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Changing States: Using State-and-Transition Models to Evaluate Channel Evolution Following Dam Removal Along the Clark Fork River, Montana

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CHANGING STATES: USING STATE-AND-TRANSITION MODELS TO EVALUATE CHANNEL EVOLUTION FOLLOWING DAM REMOVAL ALONG THE CLARK FORK RIVER, MONTANA

DISSERTATION

A dissertation submitted in partial fulfillment of the
Requirements for the degree of Doctor of Philosophy in the
College of Arts and Sciences
at the University of Kentucky

By

Christopher Warren Van Dyke
Lexington, Kentucky

Director: Dr. Jonathan D. Phillips, Professor of Geography

Lexington, Kentucky

2015

ABSTRACT OF DISSERTATION

CHANGING STATES: USING STATE-AND-TRANSITION MODELS TO EVALUATE CHANNEL EVOLUTION FOLLOWING DAM REMOVAL ALONG THE CLARK FORK RIVER, MONTANA

Located just east of Missoula, Montana, Milltown Dam stood from 1908 to 2008 immediately downstream of the Clark Fork River's confluence with the Blackfoot River. After the discovery of arsenic-contaminated groundwater in the nearby community of Milltown, as well as extensive deposits of contaminated sediment in the dam's upstream reservoir, in 1981, the area was designated a Superfund site – along with much of the Upper Clark Fork Watershed. This motivated the eventual decision to remove the dam, perform environmental remediation, and reconstruct approximately five kilometers of the Clark Fork River and its floodplain. This study is part conceptual and part empirical. It describes a state-and-transition framework equipped to investigate channel evolution as well as the adjustment trajectories of other socio-biophysical landscapes. This framework is then applied to understand the post-restoration channel evolution of the Clark Fork River's mainstem, secondary channels, and floodplain. Adopting a state-and-transition framework to conceptualize landscape evolution lets environmental managers more effectively anticipate river response under multiple disturbence scenarios and therefore use more improvisational and adaptive management techniques that do not attempt to guide the landscape toward a single and permanent end state. State-and-transition models can also be used to highlight the spatially explicit patterns of complex biophysical response. The state-and-transition models developed for the Clark Fork River demonstrate the possibility of multiple evolutionary trajectories. Neither the secondary channels nor the main channel have responded in a linear, monotonic fashion, and future responses will be contingent upon hydrogeomorphic and climatic variability and chance disturbances. The biogeomorphic adjustments observed so far suggest divergent evolutionary trajectories and that in some instances the long-term fates of the mainstem, floodplain, and secondary channels are inescapably enmeshed with one another.

KEYWORDS: Clark Fork River, channel evolution, state-and-transition model, critical physical geography, river restoration

Christopher Warren Van Dyke

May 1, 2015

CHANGING STATES: USING STATE-AND-TRANSITION MODELS TO EVALUATE CHANNEL EVOLUTION FOLLOWING DAM REMOVAL ALONG THE CLARK FORK RIVER, MONTANA

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Lastly, I want to thank my family. They have supported and encouraged my academic pursuits unwaveringly. For that and so many other things, I'm forever indebted to them :)

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Chapter 1 – Introduction

The articles in this dissertation are focused on the complexity we can see in riverine landscapes and what concepts, methods, and frameworks are available to use to render that complexity legible. In doing so, it contributes to ongoing conversations about the purpose of river restoration and how we define the success of restoration projects that are implemented in landscapes influenced by the contingent interactions of biophysical processes. These processes, which are influenced by social phenomena, are responsible for conferring a material form to the landscape. Once conferred, the landscapes' material form is impermanent, and as new socio-biophysical processes unfold against the existing template, new landscape states arise. These states can be durable or transient (e.g., Fukami and Nakajima, 2011). A landscape state may be resilient in the face of moderate disturbances but transition to a new form under high-magnitude pertrubations. The first portion of this dissertation is conceptual, and asks what kind of frameworks and methodologies are most appropriate to make sense of complex patterns of evolution in socio-biophysical landscapes – patterns that give rise to these seemingly transient forms. The second half of the dissertation expands on these ideas in an empirical context by investigating the early-stage (< 5 years) bio-hydrogeomorphic adjustments observed on the Clark Fork River near Milltown, Montana following the remediation and reconstruction of ≈ 5 km of its main channel. Significant portions of the river's floodplain were excavated and rebuilt as well.

Discussions of channel and floodplain adjustments leverage state-and-transition models to establish baseline hypotheses that describe possible evolutionary trajectories the river is likely to take over the short- and medium-terms (i.e. 1–20 years). Flow was diverted into the reconstructed mainstem at the end of 2010. As such, one of the challenges that arose during this research was coping with a relatively narrow window to 1) observe what adjustments have occurred and 2) propose what typologies of channel evolution are most probable in the coming years. The arguments developed here may help to inform future monitoring efforts, and assess and diagnose the catalysts of morphological adjustment (Montgomery and MacDonald, 2002) – and hopefully be applicable in a wider range of contexts. The remainder of this chapter introduces readers to the study area's history and why it is of particular importance. From a geomorphological perspective, the Clark Fork River and its floodplain are interesting because restoration activities reset the biogeomorphic template. This has transformed the area into an experimental flume of sorts, affording us the opportunity to observe the evolution of the landscape from its inception. From a social perspective, the long period leading up to restoration was punctuated by moments of community activism that ultimately led to Milltown Dam being decommissioned and the river restored. While not a primary focus of this dissertation, being acquainted with this history underscores the intense social complexities associated with bringing the restoration to fruition. After reviewing these historical and social implications, I briefly outline each chapter and the intellectual contribution it makes to the literature on geomorphology, environmental management, and geography more broadly.

1.1 Introducing the Historical and Social Context

Building dams is about generating power[1] – in early-1905 when William A. Clark first explored the possibility of constructing a dam on the Clark Fork River, he imagined the electricity it would produce as being able to power a streetcar system in the growing city of Missoula. His vision quickly materialized, with construction beginning by late-1905 on Milltown Dam, located approximately 10 km upriver of Missoula near the small hamlets of Milltown and Bonner. The new structure was located on the Clark Fork River immediately downstream of its confluence with the Blackfoot River. Photographs taken during the early phases of construction show a significant portion of the Clark Fork's floodplain wiped clean of timber, some of which was used to build the dam itself. However, after visiting the construction side, Clark decided to increase the dam's size, which halted work until 1906 (see Quivik, 1984; Brooks, 2012). By December 1907 Milltown Dam was finished, and it first generated electricity in January 1908. Once power began flowing the dam supplied electricity to an electric streetcar that ran from Missoula to Bonner, wealthier homes and businesses in Missoula, timber-processing mills in Bonner, and another streetcar that navigated portions of the Bitterroot Valley.

Six months after its turbines began spinning, an unprecedented flood would

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[1] Other reasons for building dams include flood mitigation, recreation, navigational purposes, and establishing a more secure water supply.

threaten the dam. In June 1908 late-season snowfall combined with heavy rains inundated the Upper Clark Fork Watershed. Floodwaters rushed down the Clark Fork River toward Milltown Dam. Near Missoula, peak discharge was ≈ 1,360 m^3 s^{-1}. Although the dam survived the flooding, Missoula suffered widespread damage, with multiple bridges washed out and extensive significant property losses. Figure 1.1 provides a glimpse at the Milltown Dam's powerhouse as the waters spilled over the dam, and Figure 1. 2 captures a view of Missoula, looking down from Mount Sentinel. After the floodwaters receded the dam was repaired, but the most important implications of the 1908 floods – and the dam's presence as a bottleneck in the river – would remain unknown for almost 80 years.

Figure 1.1. Milltown Dam, June 1908 (Source: University of Montana Library)

Residents of nearby Milltown drew their groundwater supply from wells connected to the dam's reservoir, and confronted floods' material residues firsthand well before 1981. David Brooks (2012), writing about the history of Milltown and the dam, noted that locals had observed anomalies with their water supply for years. Some of the most visible markers included sinks, tubs, and toilet bowls accumulating black stains; laundered clothes acquiring rust-colored hues; cars and homes turning faintly yellow after they were washed; and perhaps most viscerally, tap water with a metallic taste. But until 1981 there was no explanation for the water's apparent toxicity. Samples of groundwater and reservoir sediment revealed the cause – extensive contamination by arsenic, copper, zinc, cadmium, lead, and other heavy metals. Four of the community wells registered arsenic levels between 220 and 550 µg/l. At the time the maximum allowable level under the Safe Drinking Water Act was 50 µg/l, today it is 10 µg/l (Moore and Woessner, 2003; Brooks, 2012). Initially the contaminants’ origin was unclear. The Environmental Protection Agency (EPA) named three potentially responsible parties (PRP): the Atlantic Richfield Company, Champion International Corporation, and the Montana Power Company. Suspicion of the Champion International Corporation stemmed from its ownership of a local saw mill it had purchased from the Anaconda Mining Company. Eventually it was cleared of responsibility when it became apparent that reservoir sediments were primarily responsible for the contamination. These sediments did not originate in Milltown; they came from locations far upstream of the dam.

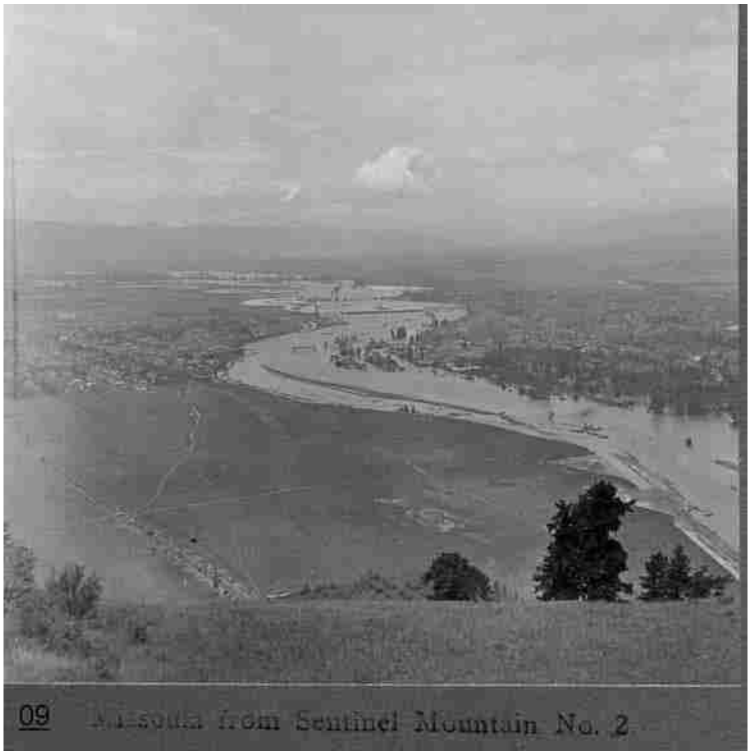

Figure 1.2. June 1908 Flood, Missoula (Source: Todd Klietz, Missoula Floodplain Administrator)

During much of the 20th century, the cities of Butte and Anaconda, Montana were mining strongholds. The cities’ (separated by ≈ 40 km) turn toward mining gathered momentum in the 1880s as the extraction of copper sulfide ores began driving economic activity in the region (Malone, 1981; EPA, 2004). The 1908 floodwaters carried with them immense quantities of sediment laced with the byproducts of copper mining, eventually reaching and settling in the dam’s reservoir. Although the 1908 flood was notable because of its overwhelming severity, waste from upstream mining activity gradually amassed in the reservoir over the next 80 years – the dam limited the passage of sediment downstream. In total, mining operations released approximately 100 million metric tons of waste into the Clark Fork's headwaters (Moore and Woessner, 2003).

A complete review of the geochemical mechanisms that led to groundwater contamination is beyond the scope of this introduction (see, e.g., Woessner, 1995; EPA, 2002; Moore and Woessner, 2003). A number of researchers studied the reservoir and its sediments. Sediment deposits ranged from 8-m thick near the dam's face to 0.5-m thick ≈ 3 km upstream of it. Although there was an oxidized zone in the upper 1.5 m of reservoir sediments, anoxic conditions generally prevailed. And while different models were proposed to explain the transport and fate of arsenic, the accepted narrative was that iron oxyhydroxides holding arsenic dissolved under the anoxic conditions in the sediment. When water seeped from the reservoir it flowed from fine-grained sediments into the pre-dam floodplain alluvium, and eventually into the adjacent aquifer (Moore and Woessner, 2003). This water carried in it traces of arsenic and other heavy metals. Eventually, the contamination led to the inclusion of Milltown among the first batch of federally designated Superfund sites in 1983. The Superfund program was established by the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA). It vested the federal government with the authority to remediate abandoned and uncontrolled hazardous waste sites. The entire Upper Clark Fork Watershed would form the largest Superfund complex in the United States. The quantity of contaminated sediments stored in the Milltown reservoir was estimated at ≈ 5.05 million m^3, with metal concentrations varying spatially and inversely in proportion to grain size.

After the initial discovery of contamination, studies proceeded throughout the 1980s and 1990s. These sought strategies to address the pollution. The push for a permanent solution was ratcheted up in the mid-1990s following two key events. First, a significant ice-scouring event occurred in February, 1996 that placed under a magnifying glass the problems contamination posed for water quality and aquatic habitat. Second, in 1998 the bull trout (*S. confluentus*) was listed as a threatened species under the United States Endangered Species Act. The 1996 ice-scour event was particularly notable because it occurred just as the EPA was finishing up a Draft Feasibility Study that examined ways to remediate the arsenic groundwater plume located underneath and adjacent to the reservoir.

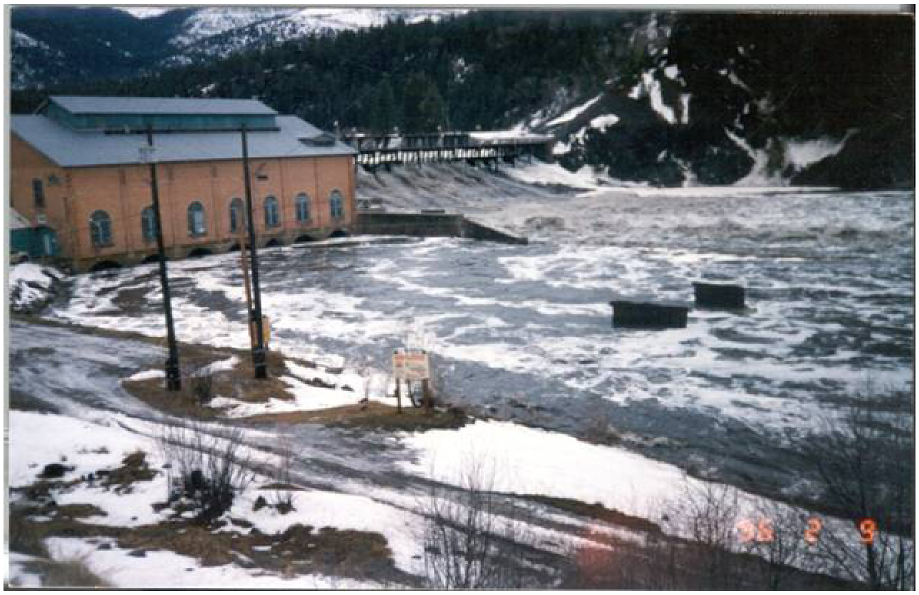

Figure 1.3. The February, 1996 ice event forced the drawdown of Milltown Reservoir to avoid impairing the dam's structure (Source: Judy Martz, Bonner Milltown History Center)

Several factors led to the ice scouring. Above normal precipitation fell across the Clark Fork River Watershed for several weeks leading up to the event. In early February, a cold snap depleted streamflow, prompting the formation surface ice on the Clark Fork and Blackfoot Rivers. This was followed by rapid temperature increases and rising waters, with discharge reaching ≈ 365 $m^3 s^{-1}$ above Missoula (USGS Gaging Station #12340500). The amplified streamflows mobilized ice jams along the Blackfoot River, conveying the ice rapidly downstream toward Milltown Dam (EPA, 2002). The ice created a jam measuring 3 m high, 12 m wide, and 8 km long that ground toward the dam at 8 km hr^{-1} (Figure 1.3). Wanting to avoid structural damage, the dam operators lowered the reservoir level 2.4 m. Doing so released significant quantities of contaminated water and sediment downstream; later that year several trout species (bull trout, brown trout, and rainbow trout) evinced significant population declines. Although there was no single cause identified for the fall in populations, exposure to water with elevated total suspended solids and metal loadings likely played an important role (EPA, 2002). The ice-scouring event delayed the release of the EPA's 1996 feasibility study and motivated development of a Final Focused Feasibility Study, released in 2001, which highlighted solutions to improve surface water quality and aquatic habitat. The feasibility studies' findings were merged in a 2002 Final Combined Feasibility Study. This study included the eight plans – first outlined in the 2001 study – to remediate and renew the Clark Fork River at Milltown (Table 1 lists and briefly summarizes these options).

