EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **37**, 1302–1312 (2012)

Published online 2 July 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.3276

Combining historical and process perspectives to infer ranges of geomorphic variability and inform river restoration in a wandering gravel-bed river

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Received 14 June 2011; Revised 27 February 2012; Accepted 2 May 2012

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ABSTRACT: Restoration approaches such as dam removal and channel reconstruction have moved beyond the realm of small streams and are being applied to larger rivers. This development has substantial economic and ecological implications but may test gaps in our understanding of larger river systems and of restoration science. We examine how information about historical ranges of geomorphic variability can inform stream restoration in the context of the Clark Fork River, Montana, focusing on a study reach where one of the largest restoration projects to date was implemented, upstream of the recently removed Milltown Dam. Analysis of historical sources and aerial photographs of the Clark Fork River's pre-mining, mining, and more recent history suggest that a wandering channel pattern has persisted despite variations in sediment supply and transport capacity. Predictive metrics for channel pattern also suggest a wandering pattern, transitional between braided and meandering, in this geomorphic setting. These analyses suggest that the creation of a single-thread meandering channel, which incorporates structures to limit erosion and channel movement, is inconsistent with the historical range of variability in this reach. The perils of restoring channels to a condition different than the historical range of variability for their geomorphic setting were illustrated on the Clark Fork by flood-induced avulsions of the restored channel that occurred soon after project construction. Application of an experimental approach to restoration, founded on the method of multiple working hypotheses, provides a means for embracing uncertainty, can maximize the potential for site-specific restoration success, and can foster advances in restoration science. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: wandering; multi-thread; dam removal; historical range of variability; historical geomorphology

Introduction

River restoration is often guided by the elusive search for a pre-disturbance reference condition. The focus on identifying this unimpaired state can come at the expense of rooting channel design within contemporary flow and sediment transport regimes, of understanding how disturbances have altered those regimes, and of allowing for historical variability in channel form (Parker 1976; Wilcock, 2004; Gillilan *et al.*, 2005; Wohl *et al.*, 2005; Gregory, 2006; Kondolf, 2006; Wheaton *et al.*, 2008). Designers often use a reference reach as a guiding image for restoration, from which channel dimensions are extrapolated, and aim for physical stability surrounding the targeted channel form (Kondolf and Larson, 1995; Gregory, 2006; Rosgen, 2006). Such approaches can conflict with the fundamental variability of fluvial processes, however, and can introduce uncertainties that are rarely examined in restoration practice (Wheaton *et al.*, 2008).

Restoration is almost always implemented in disequilibrium systems where the flow and sediment regimes controlling channel form and evolution have been fundamentally altered. Moreover, archetypal concepts of natural channel morphology that have influenced restoration practice may be incorrect as a result of human alterations to rivers (Montgomery, 2008; Walter and Merritts, 2008). In North America, the vast majority of channel reconstruction projects create single-thread meandering channels regardless of geomorphic setting or historic channel form (Kondolf, 2006). Montgomery (2008, 291pp) notes that the sinuous, meandering channel 'has come to represent a natural ideal in channel restoration design – even for rivers for which such an ideal is historical fiction.' Imposing a channel pattern that is poorly suited to its geomorphic setting can result in failure or reduced ecological benefit, however.

Complementary investigation of hydrogeomorphic fluxes and historical conditions may provide a more appropriate context for restoration than a single, fixed reference condition. Historical analysis combining documentation of former watershed conditions with perspectives on geomorphic principles and hydrologic cycles can be used to identify a historical range of variability (HRV; after Landres *et al.*, 1999; Keane *et al.*, 2009; Wohl, 2011) of channel morphology. Such analysis can in turn help (1) determine trends in flow, sediment flux, and channel condition; (2) predict future evolution; (3) identify threshold events and feedback responses to which a river may still be adjusting (Gregory, 2006); (4) transform vague concepts of uncertainty into more specific predictions of error, expectation, reliability, or risk (Wheaton *et al.*, 2008).

An emerging realm of restoration to which HRV analysis is applicable is restoration after dam removal. Dam removal can substantially alter water and sediment fluxes and channel morphology in upstream and downstream reaches (e.g. Pizzuto, 2002; Major *et al*., 2008; Walter and Tullos, 2010; Wilcox, 2010). Within formerly impounded upstream reaches, dam removal requires a fundamental choice about whether to allow fluvial erosion of reservoir sediments and subsequent channel evolution, versus active sediment management and channel 'restoration.' Two recent dam removals in the western United States illustrate these extremes. Following the 2007 removal of Marmot Dam, on the Sandy River, Oregon, a new channel rapidly developed through the reservoir reach and, within months of dam removal, the river had erased most evidence that it had been impounded for nearly a century (Major *et al*., 2008). In contrast, the 2008 Milltown Dam removal, on the Clark Fork River (CFR), Montana, entailed partial excavation of contaminated reservoir sediments and the largest post-dam removal channel restoration to date. A new, single-thread meandering channel was constructed through the reservoir reach, guided by 'natural channel design' approaches pioneered in small streams and by channel dimensions from two nearby reference reaches (State of Montana, 2005). The project is a high-profile test case for the 'natural channel design' restoration method because of its high economic cost and association with dam removal, the presence of contaminated floodplain materials, and the size of the CFR; most channel reconstruction projects have occurred on much smaller rivers.

In this paper, we (1) propose a conceptual model of the HRV of channel pattern in a reach of the CFR that encompasses the Milltown restoration based on its geomorphic setting and process domain; (2) evaluate the conceptual model using a combination of historical analysis of channel morphology, sediment loading and peak flows, and process-based metrics for predicting channel pattern; (3) discuss the applicability of our analysis to restoration, both in the context of Milltown and more broadly. We propose that the type of analysis presented here, combining historical analyses with process geomorphology, can contribute to the success of restoration of larger river systems, where the economic and ecological stakes are high yet precedents are few.

Study Area and Conceptual Model of Historical Range of Variability

Our study area is a reach of the CFR that extends from the former site of Milltown Dam, at the confluence of the CFR and Blackfoot River, upstream to Turah Bridge (Figure 1). Since Meriwether Lewis and William Clark navigated the CFR in the early 1800s, the river has had a rich environmental history, from the mining era, to construction of Milltown Dam and tailings ponds, to more recent Superfund remediation and restoration efforts (Figure 2). In some respects, land-use history along the CFR has followed a pattern typical of the American West during the last two centuries, in which a sequence of beaver trapping, mining, timber harvest, and agriculture produced changes in runoff and sediment regimes (e.g. Wohl, 2000; Wohl, 2011). However, the confluence of historically intensive mining, extreme hydrologic events, the largest Superfund site in the United States, and one of the largest dam removals and restoration efforts to date make the CFR a ripe area for investigation of historical ranges of variability in geomorphic conditions and present-day management implications.

We propose and evaluate a conceptual model of the HRV in our study area whereby the CFR was historically characterized by a wandering channel pattern (Desloges and Church, 1989; Church, 2002). Wandering rivers are gravel-bedded, alternate between unstable, aggradational multi-thread reaches and stable single-thread reaches, are avulsion-prone (Desloges and Church, 1989), carry modest bed-material loads (Church and Rice, 2009), and 'create a riverine ecosystem with an extended channel zone and adjacent floodplain distinguished by many side- and back-channels' (Church, 2002, 550pp). Wandering rivers are in some respects intermediate between meandering and braided rivers, with steeper slopes and less stable planforms than the former but lower sediment supply and more stable planforms than the latter (Church, 2006; Church and Rice, 2009). Among the variants for naming multi-thread, gravel-bed channels, which include anabranching, anastomosing, braiding, and wandering (see Nanson and Knighton, 1996, for further discussion), we consider wandering to represent the most suitable conceptual model of HRV in our study reach. Articulating such a conceptual model provides a framework for evaluating channel responses and

