al.* (2005) and Rodgers *et al.* (2004).

[3] For example, Bremner (1915), Golledge (2004), Brazier & Ballantyne (1989) and Young (1976).

[4] Note that Ferguson & Werritty (1983, p.181) refer to this reach as 'wandering' instead of braided in keeping


FIGURE 8.1: Context photographs of Glen Feshie. A) View looking South (up valley) at the study reach from Glen Feshie Lodge (star in photo B) B) View looking North (down valley) from on top of the ridge (star in A).

extensively studied by Ferguson & Werritty (1983).[5] They studied two sub-reaches of the Feshie from 1976 to 1981: the 'bridge reach' and the 'tree reach'. The 'tree reach' is a 160 m long, 60 m wide sub-reach in the middle of the 1 km long 300 m wide study reach used here (see Figure 4.1 for their respective locations). Their study was focused on mechanisms of bar development and channel evolution as inferred by tracking channel changes on an annual basis using repeat transect and planform surveys.[6] From their measurements and observations, Ferguson & Werritty (1983, Figure 3) produced a conceptual model of diagonal-bar development, which helped explain some of the observed changes in the Feshie. In the first-stages of their model, bar progradation at high-flows forces bank erosion on the opposite side of the channel at lower and intermediate flows, which feeds the growth of the next diagonal bar downstream. The process is eventually interrupted either by chute dissection of the downstream bar, or avulsion outside the channel from ponded-pool overflow. Such a simple model is an elegant example of how basic quantitative field observations, can be synthesised qualitatively to produce a clearer understanding of the channel kinematics.

At the time, the work of Bluck (1976) and Werrity & Ferguson (1980) were the first known examples of repeat surveys of bar-development and channel changes in a braided reach. As part of those campaigns, Ferguson & Werritty (1983) used instrumental levels to resurvey 60 m transects across the 160 m long reach and mapped planform changes with a tacheometric plane-table and alidade. The surveys were completed annually each summer for five years (1976 to 1981). For the transects, they surveyed elevations every 2 m along nine 60 m parallel transects, spaced 20 m apart (circa 270 points) - an impressive effort given the technology. Just 1.2 km upstream and 20 years later, Brasington *et al.* (2000) and Brasington *et al.* (2003) started undertaking repeat topographic surveying using survey-grade rtkGPS (real time kinematic global positioning system) capturing the three-dimensional geometry of fluvial

with Church & Rood (1983). That distinction is not observed here for simplicity, and the reach is simply termed braided.

[5]Building on work by Werrity & Ferguson (1980) and Werritty (1984).

[6]In other words, this was a classic 1D implementation of the morphological method (see § 3.3.1.2).

surfaces at a spatial resolution probably unimaginable 20 years earlier.[7] Brasington *et al.* (2000) surveyed a 200 m x 80 m reach in 1998 and 1999 at point densities of 0.69 to 1.10 pts/m$^2$ (circa. 10,000 to 14,000 points). In 2000, a long-term monitoring annual repeat surveying monitoring campaign[8] was resurrected in a roughly 1 km stretch of the Feshie containing the 'tree reach'. The GPS surveys were used to acquire between 30,000 and 50,000 points each year with point spacing varying between a point every 25 cm in areas of topographic complexity to up to every 2.5 m over flat areas of braid-plain (Brasington *et al.* 2004, Wheaton *et al.* 2004*a*, Wheaton *et al.* 2007). The reach can be surveyed in about 25 person-days, and this is typically now accomplished in a week's time with 3-5 rovers deployed simultaneously. Starting in 2006, the reach was also surveyed concurrently with a terrestrial laser scanner, collecting upwards of 1000 points per second, resolving grain-scale morphological features and producing overall point-clouds on the order of 25 to 50 million points (Brasington *et al.* 2007).

There is no question that advances in technology over the past 25 years have enabled an unprecedented expansion in the spatial scope and spatial resolution of data that can be collected and captured (Lane & Chandler 2003). In just these Feshie examples, the GPS pushed the volume of data acquisition up two orders of magnitude, with similar effort; whereas the terrestrial laser scanning has expanded the volume of data a whole five orders of magnitude! Impressive as the this may be, the real question is whether or not the additional data is delivering better mechanistic understanding of how such systems function? One of the premises for pursuing the second objective of this thesis[9] was that, to date, the modern high-resolution surveys have not yet effectively taken advantage of the wealth of data and information locked up in their topographic data sets. There have been very interesting and necessary methodological developments to demonstrate how to apply these new technologies and more robustly identify their inherent uncertainties.[10] However, can the increased spatial resolution and extent that comes from these developments be used to meaningfully extend the type of Ferguson & Werritty (1983) observations and inferences at the bar-scale to analyses across entire reaches? If so, a better understanding of the relative importance of different processes at bringing about observed channel changes might be revealed.

The purpose of this chapter is primarily to describe the dynamics of a braided river (for a four year period) in the Scottish Highlands (the Feshie) and secondarily to demonstrate how the methods developed in Chapter 5 for making geomorphological interpretations from morphological sediment budgets can be used when monitoring a relatively dynamic system exhibiting a broad range of fluvial processes. It is asserted that new tools or techniques[11] are needed to learn how to better exploit these more complicated topographic datasets[12], in

[7] See Figure 4.1 for relative locations of study sites.

[8] See § 4.2 for description of this field campaign.

[9] Of making more meaningful mechanistic geomorphological interpretations of repeat topographic surveys. See § 1.3.2 and § 3.4.

[10] For example, the developments in Chapter 4. See Chapter 3 for a review of these developments.

[11] Such as those proposed here (see Part II).

[12] Such topographic datasets include both those collected by conventional ground-based methods (total station and GPS), as well as terrestrial laser scanning. This chapter focuses exclusively on conventional GPS

a manner that allows a return to the mechanistic explanations of the likes of Ferguson & Werritty (1983). If such a mechanistic understanding can be upscaled from the bar-scale to larger reach-scales, then a clearer understanding of the relative importance of different styles of change and their interdependence on each other may be achieved.

This is the final of the three case studies of geomorphological channel change that comprise Part III. It will also be the most concise for the following reasons:

1. The Feshie study site does not need to be reintroduced as this was already done in § 4.2, justified in § 3.5 and § 5.3, and outlined in more detail in Appendix A.
2. Unlike the previous two chapters, the application of the DoD Uncertainty Analysis techniques from Chapter 4 does not need to be presented, as they were already reported for the Feshie in Chapter 4. Thus, the thresholded DoDs from a pathway 4 analysis presented in Figure 4.29, are the starting point for the analysis here. That is, DoDs that have had a full spatially-variably accounting of uncertainty analysis and application of a spatial coherence filter will be used. These are thresholded at a 95% confidence interval so as to be reasonably confident that real changes are distinguished from the noise.
3. As the method and utility of various masking techniques proposed in Chapter 5 have already now been demonstrated in the previous two chapters, the only mask applied here is an expert-based geomorphological interpretation masking technique.

Thus, this chapter will begin with an overview of the four year study-period from 2003 to 2007 (inclusive) and the primary drivers of change in that time. It will then proceed into the a detailed analysis of the sequence of change for each of those periods. The reader may find it helpful to refer back to § 4.6, which presented the basic sequence of change at a coarse reach scale with different pathways through a DoD uncertainty analysis. This chapter will close with a discussion of how the analyses can be used to address some more specific questions about the evolution of particular bar complexes, confluences and diffluences within the reach.

## 8.2 Overview and Drivers of Change

Four analysis periods fall out of the five annual surveys reported here. As the intermittently occupied Carnachuin Bridge gauge[13] is no longer rated, flow records for the study reach were not available. Instead, SEPA's Feshie Bridge gauge (some 7 km downstream) is used here as a proxy for the flows and event drivers of change at the site (Figure 8.2). The catchment area of the study site is roughly 47% of that at Feshie Bridge (110 km$^2$ versus 231 km$^2$). The mean

data sets as there are five years of record (only two for the terrestrial laser scan data), and even this has not yet been exploited.

[13] This gauge is located on a wooden foot bridge in the Ferguson & Werritty (1983) 'bridge reach'(Figure 4.1). The station was occupied in 1978-1981 by the University of St. Andrews (Ferguson & Werritty 1983); again in 2004 as part of the CHASM project (Soulsby *et al.* 2006), and most recently by the University of Cambridge in 2006 (p. comm Cox). To the knowledge of the author, the section was only rated in 1978-1981.

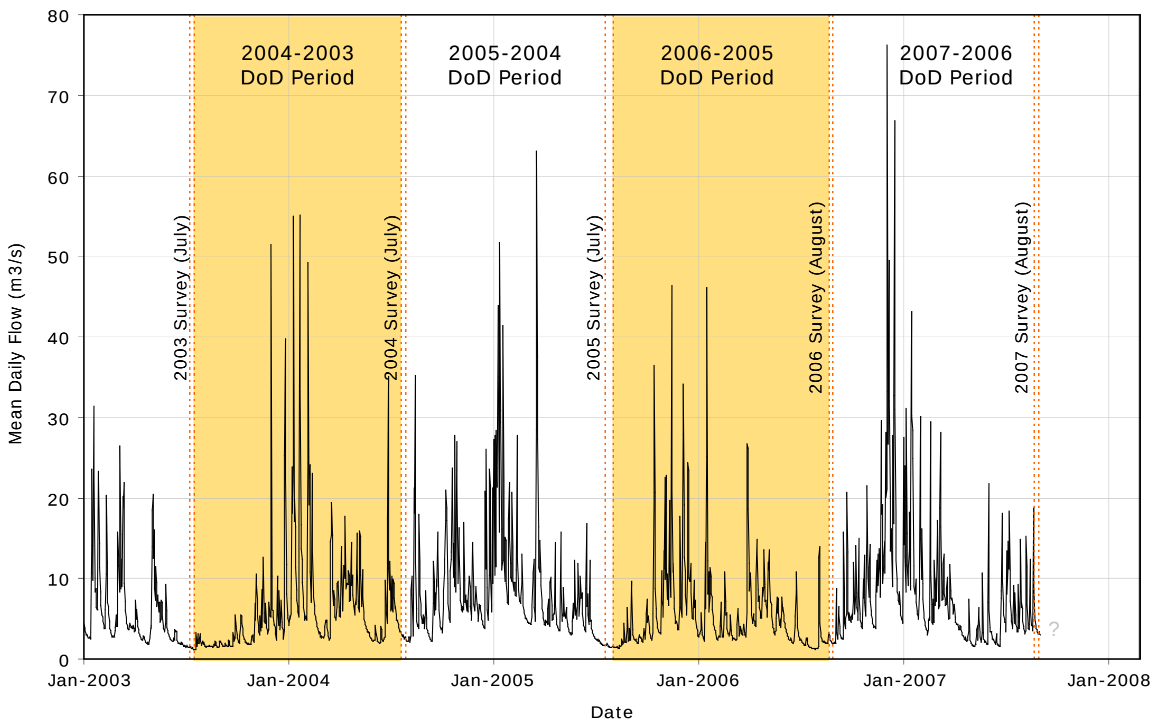


FIGURE 8.2: Hydrograph for Feshie Bridge during study period. The dashed vertical orange lines represent the start and stop dates for the five individual surveys. Data from SEPA.

flow at Feshie Bridge (based on 10 years of data) is 8.01 cumecs (Soulsby *et al.* 2006, Gilvear *et al.* 2000). Thus, the 2003 to 2004 season and 2005 to 2006 season were both less than average years; whereas the 2004 to 2005 season and 2006 to 2007 season were both higher than average years (Table 8.1). Those crude distinctions are actually enough to begin to distinguish the relative magnitude of geomorphological changes observed in both years. As the survey frequncy is only annual, the DoDs are integrating changes from a range of flow events with varying magnitude and frequency. However, some further generalisations can be drawn.

Ferguson & Werritty (1983) estimated 'bankfull' discharges for the study reach to be somewhere in the region of 20 to 30 cumecs. This might notionally correspond to a Feshie Bridge flow of 28 to 42 cumecs (p. comm Cox). A simple flow frequency and peaks-over-threshold analysis for the study period at Feshie Bridge is shown in Table 8.1. The peaks-over-threshold analysis for the range of notional discharges at which braidplain inundation might begin to occur, reveals a greater frequency of inundation in 2004-2005 and 2006-2007. Coupling this with field evidence of inundation, it is quite likely that during the 2005-2006 season the majority of the braidplain was not inundated at all.