Table 1.1– Remediation Alternatives from 2001 Focused Feasibility Study (EPA 2002)

Alternative	Description
1	No further action
2	Modification of dam and operational practices
3a	Modification of dam and operational practices with erosion/scour protection
3b	Modification of dam and operational practices with partial sediment removal and channelization, plus groundwater containment, institutional controls and natural attenuation within the aquifer plume
4	Modification of dam and operational practices with periodic sediment removal
5	Dam removal, partial sediment removal with channelization and leachate collection/treatment
6a	Modification of dam and operational practices with total sediment removal of the lower reservoir area
6b	Modification of dam and operational practices with total sediment removal of the entire reservoir
7a	Dam removal and total sediment removal of the lower reservoir area
7b	Dam removal and total sediment removal of the entire reservoir area

After the 1996 ice-scouring event, Milltown Dam began to attract more attention from nearby Missoula, particularly the thriving environmental advocacy community. What is striking is the role the community played in the EPA's (and the state's) decision-making process. So while 1996 was certainly a turning point for the river, 2000 turned out to be a watershed moment when the Clark Fork Coalition (CFC), a local environmental advocacy group headquartered in Missoula, began a very public and visible campaign to argue for the removal of Milltown Dam as part of any remediation plan. The campaign, centered on the call to "Remove the Dam. Restore the River" got underway in February 2000. The CFC released pamphlets and put up billboards in Missoula with pithy images and slogans, such as "Not All Time Bombs Tick" and "Ski Milltown! It's Toxic!" The materials released by the Coalition accentuated the dangers associated with a dam failure as well as the amount of metal-laden sediment that passed through the dam each year (Brooks, 2012). Advertisements tapped into the importance of recreation and the Clark Fork's fishing resources – the idea being to demonstrate that dam removal would strengthen the economy by supporting the activities most critical to it. Another unique feature of the campaign was its lighthearted, yet still informative advertising. It was important to highlight why the dam should be removed, but the CFC wanted to make its argument in a way that would not alienate people who did not traditionally see themselves as environmentalists (Brooks, 2012). Equally, the CFC underlined the importance of holding the responsible parties accountable – chiefly the Atlantic Richfield Company[2] (ARCO).

ARCO had historically objected to dam removal, which is understandable given the financial liability it shouldered. In the late-1990s ARCO provided financial assistance to the Bonner Development Group (BDG), which focused on community development projects in the Bonner/Milltown area. However, as the CFCs campaign to remove Milltown Dam wore on, BDG gradually became the most outspoken organization opposing dam removal, citing its importance to the local economy – the Montana Power Company was required to pay taxes on the facility – and historical importance (see Gilbertz and Millburn, 2011; Brooks, 2012; and Tyer, 2013 which reveal how community responses differed between Missoula, known for its environmental activism, and the small towns of Milltown and Bonner, which were located much closer to the dam). BDG's voice was ultimately faint and attracted much less attention than the CFC, which ran an extremely well-coordinated and managed campaign, one that not only sought public support but also the backing of politicians at the local and state level – across the political spectrum. Particularly important in Missoula was the endorsement dam removal advocates received from Barbara Evans, a Republican County Commissioner, who expressed concerns over the environmental consequences of leaving the dam and sediments in place (see Brooks, 2012). At the state level, when the Republican governor Judy Martz came out in favor of removing the dam, the structure's fate was no longer in question. Soon there was a formalized agreement between the State of Montana, EPA, the Confederated Salish and Kootenai Tribes, and the liable parties to remove the dam. From

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[2] The Atlantic Richfield Company [ARCO] became a subsidiary of British Petroleum in 2000. It had previously merged with the Anaconda Mining Company in 1977. Pursuant to Superfund legislation, because it purchased the Anaconda Company, it inherited liability for the contamination

a historical standpoint, the decision to remove the dam was significant as it was the first time the Superfund program involved taking out a dam.

Questions remained, however, over the methods that should be used to extract contaminated sediments from the reservoir and decommission and remove the dam itself. In 2003 the EPA released a draft response plan for public comment. It proposed removing ≈ 2 million m^3 of the most contaminated reservoir sediment and storing it permanently in a repository 1.5 km downstream of Milltown Dam in an area called Bandmann Flats – which is part of East Missoula. Under this plan the dam's spillway and radial gate section would be removed, but not its powerhouse. Extensive channel reconstruction, centered on segments upstream of the dam, would focus on armoring the river channel and vegetating the adjacent floodplain with grasses to prevent remaining contaminants from being mobilized. A notable feature of this plan is that it did not entail dewatering the reservoir before sediment removal. Instead, the majority of contaminated sediments were to be hydraulically dredged and pumped out of the reservoir to the permanent repository using a slurry line. The channel design envisioned by the EPA was problematic from hydrogeomorphic and ecological standpoints. The armored and riprapped trapezoidal channel would be large enough to contain a 100-year flood within its banks. While the plan stated a commitment to promoting ecological resiliency, its primary emphasis was on remediation – arguably the vision for ecological recovery was slightly underdeveloped.

In 2003, the State of Montana also released a Draft Conceptual Plan to remediate and renew the Clark Fork and Blackfoot Rivers (Figure 1.4). The state's plan differed considerably from the EPA, especially in the particulars of channel and floodplain development. Unlike the EPA's proposal, which left the dam powerhouse in place, the state wanted to remove all structures to restore the natural channel and floodplain. The Draft Conceptual Plan also envisioned rebuilding much longer stretches of the river, extending 10 km upstream of the dam site on the Clark Fork and 4 km upstream of it on the Blackfoot. Rather than accommodating a 100-year flood, the conceptual plan proposed excavating new alluvial channels that would hold channel-forming discharges – which it equated with a 1.5-year flood. It incorporated neither armoring nor riprapping materials, instead proposing to stabilize banks with a combination of vegetation and log structures. Lastly, whereas the EPA's ecological recovery plan would re-vegetate the floodplain with grass species, the state's plan imagined a more comprehensive and ambitious blueprint – one which involved planting native grasses, forbs, woody plants and trees (e.g. willow, cottonwoods), and shrubs. Table 1.2 summarizes the preliminary remediation goals specified by the EPA (2003).

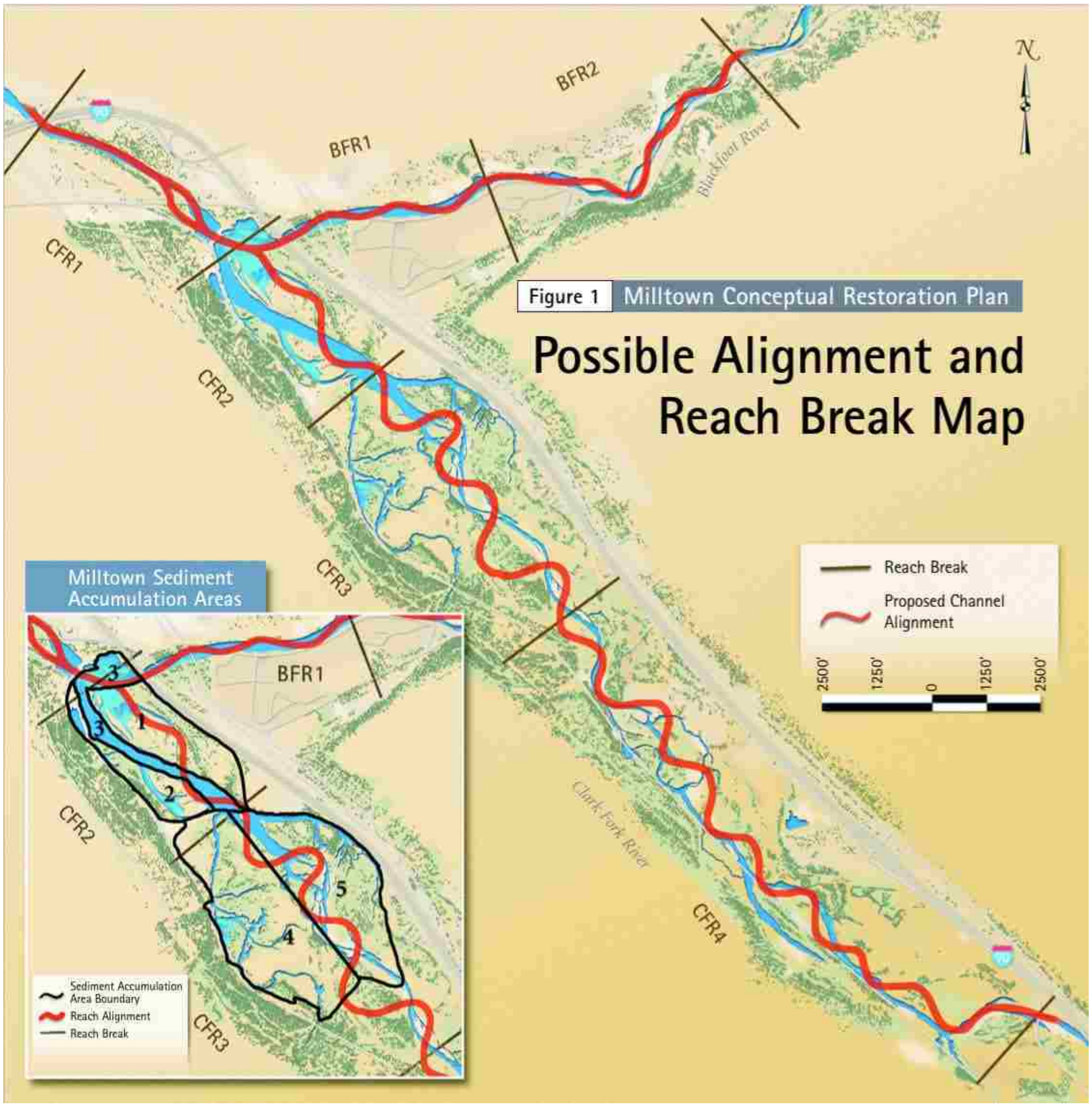

Figure 1.4 – 2003 State of Montana Draft Conceptual Plan

Plans released by the EPA and State of Montana in 2003 were *conceptual*. They did not represent what would actually be constructed (or what in fact was). However, the State of Montana's plan came under particular scrutiny because it depicted a single-threaded meandering channel. Geomorphologists in the academic community – including

Matt Kondolf (2006), Peter Wilcock, and Martin Doyle – voiced worry over the plan for various reasons. The comments from Matt Kondolf garnered the most attention. As part of his ongoing jeremiad (see Bercovitch, 2012) against natural channel design (NCD), Kondolf suggested the plan was yet one more attempt to enact a cultural landscape ideal that was incompatible with hydrogeomorphic realities[3]. I address this issue more fully in Chapter 4, but what is interesting to note here is that a conceptual plan – that would eventually be reworked over the next *five* years – became fodder for ongoing academic debates long after it had been discarded and replaced by alternative designs in later proposals.

Table 1.2 – 2003 Preliminary Remediation Goals

1.	Restore the groundwater to its beneficial use within a reasonable period using monitored natural recovery
2.	Protect downstream fish and macroinvertebrate populations from releases of contaminated reservoir sediments, which occur with ice scout and high flow events
3.	Provide permanent protection from catastrophic release through dam failure
4.	Provide compliance with the Endangered Species Act and wetland protection through consultation with the Fish and Wildlife Service, the Confederated Salish and Kootenai Tribes, and relevant State agencies

The EPA and the State of Montana each sought public comment on their respective plans, which they received in droves. By 2004 the EPA issued a reworked proposal, and later that year the record of decision. Perhaps the most significant change in the 2004 plan was involved the remediation techniques that would be used to excavate contaminated sediment. Whereas the 2003 proposal envisioned hydraulically dredging the reservoir, the 2004 plan, as well as the binding record of decision, called for mechanical excavation. And instead of storing the sediments in East Missoula at Bandmann Flats, they would be shipped via rail to Opportunity, Montana, a small community near Butte. The reasons for doing so are complex and a complete discussion is beyond the scope of this dissertation (for context, see Brooks, 2012, but especially Tyer, 2013). Local opposition to housing the sediments in East Missoula played a role, as

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[3] This is not to say the critiques of NCD are invalid (see, e.g., Kondolf, 1995; Kondolf et al., 2001; Juracek and Fitzpatrick, 2003; Nagle, 2007; Simon et al, 2007; Bernhardt and Palmer, 2011; Ernst et al., 2012). Nor do I invoke 'jeremiad' in necessarily the pejorative sense. Rather, my point is that at times the debates over NCD have gotten pointlessly heated (see Lave, 2012), which has accomplished little.

did local business interests. Another factor was that BP-ARCO managed a storage site for contaminated waste in Opportunity – the Opportunity Ponds – that is adjacent to the extreme upper reaches of the Clark Fork. Moving the sediment via rail meant that the reservoir would need to be drained, a bypass channel constructed, and a rail spur installed. EPA officials argued the revised plan had numerous benefits – it would be easier to implement, reduce the construction time, and would take advantage of an existing waste repository, which would thus impose fewer burdens on the local community (i.e. Milltown). Along with a different approach to sediment removal, the EPA abandoned plans for a highly engineered channel, instead affirming it would collaborate with the State of Montana and other parties to identify an optimal remediation-restoration solution. An updated plan had not yet been released by the state, although the EPA endorsed the general principals outlined in the Draft Conceptual Plan – attempt to create a more naturally functioning channel and floodplain that would yield benefits for recreationists, riparian vegetation, and aquatic life.

The State of Montana released updated design plans in 2005 and 2008; the 2005 plans underwent peer review and informed the final design. Ultimately, the scope of work was narrowed in the later plans. While the 2003 plan had channel restoration extending upstream to Turah, Montana and encompassing extended segments of the Blackfoot River, the later plans – and the implemented design – were more modest in their ambitions. Extensive channel reconstruction never took place on the Blackfoot River (although there work did focus on some areas near its confluence with the Clark Fork), and the length of the reconstructed the Clark Fork reach was approximately halved. And the design had been so heavily scurtinized was modified. Instead of adopting a strictly single-threaded planform, the as-built river adopted what I call a hybrid planform, which exists somewhere between a wandering planform and a single-threaded planform. The river is predominantly single-threaded, and it does meander, however, the floodplain also includes secondary channels that branch away from and reconnect to the mainstem as well as wetlands. On March 30, 2008, Milltown Dam was breached, and over the next year what remained of the dam was slowly removed. Over the next three years work continued, with the focus being on reconstructing large areas of the floodplain and channel – in late-December 2010 the Clark Fork River was rerouted from its temporary bypass channel into its newly built channel. Serendipitously, in June 2011 a large flood (35-40 year recurrence interval) impacted the Clark Fork River. As in 1908, roughly six months after the completion of a major river project, climatic anomalies intervened to reshape the Clark Fork River, producing two significant avulsions in the process. It is at this point where this dissertation's story picks up, examining the short-term adjustments of the Clark Fork, its secondary channels, and floodplain wetlands since flow was restored to the river. Arguably this is of interest because the new floodplain is a real-world laboratory that lets us observe the complex responses that have unfolded since 2010 – at least this time there was no arsenic.

1.2 The Structure of this Dissertation

The remainder of this dissertation consists of four interlinked articles all organized around the themes of channel evolution and socio-biophysical landscapes. By socio-biophysical landscapes I am referring to any biophysical landscape whose adjustment is influenced – to some degree – by economic, political, or cultural forces. A renewed river arguably stands as an exemplar of a socio-biophysical landscape because even if there are not active efforts to manage it, its initial form reflects particular social imperatives that are inflected through its design. In using this designation, my point is not to suggest that social factors are always critical for landscape adjustment – in many cases biophysical forcings acting beyond a social frame (and which are not directly influenced by it) are what drive landscape evolution. The first two articles are mostly conceptual and theoretical in scope and set up the frameworks through which I make sense of the Clark Fork River renewal. The first discusses channel evolution models and their development over the past 30 years, while the second article stretches some of the ideas outlined there in new directions to create a conceptual framework for understanding and narrating the evolution of socio-biophysical landscapes. The last two articles are more empirically grounded, looking specifically at the Clark Fork River and its post-renewal bio-hydrogeomorphic adjustments. One article takes as its focus the channel design and its appropriateness for the geomorphic setting; the second looks at the evolution of the floodplain's secondary channels. Both articles develop state-and-transition models that can be used to anticipate the future adjustment trajectories of the river under variable environmental conditions. Because the chapters function as standalone articles, they include abstracts that describe their main objectives and findings. Instead of repeating these verbatim here, I briefly reflect on the main points and intellectual contribution of each article.

- Chapter 2, "Channels in the Making — An Appraisal of Channel Evolution Models" (published in modified form in *Geography Compass*, Van Dyke, 2013)

This chapter provides a historical overview of channel evolution models (CEMs) from the 1980s to the present. CEMs were initially developed to evaluate the morphological adjustments river or stream channels undergo following channelization (Schumm et al., 1984; Simon and Hupp, 1987; Simon, 1989; 1992, Simon and Rinaldi, 2006). Although useful, these CEMs had limitations – they proposed that channel adjustments proceed in a linear, monotonic fashion after a disturbance. Echoing the logic found in classical ecological succession models, classic CEMs lack explanatory power in fluvial settings that are spatially complex due to variable flux boundary conditions (Brierley and Fryirs, 2005). Building from this observation, I describe recent CEMs that recognize channels may undergo multiple modes of adjustment. Taking a cue from ecology, I suggest that using state-and-transition models (STMs) offer a neat way to understand the linkages between formal channel states (i.e. morphology) and the governing process regimes. The purpose of using STMs is to better understand when qualitative state changes occur in a river landscape. "State" can be read broadly; on the one hand, it may refer to channel planform, but on the other hand it can refer to a more general condition, such as a channel undergoing persistent aggradation. Adopting a broad reading of state lets us apply a state-and-transition heuristic to any CEM, even classic versions that were concerned with a linear sequence of adjustments. Because STMs are scalable, they enable fine-grained readings of geomorphic–ecological dynamics and the feedbacks between the two that influence the morphological properties of a river.