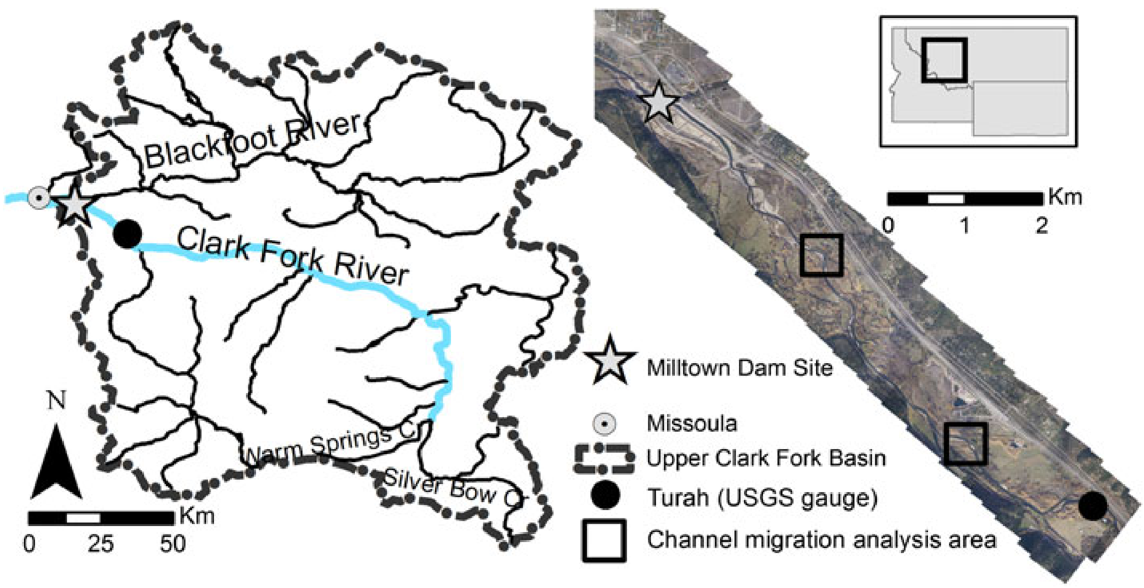

Figure 1. Study area map, including, on left panel, Upper Clark Fork River basin, Montana, and on right panel, Clark Fork River study reach, extending from Turah, Montana [site of the US Geological Survey (USGS) Clark Fork at Turah Bridge gauge] downstream to Milltown Dam site. Sub-reaches used for lateral migration analysis are also shown. Aerial photograph is from 2008. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

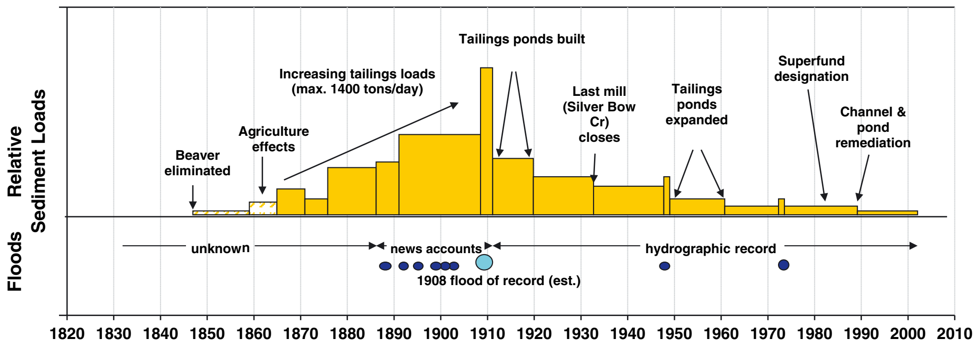

Figure 2. Timeline of relative sediment loads and floods affecting study reach, as an illustration of variations in sediment supply and transport capacity, constructed using review of mining history, data from agency reports, and data reported in Swanson (2002). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

sensitivity to changes in natural and anthropogenic drivers and as a guide for restoration.

Our conceptual model is based on evidence that multi-thread channel patterns may represent reference conditions in many unconfined alluvial rivers, as well as on the process domain concept, whereby areas with similar suites of geomorphic processes, governing conditions of hydroclimatology and valley geometry, and sensitivity to disturbance can be defined (Montgomery, 1999). The wandering channel pattern is common in the Cordilleran region of western Canada (Desloges and Church, 1989), which is geographically proximal and physiographically similar to our study area in western Montana. Wandering channel patterns are often present on unimpaired gravel-bed rivers with similar drainage areas as our study reach [O(10^4) km^2] in the northern Rocky Mountains, such as the upper Columbia River in British Columbia (Makaske *et al.*, 2009) and the Nyack reach of the Middle Fork Flathead River, Montana (Poole *et al.*, 2004; Whited *et al.*, 2007). More generally, examples of multi-thread channel patterns under unaltered conditions in other regions abound. In the unimpaired Queets River, Washington, feedbacks between large woody debris, hydraulics, and sediment erosion and deposition give rise to multi-thread channels (Abbe and Montgomery, 2003). Studies of channels in the mid-Atlantic region of the eastern United States that are incising through mill-pond sediments suggest that anastomosing channels were once prevalent in that region (Walter and Merritts, 2008). Many European rivers likely had multi-thread patterns prior to reductions in wood supply and direct channel manipulations (Brown, 1997; Montgomery, 2003; Piegay *et al.*, 2006).

Process domains have not yet been defined for northern Rockies rivers, although some of the process domains identified for rivers in the Colorado Front Range (Wohl, 2011) are applicable. For example, the HRV in our study reach and the regional examples mentioned earlier show similarities to Wohl's (2011) 'fluvial mainstem unconfined' process domain, defined as applying to systems with: 'drainage area > 50 km^2; valley width > 125 m; bed gradient < 2%; bed sediment gravel and cobbles; pool-riffle; moderate wood loads; beaver present; riparian zone wide & diverse; disturbances snowmelt and rainfall floods . . .' (Wohl, 2011, table I).

The 8-km study reach we focus on is of particular interest because it encompasses Milltown Dam and Reservoir and the area targeted for channel reconstruction following dam removal, as well as an upstream sub-reach, beyond reservoir influence, that extends to the US Geological Survey (USGS) Clark Fork at Turah Bridge near Bonner, Montana gauge (#1233455) (Figure 1). At the downstream end, Milltown Dam was built in 1907 to provide electricity for nearby Missoula, Montana. A large flood in 1908 transported millions of cubic meters of sediment and tailings from upstream mining and smelting operations and filled the reservoir. Concerns about arsenic contamination of groundwater, dam safety, and ecosystem impacts led to the 2008 removal of the dam. The study reach has, at its upstream end, a drainage area of 9431 km^2, mean annual flow of 36 m^3 s^{-1} (from 1986 to 2011, the period of record at the USGS gauge), and mean annual peak flow of 164 m^3 s^{-1}. USGS suspended sediment measurements (1986–2011) indicate an average suspended sediment yield of 5·7 tonne km^{-2} yr^{-1}. Average annual precipitation ranges from 34 cm yr^{-1} in Missoula, near the downstream end of the study area (Western Regional Climate Center, 2012), to 110 cm yr^{-1} in the headwaters (USDA, 2012).

Methods

We combine historical analysis and quantitative metrics to evaluate our conceptual model and to illustrate issues at the intersection of historical land use and channel change and modern restoration. To gain insight into the historical range of variability of channel conditions in the study area, we divide the post-European settlement history of the upper CFR basin into four periods: the exploration period (1806 to the mid-1800s); the peak mining period from the mid-1800s to the early twentieth century; the mitigation period (much of the twentieth century), and the remediation and restoration period (~1980–present) (Figure 2). Each of these periods has different sources/types of data that can be used to determine channel morphology and establish variability. Although the temporal boundaries between the periods are inexact, they provide a useful framework for investigation of the HRV in our study area.

We reviewed books, newspaper articles, railroad maps, survey drawings, and other unpublished archival material for evidence of pre-settlement, pre-mining and pre-dam conditions. We also examined Government Land Office (GLO) survey notes (GLO, 1870, 1882, 1883, 1892, 1893, 1901, 1904), which vary in detail but in some cases describe earlier channel locations, distance between banks, number of channels, and floodplain vegetation. In addition, we analyzed aerial photographs to evaluate avulsion history and lateral migration rates in recent decades. Aerial photographs from eight different years (1937, 1955, 1961, 1977, 1987, 1995, 2000, and 2004) were used. We identified and digitized channel margins and migration rates, the locations of channel avulsions, and areas that experienced recurring avulsions during this period. We found only two segments in our study reach where channels migrated laterally rather than by avulsion (Figure 2). We used these data to calculate a lateral migration rate in $m^2 m^{-1} yr^{-1}$ for six separate time intervals, not including the 1937–1955 interval, which was excluded because of poor resolution. In other reaches, measurement of lateral migration was impossible as a result of avulsions, or movement did not occur because of human structures.