The largest two individual events (76.3 and 66.8 cumecs at Feshie Bridge) occurred within two weeks of each other toward the end of 2006. These were two of only three storms over the whole study period to exceed 60 cumecs, with the other big event (63.0 cumecs) occurring

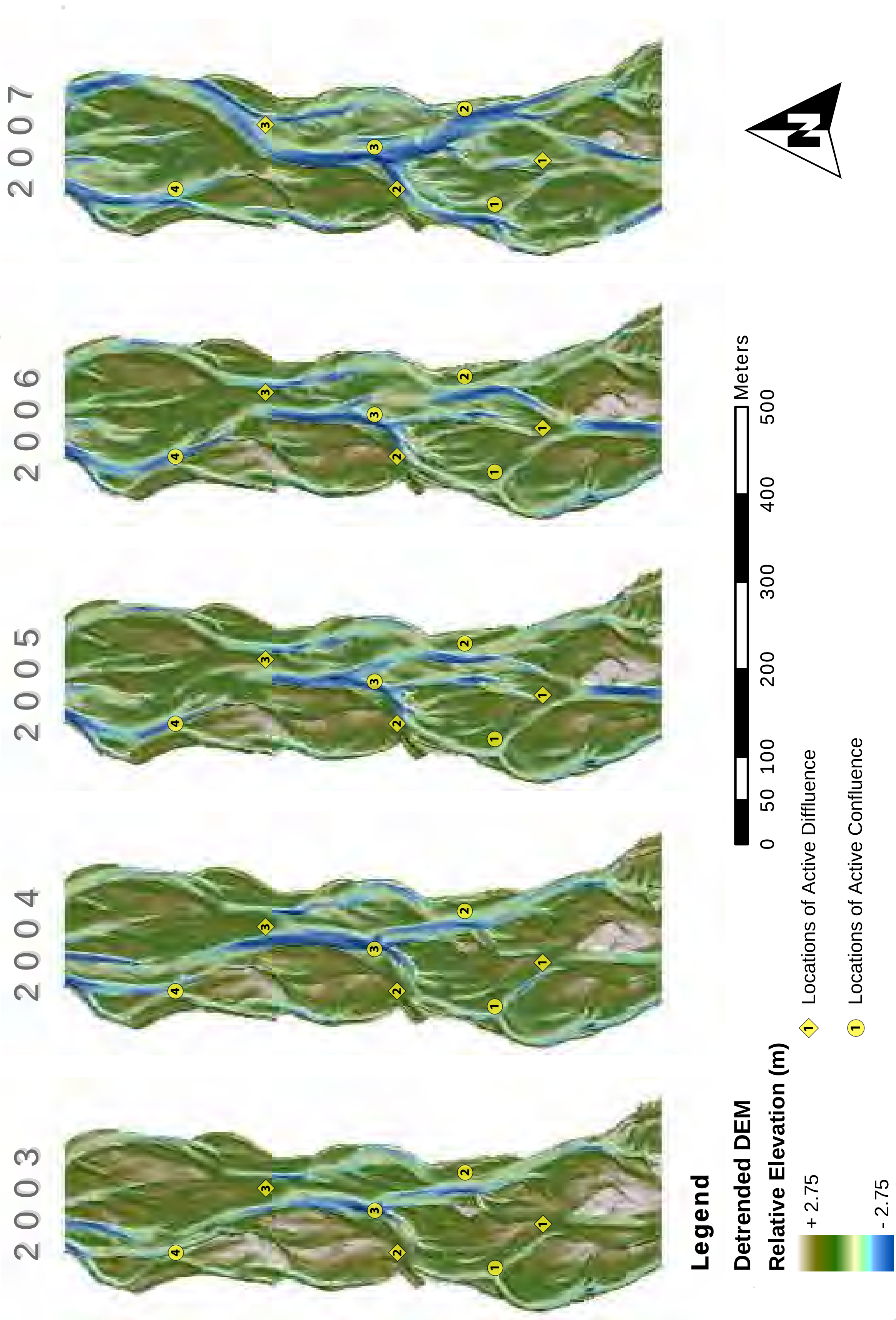


FIGURE 8.3: Detrended DEMs showing relative elevations for the five DEMs from 2003 to 2007. The small yellow diamonds indicate locations of active diffluence zones and the small yellow circles represent locations of active confluence zones that will be referenced throughout the chapter.

| Period | 2003-2004 | 2004-2005 | 2005-2006 | 2006-2007 |
|---|---|---|---|---|
| Mean Flow | 6.41 | 8.77 | 5.60 | 8.44 |
| High flow | 55.17 | 63.01 | 46.39 | 76.28 |
| 2nd high flow | 54.98 | 51.78 | 46.09 | 66.80 |
| 3rd high flow | 51.52 | 43.95 | 36.49 | 49.48 |
| 4th high flow | 49.21 | 41.39 | 34.20 | 43.14 |
| 5th high flow | 39.71 | 37.48 | 27.87 | 33.23 |
| POT (28 cumec) | 6 | 11 | 5 | 11 |
| POT (42 cumec) | 4 | 2 | 0 | 3 |
| POT (60 cumec) | 0 | 1 | 0 | 2 |
| 100th percentile | 55.17 | 63.01 | 46.39 | 76.28 |
| 99th percentile | 43.03 | 38.89 | 28.18 | 36.80 |
| 95th percentile | 17.96 | 25.57 | 14.54 | 26.38 |
| 90th percentile | 12.29 | 17.35 | 10.90 | 17.00 |
| 75th percentile | 7.25 | 10.19 | 6.39 | 9.91 |
| 50th percentile | 4.20 | 6.25 | 3.64 | 5.64 |

TABLE 8.1: Flow statistics from Feshie Bridge during study period. All flows reported in cumecs. The top half are mean and ranked flows for each water year. POT refers to peaks over threshold analysis, which counted the number of storms in each year over 28, 42 and 60 cumecs. The bottom half shows various percentage quantiles (flow that x% of the time is not exceeded in a given year). Raw 15 minute data from SEPA dating back to 1992; analysis by Cox (p. Comm).

in March of 2005.[14] A notable contrast between these large events is their timing within the season, and the subsequent effectiveness of intermediate storms. The 2006 events were followed by between eleven and three potentially floodplain inundating events (depending on what estimate of bankfull and/or P.o.T. is used). However, it is likely those three to eleven later season floods would have been less effective (geomorphologically) without those early season storms to break up the armour layer and potentially deposit fresh new unarmoured sediments. By contrast the high magnitude event in March 2005 came mid-season and was preceded by a series of intermediate storms, but was not followed by any significant events in the spring snow melt season before the next survey. None of these larger events compare to the three storms exceeding 100 cumecs (notionally >140 cumecs at Feshie Bridge) that Ferguson & Werritty (1983) reported during their five year study period at the site in the 1970s. However, the same patterns that Ferguson & Werritty (1983) observed still persist: a) most of the biggest floods tend to follow prolonged frontal rainfall in the late autumn or early winter; b) the spring-snowmelt peaks are highly diurnal, but generally produce only intermediate size floods; and c) occasional flashy summer floods from convective thunderstorms can rival those in late autumn or early winter.

For an overview of the changes these events brought about, the time series of DEMs used in the DoD analysis for this chapter are shown in Figure 8.3.[15] The DEMs were detrended

[14] Throughout this chapter, these floods exceeding 60 cumecs will be referred to descriptively as 'large' floods. By contrast, those floods in the 28 to 60 cumec range will be referred to as 'intermediate' floods.

[15] See Appendix C and § C.4 for more information on how DEMs were derived and detrended.

| | DoD Change | | | |
|---|---|---|---|---|
| DoD | Erosion $m^3$ | Deposition $m^3$ | Net $m^3$ | Total $m^3$ |
| 2006-2007 | 8581.0 | 6605.3 | -1975.7 | 15,186.3 |
| 2005-2006 | 1857.8 | 1288.5 | -569.3 | 3146.3 |
| 2004-2005 | 5794.0 | 4810.8 | -983.2 | 10,604.8 |
| 2003-2004 | 2268.1 | 1156.1 | -1111.9 | 3424.2 |
| $\mu$: | 4625.2 | 3465.2 | -1160.0 | 8090.4 |
| Total: | 18,500.9 | 13,860.7 | -4640.2 | 32,361.6 |

TABLE 8.2: Summary of volumetric estimates of erosion, deposition, net change and total volume of change (in $m^3$) for each analysis period. Calculations from a pathway 4 analysis of DoDs thresholded at a 95% confidence interval. $\mu$ refers to the mean for all four periods.

by valley slope to highlight the local relative relief exhibited by the changing morphologies. These DEMs represent the snap-shot observations recorded by the surveys, and the rest of this chapter will focus on the analyses used to interpret the geomorphological changes captured therein.

## 8.3 Geomorphological Interpretation of DoDs

The top half of Figure 8.4 shows the DEMs (digital elevation models) of difference (DoDs) that are used in this chapter to make geomorphological interpretations. These DoDs were derived from a pathway 4 analysis and thresholded at a 95% confidence interval as discussed in Chapter 4. The corresponding budget that will be used here for segregation in terms of a geomorphological interpretation is shown in Table 8.2. Elevation change distributions (ECDs) are shown in Figure 4.30 (B, D, F & H). Recall from Table 4.11 that thresholding the budget under a pathway 4 analysis resutlted in an average of a 43% reduction of the total volumetric budget. This percentage was significantly smaller for the bigger flood years (2004-2005 and 2006-2007) than the smaller flood years(2003-2004 and 2005-2006). With or without uncertainty thresholding, every individual analysis period suggests that the reach is slightly degradational (by 6% to 32% of total change), and the overall imballance over the entire study period is a net degradation (or loss of sediment from the reach) of 4640.2 $m^3$. This finding is consistent with a formely glaciated fluvial system that is slowly incising into its aluvial and fluvio-glacial valley fill (Ballantyne & Whittington 1999).

It is also worth noting the excellent correspondence between the magnitude of changes in Table 8.2 with event magnitudes in Table 8.1 by study year. Over the whole study period, an estimated total volumetric change[16] of 32,361.6 $m^3$ took place but 15,186.3 $m^3$ of that was in 2006-2007 alone - the year with the two largest floods. On the low-magnitude end as

[16]Note that total volumetric change is not the total volume of material moved, but is simply the sum of DoD recorded deposition and erosion. It is a good proxy for the relative magnitude of geomorphological work done.

well, the quietest flooding period of 2005-2006 also produced the lowest magnitude of total volumetric change. None of these observations are overly surprising, but they are contextually helpful.

As described in § 5.2.1.3, an expert-based geomorphological interpretation is a useful way of segregating the budget based on geomorphological interpretation of the DoD recorded changes. This is a multi-proxy approach that uses a mix of field observations and the DoD itself overlaid by before and after morphological classifications, facies mappings and aerial photographs.[17] The categories of change used are tailored to the known mechanisms of change in the system under study and/or particular questions of interest.

For the Feshie, the categories of change used include four depositional categories, four erosional categories and a questionable change category. The questionable change category is a mask that was used to segregate portions of the reach, which showed the least coherent and/or least reliable changes. Such areas were inferred on the basis of field observations and aerial photographs. These primarily included the tops of terrace surfaces bounding the braidplain on the west side of the study reach, as well as elevated braidplain areas (typically vegetating or vegetated). These were areas where either a) there was no clear evidence of inundation[18] (thus no fluvial mechanism for change); or b) where if there was evidence of minor change (e.g. very localised deposition of fines around vegetation), there was little confidence that such changes would be clearly detectable given the resolution of the survey relative to the roughness and/or presence of vegetation. The erosional categories used were:

- *Channel Carving* - Delineates areas where a new channel has been carved where one did not formerly exist (e.g. avulsions).
- *Channel Deepening* - Delineates areas where an existing channel has experienced erosion and its bed elevation has lowered (e.g. pool scour, confluence scour, incision, headcuts, etc.).
- *Bar Sculpting* - Areas where exposed and/or active bars have experienced erosion. This is typically either in the form of trimming around the edge of a bar margin, or dissection of a chute through a bar surface.
- *Bank Erosion* - Delineates areas where lateral erosion has occurred along a channel margin. Such channel margins are generally distinguished in the Feshie by a relatively steep bank separating a regularly inundated area (e.g. channel or lateral bar) from a less regularly inundated area (e.g. vegetated or vegetating braidplain).

The depositional categories used were:

[17] All used where available. Here aerial photographs were available for April 2005 (Figure B.11), August 2005 (Figure B.12) and August 2007 (Figure B.13).

[18] 'Evidence would include signs of sediment deposition, signs of trash-lines and flood debris, and areas that were topographically unlikely to have been inundated given the flow record for that year and other hydraulic simulations of the reach (Cox *et al.* Submitted, e.g.) not reported here.

- *Channel Filling*- Delineates areas of channel aggradation that may have raised a channel bed or caused a channel to shift laterally, exposing bars and/or riffles in the process. Such a shift differs from abandonment of the channel or avulsion in that the overall course has not dramatically changed. This can include pool-filling and large-flat sheets of in-channel deposition leading to plane bed morphologies.

- *Channel Plugging*- This is a sub-class of channel filling that is reserved to specifically delineate areas where the channel aggradation has led to an avulsion or abandonment of the channel (or chute).

- *Bar Development*- Areas that have experienced deposition resulting in the development of new bars or expansion of existing bars. This can include the development of mid-channel bars (e.g. diagonal, lobate or longitudinal bars) or bank-attached bars (e.g. lateral bars, point bars, riffles).

- *Gravel Sheets* - Delineates areas of overbank deposition (typically of coarse gravels and or cobbles) onto braidplain surfaces. These are differentiated from regular overbank deposition of finer material (typical floodplain deposits) that are often below minimum levels of detection (i.e. would be classed in a 'questionable change' category). Ferguson & Werritty (1983) referred to these deposits as overbank bars and cobble sheets, and noted how they were characterised by at least decimeter-thick deposits burying heather, moss and grass vegetation on the braidplain. Thus, the large caliber of the material is making it detectable with GPS measurements.

The bottom half of Figure 8.4 shows an overview of the geomorphological interpretations using the categories outlined above for each study period in relationship to their DoD. More detailed maps, interpretations and elevation change distributions (ECDs) are reported with each change period in the next four subsections.