The chapter wraps up with closing remarks about methodological strategies to develop STMs. One of my arguments is that STMs are well-suited to applied settings and have the potential to positively impact river management. Keeping this in mind, STMs are compatible with traditional field methods (e.g. cross-sectional surveys, longitudinal surveys) that have been standard practice in fluvial geomorphology for decades (Kondolf and Piégay, 2003). Another route is to focus on mapping geomorphological units at a broad scale to understand the relationship between river form and disturbance events. One strategy here is locational probability mapping, a simple device that is used to determine the likelihood that a specific portion of a river channel occupies a particular state (Graf, 1984, 2000). A probabilistic approach is not strictly necessary. For instance, Surian et al. (2014) used geomorphic mapping to relate the morphology of braided rivers to discharge events of varying magnitude. Recent advances in instrumentation and field photography could also potentially foster a better appreciation of the cross-scale bio-hydrogeomorphic relations that drive state changes (e.g. Carbonneau et al., 2012; Westoby et al., 2012). Ideally, we should not view the development of STMs as some theoretical exercise that does not benefit river management. STMs have long been used to guide the management of semi-arid rangelands, as well as many other landscapes throughout the American West (Bestelmeyer et al., 2003; Caudle et al., 2013). Hopefully this article will ground future discussions about the role STMs can play in how we think about river management, and demonstrate that qualitative and quantitative modes of assessment and analysis can be equally useful for interpreting fluvial environments.

- Chapter 3, “Boxing Daze – Using State-and-Transition Models to Narrate the Evolution of Socio-Biophysical Landscapes” (forthcoming in *Progress in Physical Geography*)

This chapter wields a more expansive view, arguing that STMs can be a critical tool for performing integrative studies of landscapes shaped by social and biophysical processes. A primary impetus of this paper is to engage with the still-nascent field of critical physical geography (CPG) (Lave et al., 2013). CPG proposes to fill a niche left vacant by the unfulfilled promise of political ecology by encouraging research that combines biophysical field science with a critical examination of social relations underpinning landscape dynamics – unfulfilled because when it first emerged on the scene political ecology claimed to fuse science and sociopolitical analysis, although over time the science part gradually faded away (Walker, 2005; Robbins, 2012; see Blaikie and Brookfield, 1987). Geography has traditionally been viewed as a holistic science

(Archer, 1995), and as such there was considerable hope that political ecology would lead to greater collaboration among human and physical geographers. Of course, this dream never came to pass, and there is still anxiety among researchers over the vast epistemological and theoretical distance that separate opposite ends of the disciplinary spectrum. Whether or not CPG can alleviate disciplinary tensions remains unclear. This chapter suggests that STMs offer a unifying framework for doing more interdisciplinary work, thus contributing to the potential and partial resolution of ongoing debates.

Most of this chapter is conceptual. And its organizing premise is simple – both human and physical geographers are interested in transitions and the underlying dynamics that cause transformations in landscapes, whether biophysical or social landscapes. Beginning with this assumption, I map out the common epistemological heritage that various strands of biophysical science and human geography share and show that there is a precedent for interdisciplinary work. Although it would be unreasonable to expect human and physical geographers to ever share identical methodological toolkits, STMs as a framework open up space for a conversation that can address the concerns of each intra-disciplinary camp. My journey is as follows. I begin by revisiting the application of STMs in rangeland ecology and the extension of state-transition thinking in fluvial geomorphology and other field sciences such as riparian ecology, geomorphology, and restoration ecology. From there, I return to some founding texts of political ecology, specifically Blaikie and Brookfield's *Land Degradation and Society* (1987; see also Wisner et al., 2004 Robbins and Bishop, 2012). Along with Blaikie's work on the political economy of soil erosion and AIDS in Africa (1985; 1992), this book sketches out the chains-of-explanation (CoE) approach to conceptualize the drivers of socio-ecological destruction. Like STMs, CoE's rely on box-and-arrow diagrams to trace out and summarize relationships that lead to environmental deterioration and imperil human livelihoods. As such, the epistemological and heuristic affinities between STMs and CoEs suggest a path forward. From here, I develop an STM framework for socio-biophysical landscapes that is attentive to the social, political, economic, and most importantly, biophysical dynamics that generate particular socio-biophysical landscape states. This framework views landscape states as the product of networked biophysical form-process relations and socioeconomic and power relations. A state consists of a form-process network that is durable, but which is susceptible to a state transition if some kind of social or biophysical disturbance disrupts and remakes these relations. Individual and institutional actors use narratives to frame their understanding of landscapes. Narratives in turn guide their actions, and have the capacity to influence whether a state transition takes place. In developing this framework, my point is not to enforce a particular dogma for how we read and interpret landscapes. And as I note in this chapter it is crucial to not read what it means to be "critical" too narrowly – that is, equating it with a simple, uncritical analysis of power relations (e.g. Blomley, 2006). Critical advances occur in the biophysical sciences all the time, so it is important to recognize where social analysis is appropriate and where it does not meaningfully contribute to our knowledge of landscapes. Being able to tell the difference is the definition of being critical.

- Chapter 4, "Landscape Memory in a Time of Amnesia – Recovering the Clark Fork River at Milltown, Montana" (Submitted to *Physical Geography*)

This chapter turns to questions surrounding the Clark Fork River restoration. It briefly sketches the history of Milltown Dam and the circumstances leading up to its removal in 2008. However, the primary focus of this paper is on the debates that arose surrounding the appropriateness of the channel design selected by the State of Montana. Many geomorphologists expressed reservations about the predominantly single-threaded, meandering planform constructed through much of newly developed floodplain (Kondolf, 2006; Woelfle-Erskine et al., 2012). Many of these arguments are nestled within broader conversations about river restoration that have been ongoing since the 1980s (Simon et al., 2007 Lave, 2010, 2012) and the issue of natural channel design (NCD). I remain agnostic on the meta-philosophical debates that encircle NCD. There are some contexts in which NCD may be useful and others where it is just does not work. But it is worth pointing out that restoration projects, even if they do not rely on an NCD template would likely incorporate techniques associated with it. This speaks more to the finite number of ways to restore or rebuild channels than to anything else. The question I answer in this chapter is whether the as-built design – what I term a hybrid meandering planform – falls within the historical range of variability for the river (Wohl, 2011). If so, it would stand as a defensible hypothesis for what kind of river could exist in this setting. There is no straightforward answer to this question. Strangely, despite being a well-photographed area during the late-19th and early-20th centuries, no image exists looking upstream of the Clark Fork–Blackfoot River confluence before dam construction. Lacking this definitive evidence, I turn to other sources, including General Land Office (GLO) surveys and maps, as well as mapping the location of relic tree stumps on the new floodplain surface, to demonstrate that a hybrid meandering planform does serve as a justifiable hypothesis for what river state is compatible with the valley's morphological characteristics and flux boundary conditions (Brierley and Fryirs, 2005; Fryirs et al., 2013). These lines of evidence show that a hybrid meandering planform likely existed near the confluence before dam construction. Combing sedimentological evidence with historical floodplain mapping suggests that the pre-dam channel ran parallel to present-day Interstate 90. To claim that a hybrid planform is a workable hypothesis is not to say the river must necessarily occupy that state or that it will not transition to another form down the road. It is to say this is one *possible state* among others that could exist; the materialization of particular states hinges on the hydrogeomorphic fluxes, disturbance patterns, and chance events that influence the area.

To bring the story into the present, I discuss the river's contemporary adjustments since flow was restored to the main channel in late 2010. Blending these observations with the historical reconstructions, I develop a qualitative STM that describes possible adjustment trajectories as well as the processes likely to initiate state transitions. States refer to particular river styles (*sensu* Brierley and Fryirs, 2000, 2005). The STM identifies four potential river states. This is not to argue that more states are beyond the realm of possibility. These are the four most probable states based on the short-term adjustments observed in nearby reaches.

Developing an STM, whether it is for a river that had not undergone rehabilitation or to help design a recovery plan, presents environmental managers with a way to pragmatically assess what management interventions are best suited to achieving a project's objectives. Rather than associating restoration success with a single outcome, STMs acknowledge there are multiple ways to achieve geomorphically beneficial outcomes (e.g., enhancing the morphological resiliency of rivers). Objectives and management strategies should be improvised and reworked as broader-scale phenomena (e.g. climate change, development within a watershed) apply pressure to the river segments for which there is management oversight. The Clark Fork River restoration teaches us that how we imagine rivers is important, but I think equally critical is adopting a more circumspect and modest view of river restoration – or rejuvenation or renewal. Restoration is a contested term, and while it is not my preferred one, I recognize that it is so entrenched within the literature that I am fighting an uphill battle to do away with it completely. The project attempted to make a segment of the river anew – recreating an exact replica of the past was impossible. But even if we continue to employ “restoration” as a catch-all for projects of this type, we should be careful in our application of the term. In the strictest sense of the word, any restoration is an impossible dream, whether it involves a river or a degraded forest landscape. Maybe it would be more honest to say that restoration is about modestly improving damaged and decaying environmental resources in a manner that will increase their functionality and resiliency well into the future. Restoration, like any scientific or artistic endeavor, is ongoing, and the goal of a restoration project will evolve as the landscape evolves. Project goals like landscapes and evolutionary trajectories are unfixed.

Most restoration projects are wedded to an engineering timescale of 50-100 years. But I think it is valuable to adopt a much longer perspective on questions of landscape renewal. The Clark Fork River will continue to flow – in all likelihood – for hundreds or maybe thousands of years. As the project manager who oversaw the construction and maintenance of the river is fond of telling me, in the long run the river is going to do what it wants to do. Restoring a river is about taking an educated guess on what kind of landscape design has the best chance of realizing defined social and environmental outcomes.

- Chapter 5, “Nature’s Complex Flume – Adjustment Trajectories of Secondary Channels on a Reconstructed Floodplain, Clark Fork River, Montana” (submitted to *Earth Surface Processes and Landforms*)

This chapter draws from the concepts and observations discussed in Chapters 2-4 as well as additional empirical work to develop STMs for secondary channel features incorporated into the renewed floodplain design. There is considerable morphological diversity among the secondary channels; part of this stems from intentional design choices, however, some variability is attributable to the distribution of floodplain vegetation and disturbance. Again, the 2011 flood played a critical role as it opened up new (or emergent) secondary channels at different locations throughout the lower rehabilitation zone. A consequence of the morphological variation is that evolution trajectories vary from channel-to-channel. While I develop a generalized STM that applies to the entire floodplain, there are spatial contingencies that make it important for project managers to evaluate channels on an individual basis. Morphological variability has driven spatially complex patterns of adjustment – especially for channels that are strongly influenced by riparian vegetation (primarily willow and cottonwood). This chapter applies state-transition thinking to the question of channel evolution. There is evidence of the secondary channels undergoing complex response (e.g., Schumm, 1973), with adjustment pathways dictated by the interactions of bio-hydrogeomorphic fluxes and the landscape. To render this complexity legible, and to develop a strategy river managers can use to develop polices, I combine STMs and a diagnostic approach to river assessment (Montgomery and MacDonald 2002). The idea here is that a diagnostic framework is compatible with STMs in that it asks us to partition a landscape into different states and anticipate the possible consequences of internal and external forcings. Diagnostic evaluations can be used to characterize channel evolution under multiple disturbance regimes.

The title of this chapter stems from the multiple forms of channel evolution that have been observed – ranging from the development of a micro-channel following the sequence of adjustments predicted by classic CEMs to channels incising into well-vegetated and grassy areas of floodplain to vegetation-influenced adjustments that produce braided- or wandering-like patterns. STMs, I propose are better equipped to cope with, document, and make sense of the cross-scale hydrogeomorphic interactions that shape landscape evolution – the fates of smaller scale features (secondary channels) are intimately tied to the fate of the main channel. Although the STM certainly stands as an intellectual contribution, the central lesson of this paper is that we need to be aware of the multiple forms of channel adjustment that occur in close proximity to one another.

Learning to see these complexities does not necessarily upend our expectations, but it unsettles them and in doing so implores us to reflect on the fact that the emergence of multiple states stems from the spatially tessellated interactions of differently adjusting processes and forms, which are influenced by very localized interactions between water, sediment dynamics, and plants, as well as interactions that take place at the catchment scale. Stated thusly, this observation is not groundbreaking, however, recalibrating geomorphologists' vision so that it does not miss subtle, novel variations in channel evolution is valuable for enriching our approaches to river management and restoration projects. Taken together, this dissertation is as much about questioning the realities and complexities our theories and heuristics let us see as it is about the Clark Fork River. Shifting our perceptual fields can let us tell new stories about socio-biophysical landscapes, and lets us imagine new futures – and histories – previously closed to us.

Chapter 2 – Channels in the Making: An Appraisal of Channel Evolution Models

2.1 Introduction

Developing effective management plans for alluvial rivers calls for having a detailed understanding of the biophysical factors that influence channel morphology. This task is fraught because even though hydrogeomorphic fluxes predominantly shape channel form, multiple factors influence the magnitude of water and sediment flows, riparian vegetation assemblage, and other variables that shape rivers' planform, resilience, and complexity. Management cannot be based on contemporary form-process relationships alone; it must also consider the history of past disturbances, the evolution of these relationships, and the consequences of ongoing and future climate change (e.g., Nijssen et al., 2001; Brierley, 2010). High-magnitude meteorological disturbances have increased over the past decade, and are expected to continue their upward trend as climate change accelerates (Coumou and Rahmstorf, 2012; WMO, 2013, Wuebbels et al., 2014). Disturbances, such as extreme flooding, have the potential to rapidly alter channel structure and require swift management response. Climate change also promises to gradually transform the flux boundary conditions (Brierley and Fryirs, 2005) rivers operate under. Taken collectively, increasing climatological variability and changing boundary conditions promise to significantly impact how rivers function. This is particularly true for riverine landscapes in areas likely to see the gravest consequences of climate change, like those located in arid and semi-arid regions, which are vulnerable to precipitous alterations in streamflows because of altered seasonal hydrological fluxes (Perry et al. 2012; see also Tooth, 2000). Pragmaticallys managing rivers is a fraught project and demands a set of tools that let managers plan for different climatological scenarios. Developing new strategies to understand the evolutionary trajectory of rivers is a main concern of fluvial geomorphologists. Channel evolution models (CEMs) have frequently been used to conceptualize the dynamic evolutionary tendencies of alluvial rivers. Because of their capacity to link together insights across multiple research fields (e.g. fluvial geomorphology, ecology, and hydrology) CEMs will likely be a key resource for predicting channel responses to hydrogeomorphic as well as climate forcings, providing insights that will improve adaptive management practices for river landscapes across diverse settings.

Developed and refined over the past 30 years, CEMs synthesize quantitative data and qualitative observations of river morphology to predict the sequence of channel adjustments that occur following a disturbance (Schumm et al. 1984; Simon and Hupp 1986; Hupp and Simon 1991; Simon 1989a, b, 1992, 1995; Simon and Rinaldi 2006). The initial batch of CEMs – hereafter, referred to as classic CEMs – focused on how rivers adjusted to channelization. But the geographical extent of this initial research was limited, with most rivers situated in Mississippi and western Tennessee. Classic CEMs resemble linear models of ecological succession in their representation of channel evolution, (e.g., McCook 1994; Pickett et al., 2008). Following disturbance they propose that channels respond in a predictable, sequential manner, moving from a pre-disturbance state characterized by relative stability, into a disturbance phase marked by form-process adjustments, and finally toward a new state of pseudo-equilibrium once they complete their response (Phillips, 2012). The assumptions surrounding channel evolution embedded in classic CEMs have been validated empirically. However, in riverine landscapes that exhibit greater biogeomorphic complexity than the environments they were originally keyed to, channel evolution can follow multiple pathways (Makaske et al., 2002; Leyland and Darby, 2008; Hawley et al., 2012; Toone et al., 2012). Because rivers are located in settings that have been exposed to unique combinations of geomorphic, ecological, and social disturbances, when a newly imposed disturbance arises, antecedent conditions affect response (Brierley, 2010). As such, place-based contingencies affect channel evolution. Linear CEMs can overlook the historical and spatial contingencies that play an essential role in shaping channel evolution (cf. Schumm, 1991, 2005; Phillips, 2006, 2007).

This article synthesizes previous work on CEMs and introduces frameworks better equipped to account for the contingencies that affect channel adjustments. To lay the conceptual foundations of CEMs, it begins with a review of the model pioneered by Schumm et al. (1984), which was later elaborated in fuller detail by Hupp, Simon, and Rinaldi through numerous articles. For many years CEMs dealt exclusively with the effects of channelization and incision. In the early-2000s, classic CEMs were applied to a new domain – dam removal. Studies have also revealed that classic CEMs' predictions about channel adjustment are useful for understanding channel response following dam removal (Doyle et al., 2002, 2003; Pizzuto, 2002). After this, I discuss the advent of multi-pathway CEMs. These sprang from the recognition that rivers sometimes do not follow a linear, deterministic series of adjustments following disturbance, but rather move along multiple evolutionary pathways. Adjustment pathways hinge upon setup conditions, disturbance history, and other contingent variables. Multi-pathway CEMs have set the stage for the most recent developments in channel evolution modeling, including the use of stream evolution diagrams (Brierley and Fryirs, 2005; Fryirs et al., 2012) and state-and-transition models (STMs) (e.g. Xu, 1996; Gurnell and Petts, 2002; Gurnell et al., 2012; Phillips, 2012). This paper argues that STMs offer an helpful framework to document, narrate, and predict channel evolution because they can accommodate linear forms of evolution, complex adjustment patterns, and the effects of human interventions in fluvial environments. Relying on visual techniques and intuitive box-and-arrow diagrams, STMs can improve river management through an integrated approach to the co-evolution of river channels and in-channel and riparian vegetation. The mix of qualitative and quantitative data used to construct STMs may vary according to management needs. And while classic CEMs have limitations, this is not meant to invalidate them, rather it is to situate them as an epistemic foundation that has laid the groundwork to identify, predict, and narrate more complex forms of channel adjustment.