Numerous metrics for predicting channel pattern based on geomorphic setting and processes have been developed, many of which are based on some variation of relationships between slope and discharge (Lane, 1957; Leopold and Wolman, 1957; Osterkamp, 1978) and/or sediment characteristics (e.g. Schumm and Kahn, 1972; Nanson and Knighton, 1996; Church, 2002). We apply several such predictors to our study reach, including slope–discharge relationships and Parker's (1976) stability criterion ε^*:

$$\varepsilon^* = \frac{1}{\pi}\frac{S}{F}\frac{B}{h} \tag{1}$$

where S is slope, F is Froude number, B is channel width, and h is flow depth, all of which are for some morphologically formative discharge (Parker, 1976). Parker's ε^* is based on a stability analysis that accounts the ratio of sediment transport and water fluxes and differentiates between meandering and braided channels. Meandering channels occur where $S/F << h/B$ (and $\varepsilon^* << 1$), braided channels occur where $S/F >> h/B$ (and $\varepsilon^* >> 1$), and transitional channels are found where $S/F \sim h/B$ (Parker, 1976).

For all calculations of pattern predictors, we used the Q_2 to represent Q and determined this value using log-Pearson III analysis of annual flood peaks at the CFR at Turah Bridge gauge, which indicated that $Q_2 = 150\ m^3\ s^{-1}$. We also use data on S (reach-average water surface slope = 0·0027) and h (reach-average depth = 1·7 m) from pre-dam removal geomorphic surveys in the study reach (State of Montana, 2006). We measured B at multiple locations along the study from aerial photographs, which suggested a range of 40 to 100 m.

We also borrow elements of the approach proposed by Jerolmack and Mohrig (2007) for predicting channel pattern, whereby the predominance of lateral migration versus avulsions dictates whether channels will be single thread or branching. Channels that become superelevated above their floodplain as a result of aggradation are highly susceptible to avulsion during subsequent floods, ice jams, or beaver activity (Slingerland and Smith, 2004), producing multi-thread patterns. In contrast, channels that migrate laterally faster than they fill vertically do not experience such superelevation, so avulsion is less likely and single-thread channels are maintained. These tendencies can be represented by a dimensionless ratio (M) between channel filling and lateral migration timescales (Jerolmack and Mohrig, 2007). Where both avulsions and lateral migration are important, such that the Jerolmack and Mohrig's M is between 1 and 10, channels are typically transitional, with a single main thread plus secondary channels (Jerolmack and Mohrig, 2007). In practice, the time scale for channel filling is difficult to measure for the type of application and time scale we treat here, given the paucity of data on changes in channel elevation. Nevertheless, we use our aerial photograph analysis of lateral migration rates and avulsions to provide insights into the relative importance of these mechanisms of channel movement. Flawed, uncertain, or incomplete data are typical in historical geomorphology and restoration planning, resulting in some degree of indeterminacy, but we propose that quantitative methods rooted in geomorphic process still provide a useful complement to historical evidence and tool for developing and/or testing conceptual models and hypotheses.

Results

Historical range of variability in the CFR

Exploration period

Early written descriptions of the study area from various exploratory expeditions describe a single-thread channel near the CFR-Blackfoot confluence and a multi-thread channel upstream. Camping at the confluence in early July 1806, Meriwether Lewis wrote: 'The banks build not very high but never overflow. The East fork [Clark Fork] [above] its junction with this stream [Blackfoot] is . . . about 90 [yds; ~80 m] [wide]. The water of boath are terbid but the East branch much the most so; their banks are composed of sand and gravel . . .. Neither of those streams are navigable in consequence of the rapids & shoals which obstruct their currents' (quoted in Moulton, 1993, 88-89pp). In the winter of 1860–1861, the Mullan expedition, tasked with finding a road route to connect the Missouri and Columbia Rivers, also established a camp in the vicinity of the CFR-Blackfoot confluence. The expedition's artist produced the first preserved image of the area, a lithograph showing single-thread channels for both the CFR and the Blackfoot River (Figure 3). This channel pattern was (and is) dictated by the presence of bedrock control on the left bank of the CFR at the confluence, opposite of where the Blackfoot enters, and an early Holocene terrace on the right bank that limits migration to river right.

The Mullan surveys also provided the first written documentation of the CFR's morphology upstream of the confluence. P.M. Engel, the Mullan expedition's surveyor, wrote that ~10 km upstream of the confluence, 'the river here forms many arms, which overflow at times the enclosed islands and render them miry in places' (Mullan 1863, 112pp). Mullan survey notes also show a multi-thread channel with five branches on the CFR upstream of the confluence (USACTE, 1978). These observations are consistent with the wider valley bottom (ranging from 700 to 1200 m) upstream of the confluence.

Fluvial processes in the study area were likely influenced by beaver (*Castor canadensis*) under pre-settlement conditions, consistent with the 'fluvial mainstem unconfined' process domain (Wohl, 2011). We infer likely beaver effects from current observations of less-impaired, similarly sized rivers in the region, where we observe that beaver are active in side channels and lateral areas of main channels, where their activities affect bank strength and possibly avulsion potential. In the upper CFR basin, upstream of the study reach, historical accounts of dense riparian

Figure 3. Lithograph of confluence of Clark Fork (on right) and Blackfoot (on left) Rivers produced by artist accompanying the Mullan expedition, 1860–1861. This image, the first known image of the downstream portion of the study area, illustrates single-thread channels at the confluence.

vegetation; floodplain deposits of peat, silt, and clays; and branching patterns in abandoned channels are suggestive of the geomorphic effects of beaver (Smith *et al.*, 1998). Beaver trappers moved into the basin in the decades following the Lewis and Clark Expedition and soon extirpated beaver. Direct evidence of beaver effects specific to the study reach are lacking, but elimination of beaver may have reduced flow resistance, flood attenuation, and sediment storage (Wohl, 2011) in the upper basin, all of which would affect flow and sediment supply to our study reach and possibly reduce channel complexity. Any such changes would have served as a precursor to the more extensive human-induced alterations wrought by mining.

Mining period

In the second half of the 1800s, mining transformed the upper CFR basin. Although the mining and other dominant land uses during this period were upstream of the study reach, material fluxes to the study reach were dramatically altered. Logging and agriculture, including cattle and sheep ranching, also started in the upper CFR in the mid-1800s (Horstman, 1984), but the scale of hydrogeomorphic effects resulting from these activities pales in comparison to those from mining. Gold was discovered in the upper CFR basin in the 1850s, setting off a period of placer mining (Quivik, 1998). The hydraulic mining methods that were employed produced large volumes of waste debris (gravel and sand) (Quivik, 1998), which would have produced substantial changes to flows and sediment dynamics in the upper CFR basin. In 1872, James Garfield traveled from Missoula up the Clark Fork to the Deer Lodge Valley and noted 'the beautiful [Clark Fork] River has been permanently ruined by the miners; and has been for three years as muddy as the Missouri. Before the discovery of gold, it was as clear and pure as any mountain stream could be' (quoted in Holmes and Garfield, 1956, 43pp).

Hard-rock mining for copper in the headwaters boomed in the late 1870s, and the Butte area became the world's most productive mining district for three decades (Quivik, 1998). Hundreds of millions of cubic meters of contaminated tailings (silt to fine-sand), the material that is discarded when milling and flotation are used to separate ore (Moore and Luoma, 1990), were dumped into the CFR headwaters. A series of large floods in the late nineteenth and early twentieth centuries (Figure 4) coincided with the mining boom and routed enormous volumes of mining waste through the CFR. The largest of these floods, an estimated 500-year event in 1908 (Parrett and Johnson, 2004), is documented in USGS gauge records. Other large floods in the 1880s and 1890s are suggested by newspaper accounts (Wheeler, 1974). However, there is no direct evidence that the 1880s and 1890s floods deposited tailings on the floodplain (e.g. dating of floodplain tailings deposits) or transported sediment far downstream to our study reach. The 1908 flood, however, deposited millions of cubic meters of fine-grained mill tailings and contaminated sediment across the floodplain of the upper CFR basin (Moore and Luoma, 1990) (Figure 1). It also filled Milltown Reservoir (the first impoundment downstream of the source area) with more than 5 million m^3 of sediment (Harding Lawson Associates, 1986). Although tailings thicknesses on the floodplain in headwater streams and on the CFR near the source were > 1 m (Smith *et al.*, 1998; Lauer and Parker, 2008), the thickness and continuity of floodplain deposits decreased downstream, and no tailings deposits have been found within the vicinity of our study reach outside of the reservoir (Moore and Luoma, 1990; Smith *et al.*, 1998).