### 8.3.1 2003 to 2004 DoD

From the summer of 2003 to 2004, there were four to six flood events that might have led to partial inundation of the braidplain (§ 8.2). There are a number of small patches of generally low magnitude changes on the braid-plain shown in the DoD in Figure 8.5A. These areas were primarily zones of contiguous erosion or deposition that were recovered from the spatial coherence filter in the pathway 4 analysis. As pointed out in Chapter 4, it is certainly plausible that such changes occurred on the braidplain as a result of overbank deposition and/or minor scour from sheet-flow. However, given the lack of aerial photographs, facies maps and other evidence for 2003-2004, there is not enough information to reliably distinguish such changes from noise, and these overbank areas have been classified as questionable changes accordingly. These areas constitute 83% of the surface area of the surveyed reach (red cross hatched area in Figure 8.5B), but only account for 9% of the total volume of change because of their generally shallow depths (see centre ECD in Figure 8.6). The questionable change ECD is

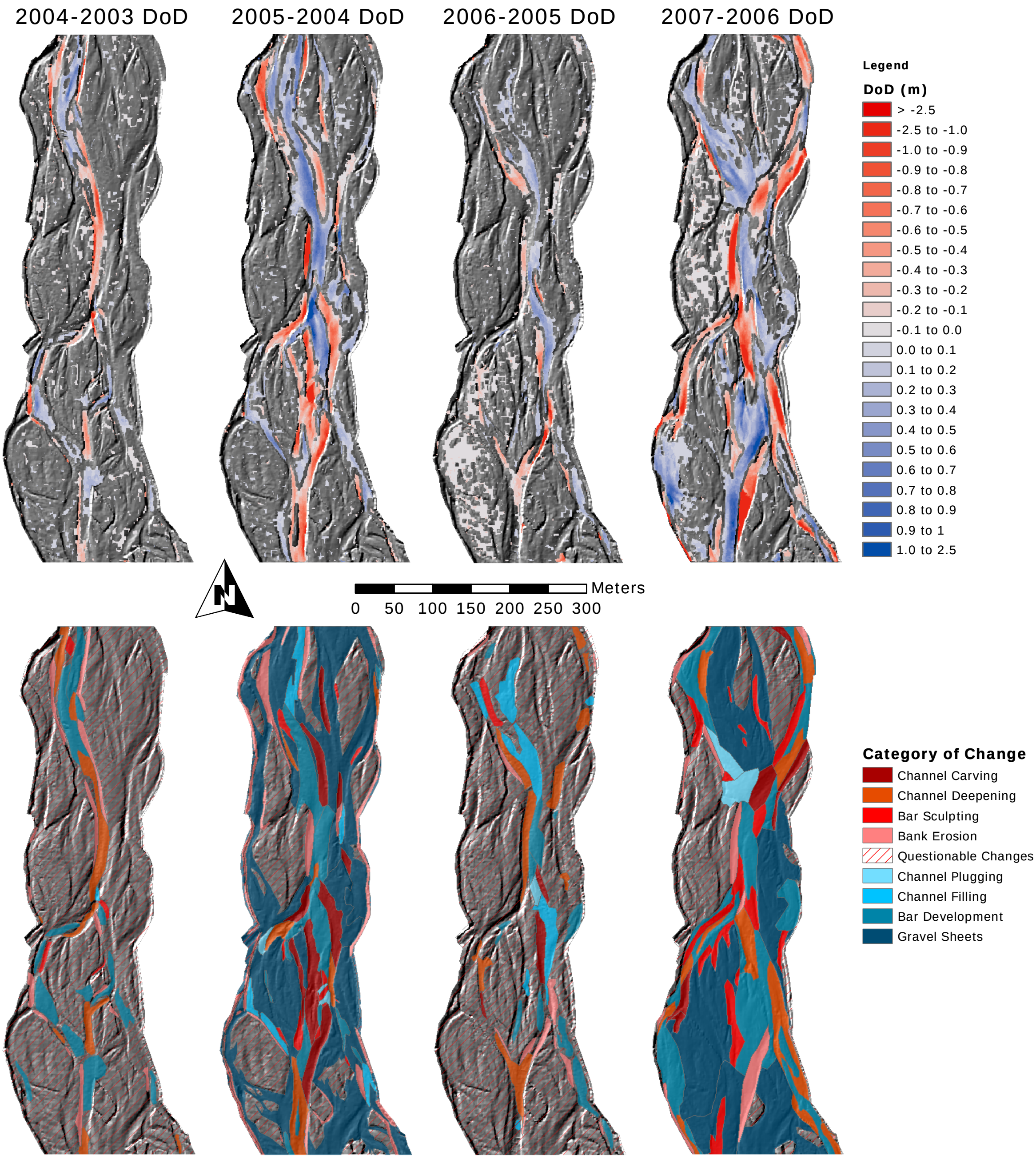


FIGURE 8.4: Overview of geomorphological interpretations (bottom) of all four DoDs (top) on the Feshie over the study period. More detailed views for each individual DoD are provided in the next subsections (§ 8.3.1, § 8.3.2, § 8.3.3 and § 8.3.4), whereas this figure facilitates inter-comparison of the DoDs.

dominated by a peak of 5-10 cm of erosion, but does pick up limited scour up to 75 cm, and has a secondary depositional peak at 5-10 cm that quickly tapers off to maximum fills of up to 45 cm.

The vast majority (91%) of DoD recorded changes are confined to the other 17% of the reach comprising the active channel network. Therein, 64% (59% of the total volume) of the changes were due to erosional mechanisms (Figure 8.5C). In broad terms, the changes were predominatntly confined to the main channel through the reach with some less extensive changes on some of the secondary anabranches. This is typical of what might be expected for a year in which the primary floods rarely or barely got out of bank, and thus concentrated their erosive energy in the channel.

As Figure 8.5C indicates, there were three dominant categories of change: bank erosion (33%), channel deepening (25%), and bar develpoment (31%). Throughout the reach, there are eight coherent zones where bar development appears to be working in concert with bank erosion. That is, the growth of bars is either constricting effective flow width or forcing the flows to be directed outward at banks and causing lateral migration of the channel via bank erosion. The bar development (light blue in Figure 8.5B) appears to be taking place anywhere there is a flow-width expansion and/or change in channel gradient. Of the eight coherent zones, half are associated with mid-channel bar development (primarily diagonal bars) and half are associated with lateral or point bar development. The 1056 $m^3$ of bar development was associated with fill depths of up to 80 cm, but is generally consistent with much shallower fills over broader areas as indicated by the ECD in Figure 8.6H with a peak at 20 to 30 cm of fill.

The bank erosion occurring on the opposite banks of the bar development is much less areally extensive (accounting for half of the surface area of bar development), but the erosion is generally much deeper than the bar development fills (Figure 8.6D). This depth of scour is more a reflection of the average heights of the adjacent braid-plain and terraces that are being eroded into. Scour depths associated with bank erosion have a broad ECD extending up to 130 cm of cut, but with peaks between 50 and 75 cm. These coupled zones of bar development and bank erosion reflect gross changes from what is likely a more complex sequence of events. Logically, the bar development probably precedes the onset of bank erosion and is likely primarily occurring at high stages and at the beginning of the recession from the flood peak, when flow energy and transport capacity begins to decrease (Dinehart 1992). The new or expanded bar forms confine the effective flow width and force flows away from themselves, hence directing flow at the banks. During the recession limb as stages are dropping, but flow energy is relatively high, these outward directed flows are likely accelerated as flow is concentrated into a narrower and narrower cross section. This process could easily repeat itself with successive intermediate floods and continue to accentuate both bar development and bank erosion. Such a conceptual explanation of these mechanisms of change is quite similar to what Ferguson & Werritty (1983) reported on the Feshie for diagonal bar evolution[19], but here we see similar mechanisms taking place for both mid-channel bars (e.g. diagonal bars)

[19] This was reviewed briefly in the introduction (§ 8.1).

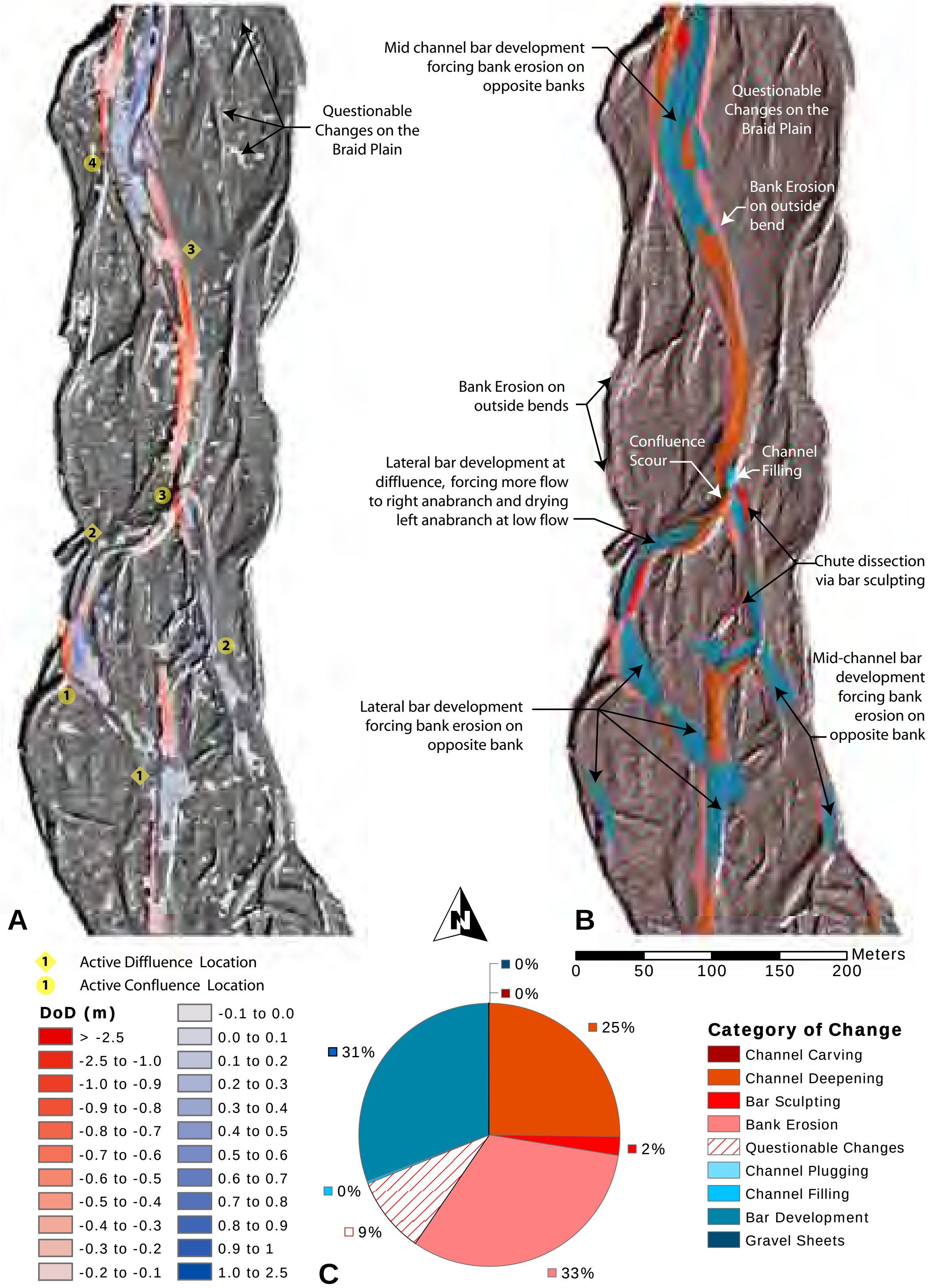


FIGURE 8.5: Map of the 2003 to 2004 DoD (A), its geomorphological interpretation (B), and the relative proportion of each category of change (C). Relative proportions are calculated volumetrically with reference to the total volume of material net change recorded by the DoD (both erosion and deposition). The flow direction is up the page.

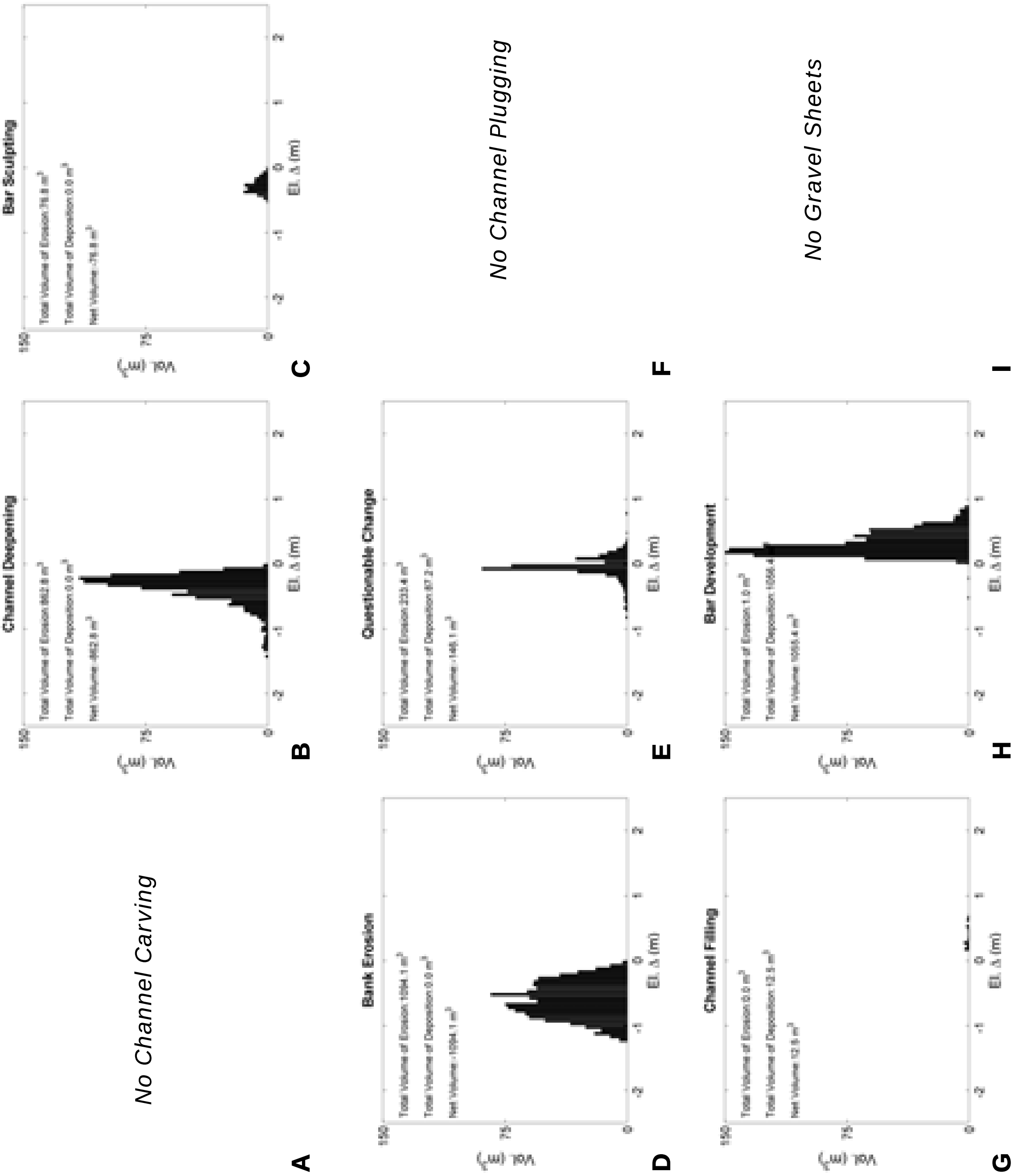


FIGURE 8.6: Elevation change distributions corresponding to the geomorphological interpretation mask of the 2003 to 2004 DoDs shown in Figure 8.5B. The categories of change are A. Channel Carving, B. Channel Deepening, C. Bar Sculpting, D. Bank Erosion, E. Questionable Change, F. Channel Plugging, G. Channel Filling, H. Bar Development, I. Gravel Sheets (see § 8.2 for explanation of categories).

and lateral bars.