2.2 An Overview of Classic Channel Evolution Models

Alluvial rivers are dynamic landscape features that are in a constant state of flux. However, the spatial and temporal periods over which morphological change occurs varies. CEMs are concerned with the processes that systematically reshape streams or rivers over short timeframes – usually fewer than 100 years – by documenting the spatial and temporal variability of channel adjustments. Because they work from a large-scale view of the river, CEMs focus on qualitative state transitions, not ephemeral process changes such as localized scour. A qualitative change in landscape state refers to channel planform and geometry undergoing significant landscape modifications (e.g., progressive channel widening through mass bank failures, channel narrowing due to the encroachment of riparian vegetation). From a process perspective, CEMs identify processes driving morphological changes such as aggradation, degradation, and fluctuations in stream power (Simon 1995).

Classic CEMs partition channel evolution into a set of discrete stages, with each state being defined by characteristic processes and forms. One way to conceptualize this is that at any moment a river channel is distinguished by two interacting states – a formal state and a process regime. A formal state refers to the planform and morphology of a channel[4], whereas process regimes encompass the dominant actions that work to reshape a channel's formal composition (e.g. degradation). Reframing channel evolution in terms of formal states and process regimes lets researchers neatly catalog all the interactions that influence morphological adjustments. Another advantage of using this terminology is that it improves our ability to frame the magnitude and variety of channel evolution occurring. Two types of state transition are possible. First, when river metamorphosis takes place (as when a meandering planform transitions to a braided planform), a regime shift occurs (e.g. Bestelmeyer et al., 2015). Second, if channel adjustments leave a river's antecedent form largely intact – albeit with significant adjustments to the morphology, spatial structure, or channel geometry – a within-state transition takes place. Both are examples of state changes – however, regime shifts are not easily reversed and lead to significant landscape transformations. Establishing terminological standards will produce clearer narratives of river channel evolution. A state change can manifest in a variety of ways and does not necessarily entail wholesale planform shifts.

Briefly revisiting the physical principles CEMs build from clarifies why transitions from one evolutionary stage to another occur. Nanson and Huang (2008) characterized alluvial rivers as directional iterative systems that undergo repetitive changes over time. Directional iterative systems "are those where the change in a particular direction is more probable than changes in other directions" (Nanson and Huang, 2008: 937). The underlying premise of CEMs, is that morphological adjustments following a disturbance reduce flow velocity for a specific discharge, minimize work, and maximize energy dissipation (cf. Simon, 1992, 1995). This results in a characteristic sequence of adjustments. Invariant physical laws are a key driver of adjustments in

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[4] Inclusive of channel geometry.

fluvial settings, however, these forcings occur in particular settings. As such, the way in which channel evolution unfolds is impacted by place-based contingencies that influence the direction, speed, and magnitude of channel adjustments. Schumm et al.'s (1984) CEM included five stages, however, the rest of this section discusses the six-stage model later refined by Simon and Hupp (1986, 1987, 1992; see also Simon, 1989a,b; 1992; 1995; Harvey and Watson, 1986; Hupp, 1992; Hupp and Simon, 1991; Simon and Rinaldi, 2000, 2006; Gellis et al., 1991; Schumm et al., 1996; Watson et al., 2002). This model is probably the one most frequently cited today (see Thorne, 1999 for a discussion of what distinguishes the five- and six- stage models). Classic CEMs assume that disturbance introduces excess stream power or flow energy "relative to the load of hydraulically controlled sediment (sands and gravels) delivered from upstream" (Simon and Rinaldi 2006, p. 368). When a channel passes from one evolutionary stage to another, a geomorphic threshold is crossed (e.g. Bull 1979, 1991; Church 2002). To detect these transitions, channel evolution studies rely on data on morphology, fluvial processes, and vegetation. What follows is a summary of the six-stage model; particular attention is placed on the form and process states that govern evolution during each stage.

Figure 2.1 depicts the progression of channel evolution on an incising channel. Initially, the channel is unmodified and unexposed to disturbance. While the formal state varies by setting, the dominant processes regimes are typically aggradation, slight bank erosion, and lateral migration. Moving into Stage II, a disturbance occurs. In Simon and Hupp's (1987) model the disturbance is channelization. However, there are other types of disturbance that can produce orderly and systematic evolution, such as dam removal, urbanization, or significant floods. Usually the upstream-most location of channelization work is described as the area of maximum disturbance. Channelization itself radically alters channel form by straightening meanders, steepening banks, and increasing the energy slope, which produces localized increases in stream power. Following channelization an upstream-migrating knickpoint develops, which serves as an important marker of channel evolution (Simon and Rinaldi 2006). Knickpoints are important features to follow because CEMs rely on a space-for-time substitution to determine how channel adjustments proceed in upstream and downstream directions. Tracking a knickpoint's movement upstream indicates what evolutionary stage a channel reach is at based on: 1) knickpoint position, 2) channel geometry, and 3) the dominant processes acting on that reach. Channelization leads to total vegetation loss within the channel, disconnecting the channel from its historical floodplain. This disturbance creates the setup conditions influencing subsequent channel adjustments.

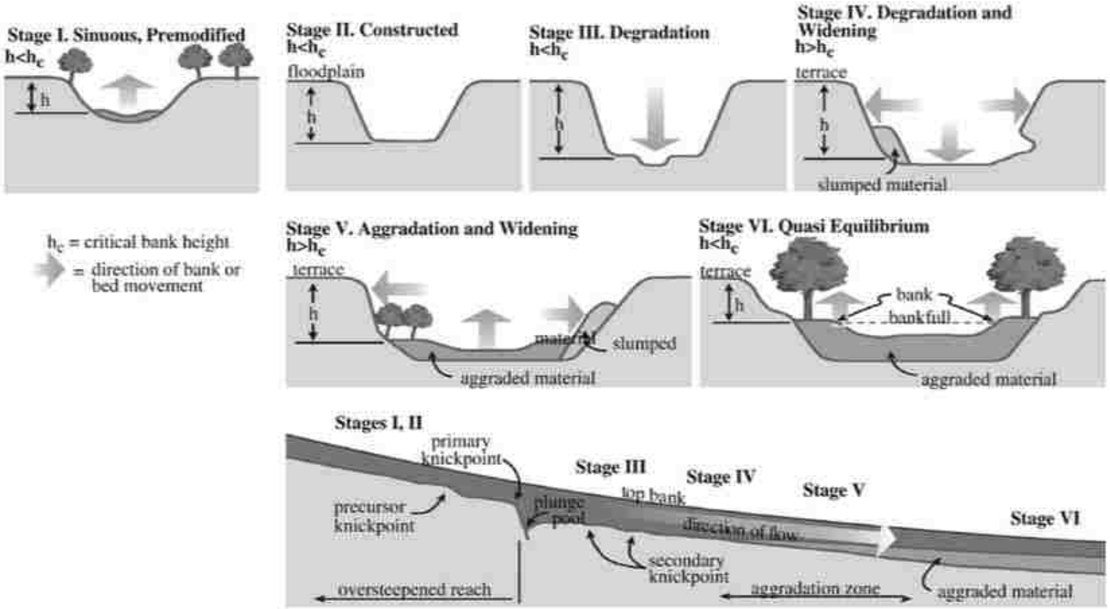

Figure 2.1 From Simon and Rinaldi (2006). A visual representation of the adjustment pathways proposed by classic CEMs. It illustrates reach-specific effects as well as a longitudinal profile of evolution.

Dramatic form and process transitions unfold as a channel enters Stage III. Downcutting instigates bed erosion, which in turn creates an incised channel. Meanwhile, as the knickpoint retreats upstream sediment yields increase. This sediment is transported into lower reaches. Widespread degradation flattens channel gradients and reduces the amount of energy available for a given discharge – effectively lowering stream power (Simon and Rinaldi 2006). Stage IV is a threshold stage during which erosion persists, contributing to the fluvial undercutting of banks, steepening them to the point of failure. As banks fail, mass wasting ensues, introducing large volumes of sediment into the channel. Sediment from bank failures moves downstream, enhancing aggradation and producing further declines in energy conditions. As a channel transitions to Stage V mass wasting tapers, which promotes channel widening. By this time, flattened channels are unable to transport increased sediment loads, which creates depositional surfaces adjacent to the banks. These surfaces promote vegetation recruitment (Hupp and Simon 1991). As vegetation colonizes new surfaces, channel roughness increases. The result is surfaces that are able to capture and retain sediment, reinforcing depositional trends. Emergent vegetation plays a key role in stabilizing banks, demonstrating that the ecological-geomorphic components of the landscape co-evolve over short-medium temporal scales (cf. Corenblit et al., 2010, Gurnell, 2012, 2014). As the channel pushes into Stage VI, it completes its response to the imposed disturbance. Even so, adjustments will continue as vegetation becomes more densely established, new bar features develop, and lateral migration slowly recommences. At this point adjustments switch from being primarily vertical in nature (e.g. bed-level adjustments) to being inflected laterally (e.g. meandering). While the classic CEM suggests the end of evolution brings a new permanence to channel form, this stability has been variously characterized as quasi-equilibrium and dynamic equilibrium, although pseudo-equilibrium (Phillips, 2012) is a more accurate description because it conveys the sense that no period of stability is permanent when viewed within the broader context of landscape evolution. Thorne (1999) notes, adjustments do not stop with Stage VI, and proposes a Stage VII, which is characterized by the emergence of cross-sectional asymmetry.

The assumptions of classic CEMs do not hold true across all fluvial environments (Simon and Rinaldi, 2006). Simon (1992) described channel evolution in the Toutle River after the eruption of Mt. Saint Helens in 1982. Because the Toutle River is dominated by coarse-grained material, energy dissipation took place mainly via lateral channel adjustments, such as channel widening. This is because coarser bed materials are more resistant to incision and other vertical adjustments. Another example of streams not following the classic CEM progression is in small tributaries of the Southeastern United States. Davis (2007, 2009) found that homogenous bank materials promote simultaneous widening and incision. Rhoads and Urban (1997; Urban and Rhoads 2003) demonstrated that channelization did not produce significant bed-level changes in the Embarras River, Illinois due to a combination of low stream power and extremely resistant bed materials. Landwehr and Rhoads (2003) observed that the Spoon River in Illinois violated the assumptions of classic CEMs following its channelization. Rather than incising or adjusting its gradient, aggradation and bar development occurred alongside the emergence of a stable inset channel. Low values of stream power contributed, which prevented erosion and led to widespread deposition instead. These studies are consequential because they illustrate the limitations of classic CEMs in places such as the U.S. Midwest and Southeast, the settings in which CEMs were originally devised. This speaks to the effects local contingencies have on channel adjustment, and suggests that evolution is path-dependent (Phillips 2006). While less successful in these settings, classic CEMs have proven useful for other settings.

2.3 Dam Removal

Over the past 10 years classic CEMs have found a new outlet for their application – channel adjustment trajectories following dam removal (Doyle et al., 2002, 2003; Pizzuto, 2002). Although these models closely mirror classic CEMs, there are a few notable differences. Doyle et al. (2002, 2003) proposed a six-stage model to describe how channels respond to dam removal (Figure 2.2). Stages A and B correspond to Stages I and II in the Simon and Hupp (1987) model, with Stage A representing a pre-disturbance state and Stage B the disturbance that accompanies dam removal. The removal of a dam instantaneously lowers a channel's local base level, which controls later phases of adjustment. As evolution progresses into Stage C, channels degrade through incision into sediments that previously occupied the reservoir. Incision follows an upstream-migrating knickpoint. As incision persists, water is funneled into a narrow, steep-banked channel. This increases stream power and accelerates the movement of sediments downstream. If banks exceed critical angles and heights, mass wasting occurs, introducing significant quantities of sediment to the channel as long as stream power remains sufficiently high, these materials are moved downstream. As evolution slows during Stage E, the sediment that originated in upstream reaches prompts aggradation. Sediment deposition stems from vertical and lateral adjustments that reduce the local energy slope – coarse sediments are typically deposited while fine-grained sediments are flushed downstream. As the channel finishes its response to dam removal it enters Stage F, which ushers in relative stability. Groundwater levels typically lower during this period and vegetation recruitment accelerates.

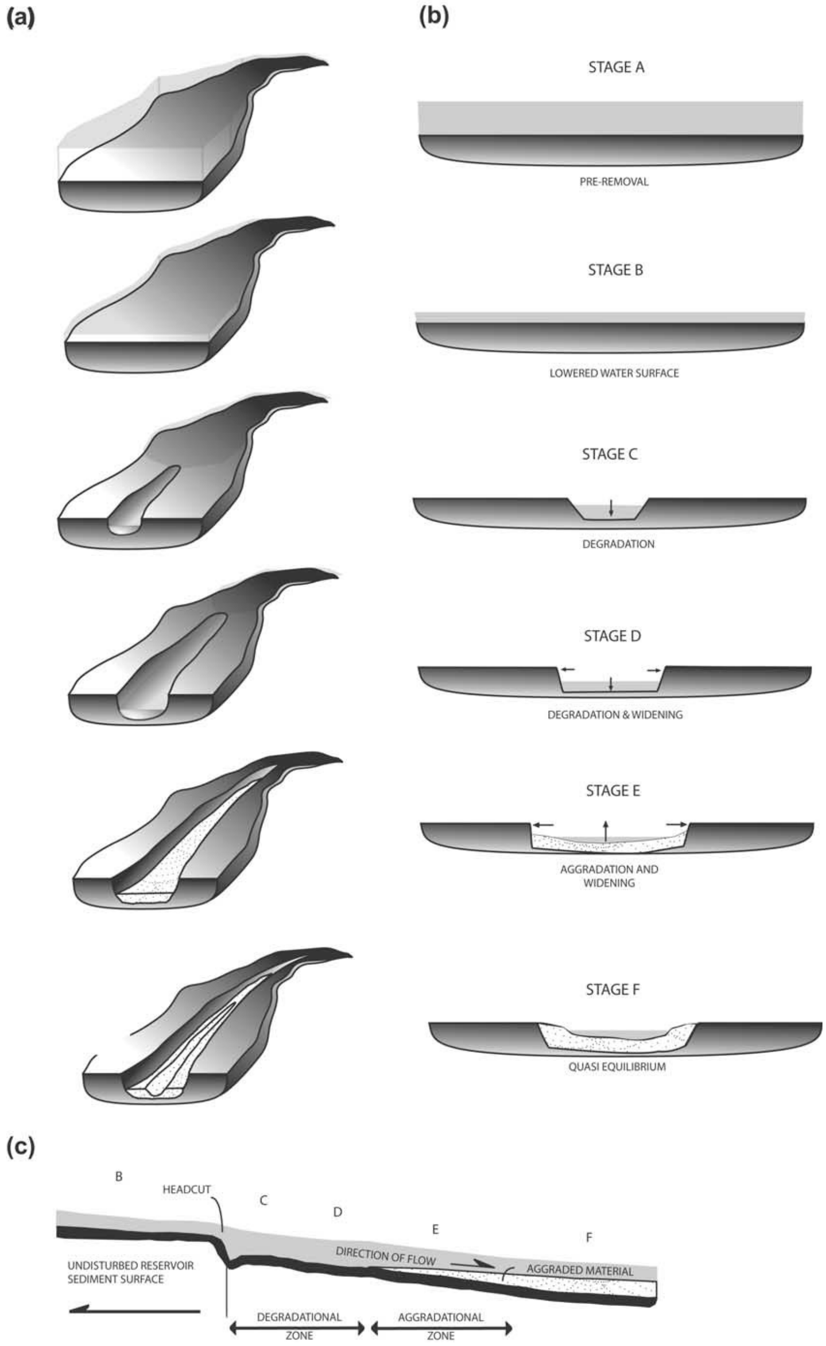

Figure 2.2. From Doyle et al. (2003). Stages of channel evolution that unfolds following the removal of a low-head dam. The focus is on upstream channel formation into former reservoir sediment.

A number of studies have lent empirical support to this model (e.g,. Burroughs et al., 2009; Cannatelli et al., 2004; Cheng and Granata, 2007; Draut et al., 2011; Evans, 2007; MacBroom, 2009; Major et al. 2008; Major et al., 2012; Neave et al., 2009; Rumschlag and Peck, 2007; Sawaske and Freyberg, 2012; Wildman and MacBroom, 2005). Not all channel responses will conform perfectly to Doyle et al.'s (2003) model because local environmental conditions, such as the amount and caliber of reservoir sediment and the method of dam removal, vary. Channel responses can also be influenced by sediment influxes, local geology, and the large woody debris located in the channel (Draut et al. 2011). Antecedent channel geometry can also influence adjustment pathways (Wildman and MacBroom 2005). Evans (2007) revised Doyle et al.'s (2003) CEM based on observed channel responses following the failure of the IVEX Dam on the Chagrin River, Ohio. Channel evolution largely conformed to the morphological changes predicted by Doyle et al. (2003), however it differed in several key respects. First, longitudinal scouring occurred in reservoir sediments prior to failure. Second, Evans's (2007) amended CEM includes a modified Stage B to accommodate the emergence of an early-breach drainage network. It makes slight changes to Stage E as well; the revised model suggests extensive lateral migration can accompany vertical bed-level adjustments, leading to the formation of new terraces. For most dam removals, the drop in local base level is what principally controls channel response. However, if dam removal is followed by extensive remediation and channel reconstruction – as is the case with the Clark Fork River – the subsequent adjustments are unlikely to be influenced by falls in local base level (see Woelfle-Erskine et al., 2012). Dam removal studies indicate that channel evolution does not follow a one-way street. Channels potentially accommodate multiple modes of adjustment. This raises the challenge of revising current models to account for forms of channel evolution that are spatially variable or proceed along multiple pathways. Classic CEMs are not equipped to deal with complex responses and the contingencies that affect morphological evolution, but new modeling approaches have been developed to better reflect contingencies.