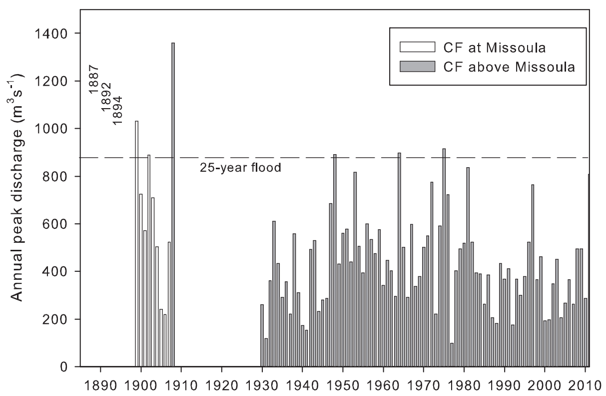

Figure 4. Peak flows on the Clark Fork River near Missoula, Montana. Columns show peak flows documented by the USGS at the Clark Fork (CF) at Missoula gauge (#12341500; 1899–1907) and CF above Missoula gauge (#12340500; 1908, 1930–2010). Year notations on upper left of graph illustrate estimated peak discharges in 1887, 1892, and 1894, which were ranked in terms of relative magnitude from newspaper accounts and in comparison to the post-1899 measured discharges; the exact magnitude of these events is not known (Wheeler, 1974). The 25-year flood magnitude for gauge #12340500 (Parrett and Johnson, 2004) is shown to illustrate the frequency of such events in the 1887–1908 period (6 > 25-year events) versus in the 1930–2010 period (3 > 25-year events).

Railroad construction during the mining era also imposed constraints on channel pattern along the study reach. The Northern Pacific Railroad, completed in 1883 along the north bank, and the Milwaukee, Chicago and St Paul Railroad, completed in 1909 along the south bank, flank the study reach (Milltown Superfund Redevelopment Working Group, 2011). A railroad survey map showing the proposed path of the Milwaukee railroad (and therefore inferred to date from approximately 1908, because Milltown Dam and Reservoir are depicted) indicates a multi-thread channel in the study reach upstream of the reservoir and cutoff side channels by the railroad (MPC, n.d.) (Figure 5). Aerial photographs, discussed later, show that railroad effects on channel movement persisted in the twentieth century, particularly along the south bank in the upstream half of the study reach.

During the mining era, substantial ecosystem impacts and changes in water quality clearly occurred. Yet we found no evidence that overall channel morphology within the study reach, other than the portion submerged by Milltown Reservoir, shifted beyond the pre-impact range of variability. On the one hand, fine-grained sediment supply increased dramatically as a result of tailings disposal in streams (Figure 2). On the other hand, this increase in fine-grained sediment supply was accompanied by increased transport capacity associated with large floods, such that fine-grained sediment is unlikely to have deposited within the active channel in a manner that would have altered bed elevation or other aspects of channel morphology. Although changes in the balance of supply and transport capacity during this period are difficult to quantify, these qualitative inferences are consistent with the historical observations of persistent multi-thread channel patterns, with single-thread sections, in the study reach.

Mitigation period

The mitigation period started in the 1910s when tailings ponds were built at the confluence of Warm Springs and Silver Bow Creeks (Figure 1) to reduce the flow of mining waste into the CFR (Quivik, 1998). The tailings ponds were expanded several times, through the 1990s (Hornberger *et al.*, 1997; Quivik, 1998). These impoundments block sediment delivery from 17% of the upper basin, and they likely caused substantial decreases in sediment loads in the upper CFR during the twentieth century compared to the mining era (Figure 2) (Moore and Luoma, 1990; Lauer and Parker, 2008).

Changes in hydrology after 1908 also altered the conditions governing channel morphology in the CFR. Whereas in the period between 1887 and 1908, during the height of the mining years, six floods with recurrence intervals greater than 25 years occurred, only three such events were documented from 1930 to 2010 (Figure 4). This suggests that the reduction in sediment supply resulting from mitigation efforts was accompanied by reductions in transport capacity during this period. Channel form and process can be documented for this period starting in the 1930s as a result of aerial photograph availability. A 1930s photograph shows a multi-thread channel with patchy vegetation upstream of Milltown Reservoir (Figure 6). Between 1937 and 2005, vegetation density increased and the channel frequently shifted, but no overall changes in pattern are evident: the channel consistently alternates between single and multiple threads flowing around vegetated islands (Figure 7). Evolution and lateral movement of portions of the upper third of the study reach were inhibited by road and railroad embankments, against which the CFR remained pinned for decades (Figure 7). Additional discussion of aerial photograph analysis is provided later, in the context of analysis of channel pattern.

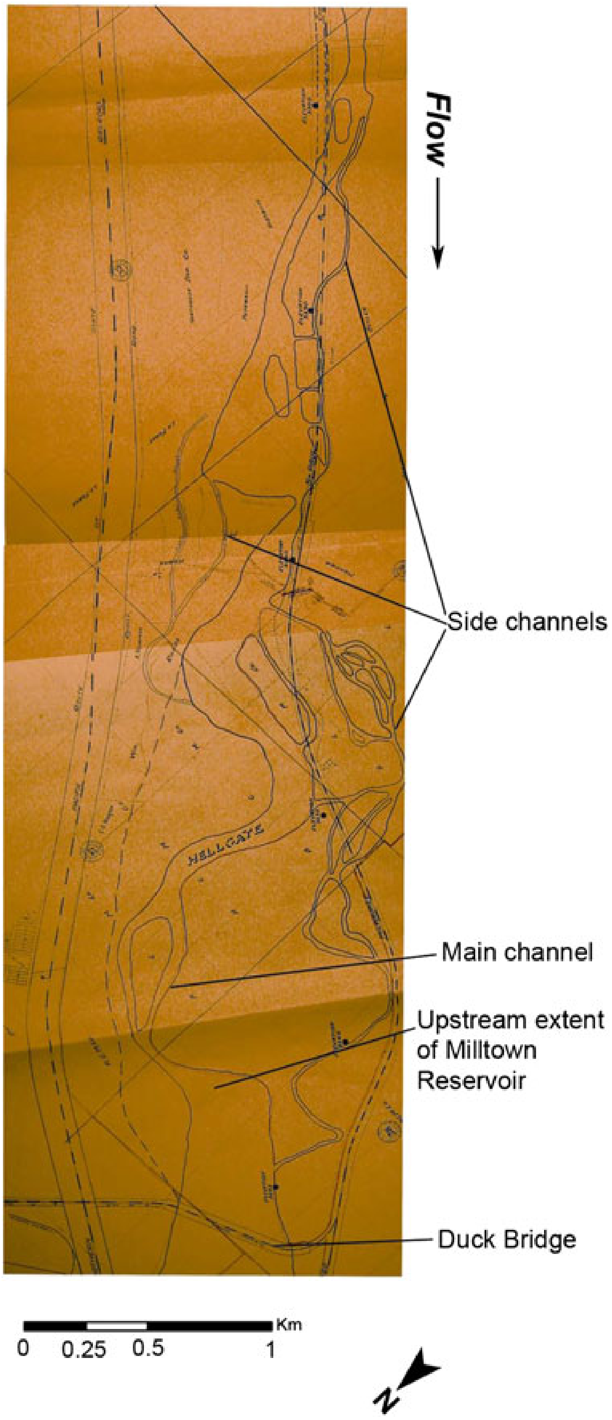

Figure 5. Railroad survey map of study area *c.* 1908, showing evidence of multi-thread channel pattern in the reach of the Clark Fork upstream of Milltown Reservoir (which is evident as the wide channel section at the bottom of the map) (MPC, n.d.). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Figure 6. 1930s view of the study area under high-flow conditions looking upstream. Milltown Dam is center bottom, Blackfoot River enters at lower left, and a multi-thread channel is visible upstream of the bridge spanning the channel in the center of the photograph. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

The lowermost portion of the study reach was inundated by Milltown Reservoir during this period. The resulting reduction in transport capacity would be expected to produce sediment deposition and channel aggradation, but the amount of reservoir deposition after the 1908 flood and during the ensuing decades of the mitigation period is unknown. More recent (1985–2005) USGS data suggest that no net deposition occurred in Milltown Reservoir during that period, based on comparison of suspended sediment fluxes into (at the Turah gauge) and out of Milltown Reservoir (Sando and Lambing, 2011). These data treat suspended load only, however, and it is likely that earlier in the mitigation period, our study reach behaved as a sink for coarse sediment as a result of deposition in the reach where the CFR enters the reservoir. The volume of such deposition was likely small however, compared to 1908 deposition.