Not all of the 1094 $m^3$ of bank erosion was associated with forcing due to bar development. Particularly between the deep confluence pool at confluence junction 3 and what is labeled as diffluence junction 3 in Figure 8.5A, there is a long coherent sliver of bank erosion on the inside bend adjacent to a large coherent zone of channel deepening. While it is odd to have bank erosion on an inside bend, here this can be explained by the high-stage flow geometry. At high stages the flow coming from the right-hand anabranch at confluence junction 3 is directed straight down valley and across the channel at this inner bank; whereas at low flows it takes a left-hand bend into the confluence pool. The lack of bar development in this zone and wider pattern of shallow channel deepening can also be explained by the high-stage flow geometry. With the high flows for the 2003-2004 season probably never leaving the banks here, the entire flow through the reach was confined to this single channel[20] creating an erosive funneling effect. At 862 $m^3$, channel deepening comprised 25% of the overall budget. As the ECD in Figure 8.6B shows, most of this was relatively shallow scour (25-30 cm) as described above.

One final, somewhat speculative, observation is that every single bar unit that showed growth appears to be associated with either a sliver of bank erosion or a concentrated zone of channel deepening upstream of it, recalling that the bar deposition is always associated with a flow width expansion. If one moves upstream of each bar unit, a coherent zone of bank erosion, channel deepening or, in some cases, bar-sculpting is always encountered. The volume of sediment derived from these coherent zones of erosion roughly scales to the volume of deposition in the bars, suggesting a crude potential source and morphological control on average step-lengths for transported material (Pyrce & Ashmore 2003, Richard S. Pyrce 2003, Pyrce & Ashmore 2005). It is also interesting that these coherent zones of erosion, either a) always occur before the next flow-width expansion upstream and associated bar; or b) occur coincident with the next zone of bar development and bank erosion (source) on its opposite bank. For example, the largest zone of mid channel bar development (downstream of diffluence 4) is the first depositional zone downstream of the largest area of coherent bank erosion and channel scour described in the previous paragraph. Without detailed tracer-experiments, these ideas can not be verified. It is likely that the bar development is comprised of source material from sources encompassing a wide variety of distances upstream (Sear 2004). None-the-less, the relatively simple observation of apparent correlations is mechanistically plausible.

### 8.3.2 2004 to 2005 DoD

The first thing to note about the 2004 to 2005 DoD (Figure 8.7A) is the relatively straight scar or band of erosion and deposition that was ripped through the middle of the reach, with little regard for the *normal* main channel path during lower flows. By contrast to the 2003-2004 DoD, in which all the changes paid respect to the initial channel network configuration, here

[20] Elsewhere there are at least 2-4 anabranches two split the flow.

the simplest path was taken. This path departs from the main channel at the first active diffluence (1), extends downstream avoiding the first two confluences, opting instead for the a new path through the braidplain, and reconnects with the main channel at confluence 3, remaining in and significantly widening the main channel the rest of the way through the reach.

As indicated by the large areal extent of 'gravel sheets' (dark blue areas in Figure 8.7B)[21], there was extensive overbank deposition, such that changes were recorded in 75% of the study reach. These gravel sheets themselves accounted for 41% of the area of the reach, but only 7% of the total volumetric change. As the gravel sheet ECD in Figure 8.8H shows, they accounted for 546 $m^3$ of predominatly low magnitude (decimeter thick) deposition, but occasionally reached fill depths of up to 80 cm. There was also a minor (168 $m^3$) erosional fraction of primarily low magnitude braidplain scour (peak of 10-15 cm) recovered in the gravel sheet ECD, which reflects erosion[22] across the braidplain at high flows.

The questionable change areas were delineated and inferred as before, but this time only constituted 25% of the reach and less than 1% of the total volume of change. It is certainly plausible that real changes were being recorded from the DoD in these areas, but as the ECD in Figure 8.8E indicates, they amounted to low magnitude changes if they were real (17 $m^3$ of erosion and 63 $m^3$ of deposition).

At 32% of the total volume of change, bar development again played a very prominent role volumetrically (3288.5 $m^3$). The bar development fraction of the 2004-2005 budget alone almost matched the total volume of change in the 2003-2004 season. As the bar development ECD shows (Figure 8.8H), bar development was constituted by greater fill depths this time, with an average fill depth of 50 to 65 cm and fill depths of up to 2.4 meters. Again, bar development appears to take place only where there is a flow width expansion and seems to be associated with forcing bank erosion or channel deepening. However, this appears to be occuring at two scales. In the anabranches that were not part of the high stage swath through the centre of the reach, the process of bar growth forcing bank erosion is taking place at a scale very similar to in 2003-2004. However, up the main high-stage swath through the centre of the reach, the scale of the bar features dwarfs those in the other anabranches. Within this high stage channel, very large diagonal mid-channel bars developed that tend to alternate back and forth spatially between favouring one side of the main channel. For example, the diagonal bar located just downstream of diffluence 1 is favouring the left side of the channel and shedding flow diaganoly from the left towards the right. Moving downstream through the large channel carving zone (discussed below), the next large bar is favouring the right hand side of the channel, and sheds its flow diagnolly from right to left into confluence 3. The process is reset downstream of confluence 3, due to the strong input from the left hand anabranch (low-stage main channel) pushing the bar towards the right. However, the pattern then persists at least

[21]These areas were delineated on the basis of field observations of fresh gravel and cobble deposition and aerial photograph evidence (Figures B.11 and B.12)

[22]Recall that these areas were delineated largely on the basis of exposed gravel, which often implies deposition; but can imply erosion of braid-plain vegetation leaving exposed braidplain sediments.

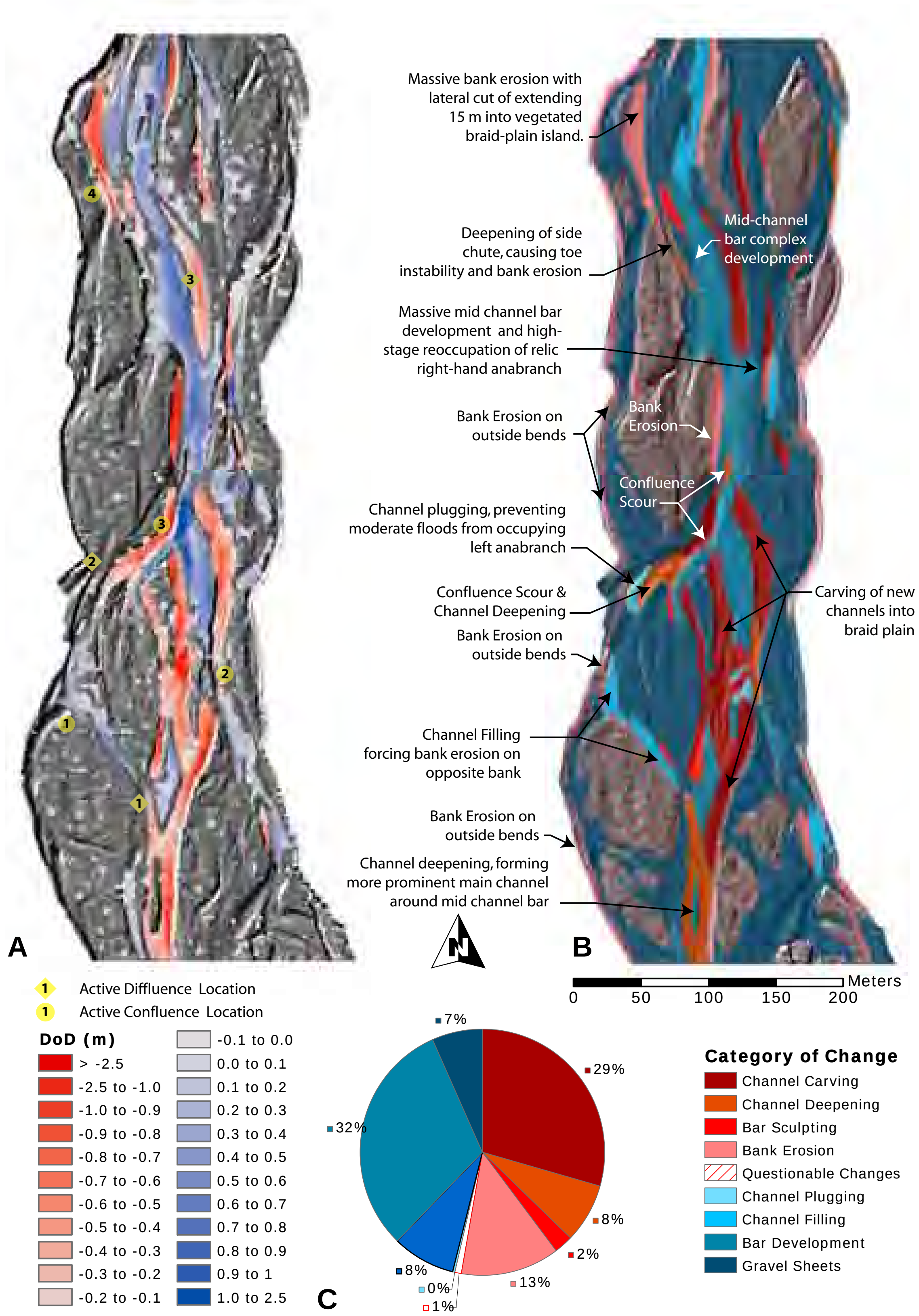


FIGURE 8.7: Map of the 2004 to 2005 DoD (A), its geomorphological interpretation (B), and the relative proportion of each category of change (C). Relative proportions are calculated volumetrically with reference to the total volume of material net change recorded by the DoD (both erosion and deposition). The flow direction is up the page.

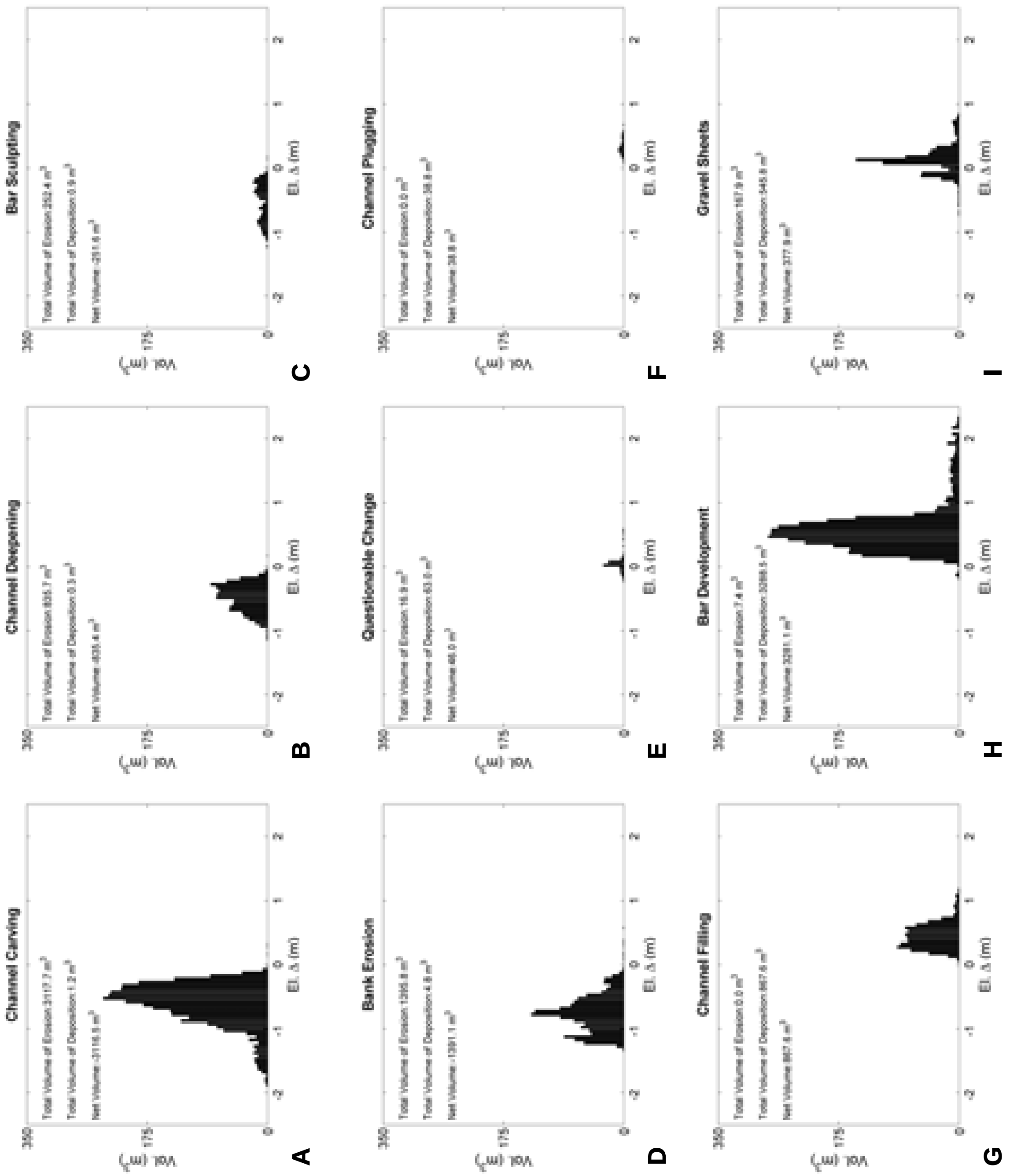


FIGURE 8.8: Elevation change distributions corresponding to the geomorphological interpretation mask of the 2004 to 2005 DoDs shown in Figure 8.7B. The categories of change are A. Channel Carving, B. Channel Deepening, C. Bar Sculpting, D. Bank Erosion, E. Questionable Change, F. Channel Plugging, G. Channel Filling, H. Bar Development, I. Gravel Sheets (see § 8.2 for explanation of categories).