2.4 Multi-Pathway Channel Evolution Models – Recognizing the Contingency of Channel Adjustment

A number of researchers have pointed out classic CEMs are limited in their reach. Hawley et al. (2012:3) observed that classic CEMs "do not adequately represent the diverse stream responses and alternative channel states often observed in semi-arid regions." Taking a slightly different approach, Cluer and Thorne (2014) suggested that classic CEMs have naturalized single-threaded channels as exemplars of how dynamically stable rivers should look and behave, yielding inconsistent results for river restoration projects that use them as a starting point. They extended this argument by noting the failure of classic CEMs to incorporate complex disturbance histories, which has distorted our understanding of what a natural river is supposed to look like. Building off of this critique, linear CEMs, it appears, are poorly suited to conceptualize the subtleties of channel adjustments in high-energy or spatially complex fluvial environments. In response to these limitations, a new batch of multi-pathway CEMs has emerged. These models recognize that most rivers adjust not just in response to a discrete event (e.g., channelization) that is isolated in time. Rather, fluvial landscapes are reshaped through the imprint of multiple disturbances that unfold over multiple spatial and temporal scales. Channel response hinges on the landscape context and environmental history a river is situated in as well as the sequence of disturbance events a river is exposed to throughout time (e.g. Phillips, 2006; Fryirs and Brierley, 2013).

Multi-pathway CEMs are equipped to describe the range of adjustments on river landscapes that do not evolve linearly. Much of this research has focused on gravel-bed rivers, comparable to the Clark Fork. Rinaldi (2003) and Surian and Rinaldi (2004, 2006) demonstrated that classic CEMs are unsuited for documenting the evolutionary patterns of Italian rivers that emerged in the aftermath of large-scale river engineering projects. Variable response stemmed from the dramatic morphological disparities among Italy’s rivers, where, in addition to single-threaded rivers, braided and wandering landscapes are common. Although single-threaded rivers responded to engineering primarily through incision, braided rivers have undergone mostly lateral adjustments (e.g., channel narrowing). As such, planform and sediment are crucial determinants of channel adjustment. While Schumm et al. (1996) applied a modified version of the classic CEM to channel response in anastomosing rivers, other studies indicate that multi-pathway models are necessary to describe the general dynamics of channel evolution explicitly or implicitly (e.g. Cannatelli et al., 2012; Dean and Schmidt, 2009; Elliott et al., 1999; Gurnell et al., 2001; Julian et al., 2012; Makaske et al., 2002; Toone et al., 2014; Zilani & Surian, 2012). Zilani and Surian (2012) argued that channel adjustments may occur in a spatially discontinuous manner. That is, there may not be an orderly spatial migration in channel evolution that enables the use of space-for-time substitution. Toone et al. (2014)

demonstrated the presence of complex response on rivers where there is inter-reach variability in boundary conditions, especially where transitions from confined to partly- or unconfined segments occur. A brief example illustrates a multi-pathway CEM accommodates the contingencies that influence channel adjustment.

Makaske et al. (2002) developed a CEM for a portion of the Upper Columbia River in southeastern British Columbia, a highly dynamic anastomosing river landscape in which avulsions and channel abandonment are common. Anastomosing rivers are intricately complex landscapes that are made up of at least two interconnected channels that enclose floodbasins (Makaske, 2001). Because of channel divergence and complex bar topologies, a linear CEM would not be able to capture the range of evolutionary pathways available to an anastomosing river. Makaske et al.'s (2002) CEM (Figure 2.3) is a four-stage model that illustrates under what conditions divergent evolution is possible. Stage 1 begins with the development of a channel on a crevasse splay. Over time, scour deepens the channel, while the entrainment of splay sediments contributes to levee deposition. As the channel passes into Stage 2, banks oversteepen due to continued bank-toe and bed scour, widening the channel. There are similarities between classic CEMs and this model. That is, the channel responds vertically before adjusting laterally. Following Stage 2 multiple development trajectories emerge. At Stage 3 adjustment is contingent upon in-channel sedimentation. When there is an insufficient supply of bedload sediment, channels infill via lateral processes (C1), however, if there is an abundant supply of coarse bedload the channel will experience vertical infilling (C2). Stage 4 represents a moment of temporary stability, which is impermanent in anastomosing rivers because of frequent flooding and avulsive activity. During this period channel abandonment takes place, and newly deposited sediment promotes vegetation recruitment. The main control on future adjustments is the proximity of abandoned channels to active channels. Under Scenario D1, the abandoned channel remains well-defined but located at a considerable distance from active channels, which lowers sediment availability. Thus channels fill with sediment very slowly and levees are indistinct. With scenario D2 the deserted channel lies near active channels, generating a steady supply of sediment and leading to brisk infilling. Because of this the channel becomes integrated into the levee complex surrounding active channels.

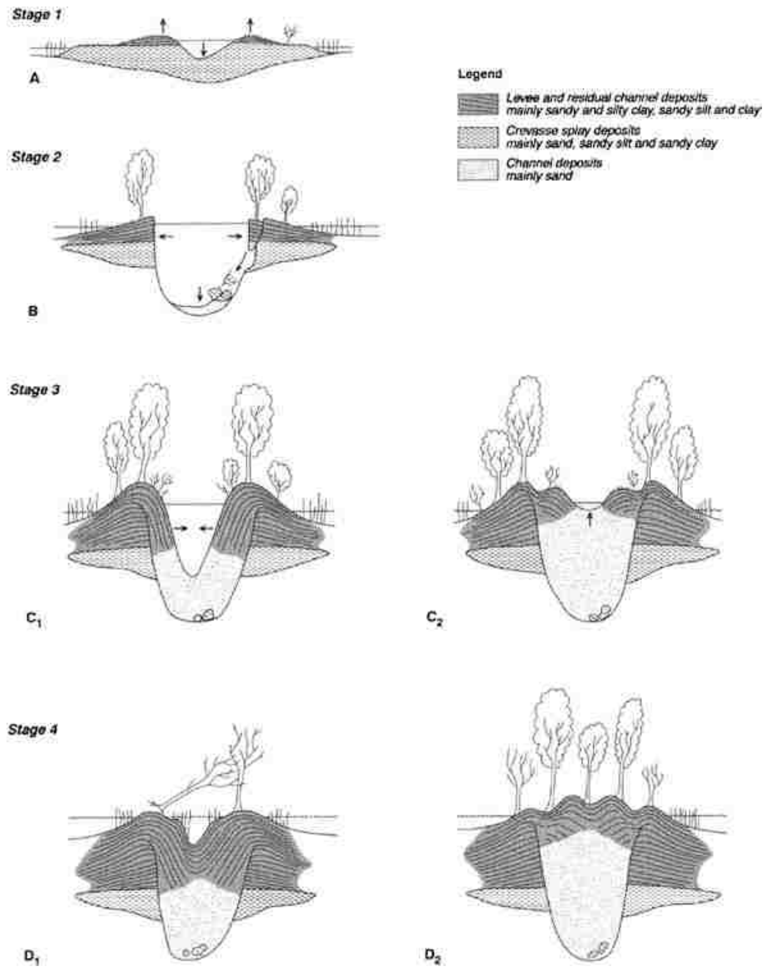

Figure 2.3. The multiple evolutionary pathways of anastomosing rivers (from Makaske et al., 2002).

The evolution of anastomosing rivers offers a good example of why sometimes a different modeling approach is needed. While the Makaske et al. (2002) CEM shares similarities with the classic versions (e.g., the sequence of process states is such that erosion promotes fluvial undercutting, which leads to bank failure and channel widening), a number of contingencies affect the evolution of individual channels. Where a channel is situated on the floodplain, its relationship to other channels (themselves at different evolutionary stages), and sediment supply significantly influence the landscape's evolution. Although this is one example, multi-pathway CEMs have been used in a variety of settings, and by demonstrating that channel evolution is not a monotonic deterministic process, they offer a good framework to explore different disturbance scenarios. For example, Hawley et al. (2012) developed a multi-pathway CEM for the multiple modes of adjustment that occur in rivers affected by urbanization.

Multi-pathway CEMs serve as a bridge between classic approaches to channel evolution modeling and emergent methods that adopt a state-and-transition framework.

2.5 Using State-and-Transition Models to Understand Channel Evolution

Multi-pathway CEMs have given researchers a framework to model channel adjustments when multiple outcomes are possible; however, they lack flexibility. Typically they are ideal for working with a limited number of disturbance scenarios. For some rivers this may be entirely reasonable. However, in landscapes with greater river complexity – especially those that exhibit a variety of planform states – a different approach could be useful. The implementation of STMs offers a promising framework to examine channel evolution in a spatially explicit manner. Initially STMs were developed after rangeland ecologists documented that vegetation succession in semi-arid and arid landscapes failed to conform to the expectations of classic successional models in some instances (e.g., Clements, 1899; Dyksterhuis, 1949). STMs do not exclude the possibility of linear succession entirely. They instead demonstrate that landscapes may experience abrupt state transitions that fundamentally alter the composition, spatial structure, and ecological functionality of landscapes (e.g., Bestelmeyer et al., 2003, 2009, 2011, 2015; Stringham et al,. 2001). Baker and Walford (1995:321) nicely summarized the logic and purpose of STMs – they do "not predict that a single state may develop or stabilize on a particular site; [they offer] instead a catalog of possible states and the conditions required for transition between the states." Once completed, STMs consist of box-and-arrow diagrams, which are underwritten by detailed fieldwork and supplemented by narrative descriptions of states and the drivers of transitions. Organizationally, STMs provide benefits that can aid researchers in thinking about the evolutionary trajectories of ecological and fluvial landscapes – they synthesize a large amount of information; provide a succinct way to visualize landscape dynamics; and in using a combination of quantitative and qualitative methods in a graphical, narrative format, they can pinpoint where transition nodes exist and what causes state transitions (Bestelmeyer et al., 2003). In this sense, STMs are not prescriptive or excessively normative – the idea is to think about what is possible in a given landscape and what the appropriate management response may be when transitions occur.

The use of STMs has rapidly grown in ecology, and they have increasingly been applied to geomorphic landscapes (e.g., Phillips, 2011, 2012, 2014) and to explain vegetation change in riparian settings (see Petts and Gurnell, 2002; Scott et al., 2012; Stringham and Repp, 2010; Zweig and Kitchens, 2009). Some previous work in fluvial geomorphology, such as Schumm's (1969) discussion of river metamorphosis and Xu's (1996) descriptive model of channel response to dam construction employed a logic similar to that found in STMs – each traced the implications of changing process regime for channel morphology. And indeed, this is roughly the idea of using STMs to understand rivers – clarifying the relationships between process regimes and formal states and how they influence channel evolution. Broadening STM frameworks to accommodate channel evolution lets us develop more accurate qualitative predictions of how high-magnitude disturbances (e.g., catastrophic flooding, unexpected sediment influxes) will resonate throughout fluvial landscapes. STMs are fully attuned to the path dependencies underlying channel evolution. As such, they can be used to predict future trajectories or infer evolutionary histories based on the current forms and processes that occupy a landscape (Beven, 2015). In rangeland ecology, one of the main purposes of STMs is to understand the effects of spatial structure and spatial heterogeneity on vegetation dynamics (Briske et al., 2005; Bestelmeyer et al., 2011; Steele et al., 2012). Applied in a river context, STMs let researchers model channel evolution on a reach-by-reach basis, making it possible to summarize the effects of spatial heterogeneity on river behavior in individual reaches. By examining individual reaches, and then assembling a composite narrative that relates the adjustments in each reach to one another, the result is a model attuned to the ways in which channel evolution unfolds across space, and how emergent morphological assemblages shape river dynamics.

I briefly review work that has affinities with state-transition thinking, beginning with Xu's (1996) flow-charting framework to describe changes in river channel patterns downstream of a reservoir. Figure 2.4 portrays the Xu (1996) model, which decomposes morphological adjustment into three stages. This models suggests that wandering rivers respond complexly to dam construction, with an initial period of incision followed by an increase in width-to-depth ratios. This in turn magnifies bank erosion, introducing sediment to the channel, helping to construct mid-channel bars. Eventually, channel slopes flatten and width:depth ratios and sinuosity stabilize, leading to a pseudo-equilibrium condition. What is distinctive about Xu's (1996) qualitative model is that it relates particular river states to geomorphic processes.

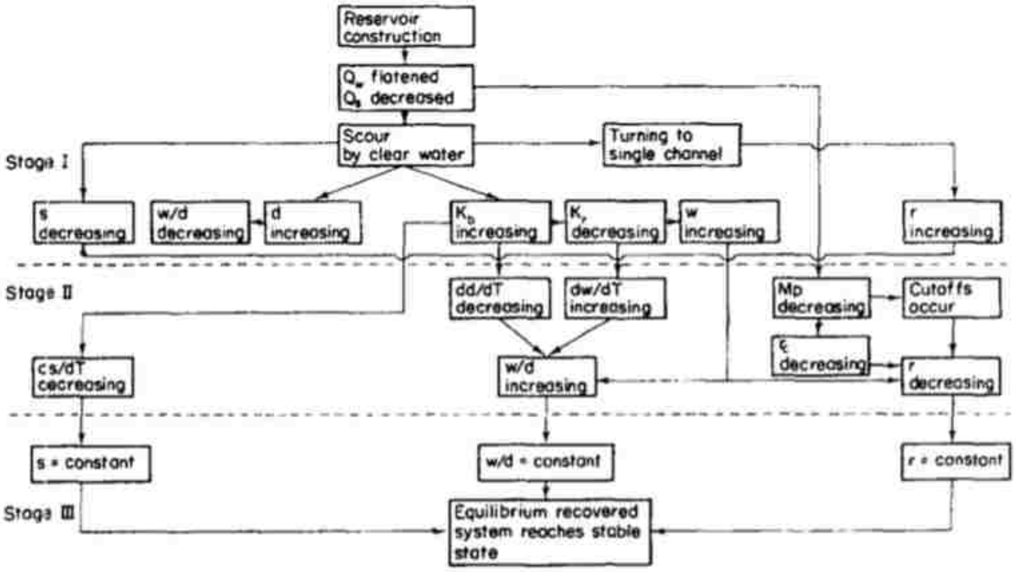

Figure 2.4. From Xu (1996). A box-and-arrow diagram used to describe the complex response of wandering braided rivers downstream of reservoirs.

Gurnell and Petts (2002) created a model that unpacks the relations between vegetation, island-building, and hydrogeomorphic fluxes in braided rivers (Figure 2.5). Very basically, reading from right to left, there are a number of possible states depending on the interplay of formal states and process regimes. So, when sediment deposition and wood availability increases, braided rivers grow and develop a more complex topology, fostering the expansion of riparian and in-channel vegetation. Vegetation snags incoming sediment, which fosters the growth of islands. Unit stream power would not be excessive during this phase and the river would be in a transport-limited state, although occasional high flows would have to be sufficient to move large woody debris and introduce new propagules to the landscape. During high-magnitude flooding, stream power increases as does the amount of work that the flows accomplishes. High flows can uproot and redistribute vegetation, yielding a patchier biogeomorphic structure. If flooding is severe enough, it may reset the channel, effectively wiping out all in-channel vegetation, flushing out large woody debris, and flattening gravel islands (Dean and Schmidt, 2011 described channel resetting along the Rio Grande River due to high discharge events). At the same time, occasional flooding can provide the setup to re-establish a more complex channel morphology through propagule dispersion and sediment recruitment close to newly deposited wood. Thus, landscape response is complex and contingent upon disturbance history and the template of formal states against which process regimes act. Although this is a relatively basic framework, modeling biogeomorphic dynamics along river corridors is still in its infancy (see Zweig and Kitchens, 2009, Figure 3, for a similar approach).

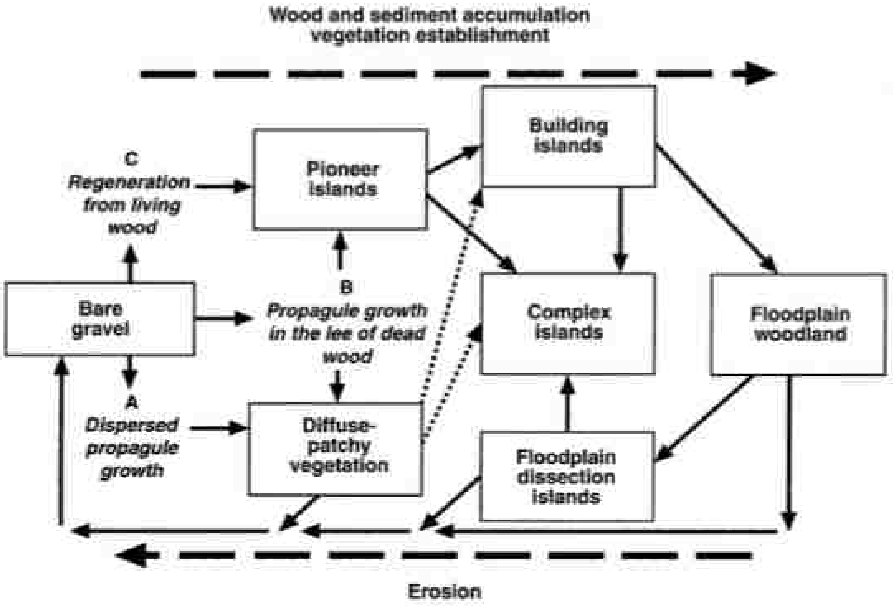

Figure 2.5. From Gurnell and Petts (2002). A conceptual model describing the evolution of braided rivers, with specific emphasis on in-channel geomorphic units (islands) and vegetation. Wood and sediment accumulation promotes island growth and vegetation recruitment; increased erosion (higher stream power) leads to patchier vegetation. If flooding is severe enough, the complete removal of islands and vegetation takes place, resetting channel dynamics.