Remediation and restoration period

The 1981 discovery of arsenic-contaminated groundwater adjacent to Milltown reservoir (Moore and Woessner, 2003) triggered designation as a Superfund site. This gave rise to the remediation and restoration period. Studies of how to address the arsenic emanating from Milltown sediments, bolstered by concerns about dam safety and fish passage, culminated in the decision to remove Milltown Dam and excavate contaminated reservoir sediments (USEPA, 2004). The key events in this multiyear dam removal project involved progressive reservoir drawdowns, construction of a temporary bypass channel through the reservoir reach, removal of the dam's powerhouse and spillway, breaching of the dam in March 2008, and excavation of approximately 2·2 million m^3 of contaminated sediment (~45% of total contaminated sediment) (USEPA, 2010; Wilcox, 2010). Following dam removal, a multimillion dollar channel and floodplain restoration project was implemented on the CFR in the former reservoir (State of Montana, 2005, 2008a), which we discuss further later.

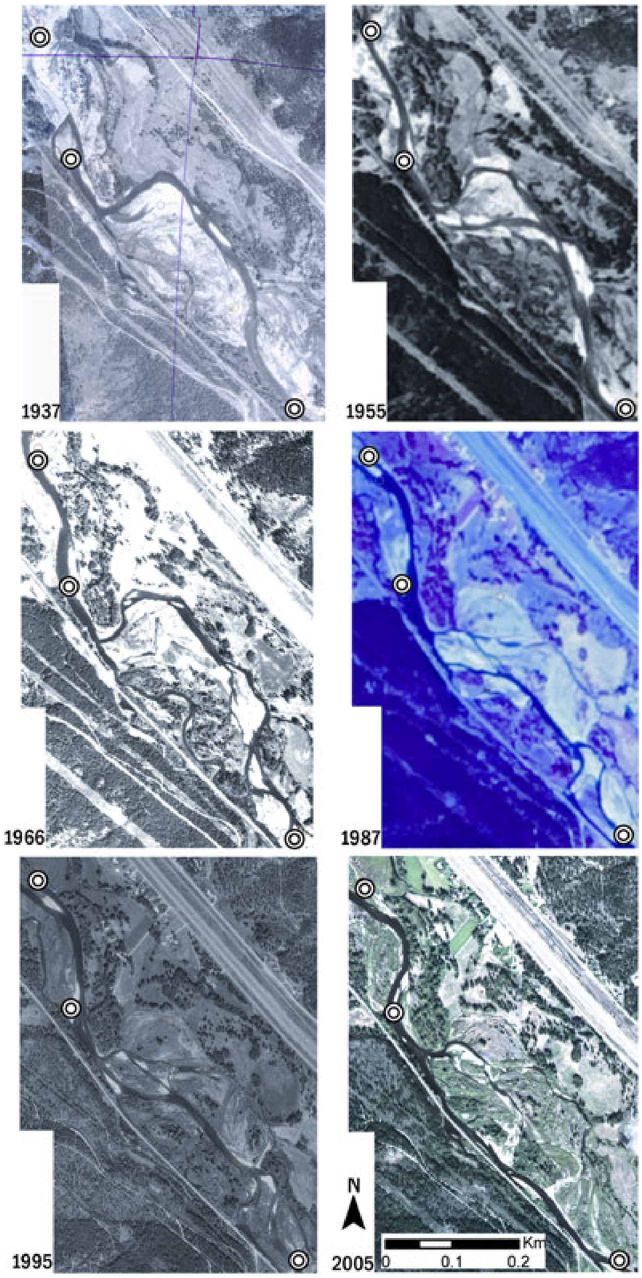

Figure 7. Aerial photograph chronology of a portion of the study reach 4 km upstream of Milltown Dam site showing channel movement by avulsion. Three avulsion nodes, denoted by bulls-eye symbols, are evident. Valley width, between railroad levee in lower left and road in upper right, is approximately 600 m. By 2005, the channel has become pinned to the railroad levee. Flow is from lower right to upper left. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Predictive analysis of channel pattern

Here we complement our historical analysis by evaluating process-based predictors of channel morphology. On Leopold and Wolman's (1957) slope–discharge plot, our study reach falls in the braiding realm, although near the meandering-braided transition. When plotted on a more recent slope–discharge plot that delineates a greater number of channel patterns (Church, 2006), our reach places firmly in the wandering realm (intermediate between braided and meandering) and at the lower limit of braided gravel channels. Calculations of ε^* and its components (S/F and h/B) (Parker, 1976) indicate values in the transitional regime between braiding and meandering.

Our aerial photograph analysis also provides insight into mechanisms of channel movement in recent decades. Aerial photographs indicate that channel adjustment occurred primarily by avulsions, which were evident in each set of aerial photographs and were distributed across the study reach (Figure 8). Avulsions were often nodal, recurring at similar positions (Slingerland and Smith, 2004); only two meander bends experienced fewer than two avulsions. We identify eight avulsion nodes where more than three avulsions occurred between 1937 and 2005 in the study reach, six of which are shown in Figure 8. Two study segments adjusted by lateral migration rather than avulsion at rates averaging $1{\cdot}5 \pm 0{\cdot}6$ m yr^{-1} from 1955 to 2005 (range = 0·6–2·4 m yr^{-1}). Despite visual evidence on aerial photographs of an overall increase in channel stability as a result of vegetation establishment between 1937 and 2005, no temporal trend in lateral migration was evident (Figure 9). Migration rates were highest in the 1977 to 1987 interval (Figure 9). These rates are higher than migration rates for various reaches of the upper CFR (R2 Resource Consultants, 1997, as cited in

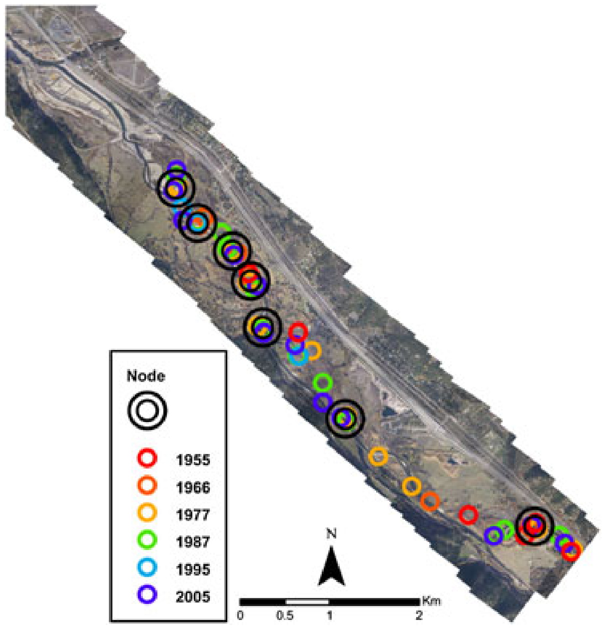

Figure 8. Avulsion nodes (black bulls-eyes) and avulsions (colored circles) identified on aerial photographs, 1955–2005. Avulsion frequency is low where the Milwaukee railroad levee confines the channel belt on river left. Flow is toward the northwest; Milltown Dam is in upper left. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

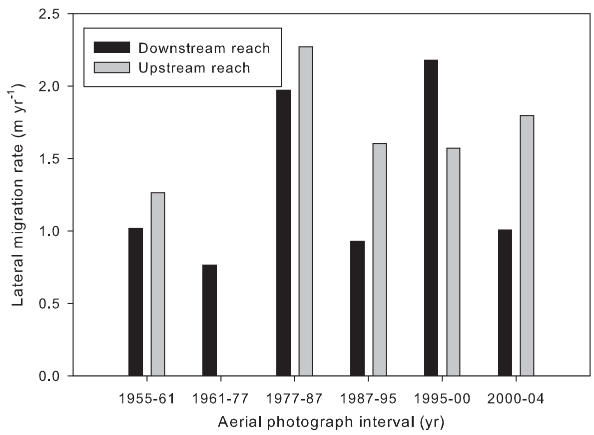

Figure 9. Lateral migration rates calculated from aerial photograph analysis for two study segments, located in the downstream and upstream portions of the study reach.

Swanson, 2002; Smith *et al.*, 1998), but within the range of rates (scaled as a percentage of channel width) reported for wandering rivers (as reviewed by Burge, 2005). In the context of the Jerolmack and Mohrig (2007, 1460pp) mobility analysis discussed earlier, we interpret our aerial photograph analysis results as indicative of conditions that are transitional between branching and single thread, in which adjustment occurs by both lateral migration and avulsion.