down through diffluence 3 to confluence 4. Thus, the extensive diagonal bar development through the centre of the reach seems to be shunting the high stage flows from side to side, creating swaths of erosion (primairly channel carving and some bank erosion).

Channel carving was the second most dominant category of change at 29% and the most dominant erosional mechanism. The high stage flood ripped 3117.7 $m^3$ out of the braidplain to accommodate a 30 to 50 m high-stage channel. Most of this channel carving took place between diffluence 1 and confluence 3 via confluence 2. This was most likely in response to the largest flood(s), which found a more direct route staight down the braidplain, preferable to the left-hand anabranch via confluence 1. In terms of reoccupation of relic channels and anabranches, the diagonal bar that developed between confluence 2 and 3 and the channel carving on its right hand side were of key importance. The channel carving did not carve a direct connection to the the relic anabranch down the right hand edge of the reach. However, it did remove a section of the braidplain that acted as a high flow barrier, and allowed the larger (i.e. >20 cumec) floods to reoccupy this relic channel, which was very active through the 1990's, but appeared to be abandoned around 2000.[23] Some additional, small-scale channel carving though this temporarily unoccupied braidplain meant the re-establishement of a viable anbranch down the right-hand side of the reach at low to medium flows (Figure B.11). Flow in this secondary anabranch and the main anabranch both curved toward one another downstream of confluence 3, but never quite met (at low flows), both going their separate ways around the braidplain downstream of diffluence 3. The small bar separating these two anabranches was only about 10 m wide and less than 75 cm in relief (Figure B.11). This is a Site to watch closely in the next two seasons.

### 8.3.3 2005 to 2006 DoD

The 2005 to 2006 monitoring period showed experienced the lowest number of floods and the lowest peak flow (Table 8.1). It appears unlikely that flows ever got out overbank, instead concentrating their energy in the low-flow channel network as shown in Figure 8.9. As in 2003-2004, there was a return to the majority of the reach (81%) being classified as questionable change, because of the lack of evidence of braid-plain inundation. Moreover, because of the low overall magnitude of changes (3146.3 $m^3$ of total change; see Table 8.2), the questionable areas were occupying a noteable percentage (15%) of the overall budget (Figure 8.9C). The questionable change ECD (Figure 8.10B) shows the characteristic signature of an error distribution centred around zero but with a shorter tail in deposition then erosion.

Returning to the potential for diffluence 3 to finally connect at low stages[24], recall the precarious small bar separating the right-hand anabranch from the main channel. It appears the diffluence was connected during at least the peak flows during 2004-2005. However, as flow would have been diverging over this bar in an unconfined area of flow expansion, this bar (a lateral bar to the main channel at the time) actually grew. At the same time, the channels

[23]See aerial photographs from 1993 (Figure B.8), 1997 (Figure B.9) and 2000 (Figure B.10) for evidence.
[24]Discussed at end of previous section (§ 8.3.2).

on both sides experienced some degree of channel deepening and as such the relative relief between the right-hand anabranch and main channel grew. In the main channel in particular there was headward incision from the thalweg on the left up through the riffle into the plane-bed reach between confluence 3 and diffluence 3 (Figure 8.9B). These changes and some bank erosion were further encouraged by the plugging of the main channel route, following a more central path downstream of diffluence 3 in 2005.

The greatest magnitude and concentration of bank erosion occurred in 2005-2006 around confluence 2. To start, focus attention upstream at diffluence 1, which experienced some channel deepening extending into both its right-hand and left-hand anabranches. However, with more extensive erosion and a steeper gradient into the right-hand anabranch this anabranch was now diverting more flow. These flows shaved off sediment on the outer flanks of its two chutes before being funneled into confluence 1. This jet of water was now directed at the opposite bank downstream of the confluence, inducing 5-10 m of lateral bank erosion. Upstream of confluence 2 on the right-hand feeder anabranch, a persistent pattern of areally extensive mid-channel bar development, inducing bank erosion on the opposite banks was also recorded (much as described for 2003-2004 in § 8.3.1).

Moving just downstream of confluence 2, the bank erosion on the far bank of confluence 2 appeared to make a more direct path for the flows from the right-hand anabranch. Subsequently this has caused the channel to migrate toward the centre of the reach and the old channel has filled up with sediment. This channel filling upstream of confluence 3, and the channel filling downstream of diffluence 3, constitute the vast majority (85%) of the 694 $m^3$ in the channel filling ECD in Figure 8.10G. The ECD is very similar to the bar development ECD, with a peak at 25-35 cm and fills not exceeding 70 cm in depth. Here, channel filling comprises 22% of the budget (Figure 8.10C) as compared to the 13% comprised of bar development. Technically one might argue that in these examples the channel plugging is simply a form of bar development (primarily lateral bars in in this case), but the distinction was drawn here because the deposition filled the whole of the existing channel and caused the whole channel to shift. If one did combine these two into one, they would comprise 33% of the total volume of change, and 92% of the total deposition.

There was a very small zone designated as channel plugging, where the prominent chute connecting the channel at confluence 3 was plugged completely and a new chute was carved just downstream (Figure 8.9B). The deposition itself was actually part of a continuous train of deposition that extended from confluence 2 all the way down past diffluence 3. However, it was distinguished within this category of change because of the result it had on the morphology and channel network. Its ECD ranges from 10 to 50 cm with a peak at 35-40 cm, constituting 90 $m^3$ of fill (Figure 8.10F). The significance of this is that it shifts the location of confluence 3 downstream a further 35 m (Figure 8.13). Thus what was the deepest pool (c. 1.5 m deep) in the reach in 2003 and 2004, had diminished to a shallow pool less than 0.5 m deep in 2006. The left hand feeder anabranch to confluence 3 enters the pool with a relatively steep slope, and the grade break has remained at a relatively stationary position. Although the right hand anabranch also enters with a steep slope, its confluence shifted 20 m downstream from

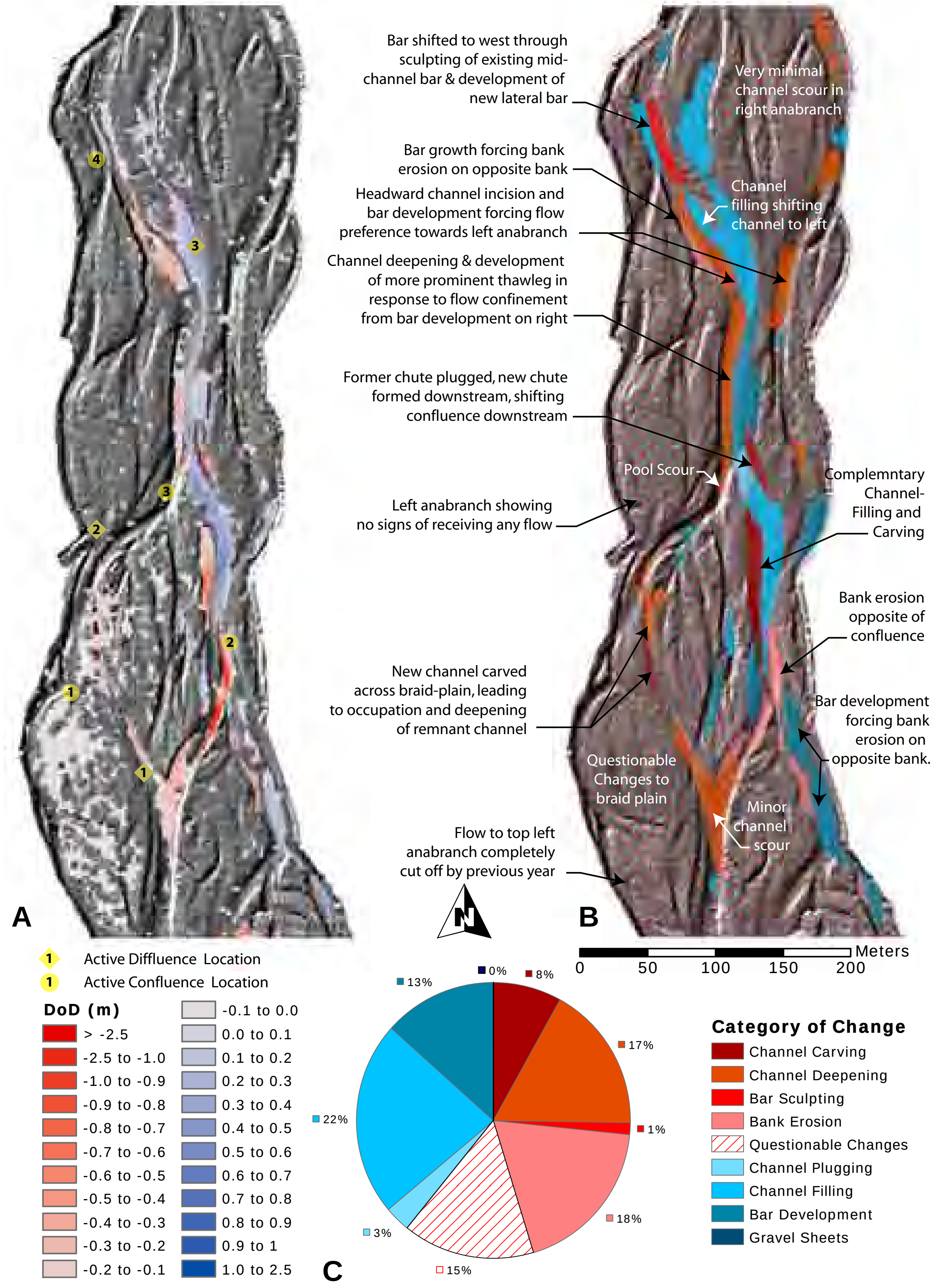


FIGURE 8.9: Map of the 2005 to 2006 DoD (A), its geomorphological interpretation (B), and the relative proportion of each category of change (C). Relative proportions are calculated volumetrically with reference to the total volume of material net change recorded by the DoD (both erosion and deposition). The flow direction is up the page.