Phillips (2012) sketched the contours of a flow channel fitness model, which also imports an STM-like logic. Its purpose is to identify under what circumstances a channel will shift between fitness states (e.g., from a state of persisting fitness to one of underfitness). The measures used to make predictions are stream power and shear stress. The flow channel fitness model uses a fixed set of parameters and decision-tree-like structure, and it offers a template for users to understand the implications of interlinked contingencies on channel fitness. This model does not explicitly account for historical and spatial contingencies, but they are implicit. Channel fitness is largely determined by the relationship between observed stream power and critical stream power. Critical stream power is evaluated based on variations in sediment load and caliber as well as hydraulic roughness (Bull, 1979). Sediment availability hinges on factors such as lithological controls, catchment morphometrics, and disturbance – all of which are influenced by historical legacies. Even if an STM is selective in the variables it considers it is still possible to account for the role of contingency in sculpting channel morphologies. Phillips (2013) does not address biogeomorphic interactions that influence the evolution of fluvial landscapes head on, although importantly his model does not make *a priori* assumptions about channels inevitably being attracted toward an equilibrium state. And it is one of the clearest statements to date on the potential state-transition thinking holds for understanding fluvial dynamics.

As the Gurnell and Petts (2002) model hints at, STMs for fluvial landscapes would ideally implicitly or explicitly acknowledge that biogeomorphic dynamics are instrumental in channel evolution. A full consideration of river-ecology dynamics are beyond the scope of this chapter, however its influence has long been known even if studies in this area remained scarce until 15-20 years ago (e.g. Zimmerman et al., 1967; Schumm, 1973; Hickin, 1984). There is and emerging agreement that prior to the evolution and expansion of vascular plants, rivers were primarily unstable bed-load systems characterized by sheet-like flow and high width-to-depth ratios (e.g., Gibling and Davies, 2010, 2012; Davies and Gibling, 2011). As trees proliferated across the landscape during the Carboniferous period, vegetation contributed to bank stabilization and by providing root reinforcement (Davies and Gibling, 2011). This established the conditions necessary to generate meandering rivers. Vegetation enhances channel stability by increasing bank cohesion and mitigating erosion, which enables the development of narrower and deeper channels. Studies looking at modern fluvial landscapes have largely confirmed the important role vegetation plays in river evolution (e.g., Gurnell, 2014; Corenblit et al., 2015). Vegetation traps sediment, stabilizes banks, and leads to the increased resiliency and stability of channel form (Gurnell, 2014). But vegetation effects on channel evolution are contingent on a number of variables, which include the species present and potential interspecies interactions (e.g. Abemethy and Rutherford, 2001). The abundance and spatial structure of vegetation exerts strong influences over bank stability and patterns of sediment entrainment and mobility. Researchers typically partition the effects of vegetation into mechanical and hydrological components (Pollen, 2007; Simon and Collison, 2002). Oftentimes, mechanical effects are beneficial, as when anchored tree roots supporting above-ground biomass reinforce the soil matrix, enhancing bank stability. But as trees mature their increased mass adds load to stream banks, reducing bank stability under some circumstances. The hydrological effects of vegetation relate to plant-water interactions. For example, the vegetation canopy often intercepts water, reducing the amount available for infiltration, which enhances matric suction and reinforces stream banks. However, stems and roots at the soil's surface boost infiltration rate, which carves out preferential flow paths that may negatively influence bank stability (Pollen, 2007). Vegetation plays can thus play an integral role in stabilizing banks, islands, and bars; constraining channel widths; shaping flow velocity and depth; promoting deposition of suspended sediment; and initiating landform development within channels (see Tal et al., 2004; Corenblit et al., 2007; Gurnell, 2013; and Gurnell et. al, 2012 for a more detailed treatment of fluvial biogeomorphic processes; Tal and Paola (2007, 2010) discuss the observed effects of vegetation on morphodynamics in experimental settings). Hydrogeomorphic fluxes interact with vegetation to significantly impact the rate at which morphological evolution occurs (Francis et al., 2009). Although these generalized conclusions hold in many settings, the precise effects of vegetation are context-specific. For example, in response to Gurnell (2014), Greenwood and Kuhn (2015) observed that research on plant-river dynamics has privileged studies focused on humid temperate landscapes dominated by perennial vegetation. They argued that some invasive plants (e.g., *I. glandulifera*) can actually increase erosion along banks and through riparian zones, undermining channel stability. Irrespective of particular vegetation effects, an STM approach gives users the opportunity to be highly specific in variable selection. For example, a fine-grained analysis could examine the effects different species (individually or in assemblages) have on localized and system-wide channel adjustments.

If STMs are a practical tool for documenting river transformation, the question becomes what kind of methods are useful for capturing the relationship between process regimes and formal states in a manner compatible with state-transition thinking. Brierley and Fryirs (2000, 2005, 2013) pioneered the River Styles system, which includes methods for characterizing channels based on structural properties such as channel geometry, in-channel and floodplain geomorphic units, and vegetation abundance and distribution. In its more formulaic manifestations, river classification can be problematic, especially when they are used to guide river renewal projects (see Juracek and Fitzgerald 2003; Simon et al., 2007; Lave, 2010, 2012). Strictly speaking, the River Styles framework is not a classification system in the same vein as Rosgen's (1994); rather, its purpose is to *characterize* rivers – it does not purport to be a rigid classification system. The River Styles framework emphasizes that river channel morphology is perpetually reworked by the interplay of internal and external forcings that reshuffle the geomorphic template. By not relying on river planform alone for characterization purposes, the River Styles approach situates them within broader spatial and temporal contexts, taking a multi-scalar approach to characterization lacking in Rosgen's system (Brierley and Fryirs, 2000). Although using planform as a kind of shorthand for state can be valuable because it is often linked to similar geomorphic features across a range of landscapes.

STMs are compatible with numerous field methods, from traditional surveying techniques to more sophisticated, technologically advanced mapping strategies (e.g. Graf, 1984, 2000; Kondolf and Piégay, 2003; Carbonneau et al., 2012; Surian et al., 2014). Here I briefly touch on a few methods that are well suited to identifying formal states. One method of change detection for river landscapes is to conduct a patch-based analysis of geomorphic units to determine how their size and statistical properties shift throughout time, which can indicate where and when a river experiences transitional behavior (Bestelmeyer, et al. 2011; Poole, 2002). This kind of strategy, which has its affinities with landscape ecological analysis, lets researchers correlate changes in a river's state with hydrogeomorphic fluxes. These fluxes are often evident from examining streamflow data. While not explicitly developed to understand channel evolution, Graf's (1984, 2004) locational probability analysis could be applied to assess the likelihood that different geomorphic elements are present in fluvial landscape. Particular geomorphic features or trends can be linked to changing states. Surian et al. (2014) used aerial photos to map vegetation turnover and adjustments to channel planform. While their methods do not align perfectly with Graf's – they do not develop a probabilistic framework – they are motivated by the same question – how does the spatial distribution of river states change over time and what does this signify about the relations between channel structure and bio-hydrogeomorphic fluxes? While the availability of remotely sensed data can be spotty, and not immediately available following a significant disturbance event, these spatially explicit methods can help construct instructional narratives nonetheless.

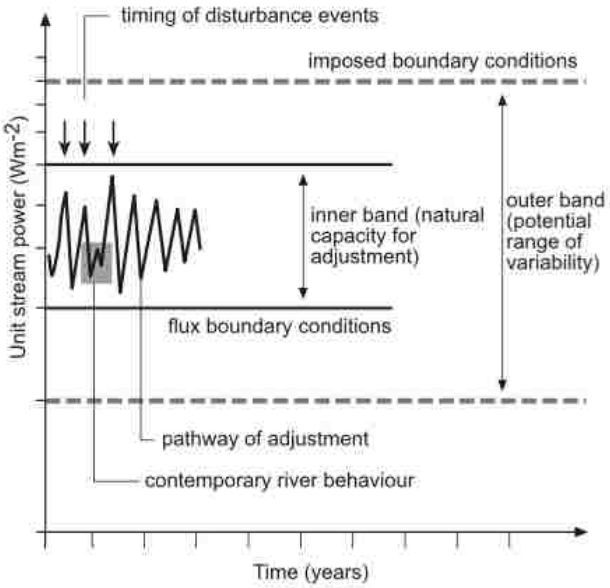

Figure 2.6. From Fryirs et al. (2012). A stream evolution diagram, which relates unit stream power to the channel’s capacity for adjustment. The outer dashed banned represents the imposed boundary conditions that restrict the range of potential channel adjustments. Flux boundary conditions – signified by the inner band – include the contemporary range of flow, sediment, and vegetation conditions. Within this range of variability, a river can assume a variety of morphological forms. Potential evolutionary pathways are dictated by the landscape’s history and memory (see Brierley, 2010).

Another potentially useful tool is the stream evolution diagram (Brierley and Fryirs, 2005; Fryirs et al., 2012). As an extension of the River Styles methodology, these diagrams are used to determine possible channel adjustment pathways (Figure 2.6). They rely primarily on unit stream power to predict changes; this is a convenient and effective measure because it reflects how energy is generated and expended in a given setting (Fryirs et al., 2012). The imposed and flux boundary conditions shape rivers’ capacity for adjustment. Imposed boundary conditions remain fixed over engineering or geomorphic time scales and are set by factors such as valley setting, slope, and lithology. Flux boundary conditions include the contemporary flow and sediment regimes under which a reach operates.

Other factors that influence a channel’s natural capacity for adjustment include the structure and composition of riparian vegetation, large woody debris, and the landscape’s disturbance history. Stream evolution diagrams can be used to pinpoint when river metamorphosis takes place (e.g., a planform shift), however, they are equally useful for pinpointing when smaller, less transformative states change. Because morphological states are defined by the flow energy, sediment caliber and abundance, and spatial distribution of riparian vegetation, stream evolution diagrams can provide assistance constructing STMs. As such, STMs can be used to predict what drives a river across a threshold into an entirely different behavioral regime and morphological state.

2.6 Conclusion

CEMs have grown more sophisticated and now paint a more geomorphically and ecologically realistic picture of channel evolution. Nevertheless, exploring the use of STMs to understand channel adjustments is valuable because it establishes an epistemologically plural framework to work through the consequences of different permutations of process regimes and formal states working together. The goal of state-transition thinking is to seize on the interactions or disturbance events that can trigger a state change in rivers. There are potential criticisms associated with STMs. One argument is they are too reliant on description and observation, which makes them too focused on the past. Another critique is that when the number of evolutionary trajectories multiplies STMs lose predictive utility. Indeed, there is some danger that arises if we view STMs as tools we use to passively catalogue every imaginable state a river could ever occupy. However, reviewing historical precedents and the path dependencies associated with particular adjustment trajectories lets us identify what states are most probable in a landscape. True, classic CEMs have the advantage of being more deterministic in their outlook, precisely forecasting evolutionary trajectories. But it is critical not to conflate precision with accuracy. Models can be very precise, but if they are highly inaccurate they are functionally meaningless. In spatially complex rivers subjected to spatially prismatic disturbances and human influences, the classic, deterministic CEM loses its value because river managers need the knowledge to predict channel adjustment under a number of different scenarios. Having a solid intuition about what potential river states look like can economize river management and refocus it on probabilistic assessment of the landscape. Ultimately, researchers and practitioners must decide the level of specificity included in an STM. A final point to keep in mind is that while an STM-based approach to channel evolution modeling could become intractable if the modeler attempts to foresee every possible evolutionary trajectory – not all pathways are equally probable.

Unlike classic CEMs, an STM-based framework does not begin with a normative view holding that rivers invariably adjust toward equilibrium (Phillips, 2012). In arguing for the use of STMs, my purpose is not to invalidate classic CEMs, but to suggest STMs let us more exhaustively document how the coupling, or decoupling, of ecological and geomorphic components of rivers affects their co-evolution. In doing so, they propose a view of channel evolution steeped in the principles of biogeomorphology – a necessary step to understand the connections and relations that shape the evolution of any complex fluvial landscape (Schumm, 2005). STMs are a much-needed intervention in debates over channel evolution. They predict channel evolution and possible river futures (e.g., Brierley and Fryirs, 2008) in a manner that lets researchers strike an appropriate balance between geomorphic realism and simplifying assumptions. This balance is crucial to maximize the real-world utility of any model, and to ask what strategies will best work to preserve the resiliency of fluvial landscapes in the face of climate change and other uncertainties.

Chapter 3 – Boxing Daze: Using State-and-Transition Models to Explore the Evolution of Socio-Biophysical Landscapes

3.1 Introduction

Life is in the transitions as much as in the terms connected

William James (1904)

The emergence of critical physical geography (CPG) represents an opportunity for physical and human geographers to collaboratively work on questions related to socio-biophysical landscapes. While many conversations have taken place about the *possibility* of blending physical and critical human geography (e.g. Harden, 2012; Lane, 2001; Massey, 1999), and despite the fact there has been an impressive amount of work that knits together biophysical science and critical human geography (e.g. Duvall, 2011; Inkpen, 2011; Inkpen and Wilson, 2013; Inkpen et al., 2007; Lane et al., 2011; Lave, 2009, 2012; Robbins, 2000, 2001; Turner and Robbins, 2008; Whatmore, 2002) there is still no consensus on how to bring these supposedly opposing sides together. Because of the collaborative hurdles researchers interested in interdisciplinary work must overcome, if CPG is to prove successful, practitioners will need to develop shared – or compatible – research frameworks and methodologies that dissolve boundaries between human and physical geographers (Lave et al., 2014; Tadaki et al., 2014).

This paper highlights one framework that can weave together the epistemological strands that run through physical and critical human geography research. It proposes that STMs can facilitate the development of complex, innovative, and critical narratives to interpret the interplay of biophysical and social drivers that drive adjustments in socio-biophysical landscapes. Whereas previous discussions about collaboration were often conducted at a metaphilosophical level, in drawing attention to STMs, my purpose is to provide researchers with a pragmatic conceptual solution to execute cross-disciplinary work. The appeal of STMs rests in their potential to accommodate a methodological pluralism that melds biophysical field science and critical social science. Relying on summary box-and-arrow diagrams and analytical narratives, STMs describe and anticipate significant transitions in landscape form and composition (e.g. Bestelmeyer et al., 2003, 2006; Stringham et al., 2001; Westoby et al., 1989). What distinguishes them from previous efforts that attempted to blend critical human and physical geography perspectives is their integration of descriptive and analytical narratives. These narratives can potentially include critical social science perspectives that are important for understanding socio-biophysical landscape dynamics. From critical development studies (e.g. Carr, 2010; Fairhead and Leach, 1995, 1996, 2003; Ferguson, 1994) to geomorphology (Baker, 1999; Phillips, 2012; Tadaki et al., 2012, 2014**)**, researchers have noted the importance narratives play in shaping research, the interpretation of empirical findings, policymaking, landscape dynamics, and communities' livelihoods (Leach and Scoones, 2013; Leach et al., 2010). Identifying state transitions entails (1) cataloguing alternative states that can potentially exist on a site, (2) correlating threshold behaviors with observed biophysical process regimes and their associated social dynamics, and (3) critically appraising the multivariate drivers of transitional dynamics (e.g. Sayre et al., 2013)[5].

The rest of this paper explores work on state transitions across the biophysical and social sciences and makes the case for using STMs to frame discussions of socio-biophysical landscape evolution. Working through the implications of theoretical approaches in ecology, geomorphology, and political ecology suggests that STMs are ideal to create the kinds of trans-disciplinary narratives CPG calls for. Section 3.2 introduces STMs, describes their origins in rangeland ecology, and highlights work throughout the biophysical sciences on state transitions, including fluvial geomorphology. This review demonstrates that a nuanced modeling framework is necessary to account for the spatial and temporal contingencies that produce landscape transitions. Section 3.3 discusses critical political ecology and the chains-of-explanation (CoE) framework that has been used to account for socio-environmental changes (Barnett and Blaikie, 1992; Blaikie and Brookfield, 1987; Robbins and Munroe Bishop, 2008; Wisner et al., 2004). CoEs, like STMs, synthesize information about the setup and trigger events that catalyze environmental degradation or that leave communities ill-prepared to

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[5] Definitions of state transitions vary from discipline to discipline, but this paper adopts the view put forward by Phillips (2014: 208), who established a generalized interpretation that could extend to socio-biophysical landscapes: "[a state transition] is a change that results in a qualitatively different landform, geomorphic environment, or landscape unit." Getting more specific than this would be a mistake because what constitutes a state transition varies greatly between settings.

deal with hazards. What this literature synthesis indicates is that physical and critical human geographers alike have been preoccupied by questions of transitional dynamics. Ultimately it is this concern with transitions that can unite future research programs.