In sum, the various metrics for differentiating among channel patterns, as well as the aerial photograph analysis of migration processes, place our study reach in the multi-thread to transitional ranges. This is consistent with both our historical analysis and our conceptual model of a wandering channel. As Church and Rice (2009) note, the 'essence' of the wandering condition is when a channel 'is poised between a regime in which medial bar building and low-order braiding dominates, and one in which lateral bars alternate in a single-thread channel.'

Discussion

Post-dam removal channel restoration on the CFR

In the following section we discuss the Milltown restoration project, as a useful case study of the intersection of geomorphic variability and restoration, and broader implications for river restoration. The restoration channel constructed following the removal of Milltown Dam extends through much of our study reach, from the dam site to 5 km upstream (Figure 10). This encompasses areas of the reservoir where contaminated sediments were excavated or were left in place following dam breaching, as well as areas upstream of the former reservoir (USEPA, 2010; Wilcox, 2010).

The post-dam removal channel was constructed based on a 'natural channel design' approach (State of Montana, 2005). The design includes a single-thread meandering channel with chutes at the inside of meander bends that are accessed at high flows, engineered log jams on the outsides of channel bends to prevent lateral erosion, boulders placed in the channel bed to prevent incision, floodplain wetlands, and bank and floodplain re-vegetation (Figure 10). Channel dimensions are based on two reference reaches: the Blackfoot River near Ovando, Montana (a single-thread reach ~80 km upstream of the Blackfoot's confluence with the CFR) and a short CFR reach just upstream of Milltown Reservoir (State of Montana, 2005).

The CFR was routed into its constructed channel in December 2010. Several months later, in spring 2011, a large snowpack produced runoff with a high magnitude (peak of 380 m^3 s^{-1}, corresponding to a 30–40 year recurrence interval at the Turah gauge) and long duration (> 60 days above bankfull). Many portions of the constructed channel remained intact, but two avulsions occurred. In each of these the channel cut a new path directly across the inside of a meander bend. In the following months, project managers rerouted the avulsed channel back into the constructed channel, and the avulsion cutoff was refilled with sediment.

Project documents suggest that a single-thread, meandering planform is one that is most likely to achieve project goals and objectives, the broadest of which is to restore the targeted reach of the CFR 'to a naturally functioning, stable system' without jeopardizing surrounding property, infrastructure, or contaminated sediments left in place (State of Montana, 2005). Project documents recognize that, on the one hand, erosion and channel migration are essential aspects of fluvial function, but on the other hand, suggest that structures are needed to stabilize the channel in the short-term (15–25 years), until vegetation can establish (State of Montana, 2005). Project documentation also acknowledges that 'the CFR had a multi-thread channel in the upstream part of the reservoir and upstream of that, even before the dam was completed. It should be expected to adjust to a similar planform in the upstream reservoir following dam removal and will continue to maintain that pattern further upstream. A single thread meandering channel would not be expected unless it will be a structurally maintained channel' (Envirocon, 2004, p. 3). A single-thread, meandering planform was nevertheless implemented because 'most objectives [protecting contaminated sediments, aesthetics] . . . would be defeated or achieved to a lesser degree by a braided channel system' (State of Montana, 2005).

The Milltown project shares with many restoration projects its roots in a conceptual model of a single-thread meandering channel as a preferred condition and a restoration design that emphasizes structural approaches, at the expense of permitting lateral or vertical channel movement. But the Milltown restoration effort is unique in many respects. The incorporation of features such as off-channel wetlands and side channels that are activated at high flows, which were added based on comments submitted by peer reviewers (State of Montana, 2008b), illustrates a departure from a strict single-thread form. In addition, the type of historical analysis called for here was completed as part of project studies, using some of the same historical material evaluated here. In addition, the Milltown project incorporates a key element of an experimental approach to restoration that is often absent from restoration efforts: extensive monitoring that is linked to a set of defined project objectives (State of Montana, 2008b). Monitoring provided detailed information on where and why

Figure 10. Milltown restoration reach. Left image shows newly constructed channel in April 2011 (courtesy of G. Matson); right image shows restoration reach in June 2011 at high flows; former Milltown Dam site is in lower left (courtesy of J. Bean). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

the channel avulsed during 2011 floods. But because the project remains rooted in a single-thread, meandering channel framework, the response to this monitoring was to return the river to its constructed channel, as opposed to a recognition of the consistency of avulsions and channel evolution towards multiple threads with the reach's HRV.

Implications for river restoration

Data gaps, modeling simplifications, or natural variability lend considerable uncertainty to restoration predictions (Wheaton *et al.*, 2008). Philosophies of dealing with such uncertainty in restoration practice span a range of ignoring, eliminating, reducing, coping with, or embracing uncertainty (Wheaton *et al.*, 2008). Where uncertainty is ignored or downplayed, channel evolution that deviates from design may be treated as failure (Wheaton *et al.*, 2008) and/or as demanding repair. Many restoration projects implicitly attempt to reduce or eliminate uncertainty using engineering practices with high factors of safety, although constructing failure-proof channels runs counter to goals of restoring physical and ecosystem processes. For example, the use of in-channel structures to limit erosion is a common approach to addressing uncertainty in sediment fluxes and erosion dynamics (Gillilan *et al.*, 2005). One of the greatest uncertainties facing restoration projects is post-construction flows. Large floods occurring soon after project construction, before vegetation has established on banks and the floodplain, can have a much greater effect than those occurring later, as was starkly illustrated at Milltown.

An alternative but rarely implemented strategy for river restoration is to embrace uncertainty and to adopt multiple working hypotheses (Chamberlin, 1890) regarding project outcomes. Chamberlin's method of multiple working hypotheses is intended to avoid bias toward preferred outcomes and maintain openness to unexpected ones,and to accommodate the possibility of multiple explanatory mechanisms for a given result (Chamberlin, 1890; Elliott and Brook, 2007). Application of the method of multiple working hypotheses to river restoration lays the groundwork for an adaptive management approach in which river restoration projects are framed as full-scale, real-time experiments. Monitoring is used not only to measure deviation from design parameters but also to evaluate hypotheses about project outcomes. The resulting data are used to increase knowledge of geomorphic and ecological responses in a manner that allows project managers to adjust decisions in the face of uncertainty, and can inform restoration projects elsewhere (Wheaton *et al.*, 2008). Adaptive management, rooted in the method of multiple working hypotheses, can therefore increase river restoration success on technical, social, and political fronts (Pejchar and Warner, 2001; Wohl *et al.*, 2005). Few river restoration projects, however, adopt either the experimental, hypothesis-driven perspective that allows learning, or the long-term monitoring necessary to evaluate project success based on specific ecological, geomorphic, or social goals (Gillilan *et al.*, 2005; Palmer *et al.*, 2005).

Restoration project managers and designers operate under a range of constraints that can make implementation of an experimental, multiple working hypotheses approach difficult. These include constraints on lateral channel movement, public expectations, and funding. Human structures are the most common constraint to allowing rivers to evolve and migrate. In the Milltown restoration area, the restoration area is an unconfined valley slated to become a state park, so this constraint is absent. The ongoing presence of contaminated sediments in the reach formerly occupied by Milltown Reservoir confounds an experimental approach to some extent, even if the risk posed by erosion of such sediments is ambiguous, given that the most highly contaminated materials have been removed (USEPA, 2010).

In the sociopolitical realm, ignoring or failing to communicate uncertainty can create unrealistic expectations that a given restoration outcome will not deviate from design. Moreover, 'restored' channels that are not permitted to move can reinforce public views of rivers as static. Communicating uncertainties and explaining a multiple working hypotheses approach could reduce the chance that the public may perceive variable outcomes, even if ecologically beneficial, as failure.

The restoration of the Provo River, Utah, the largest US project to reconstruct a multi-thread channel (Utah Mitigation Commission, 2004), is a notable exception to standard restoration approaches. The Provo design was based on consideration of water and sediment fluxes, land acquisition has reduced constraints on channel migration, and extensive monitoring has occurred in an adaptive management framework. Clear Creek in northern California is another example of restoration in which channel migration has been embraced, in that case in the context of a single-thread channel.

A more experimental, multiple working hypotheses approach to the Milltown channel reconstruction would manifest in both channel design and subsequent reaction to deviations from the design. For example, a designed channel could be considered as a hypothesis about the channel morphology best suited to the geomorphic setting, rather than a fixed endpoint. This approach would provide the opportunity to learn about the channel pattern to which the CFR would evolve in the study reach and how it would adjust in response to factors such as floods, woody debris jams, or beaver; it would also reduce costs associated with maintenance of a specific channel form in the face of these processes. Such an approach would also limit channel hardening (e.g. along areas with uncontaminated floodplain sediments) and allow for both channel movement (e.g. by avulsion or lateral migration) and evolution between single- and multi-thread reaches. Whether at Milltown or elsewhere, channel design carried out in the multiple working hypothesis framework and that is consistent with the HRV and geomorphic setting of a targeted reach can maximize the potential for site-specific restoration success and for contributing to advances in restoration science.