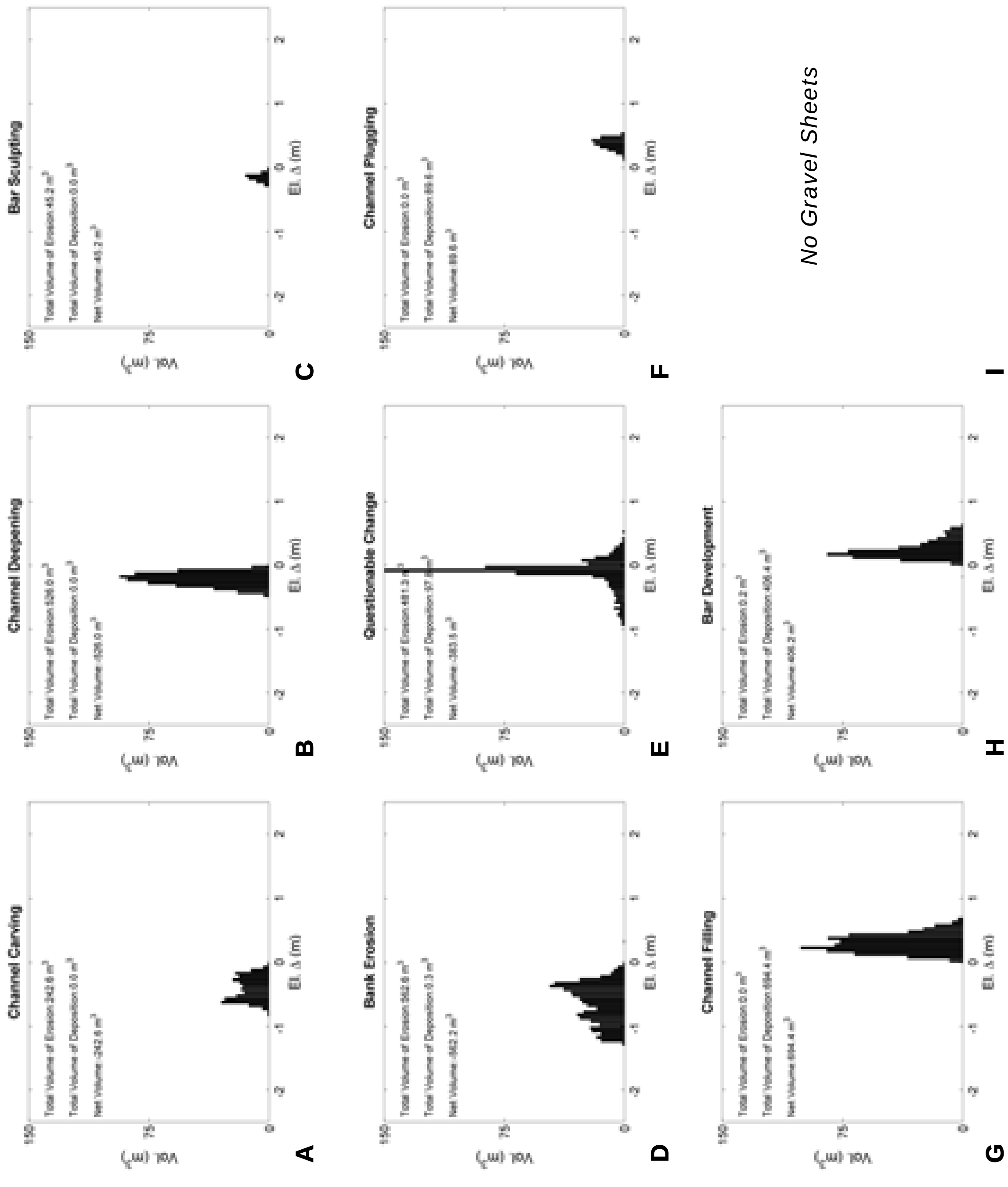


FIGURE 8.10: Elevation change distributions corresponding to the geomorphological interpretation mask of 2005 to 2006 DoDs shown in Figure 8.9B. The categories of change are A. Channel Carving, B. Channel Deepening, C. Bar Sculpting, D. Bank Erosion, E. Questionable Change, F. Channel Plugging, G. Channel Filling, H. Bar Development, I. Gravel Sheets (see § 8.2 for explanation of categories).

2004-2005 and another 35 m from 2005-2006. Thus, the two anabranches are now coming together after the left-hand anabranch has dissipated most of its elevation head. Subsequently the two anabranches are not combining all their energy head into one focal point to create the deep pool of years past.

Thus, the overall story for this low-flow year is very similar to 2003-2004. The bar-development and bank erosion signatures of the ECDs in 2005-2006 (Figures 8.10D and I) are strikingly similar to those in 2003-2004 (Figures 8.6D and I), varying only in their precise magnitudes.[25] The reach is still slightly degradational, but this time channel deepening and carving played more prominent roles. Bank erosion was still the dominant source of erosion.

### 8.3.4 2006 to 2007 DoD

The 2006-2007 season boasted the largest floods (Table 8.1 & Figure 8.2), the largest volume of change (Table 8.2) and the most dramatic morphological changes (Figure 8.11). This is explained by the occurrence of two early-season floods, within two weeks of each other, that were of greater magnitude than any of the other floods during the study period. Like in 2004-2005, there is a major swath of change located down the middle of the reach, clearly reflecting the impact of the high-stage floods. However, there are three major morphological differences:

1. Roughly half (47% of 837 $m^2$) of a large stable vegetated island at the top centre of the reach was washed away from a massive swath of bank erosion extending 9 m to 16 m laterally into the island.[26]
2. The drying up of the main channel in the centre top of the reach, and the subsequent splitting of the flow (upstream of study boundary) into the left-hand anabranch (previously dry) and the right-hand anabranch
3. The avulsion at diffluence 3 in which the main channel (on left) was completely plugged at low flows, and the new main channel carved across the bar formerly dividing the right hand anabranch and main channel, to reoccupy the right hand anabranch.

It is likely that one or both of the large early-season floods were responsible for 1, and the main swath of change down the centre of the reach. However, there were roughly 11 intermediate size floods later in the season, at least 1 of which resulted in some floodplain inundation (Table 8.1). These three major morphological differences will be described first, and then the remaining changes will be reported.

The island at the top of the reach that was carved in half, is a remnant of a large vegetated island, which formed sometime after 1964 (Figure B.6), but was well established by 1989 (Figure B.7). The island was substantially trimmed down between 1993 (Figure B.8) to a

[25]Add also to this the channel filling ECD as discussed above.
[26]Compare the 2005 (Figure B.12) and 2007 (Figure B.13) aerial photographs.

shape and size it largely maintained up until 2000 (Figure B.10). During the 2006 to 2007 period, it appears an extensive broad cobble sheet washed in with the high flows upstream of confluence 1 (Figure 8.11B). This sheet spread out across the braidplain to the left and, to a lesser extent, around the island to the right. Deposition in these areas was typical of the 1-2 decimeter thick sheet exhibited in the 2004-2005 season. However, complete burial of what was the main channel resulted in deposition of up to 1 m, but leaving a flat smooth morphology across the surface. These two styles of deposition are exhibited in the bimodal ECD of Figure 8.12*I*. The ECD shows fill depths of up to a 105 cm with a secondary peak at 80 to 85 cm of fill, which is entirely made up of deposition in this channel zone. The rest of the shallow gravel sheet deposition across the braidplain contributes to the primary peak at 20 to 35 cm of fill. This volume of net deposition at this location only makes sense to be associated with high-stage flows, when flow width is extensive enough and the energy grade-line flat enough for the flow to drop its load in a broad sheet like it did.

It appears that this large grave sheet fill, in the main channel, shunted the flow into the western edge of the vegetated island. Even though the surface of the island was vegetated and 'stable', the island fill was comprised almost entirely of easily erodible non-cohesive sediments. The slice through this island is an incredibly linear feature, suggestive of a change in flow direction from straight down the valley (North) to about 20° east of north. The bank erosion extends along this line downstream into the braidplain and does not end until it reaches the left-hand anabranch at confluence 2. The change probably occurred gradually over the course of the flood(s), pivoting around the head of the island, and slicing like the second hand on a clock from 12:00 into the island at 2:00 (Figure 8.11A). With each second, shaving a little more. To drive this second hand on the clock into the island suggests that there was a rather continual supply of sediment from upstream building that gravel sheet faster than it could be evacuated. Such a large supply is probably only possible during a large event and it is likely that when this ceased, the second hand stopped and the rest of the island was spared.

The second major change listed above was the partial abandonment of the main channel in the centre of the reach at the top. In the scar of the bank erosion described above, a thalweg was carved that still received overflows at intermediate floods, and was recharged with groundwater at low flows. However, as the low flow inundation map in Figure 8.13 shows, the flow was predominantly split between anabranches running down the opposite sides of the reach. From the data it is difficult to pinpoint when this occurred, but it is speculated that it was probably in the recession of the second major flood. With the extensive gravel sheet deposition described above, the centre of the reach upstream of confluence 1 was now elevated relative to the anabranches flanking both sides. Thus, these two channels became the preferential paths for flow being split at the confluence upstream of the study reach boundary.

The third major change was the plugging of the high stage diffluence (labeled diffluence 3 in Figure 8.11A) in the bottom third of the reach. There are substantial areas of deposition downstream of the diffluence. These include areas of gravel sheet deposition down the centre swath of braidplain (much the same as in 2004-2005), as well as the familiar patterns of extensive mid-channel bar development inducing bank erosion and or channel scour on opposite

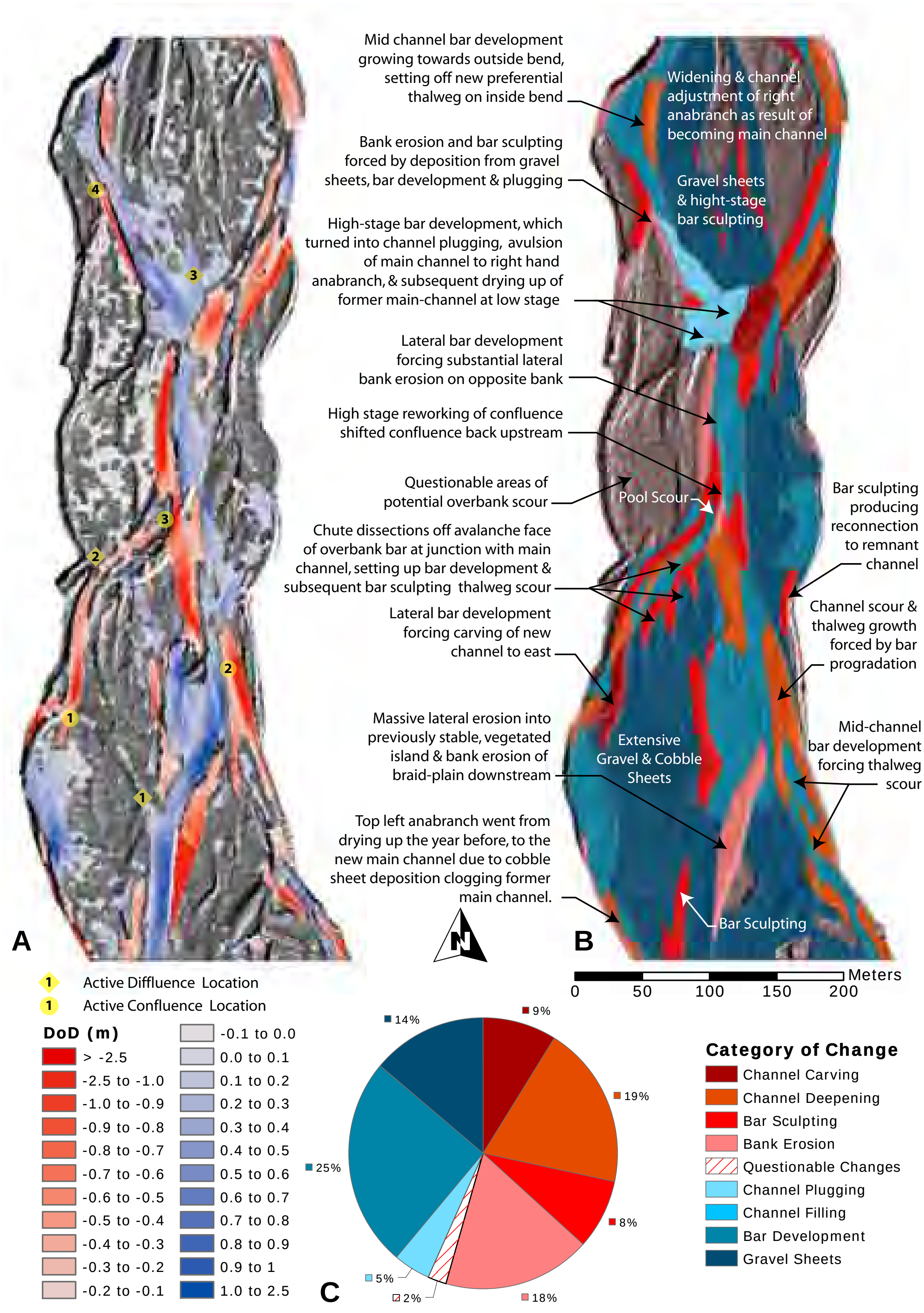


FIGURE 8.11: Map of the 2006 to 2007 DoD (A), its geomorphological interpretation (B), and the relative proportion of each category of change (C). Relative proportions are calculated volumetrically with reference to the total volume of material net change recorded by the DoD (both erosion and deposition). The flow direction is up the page.