Section 3.4 proposes a unified STM framework to investigate socio- biophysical landscapes. STMs leverage relational thinking – comparable to actor-network theory (ANT) – to organize information about landscape states. Because their main purpose is to *organize* knowledge about landscape dynamics, they prove ideal for creating empirically based relational mappings that document the heterogeneous associations that either stabilize or unsettle particular landscape states (cf. Murdoch, 2001). While my epistemological commitment is to a relational view of landscapes, my aim is not to endorse specific analytical techniques. STMs provide a framework in which multiple research methods – from remote sensing to discourse analysis – can be used to advance incisive landscape interpretations that bridge sub-disciplinary divides that have often stymied trans-disciplinary research. A further advantage of STMs rests in their capacity to include, and help adjudicate between, lay and expert knowledge. This could encourage a more participatory form of model development and citizen science more broadly (Knapp and Fernandez-Gimenez, 2009; Knapp et al., 2011).

Finally, Section 3.5 reflects on what it means to practice CPG. For CPG to gain traction researchers must adopt an expansive definition of criticality, one that recognizes neither side of the discipline should claim ownership of the term “critical.” Sometimes drawing from critical social theory will crystallize landscape dynamics. Other times, it is sufficient to invoke only biophysical explanations. Adopting a critical perspective means carefully reading landscapes to determine when – and where – biophysical and social processes interact with one another to generate distinctive material signatures.

3.2 A Brief History of State-Transition Thinking in Rangeland and Fluvial Landscapes

Thinking about biophysical landscapes in terms of states and transitions has gained momentum rapidly in many scientific disciplines. The emergence of STMs, and their use among academic researchers and governmental agencies in the United States, has contributed to this. Underwriting STMs is a rather simple premise – that biophysical landscapes manifest different states (e.g. vegetation communities) that are contingent upon spatial and temporal variations in physical and biological processes. Relationships between states and process regimes adjust over time and developing STMs helps us to decode why state transitions occur. This section introduces the application of STMs in biophysical contexts – first by discussing their use in rangeland ecology, and then by looking at other disciplines that have incorporated state-transition thinking. Because STMs have their origins in rangeland ecology, I draw from that literature to illustrate their structure and main features. After this, I shift my discussion to fluvial landscapes to illustrate the use of state-transition thinking in a different biophysical context.

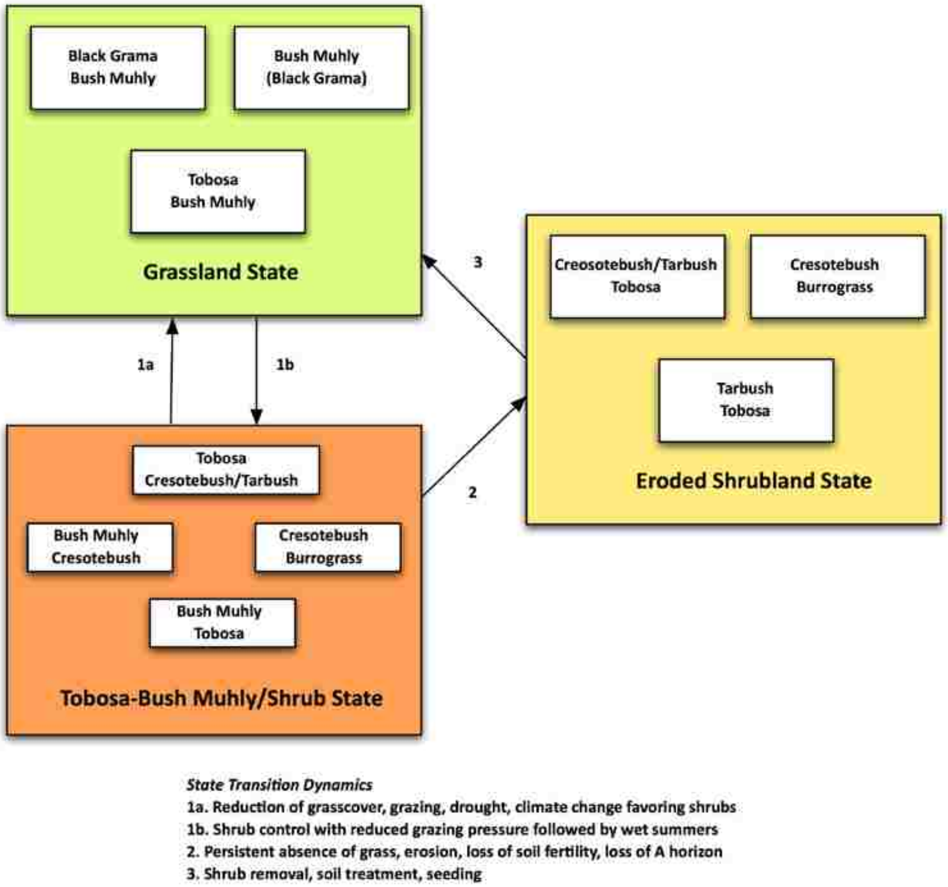
3.2.1 Home on the Rangeland Tradition

Rangeland ecologists devised STMs to improve their predictions of vegetation community dynamics in arid and semi-arid settings. Until the 1970s, applied ecologists largely relied on Clements' theory of linear, deterministic vegetation succession (1916; see Pickett et al., 2005, 2009; Platt and Connell, 2003, for reviews, and Eliot, 2007, who disputes the popularized caricature of Clements' work). This view of succession underwrites the range model (Dyksterhuis, 1949; Sampson, 1917, 1919), which guided rangeland management in the United States throughout much of the 20th century. The range model proposes that grazing is the main control on vegetation dynamics in rangelands. In the absence of grazing, it states that rangelands evolve toward a final, persistent vegetation state (i.e. a climax state). Westoby et al. (1989) proposed the use of STMs because of the range model's deterministic assumptions and its neglect of nonlinear ecological dynamics. STMs, they argued, offer a "practicable way to organize information for management, [and] not because [they follow] from theoretical models about dynamics" (268; see also Bestelmeyer et al., 2003, 2009; Briske et al., 2005, 2006; Twidwell et al., 2013, on the application of STMs to management.

Rangeland STMs are embedded within ecological site concepts. Ecological sites are spatially defined units of the landscape classified "based on recurring soil, landform, geological, and climate characteristics" (Caudle et al., 2013:12; see also Brown, 2010). Developing ecological site concepts requires linking changes in plant environments to the spatial variability of an area's physical geography (Moseley et al., 2010; see also Steele et al., 2012). Defining an ecological site concept hinges on piecing together multiple forms of knowledge, including published research, interviews with experts, maps, historical descriptions, and landscape photographs. Interviews typically solicit knowledge from institutional experts, however, recent work has sought to integrate more local knowledges (e.g., that of ranchers and farmers) into STMs to crystallize our understanding of ecological dynamics (Knapp and Fernandez-Gimenez, 2006; Knapp et al., 2011; see also Reid et al., 2011; cf. Robbins, 2006). Reconciling scientific expertise with local, experiential knowledge to improve environmental management remains an ongoing project, arguably one that CPG and state-and-transition modeling can help advance.

In the United States, the US Department of Agriculture's Natural Resource Conservation Service (NRCS) maintains an extensive database of ecological site concepts. Site concept include an STM that consists of a box-and-arrow diagram and explanatory narratives that describe what factors influence plant community structure and composition. STMs identify the alternative that states could exist on an ecological site and hypothesize what shifts in form–process relations catalyze state transitions. In rangeland ecology, "state" has a more specific definition than that cited above. States are "climate/soil/vegetation domains that encompass a large amount of variation in species composition" (Stringham et al., 2003:107 ; see also Bestelmeyer et al., 2003; Stringham et al., 2001). Transitions signify possible directions of change. When a transition occurs, significant management and energy inputs can reverse the trajectory, and a linear reversal is not possible because the biogeomorphic processes operating on the site have been fundamentally transformed.

An example STM from the NCRS clarifies the structure of STMs and demonstrates the central role accorded to narrative and knowledge organization. Figure 3.1 is an STM for the Gravelly Loam ecological site found in southern New Mexico and western Texas. The ecological site concept organizes information on climate, hydrology, pedology, plant communities, historical reference conditions, and animal communities that can affect ecological dynamics. It also contains historical photography that aids with identifying vegetation states (and transitions). The narratives expand upon the summary box-and-arrow diagram. Returning to Figure 3.1 there are three primary states:



State Transition Dynamics
1a. Reduction of grasscover, grazing, drought, climate change favoring shrubs
1b. Shrub control with reduced grazing pressure followed by wet summers
2. Persistent absence of grass, erosion, loss of soil fertility, loss of A horizon
3. Shrub removal, soil treatment, seeding

Figure 3.1. This state-and-transition model (STM), which was developed by the Natural Resource Conservation Service (NRCS; see also Bestelmeyer et al., 2003, 2009), illustrates the box-and-arrow diagram format used to summarize ecological dynamics on an ecological site. This site (Gravelly Loam) is located in Major Land Resource Area (MLRA) 042 – Southern Desertic Basins, Plains, and Mountains. The large boxes represent states, while the smaller boxes are community phases. Arrows depict identified transitional pathways. There can be between-state transitions or intra-state transitions (shifts in community phase). Between-state transitions cannot be reversed without significant management interventions. The NCRS maintains an extensive database of ecological site concepts and it is updating older range site descriptions originally produced by the Soil Conservation Service. This STM and ecological site concept are available at https://esis.sc.egov.usda.gov/.

(1) Grassland; (2) Eroded Shrubland; and (3) Tobosa-Bush Muhly/Shrub. The first two have three community phases, while the latter has four. The arrows represent directed transitions. For example, the Tobosa-Bush Muhly/Shrub state can flip to either a grassland state or an eroded shrubland state – if shrub control is introduced and grazing pressures reduced, these areas can revert to grassland under a favorable precipitation

regime. But if grass cover remains depleted and erosion does not subside, declining soil fertility and the loss of topsoil drive the area to an eroded shrubland state, negatively impacting its resiliency and resistance to future disturbances. Narratives discuss empirical indicators that signal a state transition has either happened, or is in-process (see Bestelmeyer et al., 2011a, 2011b; Carpenter and Block, 2006; Scheffer et al., 2012 for strategies used to detect state transitions).

Perhaps what is most salient to this discussion is that STMs promote the organization of knowledge into cohesive landscape narratives. Narratives situate us epistemologically and help orchestrate our management, interactions with, and interpretations of landscapes (Phillips, 2012). The NRCS's ecological site concepts adhere to a fixed template, but the narratives gloss over the social factors that operate with and biophysically modify their ambient environments, or focus primarily on the role of management interventions. Today, the construction of STMs remains largely in the hands of experts. Local knowledges integrated into STMs (cf. Knapp and Fernandez-Gimenez, 2009; Knapp et al., 2011) are interpreted through the lens of expertise. Nevertheless, the potential exists to inject critical analyses of social dynamics into the conceptual spaces carved out by STMs, which can stimulate our imaginations as to how and why particular socio-biophysical interactions materialize.

3.2.2 Extending state-and-transition thinking beyond rangelands

Outside of rangeland ecology geomorphologists, biologists, and other scientists have applied state-transition thinking. Recent theoretical and empirical work in ecology has focused on alternative stable states and hysteresis – the latter emerges when disturbance or another process causes a landscape to occupy a new pseudo-equilibrium condition. And like rangelands, when other landscapes make a state transition, linearly reversing processes to their pre-disturbance strength is insufficient to recover the earlier state. Landscapes may have multiple points of stability, which are contingent upon disturbance history and their components undergoing shifts in their interactions with one another (e.g. Beisner et al., 2003; Phillips, 2003, 2011a; Scheffer, 2009; Scheffer et al., 2001**)**. There are numerous examples of work on state transitions in biophysical settings (Table 1 has a non-exhaustive sampling). This research demonstrates the rise of state-transition thinking since the 1970s, when theoretical ecologists initially demonstrated the possibility of alternative stable states in ecosystems (e.g. May, 1977). What follows is an abridged history of fluvial geomorphologists' effort to understand river patterns and evolution in terms of states, transitions, and thresholds.

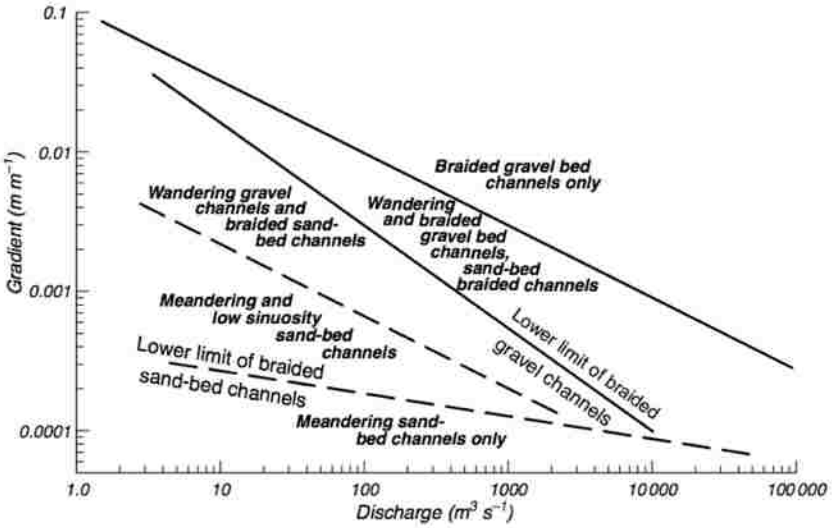


Figure 3.2. Expanding on Leopold and Wolman's (1957) work on channel patterns that discriminated between morphologies on the basis of channel forming discharge and slope, Church (2002) produced a refined stability diagram that accounts for effects of sediment caliber on river morphology. Whereas Leopold and Wolman distinguished between braided and meandering planforms, the inclusion of sediment caliber presents a fuller picture of the conditions under which specific river states exist.

Two early statements on state transitions in fluvial geomorphology are Leopold and Wolman's (1957) work on river channel patterns and Schumm's (1969) analysis of river metamorphosis. Leopold and Wolman addressed a simple yet vexing question – how can we distinguish between channel planforms based on state and process variables? Combining empirical and quantitative analysis, they derived a power function that plots channel slope against bankfull discharge to identify pattern thresholds (i.e., where conditions shift from favoring a meandering planform to a braided one). Since this initial work, many researchers have created geomorphic indices to characterize planform states (Beechie and Imaki, 2014; Bledsoe and Watson, 2001; Chang, 1986; Church, 2002; Eaton et al., 2010; Ferguson, 1987; Lewin and Brewer, 2001; Mueller and Pitlick, 2013, 2014; Parker, 1976; Van den Berg, 1995). Figure 3.2 provides an example of one such discriminant function – Church (2002) modified Leopold and Wolman's original work to include sediment caliber to aid in the identification of channel forms. Discriminant functions, however, are imperfect predictors of channel pattern and have a limited domain of application because they do not account for the complex sequence of process-state adjustments often associated with channel evolution and planform transitions (cf. Graf, 1988). They also neglect place-based contingencies that influence the operation of physical processes because they are generalized functions that typically use only three or four variables to establish empirical relationships. Since the 1980s, studies of channel evolution have emerged that read the concept of state more expansively by not equating it with planform alone. They instead focus on the dynamic modifications that drive channel adjustments. It is from these that STMs for riverine landscapes have emerged.

Figure 3.3. From Simon and Rinaldi (2006). CEMs predict the sequence of channel adjustments following disturbance. Originally designed to explain how rivers adjust to channelization, they break response into six stages. Each stage represents a qualitatively different landscape state. While the linear sequencing is valid in many settings, when spatially and temporally uneven patterns of disturbance interact with discontinuities in channel morphology (e.g. Knighton, 1998; Toone et al., 2014) the result can be more complex forms of adjustment and evolution.

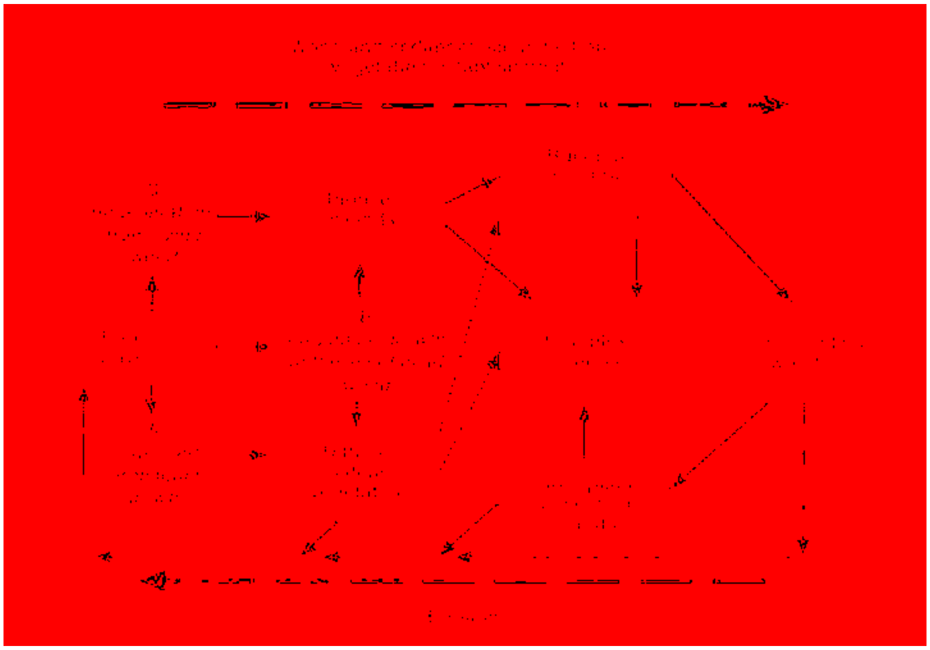


Figure 3.4. Gurnell and Petts (2002; see also Gurnell et al., 2001, 2012) developed a state-and-transition framework to explain the dynamics of island lifecycles and channel evolution of a braided gravel-bed river (Tagliamento River, Italy). In many ways this model embodies the logic found in STMs, paying attention to states and processes (e.g., hydrogeomorphic and biogeomorphic fluxes). Braided rivers are often dominated by a flashy hydrological regime. Increasing discharge accelerates erosion, which reduces the ubiquity of vegetated islands. High-magnitude floods reset the system's biogeomorphic template as they distribute seeds, propagules, and large woody debris necessary for another round of island building and vegetation growth.