Conclusion

Historical reconstructions such as this one, which apply limited historic data to a system that may have experienced considerable variability over the time period studied, are typically underdetermined, i.e. the available evidence is inadequate to conclusively support any single interpretation (Kleinhans, 2010). Historical documents extend the period of record of hydrological and geomorphic data, but they cannot define with certainty what conditions existed in a given time and place, when threshold-crossing events occurred, or quantitative aspects of channel form and process. Nevertheless, combining perspectives on a river system's historical range of variability and its current sediment and water fluxes offers the potential to improve restoration success.

In the CFR, legacy effects of land uses, including reduction in beaver populations, contaminated sediments stored in the channel and floodplain of the upper basin, sediment detention structures, water diversion, and channel confinement by transportation infrastructure and floodplain development makes restoration to pre-settlement conditions unlikely on human time scales. Although basin-specific details vary, legacy effects and altered hydrogeomorphic fluxes characterize most restoration settings, highlighting the need to recognize variability in channel form and the problems with using fixed target conditions to guide human intervention.

Uncertainty and underdetermination highlight the importance of treating river restoration as an adaptive experiment with multiple possible outcomes from which new insights into fluvial processes and restoration practice can be derived. This is especially true in the case of river restoration following dam removal, which carries a unique set of uncertainties because, for example, reservoirs obliterate earlier channel forms and upstream propagation of reservoir erosion may affect flow and sediment dynamics in reaches targeted for restoration. River restoration projects on larger rivers, as well as other upcoming large dam removals in the Pacific Northwest, carry substantial ecological and economic risk, highlighting the need for improved restoration science.

Acknowledgments—Funding was provided by NSF (EAR-0809082, EAR-0922296, EPS-0701906), the Montana Water Center/US Geological Survey 104(b) Water Resources Research Program, and an Undergraduate Research Award and Watkins Scholarship from the University of Montana. The authors also thank reviewers for comments that greatly improved the manuscript.

References

Abbe TB, Montgomery DR. 2003. Patterns and processes of wood debris accumulation in the Queets river basin, Washington. *Geomorphology* **51**: 81–107.

Brown AG. 1997. Biogeomorphology and diversity in multiple-channel river systems. *Global Ecology and Biogeography Letters* **6**: 179–185.

Burge L. 2005. Wandering Miramichi rivers, New Brunswick, Canada. *Geomorphology* **69**: 253–274.

Chamberlin TC. 1890. The method of multiple working hypotheses. *Science* **148**: 754–759. (Reprinted in 1965.)

Church M. 2002. Geomorphic thresholds in riverine landscapes. *Freshwater Biology* **47**: 541–557.

Church M. 2006. Bed material transport and the morphology of alluvial river channels. *Annual Review of Earth and Planetary Science* **34**: 325–354.

Church M, Rice S. 2009. Form and growth of bars in a wandering gravel-bed river. *Earth Surface Processes and Landforms* **34**: 1422–1432.

Desloges JR, Church M. 1989. Wandering gravel-bed rivers. *The Canadian Geographer* **33**: 360–364.

Elliott L, Brook B. 2007. Revisiting Chamberlin: multiple working hypotheses for the 21st century. *Bioscience* **57**: 608–614.

Envirocon. 2004. Milltown Reservoir Dry Removal Scour Evaluation – Addendum 1. Proposed Plan Updated Scour Evaluation, October version, Prepared by Envirocon, Inc. and EMC2 for the Atlantic Richfield Company: La Palma, CA; 121, 3 appendixes.

Gillilan S, Boyd K, Hoitsma T, Kauffman M. 2005. Challenges in developing and implementing ecological standards for geomorphic river restoration projects: a practitioner's response to Palmer *et al.* (2005). *Journal of Applied Ecology* **42**: 223–227.

Government Land Office (GLO). 1870, 1882, 1883, 1892, 1893, 1901, 1904. Government Land Office T13NR18W survey notes. On file at the Bureau of Land Management regional office, Missoula, MT.

Gregory KJ. 2006. The human role in changing river channels. *Geomorphology* **79**: 172–191.

Harding Lawson Associates. 1986. *Milltown Reservoir Feasibility Study*. Montana Department of Health and Environmental Sciences: Helena, MT; 198.

Holmes OW, Garfield JA. 1956. Peregrinations of a politician: James A. Garfield's diary of a trip to Montana in 1872. *Montana: The Magazine of Western History* **6**: 34–45.

Hornberger MI, Lambing JH, Luoma SN, Axtmann EV. 1997. Spatial and Temporal Trends of Trace Metals in Water, Bed Sediment, and Biota of the Upper Clark Fork Basin, Montana, 1985–1995. *US Geological Survey Open File Report 97–669*. US Geological Survey: Reston, VA; 127.

Horstman MC. 1984. Historical Events Associated with the Upper Clark Fork River Drainage. A summary prepared for the Montana Department of Fish, Wildlife, and Parks, Project 8241. Montana Department of Fish, Wildlife, and Parks: Helena, MT.

Jerolmack DJ, Mohrig D. 2007. Conditions for branching in depositional rivers. *Geology* **35**: 463–466.

Keane R, Hessburg P, Landres P, Swanson F. 2009. The use of historical range and variability (HRV) in landscape management. *Forest Ecology and Management* **258**: 1025–1037.

Kleinhans MG. 2010. Sorting out river channel patterns. *Progress in Physical Geography* **34**: 287–326.

Kondolf GM. 2006. River restoration and meanders. *Ecology and Society* **11**: 42–60.

Kondolf GM, Larson M. 1995. Historical channel analysis and its application to riparian and aquatic habitat restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems* **5**: 109–216.

Landres P, Morgan P, Swanson F. 1999. Overview of the use of natural variability concepts in managing ecological systems. *Ecological Applications* **9**: 1179–1188.

Lane EW. 1957. A Study of the Shape of Channels Formed by Natural Streams Flowing in Erodible Material. US Army Corps Engineering, Missouri River Division: Omaha, NE; 106.

Lauer JW, Parker G. 2008. Modeling framework for sediment deposition, storage, and evacuation in the floodplain of a meandering river: application to the Clark Fork River, Montana. *Water Resources Research* **44**: W08404.

Leopold LB, Wolman MG. 1957. *River Channel Patterns: Braided, Meandering and Straight*, US Geological Survey Professional Paper 282-B. United States Government Printing Office: Washington, DC.

Major JJ, O'Connor JE, Grant GE, Spicer KR, Bragg HM, Rhode A, Tanner DQ, Anderson CW, Wallick JR. 2008. Initial fluvial response to the removal of Oregon's Marmot Dam. *Eos Transactions, American Geophysical Union* **89**: 241–242.

Makaske B, Smith DG, Berendsen HJA, de Boer AG, van Nielen-Kiezebrink MF, Locking T. 2009. Hydraulic and sedimentary processes causing anastomosing morphology of the upper Columbia River, British Columbia, Canada. *Geomorphology* **111**: 194–205.

Milltown Superfund Redevelopment Working Group. 2011. The Railroads. http://tworivershistory.net/the-railroads.html [7 October 2011].

Montana Power Company (MPC). No date. Montana Power Company Collection, K. Ross Toole Archive, Mansfield Library, University of Montana, Missoula, MT.

Montgomery DR. 1999. Process domains and the river continuum. *Journal of the American Water Resources Association* **35**: 397–410.

Montgomery DR. 2003. *King of Fish: The Thousand-Year Run of Salmon*. Westview Press: Cambridge, MA.

Montgomery DR. 2008. Dreams of natural streams. *Science* **319**: 291–292.

Moore JN, Luoma SN. 1990. Hazardous wastes from large scale metal extraction: a case study. **24**: 1278–1285.

Moore JN, Woessner WW. 2003. Arsenic contamination in the water supply of Milltown, Montana. In *Arsenic in Ground Water*, Welch AH, Stollenwerk KG (eds). Kluwer Academic Publishers: Boston, MA; 329–350.

Moulton GE. 1993. *Journals of the Lewis and Clark Expedition, Volume 8*. University of Nebraska: Lincoln, NE.

Mullan J. 1863. *Report on the Construction of a Military Road from Fort Walla-Walla to Fort Benton*. Government Printing Office: Washington, DC.