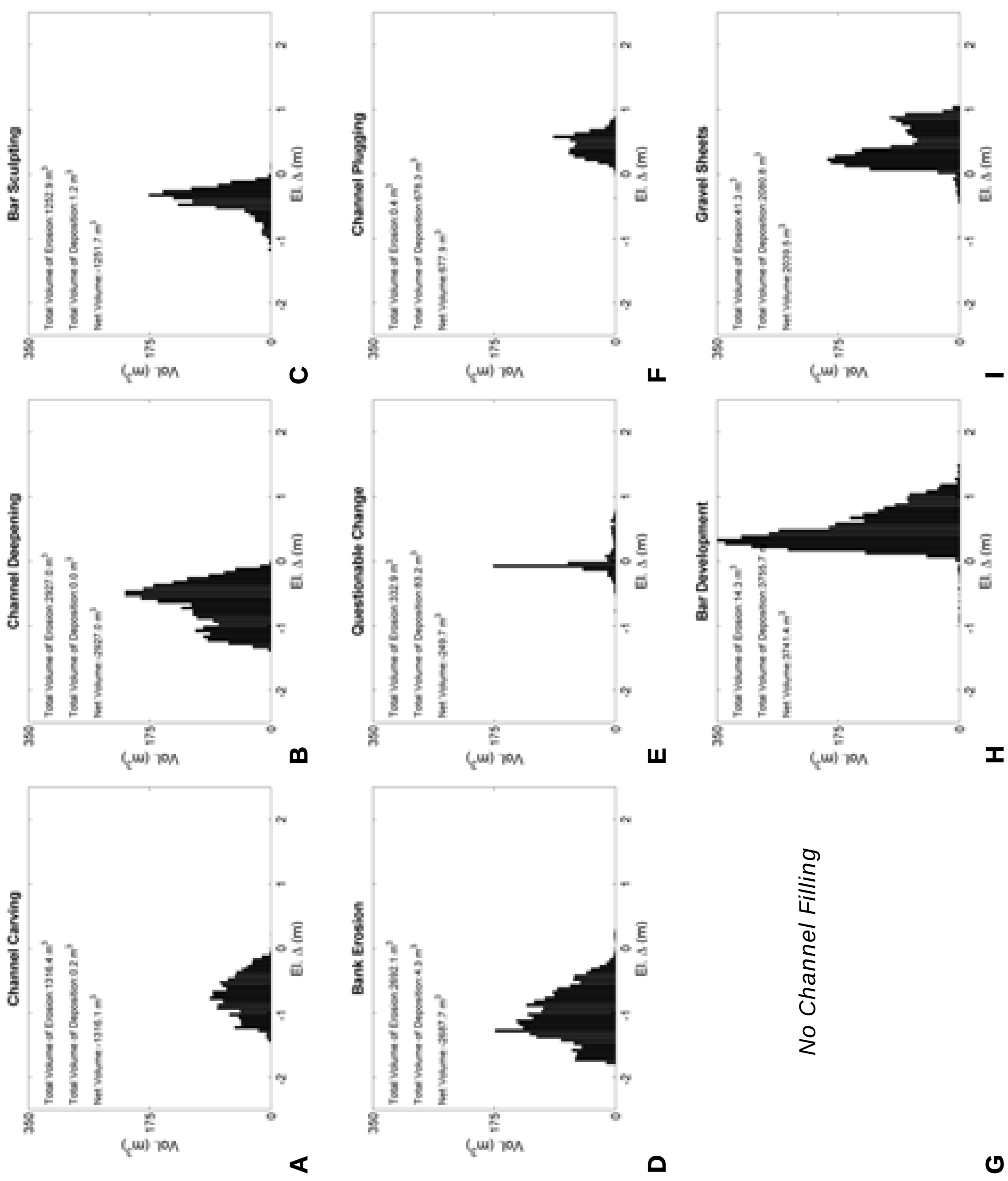


FIGURE 8.12: Elevation change distributions corresponding to the geomorphological interpretation mask of the 2006 to 2007 DoDs shown in Figure 8.11B. The categories of change are A. Channel Carving, B. Channel Deepening, C. Bar Sculpting, D. Bank Erosion, E. Questionable Change, F. Channel Plugging, G. Channel Filling, H. Bar Development, I. Gravel Sheets (see § 8.2 for explanation of categories).

banks. The gravel sheets almost certainly could only have occurred during one or both of the major early season floods. The changes in what was the main channel from the mid 1990s (Figure B.1) could have occurred during intermediate floods, as it appears the plugging only blocks the channel at low flow. The channel plugging ECD (Figure 8.12F) shows a peak of deposition at 60 to 65 cm and deposition up to 90 cm. This magnitude of elevation change is larger than average bar development changes, suggesting they were deposited by the higher magnitude floods. The 678.3 $m^3$ of channel plugging was essentially mid-channel bar development that, while only constituting 5% of the toal volumetric changes (Figure 8.11C), exerted a fundamental control on switching the main channel over to occupy the right-hand anabranch, whereby intermediate floods could concentrate their energy on shaping that channel.

In terms of the overall picture of change during 2006-2007, the three major changes certainly dominated the picture, but a wide variety of other interesting changes also took place. As Figure 8.11C suggests, the 3756 $m^3$ of bar development constituted 25% of the overall volumetric changes, with the gravel sheets (2080 $m^3$) constituting another 14%. As discussed above, the gravel sheets are likely almost entirely due to the two large floods, but the bar development likely involves a complicated mix of changes from both the large and intermediate floods. The bar development ECD in Figure 8.11H has the same characteristic shape we have seen throughout the study period with a shallow fill peak of about 30-35 cm. However, this ECD extends much further into deeper fills with a maximum fill depth of 1.5 m. The portion of the ECD making up those deeper fills are most likely associated with the bigger floods, but this is impossible to segregate out spatially in Figure 8.11 without more evidence from throughout the year.

On the erosional side (54% of total budget), there are a number of interesting changes with the erosional budget being split between channel deepening (35%), bank erosion (33%), channel carving (17%) and bar sculpting (15%; see Figure 8.11C). There is a much greater degree of erosion seen in both the left-hand and right-hand anabranches flanking both sides at the top of the reach. This is one of the reasons that it is speculated that the main mid-channel at the top of the reach was shut off early in the season by the large floods. At the time there may well have been much more extensive deposition in both branches, but the intermediate floods through the rest of the winter and spring would be confined to working primairly within these areas. Starting with the left hand side near confluence 1, bar development against the left hand side (possibly an extension of gravel sheet deposition at high floods later disected) forced the carving of a new channel through the braidplain. There was considerable sculpting of the lateral bar between diffluence 2 and confluence 3 that also appears to have been forced by progradation of gravel sheets into this section of channel from upstream. There was also dissection of some chute features in this vicinity.

Confluence 3 was also substantially rearranged, with the net result being that, having previously moved 50 m downstream, it had now moved 70 m back upstream. What is labeled as pool-scour in Figure 8.11B was actually bank erosion of a triangular wedge-shaped island, which consequently scoured to become a pool.

Similar to 2004-2005, the questionable changes cover 24% of the reach, but only constitute 3% of the total volume of change (15,186 $m^3$).The questionable change ECD (Figure 8.12E) is biased towards erosion (333 $m^3$ of erosion verus 83.2 $m^3$ of deposition), but this is composed primarily of low magnitude elevation changes (5-10 cm). Some of this could reflect inundation and scour across the braidplain, but this can not be established reliably here.

## 8.4 Discussion

With respect to the preceding results, there are a few broader themes that are helpful to draw attention to. Here, the overall trends observed across all the analyses are discussed to sythesise the sequence of changes observed during 2003 to 2007. In addition, some broader observations about the utility and limitations of the geomorphological interpretation masks are discussed.

### 8.4.1 Overall Trends on Feshie

After delving into the details of the geomorphological interpretation of the DoD recorded changes from each year, it may be difficult to keep track of the overall trends that emerge from looking at four years of change data. Returning to the drivers of this change (§ 8.2), there were crudely two wetter years with large magnitude floods, and two drier years with limited if any inundation of the braidplain. While Figure 8.4 showed all the DoDs maps and their geomorphological interpretation together as an overview of the different changes from year to year, another, even simpler way is to compare the low-stage inundation maps from year to year (Figure 8.13). The low-stage channels represent the primary channel network and in Figure 8.13 are shown for each year with their water depths at the time of survey and then the previous year's outline in grey as a reference point for changes to the channel network. In both 2004 and 2006, there is minor accentuation of the channel network, and some stage-dependent changes, but the overall networks are largely unchanged. Contrast this to 2005 and 2007, where there are substantial changes to the channel network with whole anabranches being shut off, and other anabranches being reactivated or created.

With this simplistic overview in mind, Table 8.3 provides a summary of the overall trends between different geomorphological categories of change. The table contrasts these different mechanisms of change in both areal terms (as a percentage of total surface area of study reach) and volumetric terms (as a percentage of the total volume of change). Looking first at the areas of questionable change, in areal terms this is essentially the percentage of the reach that probably was not inundated. In the dry years, it is 83% and 81% of the reach, which drops to 25% and 24%, respectively in the wet years. Volumetrically, in the dry years the questionable change areas also comprised a larger perctange of the total volume of change (at 9% in 2003-2004 and 18% in 2004-2005) than in the wet years (at 1% in 2004-2005 and 3% in 2006-2007).

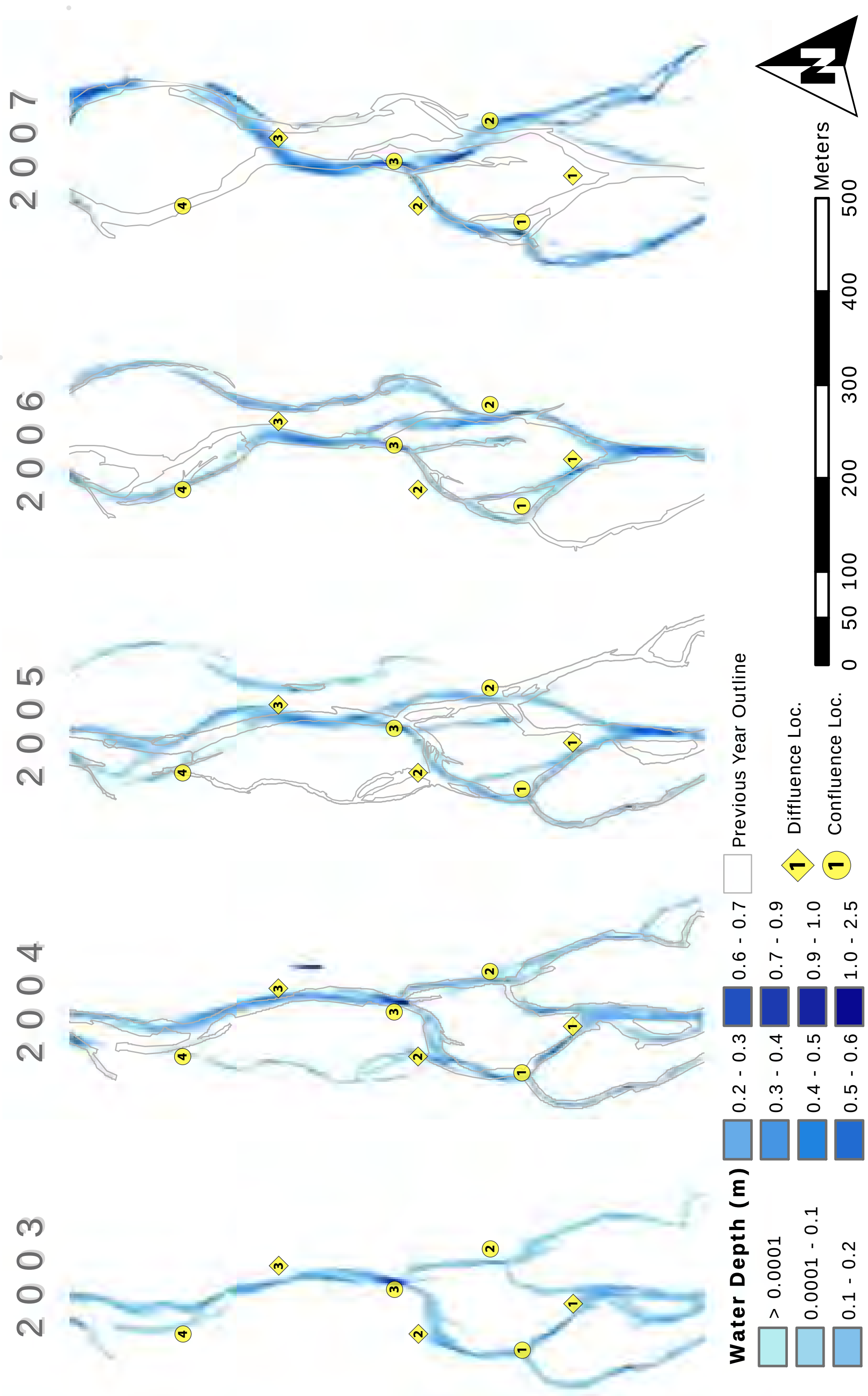


FIGURE 8.13: Maps of low-stage channel network, showing flow depths at time of survey for each year and patterns of change in the primary channel network. For 2004-2007, the previous year's channel network outline is shown in grey for reference.

| | 2004-2003 % of Total | | 2005-2004 % of Total | | 2006-2005 % of Total | | 2007-2006 % of Total | |
|---|---|---|---|---|---|---|---|---|
| | Volume | Area | Volume | Area | Volume | Area | Volume | Area |
| Channel Carving | 0% | 0% | 29% | 8% | 8% | 1% | 9% | 3% |
| Channel Deepening | 25% | 5% | 8% | 3% | 17% | 5% | 19% | 8% |
| Bar Sculpting | 2% | 1% | 2% | 1% | 1% | 1% | 8% | 7% |
| Bank Erosion | 32% | 4% | 13% | 8% | 18% | 2% | 18% | 4% |
| Questionable Change | 9% | 83% | 1% | 25% | 18% | 81% | 3% | 24% |
| Channel Plugging | 0% | 0% | 0% | 0% | 3% | 0% | 4% | 2% |
| Channel Filling | 0% | 0% | 8% | 3% | 22% | 5% | 0% | 0% |
| Bar Development | 31% | 8% | 31% | 10% | 13% | 4% | 25% | 17% |
| Gravel Sheets | 0% | 0% | 7% | 41% | 0% | 0% | 14% | 34% |
| Summary | | | | | | | | |
| Erosional | 59% | 9% | 53% | 20% | 44% | 9% | 54% | 22% |
| Depositional | 31% | 8% | 46% | 55% | 38% | 10% | 43% | 54% |
| Questionable | 9% | 83% | 1% | 25% | 18% | 81% | 3% | 24% |

TABLE 8.3: Summary comparison of areal and volumetric percentages by the expert-based geomorphological interpretation categories of change. Percentages are calculated as a percentage of the total DoD thresholded volumetric change and area of change (i.e. deposition + erosion)

Across all the years, the erosional categories of change constituted higher percentages volumetrically than the depositional categories. However, in three of the four years that trend was reversed for the areal percentages and considerably so for the wet years. In 2004-2005, 55% of the reach was depositional with only 20% showing erosion. Similarly in 2006-2007, 54% of the reach was depositional with only 22% showing erosion. This reversal in volumetric versus areal dominance can be explained as an extension of an observation Brasington *et al.* (2003) raised about generic contrasts between fluvial erosion and deposition. As fluvial erosion is more often the result of flow being concentrated in a particular location, it is generally less areally extensive but can produce quite high magnitudes of elevation change. For example, bank erosion may only carve a sliver in plan-form area off the edge of a braidplain, but if that braid plain is 2 m high, this can amount to a substantial volume of material. By contrast, deposition tends to take place where flows are dissipating. Thus, deposition often takes place in broad, areally extensive layers and/or sheets of relatively low magnitude fill depths. With lower magnitude elevation changes, a much greater surface area is required to match the volume of a high magnitude elevation change over a smaller surface area. As such, even though erosion dominates the volumetric budget of the Feshie, it is not surprising to see a greater surface area of the reach covered in deposition. This has important implications for qualitiative interpretations that might be made on the basis of visual evidence alone. As the signature of deposition may cover a broader area, it is very likely that this may give the false impression that deposition is the dominant process.