Nanson G, Knighton A. 1996. Anabranching rivers: their cause, character and classification. *Earth Surface Processes and Landforms* **21**: 217–239.

Osterkamp W. 1978. Gradient, discharge, and particle-size relations of alluvial channels in Kansas, with observations on braiding. *American Journal of Science* **278**: 1253–1268.

Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, Carr J, Clayton S, Dahm CN, Shah JF, Galat DL, Loss SG, Goodwin P, Hart DD, Hassett B, Jenkinson R, Kondolf GM, Lave R, Meyer JL, O'Donnell TK, Pagano L, Sudduth E. 2005. Standards for ecologically successful river restoration. *Journal of Applied Ecology* **42**: 208–217.

Parker G. 1976. Cause and characteristic scales of meandering and braiding in rivers. *Journal of Fluid Mechanics* **76**: 457–480.

Parrett C, Johnson DR. 2004. Methods for Estimating Flood Frequency in Montana Based on Data through Water Year 1998. *US Geological Survey Water-Resources Investigations Report 03–4308*. US Geological Survey: Reston, VA; 101.

Pejchar L, Warner K. 2001. A river might run through it again: criteria for consideration of dam removal and interim lessons from California. *Environmental Management* **28**: 561–575.

Piegay H, Grant G, Nakamura F, Trustrum N. 2006. Braided river management: from assessment of river behaviour to improved sustainable development. In *Braided Rivers: Process, Deposits, Ecology and Management*. Sambrook-Smith GH, Best JL, Bristow CS, Petts GE (eds), Special Publication 36 of the International Association of Sedimentologists. International Association of Sedimentologists: Gent; 257–275.

Pizzuto J. 2002. Effects of dam removal on river form and process. *BioScience* **52**: 683–691.

Poole GC, Stanford JA, Running SW, Frissell CA, Woessner WW, Ellis BK. 2004. A patch hierarchy approach to modeling surface and subsurface hydrology in complex flood-plain environments. *Earth Surface Processes and Landforms* **29**: 1259–1274.

Quivik FL. 1998. Smoke and Tailings: *An Environmental History of Copper Smelting Technologies in Montana, 1880–1930*. PhD Thesis, University of Pennsylvania, Philadelphia, PA; 544.

R2 Resource Consultants. 1997. Upper Clark Fork River Streambank Erosion Rates. Prepared for the Clark Fork River Geomorphology Committee, Clark Fork River Operable Unit of the Milltown NPL Site, Redmond, WA; 64.

Rosgen DL. 2006. River restoration using a geomorphic approach for natural channel design. *Proceedings, 8th Federal Interagency Sedimentation Conference*, Reno, NV; 394–401.

Sando SK, Lambing JH. 2011. Estimated Loads of Suspended Sediment and Selected Trace Elements Transported Through the Clark Fork Basin, Montana, in Selected Periods Before and After the Breach of Milltown Dam (Water Years 1985–2009). *US Geological Survey Scientific Investigations Report 2011–5030*. US Geological Survey: Reston, VA; 64.

Schumm SA, Kahn HR. 1972. Experimental study of channel patterns. *Geological Society of America Bulletin* **83**: 1755–1770.

Slingerland R, Smith ND. 2004. River avulsions and their deposits. *Annual Review of Earth and Planetary Sciences* **32**: 257–285.

Smith JD, Lambing JH, Nimick DA, Parrett C, Ramey M, Schafer W. 1998. Geomorphology, Floodplain Tailings, and Metal Transport in the Upper Clark Fork Valley, Montana. *US Geological Survey Water-Resources Investigations Report 98–4170*. US Geological Survey: Helena, MT.

State of Montana. 2005. *Restoration Plan for the Clark Fork River and Blackfoot River Near Milltown Dam, I*, prepared by River Design Group, WestWater Consultants, Inc., and Geum Environmental Consulting, Inc. for the State of Montana Department of Justice Natural Resource Damage Program. State of Montana Department: Helena, MT.

State of Montana. 2006. *Geomorphic Data Summary Report: Restoration Plan for the Clark Fork River and Blackfoot River Near Milltown Dam*, prepared by River Design Group and WestWater Consultants, Inc. for the State of Montana Natural Resource Damage Program and Montana Fish, Wildlife & Parks. Montana Department of Fish, Wildlife, and Parks: Helena, MT.

State of Montana. 2008a. *Design Summary and Implementation Plan: Restoration Plan for the Clark Fork River and Blackfoot River Near Milltown Dam*, prepared by River Design Group, WestWater Consultants, Inc., and Geum Environmental Consulting, Inc. for the State of Montana Natural Resource Damage Program and Montana Fish, Wildlife & Parks. Montana Department of Fish, Wildlife, and Parks: Helena, MT.

State of Montana. 2008b. *State Restoration Monitoring and Maintenance Plan (Draft): Restoration Plan for the Clark Fork River and Blackfoot River Near Milltown Dam*, prepared by Geum Environmental Consulting, Inc., River Design Group, and WestWater Consultants, Inc., for the State of Montana Natural Resource Damage Program and Montana Fish, Wildlife & Parks. Montana Department of Fish, Wildlife, and Parks: Helena, MT.

Swanson B. 2002. Bank Erosion and Metal Loading in a Contaminated Floodplain System, Upper Clark Fork River Valley, Montana. MS Thesis, The University of Montana, Missoula, MT.

United States Army Corps of Topographical Engineers (USACTE). 1978. Mullan Road Survey Notes, 1859–1860, Complete. US National Archives: Washington, DC.

United States Department of Agriculture (USDA). 2012. Warm Springs, MT Snotel Data. http://www.wcc.nrcs.usda.gov/ftpref/data/climate/mtn_prec/table/history/montana/13c43s.txt [14 January 2012].

United States Environmental Protection Agency (USEPA). 2004. Milltown Reservoir Sediments Operable Unit of the Milltown Reservoir/Clark Fork River Superfund Site Record of Decision. USEPA Region 8: Helena, MT.

United States Environmental Protection Agency (USEPA). 2010. Milltown Reservoir Sediments Operable Unit Monthly Updates. USEPA Region 8: Helena, MT.

Utah Mitigation Commission. 2004. Provo River Restoration Project Fact Sheet. Utah Reclamation Mitigation and Conservation Commission: Salt Lake City, UT.

Walter RC, Merritts DJ. 2008. Natural streams and the legacy of water-powered mills. *Science* **319**: 299–304.

Walter C, Tullos DD. 2010. Downstream channel changes after a small dam removal: using aerial photos and measurement error for context; Calapooia River, Oregon. *River Research and Applications* **26**: 1220–1245.

Western Regional Climate Center. 2012. Missoula WSO AP, Montana (245745), 1948–2011. http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?mt5745 [14 January 2012].

Wheaton JM, Darby SE, Sear DA. 2008. The scope of uncertainties in river restoration. In *River Restoration: Managing the Uncertainty in Restoring Physical Habitat*, Darby SE, Sear D (eds). John Wiley & Sons: Chichester.

Wheeler RJ. 1974. *Water Resources and Hazard Planning Report for the Clark Fork River Valley above Missoula, Missoula County, Montana*, Montana Water Resource Report 51. The University of Montana Department of Geology: Missoula, MT.

Whited DC, Lorang MS, Harner MJ, Hauer FR, Kimball JS, Stanford JA. 2007. Climate, hydrologic disturbance, and succession: drivers of floodplain pattern. *Ecology* **88**: 940–953.

Wilcock PR. 2004. *Sediment transport in the restoration of gravel-bed rivers*. In *ASCE Environmental and Water Resources Institute Annual Congress*. American Society of Civil Engineers: Salt Lake City, UT.

Wilcox AC. 2010. Sediment transport and deposition resulting from a dam-removal sediment pulse: Milltown Dam, Clark Fork River, MT. *Eos Transactions*, *American Geophysical Union* Fall Meet Supplement, Abstract H31E-1045.

Wohl EE. 2000. *Virtual Rivers: Lessons from the Mountain Rivers of the Colorado Front Range*. Yale University Press: New Haven, CT; 224.

Wohl E. 2011. What should these rivers look like? Historical range of variability and human impacts in the Colorado Front Range, USA. *Earth Surface Processes and Landforms* **36**: 1378–1390.

Wohl E, Angermeier PL, Bledsoe B, Kondolf GM, MacDonnell L, Merritt DM, Palmer MA, Poff NL, Tarboton D. 2005. River restoration. *Water Resources Research* **41**: W10301.