In terms of dominant mechanisms of change, on the erosional side these vary from year to year. Bank erosion varies between 13% and 32% of the total volume of change, but never covers more than 4% of the surface area of the reach (Table 8.3). Over all four years, bank erosion was the most effective mechanism of erosion with over 5743 $m^3$ of erosion constituting 31% of the total volume of erosion. Channel deepening ranges between 8% and 25% of the total volume of change and never covers more than 5% of the reach. Over all four years, channel deepening comprised 27% of the total volume of erosion (5151 $m^3$). Channel carving was quite important in 2004 to 2005, at 29% of the total budget, but was not present at all in 2003 to 2004 and only accounted for 8% to 9% in other years. However, channel carving did account for 467 $m^3$ of change over the whole study, thus comprising 25% of the total volume of erosion. Overall, bar sculpting was the smallest agent of fluvial erosion, but still amounted to 1627 $m^3$ (8%) of erosion, with the remaining 8% in the questionable change category.

On the depositional side, bar development is the most prominent depositional mechanism in every year except 2005 to 2006 (the range is 13% to 31% of total volume of change). Over the entire study period, there was over 8507 $m^3$ of bar development making it not only the most effective depositional mechanism of change (61% of total volume of deposition), but also the most effective mechanism of change overall (at 26% of the total volumetric budget). This deposition was primarily in the form of diagonal bars as described by Ferguson & Werritty (1983), but there was also extensive lateral bar development. Another type of bar develoment, gravel sheets, was only present in the high water years, but would cover 41% and 34% of the reach in 2004-2005 and 2006-2007 respectively (Table 8.3). Due to the generally shallow depth of these fills, they were more modest as a percentage of the total volume in each year at only 7% and 14%. However, at 2625.8 $m^3$ they still made up a respectable 19% of the overall erosional budget for the entire study period. Channel plugging played only a minor role volumetrically in later years, but played a fundamental role in forcing anastamosis on the reach. Channel filling was very pronounced in 2005-2006 at 22% of the total budget, but over the entire four years, only amounted to 1574 $m^3$ over the entire four years (11% of total volume of erosion).

What is particularly interesting is that on the surface the reach is dominated by different types of bar development (including gravel sheets), and even volumetrically this is the most dominant agent of change. This may leave even the trained geomorphologist with the impression that the reach is aggradational. After-all, braided rivers are supposed to be zones of deposition where transport supply is exceeded by transport capacity (Knighton 1998). However, the overall story reveals that the reach is consistently degradational and that three main mechanisms of change (bank erosion, channel carving and channel deepening) are accomplishing this change without leaving a large mark on the reach in terms of areal extent. On average, these processes are only shaping 13% of the surface area of the reach!

### 8.4.2 Why is There Questionable Change?

With up to 83% of the reach being classified as showing questionable changes (Table 8.3), it is fair to ask why such areas were not removed during the DoD uncertainty analysis? Recall from Chapter 4 that the purpose of the DoD uncertainty analysis is to produce the *best* estimate of what DoD changes can reliably be distingusihed from noise. It produces a better estimate than has been yielded from traditional, simple, minimum level of detection techniques ($_{min}$LoD), but it is by no means perfect. It still has the potential to include some changes that are not real, and discard other changes that probably are.

The pathway 4 DoD Uncertainty analysis used here is working in three steps. First, spatially variable uncertainties in the DEM surface representation are approximated on a cell-by-cell basis using a fuzzy inference system. These uncertainty estimates from both DEMs are propagated through into an estimate of DoD uncertainty, which can be represented probabilistically. In a pathway 3 analysis, a confidence interval would be selected to threshold the DoD, discarding changes that have probabilities of being real below the threshold. While this does a better job than spatially uniform uncertainty estimates, it is still prone to discarding large segments of low-magnitude elevation changes that probably are real.

As Figure 8.4 shows, the DoDs are capturing very coherent spatial patterns of change with clear distinctive zones of erosion and deposition. Where these cuts and fills taper down to low magnitude changes (e.g. approaching zero at their boundaries), there are still large areas of changes that are probably real, but might fall below the selected confidence interval. Under a pathway 4 analysis, an attempt is made to recover some of these changes by updating the probability that the change is real (with Bayes Theorem), based on a neighbourhood moving window analysis. For example, cells that are showing erosion, which are entirely surrounded by cells also showing erosion are given a higher probability of being real; whereas a cell showing erosion that is entirely surrounded by cells showing deposition is given a lower probability of being real. This analysis recovers significant areal and volumetric DoD predicted changes, that would otherwise be discarded. However, it may also recover patches of very small magnitude elevation changes that exhibit spatial coherence, but probably are not real. This is a trade off between using an automatic filter (as used here), versus a manual filter.

Returning to this question of why are there still questionable changes after the above analysis, recall this category is being highlighted in the context of a geomorphological *interpretation*. It is thus an opportunity to exercise geomorphological judgment, and manually incorporate evidence that may not have been considered in the DoD uncertainty analysis.[27] It is a manual filter or mask to improve upon the estimate of the pathway 4 DoD uncertainty analysis. The

[27] It should be noted that the rule-based fuzzy inference system is flexible enough that if such additional evidence can be represented via a spatial classification, it can be simply built into the rule system. However, a more complex rule system may not always be necessary or desirable.

classification of a region as showing 'questionable changes' is not necessarily saying that the changes can not be real. It is simply suggesting that this is a region in which there is less confidence that the changes are actually real and it is likely that real changes are mixed in with non-meaningful changes. In this case, there were large areas of the braid plain in which there was no or inconclusive evidence of inundation, and thus no fluvial agent for change. Using the questionable change mask allows these areas to be segregated and interpreted separately.

### 8.4.3 So What?

This chapter started with an assertion that high resolution topographic datasets from repeat surveys have not been effectively exploited to give insight into geomorphological mechanisms of change. An attempt to demonstrate how this can be rectified was made, with new analyses based on four years of monitoring data from the Feshie. Comparisons were made to analyses undertaken by Ferguson & Werritty (1983) using much simpler surveys based on the surveying technology available at the time. It is thus fair to ask whether or not this new style of analysis reveals anything that the plane table surveys and transects of (Ferguson & Werritty 1983) could not?

While this question is ultimately for the reader or practitioner performing the analysis to judge, some methodological differences and improvements are highlighted in Table 8.4 to help make that judgment. What the table highlights is that more detailed quantitative analysis can be made using the masking techniques identified in Chapter 5 and used in this chapter. In this chapter, these interpretations were made with respect to DoDs which had an uncertainty analysis applied. In principle, the masking techniques can just as easily be applied to a raw DoD with no uncertainty analysis. The, 'Chapter 4's column in Table 8.4 is shown to highlight what sort of geomorphological interpretations are possible with only a standard DoD analysis. This is largely what has been reported in the literature to date (Brasington *et al.* 2000, Fuller *et al.* 2003, Lane *et al.* 2003, e.g.). While the DoD analysis itself captures all the changes, it can only be quantitatively described at the reach scale, and any sub-reach or bar-scale geomorphological interpretations are strictly qualitative.

In terms of the quality of geomorphological interpretations that can be made using DoD masks, versus regular DoDs, versus older transect-based analyses, this is partly down to the geomorphologist casting judgment on the system. The geomorphological interpretation mask is posed as an 'expert-based' system. As such, different experts will have different levels and types of experience as well as potentially conflicting ideas[28] about how a system works. Those differences are for peers to judge. However, it is argued that interpretations and hypotheses that are formed on the basis of change analyses, can be more robustly tested if there is more quantitative data available. For example, a reasonable hypothesis from field observations, DoD measurements and the work of Ferguson & Werritty (1983) might be that central bar development is the most dominant mechanism of geomorphological change on the

[28]These are an example of a structural uncertainty (Figure 2.2).

| | Ferguson & Werritty (1983) | Chapter 4 | This Chapter |
|---|---|---|---|
| Morphological Method: | 1D (repeat transects/planform) | 2.5D (repeat topography) | 2.5D (repeat topography) |
| Uncertainty Analysis: | None (estimated at $+/-$ 10 cm based on roughness) | Pathway 4 (spatially variable and spatial coherence analysis) | Pathway 4 (spatially variable and spatial coherence analysis) + use of questionable change mask |
| Scale of Geomorphological Interpretation: | Bar-scale, quantitative in one dimension, qualitative other wise | Crude reach-scale, qualitative description of specifics | Detailed, bar-scale interpretations, quantitative |
| Spatial Extent Used: | 1-3 bar complexes (180 m subreach) | 1 km reach | 1 km reach |
| Spatial Resolution of Data Used: | 2 m transect spacing; 20 m between transects | 1 m resolution DEM used, resolving between 2.5 and 20 cm ($\mu$ 7 cm) resolution in vertical | 1 m resolution DEM used, resolving between 2.5 and 20 cm ($\mu$ 7 cm) resolution in vertical |
| Spatial Resolution of Geomorphological Interpretation | Bar scale | Reach Scale | Bar Scale |
| Quantification of elevation change | Only in 1D (along transects) | Fully spatially distributed; but integrated across reach | Fully spatially distributed and possible segregate down to resolution of raster |
| Elevation change distributions | Only for transects; not spatially integrated over whole study areas | Spatially integrated across entire reach, but not resolved locally | Spatially integrated across any area (mask) user defines |
| Sediment budgeting (storage terms only) | Either aerial (i.e. just at cross-sections), or major spatial interpolation and assumptions required | Volumetric, across entire reach | Volumetric, can be resolved down to individual bar units; here, resolved by categories of change |
| Sampling Frequency Used | Annually | Annually | Annually |
| Sampling Frequency Possible | Event-scale (down to hourly or daily for limited spatial extents; less laborious) | Event-scale (weekly for spatial extent used here, and presuming no other events occur in between; Daily or hourly possible for smaller spatial extents) | Event-scale (weekly for spatial extent used here, and presuming no other events occur in between; Daily or hourly possible for smaller spatial extents) |

Table 8.4: Comparison of geomorphological interpretation techniques used in Ferguson & Werritty (1983) study, Chapter 4 and this Chapter.

Feshie. Masking the DoDs provides a direct test of this simple hypothesis. Indeed, central bar development was, volumetrically, one of the most dominant mechanisms of change.

The masking technique provides a simple way to segregate DoDs spatially and quantitatively. While this is a helpful methodological development, the real significance is that it affords the geomorphologist more confidence in making statements about channel development and response. Specifically, this method quantitatively unlocks spatially explicit information about the magnitude of geomorphological change in accordance with the geomorphologist's interpretation of the reach. Instead of qualitatively and/or graphically highlighting, which areas of the DoD pertain to what inferred mechanisms of change, this technique allows the explicit quantification of such spatial units. The areal dominance of some styles of change may create false impressions about the relative importance of different mechanisms of change. Pre-conceptions about the relative magnitude and importance of such processes can be tested. In the case of the Feshie, the relatively modest areal signature of erosional processes like bank erosion, channel carving and channel deepening was consistently out-pacing all of the depositional processes combined.

## 8.5 Conclusion

A simple new technique presented in Chapter 5 for segregating a DEM of difference (DoD) to make more meaningful geomorphological interpretations in a fluvial morphological sediment budgeting context was applied to a four year time series. The technique relied on the definition of spatial masks, which classify the DoD recorded changes based on an expert-derived geomorphological interpretation. In principle, any and/or multiple classifications that are helpful for making a geomorphological interpretation can be used. The utility comes in that the mask allows the morphological budget to be segregated in areal and volumetric terms on the basis of the classification.

This technique was applied to four years of high resolution topographic surveys from a dynamic, braided reach of the River Feshie in Scotland. The Feshie is an interesting case study partly because of the range of fluvial processes it exhibits over annual time-scales, but also because the same reach was the subject of a similar monitoring study by Ferguson & Werritty (1983), which tracked channel changes and bar development using more traditional transect and planform surveys. Here, a similar channel change monitoring effort was undertaken with survey-grade rtkGPS to produce high resolution topographic surveys. The Ferguson & Werritty (1983) study focused primarily at the bar-scale and involved tracking the development of several diagonal bars, presenting a mechanistic conceptual model for their formation and evolution. The analysis here, was able to confirm the general applicability of this conceptual model over a much larger spatial extent.

This case study also highlighted the relative significance of a fuller range of mechanisms of fluvial change in each year across the entire study site. These included eight depositional mechanisms, eight erosional mechanisms and a questionable change category to highlight suspect areas of the DoD. It was shown that the reach was consistently experiencing overall degradation, with bank erosion being the most effective mechanism of erosion, but with channel carving and channel deepening also playing very prominent roles. Bar development was the single most-effective mechanism of volumetric change and also the most areally extensive. In years with floods exceeding 60 cumecs, deposition covered well over half of the reach with erosion only impacting less than 20% of the reach. In years with floods from only 20 to 60 cumecs, deposition still out-flanked erosion areally but these changes were confined to just the active channel network instead of extending across the braid plain. In both cases, the areal extent of deposition and the volumetric dominance of bar development creates an impression that the reach is aggradational. However, the more aerially efficient erosional mechanisms are actually outcompeting the deposition. This is consistent with the longer-term context of late Holocene incision through a fluvio-glacial valley fill.