Alluvial rivers undergo significant morphological adjustment when factors such as natural disturbance, urbanization (Chin, 2006; Chin and Gregory, 2005, 2009; Doyle et al., 2000; Gurnell et al., 2007; Violin et al., 2011; Wolman, 1967) and dam construction (Brandt, 2000; Csiki and Rhoads, 2010; Graf, 2001, 2005, 2006; Petts, 1979; Phillips et al., 2005) rework process regimes. In the 1980s, channel evolution models (CEMs) were developed to explain and predict channel adjustments following disturbances. They divide evolution into distinct stages, with each stage being typified by a distinctive process regime and channel state, much like STMs. Traditional, linear CEMs partition adjustments into five or six stages (e.g. Schumm et al., 1984; Simon, 1992; Simon and Hupp, 1987; Simon and Rinaldi, 2006; see Figure 3.3). Much like the rangeland ecologists who observed that rangeland vegetation communities do not always evolve linearly or deterministically toward a final state after disturbance, geomorphologists soon recognized that classic CEMs could not reliably predict channel adjustment in rivers of differing patterns (e.g., braided, anastomosing) or that flow through spatially complex environments with variable flux boundary conditions (*sensu* Brierley and Fryirs, 2005). In response, multi-pathway CEMs and STMs for fluvial environments have been devised to cope with this problem and account for potential nonlinear adjustments (e.g. Canntelli and Curran, 2012; Gurnell and Petts, 2002; Hawley et al., 2012; Makaske et al., 2002; Perry et al., 2012; Phillips, 2013a). Exemplifying this approach, Figure 3.4 is a state-and-transition framework developed for braided rivers. It maps the influence of discharge, erosion, and in-channel accumulations of large woody debris on the emergence and disappearance of vegetated islands (Gurnell and Petts, 2002).

This – admittedly – whirlwind tour of STMs suggests the pivotal role state-transition thinking has played in our epistemological constructions and theorization of biophysical landscapes. STMs narrate and conceptualize landscape changes, whether they follow predictable, linear adjustment paths or nonlinear trajectories fraught with complexity. Most STMs have remained disconnected from questions concerning the social dimensions of landscape change. Perhaps most notably, they generally abstain from conversations about the political economic relations and asymmetrical power arrangements that can transform landscapes. One solution to this problem lies in drawing STMs into conversation with political ecology.

3.3 State-and-Transition Models and Political Ecology

Political ecologists have long acknowledged that there is rarely a single driver underpinning transitions in socio-biophysical landscapes (e.g. Forsyth 2003; de Jonge et al., 2012; Geist and Lambin, 2002; Robbins, 2012; Shandra et al., 2011; Wisner et al., 2004). Although STMs have remained focused on the biophysical drivers of landscape change, new work in rangeland ecology has advocated for a multifactorial perspective that views state transitions as the outcome of ecological, political, and economic variables working in different combinations across multiple scales (e.g. Bestelmeyer et al., 2015; Sayre et al., 2013). This raises the question of how to more fully integrate social considerations into STMs so that they take full advantage of the knowledge that emanates from critical human geography. The history of political ecology is instructive in this regard. The CoE approach to socio-biophysical landscape analysis, although rooted in a structuralist perspective, shares affinities with STMs (e.g. Barnett and Blaikie, 1992; Blaikie, 1985; Blaikie and Brookfield, 1987; Neumann, 2008; Robbins and Monroe Bishop, 2008; Wisner et al., 2004). This section describes the similarities between CoEs and STMs similarities, attempts to build a bridge across the discipline by demonstrating that STMs are compatible with critical human geography and can foster a networked, relational view of socio-biophysical landscapes.

Like STMs, CoEs summarize research findings and patterns of causation with box-and-arrow diagrams. However, CoEs take as their focus the political economic relations that produce uneven patterns of landscape change and environmental degradation (Barnett and Blaikie, 1992; Blaikie, 1985; Blaikie and Brookfield, 1987; Wisner et al., 2004). To develop a CoE, the first step is to identify an environmental problem and the proximate drivers that contribute to it. Proximate drivers operate locally, but are also influenced by political economic constraints imposed at varying spatial and temporal scales As such, broad networks of political, economic, and social relations are implicated in local environmental dynamics (e.g. Robbins, 2012; Robbins and Monroe Bishop, 2008). Admittedly, the original CoE framework is not perfectly congruent with present-day STMs. For example, in CoEs, boxes represent particular states *or* processes, while arrows trace out networks and pathways of causation.

Wisner et al.'s (2004) Access Model (AM) provides an updated strand of this thinking (Figure 3.5). It is used to interpret the spatially uneven patterns of vulnerability that emerge before, during, and after hazard events and the effects these have on individuals' livelihoods. The AM begins with an analysis of the social conditions that exist before a disturbance. By assessing the social relations, access to resources, and structures of domination that iteratively shape livelihoods, researchers can identify how the socio-biophysical conditions in place before a hazard event influence a community's response, recovery, and future resiliency. When a hazard – a trigger – occurs, the response, recovery, and resiliency of actors are decidedly influenced by the setup conditions (Tobin, 1999). Hazards reshape the capabilities of individuals and communities and the resiliency of biogeomorphic landscapes. They establish new socio-biophysical templates against which the next hazard will unfold. These new templates undoubtedly influence community resilience – thus, hazards produce socio-biophysical transitions that rework the logic of decision making in communities, affect structures of domination, and govern individuals' access to the resources they will need to cope in the aftermath of future disasters. The AM directs our attention toward how states and processes are enmeshed in particular spatial-temporal contexts that magnify vulnerability. It reveals socio-biophysical landscapes as complex mosaics, which are made and remade in the face of hazardous events.

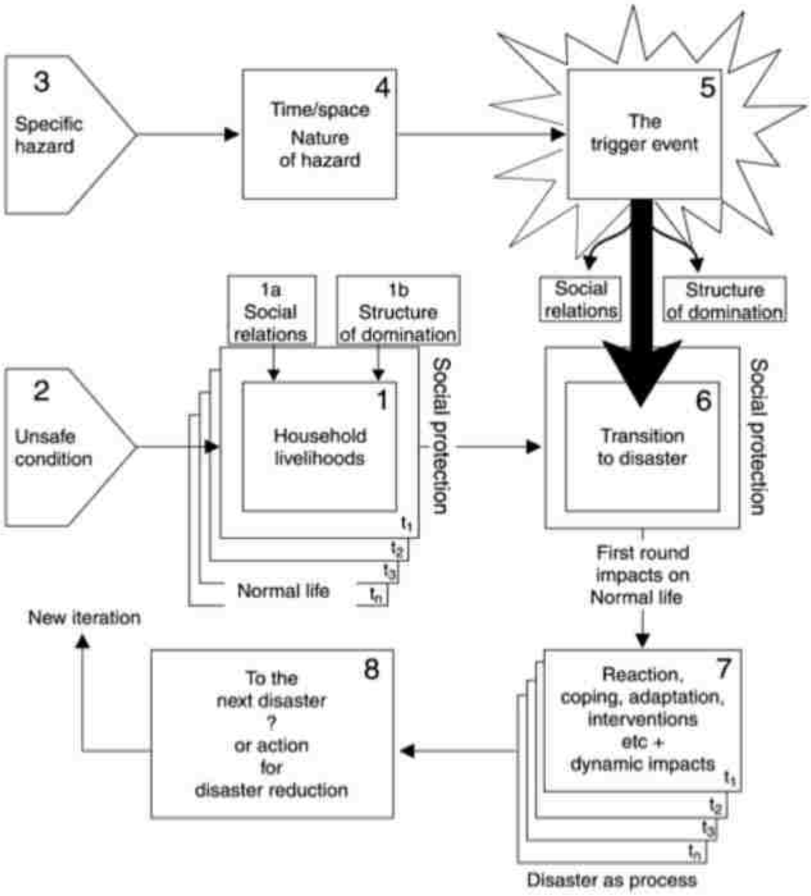


Figure 3.5. Wisner et al.'s (2004) Access Model offers a slightly updated variant of the CoE framework. Used to better understand why spatially uneven patterns of vulnerability and resilience arise in the face of natural hazards, the Access Model proposes a setup-and-trigger framework. A hazard event impacts communities influenced by structures of domination and their own internal social relations. Conditions that are in place before a hazard event can be thought of as the setup. Once a hazard occurs (the trigger), community response and resiliency are shaped by the conditions in place before the event.

CoEs and STMs have the common goal of explaining why particular transitions occur in socio-biophysical landscapes. Highlighting political ecology and CoEs demonstrates that critical human geographers have addressed socio-ecological problems by plotting relational networks that emerge among social and biophysical factors, just as STMs delineate the relations between landscape state and process regimes. Political ecology teaches us that political economic considerations, social dynamics, and complex power relations are intensely woven into the assemblage of socio-biophysical landscapes (Robbins, 2012). As such, it is clear that STMs' embedded narratives should be broadened if they are to interpret all of the dynamics that unfold in socio-biophysical landscapes. Recalibrated state-transition narratives should interrogate not only biophysical form–process relations but also the socioeconomic accomplices – or culprits – of state transitions. Many studies have used relational thinking to understand the interplay of anthropogenic and biophysical factors that activate environmental transformations, or produce destruction (e.g. Cromwell and Winpenny, 1993; Holifield, 2009; Leach and Fairhead, 2000; Owusu, 1998; Roberge, 2002; Urban, 2002). STMs, like CoEs, can accommodate relational and network epistemologies or assemblage thinking (see Anderson et al., 2012; Johnson et al., 2009; Latour, 2005; Law, 1992; Mol, 2010; Sayes, 2014). CoEs highlight the directed networks of relations that are most likely to precipitate state transitions, a strategy that has been increasingly used to develop biophysical STMs, albeit in more quantitative forms (cf. graph theoretic methodologies used in STMs; Phillips, 2011b, 2013b, 2014; in political ecology, see Rocheleau, 2008; Rocheleau and Roth, 2007). Although biophysical STMs have relied on mathematical and statistical methods to describe networked relations, enfolding more qualitative, topological analytics can enrich STMs and forge stronger connections with critical human geography (e.g. Martin and Secor, 2014).

STMs represent a continuation of the epistemological project that drove the development of CoEs while bridging intensive and extensive research approaches (sensu Birkenholtz, 2012). Intensive research leverages close readings of local process dynamics to interpret how and why broader patterns emerge, whereas extensive approaches cast a broader net, identifying widespread patterns before downscaling analysis to make inferences about generative processes (Birkenholtz, 2013: 301; see also Holifield, 2009; Neumann, 2008; Rocheleau and Roth, 2007).

STMs have traditionally started with coarse-grained, regional analysis. However, data collected during this phase are validated through more intensive sampling that drills down into the local biophysical relations. While STMs may help us make important generalizations about landscape adjustments, they are also attuned to local contexts and the possibility of nonlinear and threshold behaviors that emerge partially because of historical contingencies (Phillips, 2006, 2007, 2011a) and even chance. What STMs can learn from CoEs is the importance of properly situating the scales and spaces at which processual linkages between social and biophysical dynamics. It is possible to imagine not just STMs for individual landscapes, but thoroughly networked STMs that cover multiple landscapes and pinpoint nodes of connection that entwine spatially disparate locations. For example, these could illustrate that spatially distant landscapes are entangled with one another because they are governed by common environmental policies. If governance is altered due to biophysical changes or political economic imperatives because of events in one setting, other landscapes may feel the effects, and have the consequences of policy shifts materially etched into their environment. STMs provide researchers with a tool to organize and chart these shifting relations.

3.4 Toward an Integrative State-and-Transition Model for Socio-Biophysical Landscapes

So far I have talked about frameworks that approach landscapes in terms of states and transitions. Yet, these frameworks tend to privilege either the biophysical or social aspects of landscapes instead of adopting a fully integrative mode of analysis. There have been attempts, recently, at devising conceptual frameworks that holistically treat the social and biophysical drivers of landscape change (e.g. Chin et al., 2014; Domptail et al., 2013; Leach and Scoones, 2013; Leach et al., 2010; Ostrom, 2007, 2009; Phillips, 2014; Sayre et al., 2013; Scoones et al., 2007; Wohl et al., 2014; Wood et al., 2012). Although these frameworks are united in viewing socio-biophysical landscapes as precariously assembled through complex interactions, their treatment of contentious political and economic relations is sometimes lacking the critical-theoretical edge that CPG calls for. This section briefly reviews these approaches and proposes a STM framework that can accommodate multiple forms of analysis that seamlessly blend trenchant social theory and biophysical science. Grounded in a pragmatic epistemology (Koopman, 2013; Rorty, 1982, 1999) this framework draws on ANT and assemblage thinking (e.g. Castree, 2002) to produce maps of association that narrate how multiple subjects and objects are drawn together on the landscape to produce impermanently stabilized socio-biophysical landscape states (cf. Gareau, 2005; Murdoch, 1997, 1998; Robbins, 2004; Shaw et al., 2010**)**. Some readers may be uneasy over my invocation of ANT, thinking it agnostic on questions of power or political economy, although as Murdoch (2006) convincingly showed, ANT grew out of a concern with the uneven power dynamics responsible for shaping relational spaces (on questions of ANT and power and social relations, see Fox, 2000; Law, 1992, 2009; Murdoch, 1998; cf. Massey, 1993). Because STMs are more of a conceptual framework than a methodology per se, they open up analytical spaces compatible with multiple investigative and interpretive strategies. As such, their use does not commit a researcher to specific field methods or models of social critique. Accentuating the messy entanglements of social and biophysical processes encourages new ways of seeing landscapes and enables the improvisation of narratives previously not imaginable.

Figure 3.6. The Integrative, Interactive and Iterative (III) Framework (from Wohl et al., 2014) conceptualizes the iterative process through which socio-biophysical landscapes evolve. Social, biological, and physical processes interact to drive landscape adjustment after a perturbation. Perturbations can be of social, political, or biophysical origin. Human actions – in the form of policy responses, the adoption of new preventative measures, or shifting social relationships – combine with environmental processes to shape response and recovery trajectories. The right-hand side of the image shows that, for a given site, interactions among drivers, processes, and conditions can lead to different system states (analogous to an alternative stable state).

In geography, the Integrative, Interactive and Iterative (III) Framework for Human Landscape Change (Chin et al., 2014; Lach, 2014; Wohl et al., 2014) represents a new interdisciplinary strategy that views socio-biophysical landscapes as produced by complex relational networks of physical, social, and biological processes (cf. Murdoch, 1997). Like the AM, it understands that human interventions reshape landscapes and their capacity to recover from disturbance events. Figure 3.6 presents the state-based approach embodied by the III Framework and describes how it conceptualizes environmental changes. Wohl et al. (2014:22) likened states to alternative stable states in ecology, observing that cross-scale interactions among different components can transition landscapes toward a qualitatively different condition.

It is unclear, however, if the III Framework stands as the most viable option for CPG-inspired analyses. Most pressingly, while it acknowledges that social processes play a crucial role in structuring landscapes, it has an implicit technocratic orientation that may be incompatible with the use of critical theory, which implores us to pay attention to the power relations and uneven political economic arrangements that frequently mold socio-biophysical arrangements. In addition, although Wohl et al. (2014) recognize that nonlinear behaviors are characteristic of ecological, geomorphic, and social systems, the III Framework's integration of and compatibility with concepts of nonlinear dynamics are understated. Spatially complex form–process dynamics emerging from the spatial heterogeneity of biophysical conditions or social relations, drive landscape adjustments, and this often violates assumptions of linearity. Explaining landscape dynamics means investigating the spatial netting of biophysical and social processes without invoking *a priori* assumptions about adjustment trajectories (cf. Bestelmeyer et al., 2011a). Because STMs are used to identify *possible* landscape adjustment trajectories, it is critical that we adopt a theoretically pluralistic epistemology when employing them so that we do not overlook potential transitions.

A methodological dilemma also lies at the III Framework's core, specifically its proponents' commitment to developing common metrics to quantify biological, geomorphic, and human systems. This reflects a tendency among many geographers to place greater trust in numbers (e.g. Porter, 1996) than in qualitative forms of knowledge (see also Kennedy, 1979). This gesture, however, conflates statistical significance and qualitative significance (Ziliak and McCloskey, 2004). This is not to discount the importance of biophysical field measurements. Rather, it is to suggest that qualitative data, which human geographers rely upon, can be as informative about how particular biophysical realities materialize as data points that are represented numerically. While the III Framework erases the ontological partitions that geographers have used to separate biophysical and social spheres, it retains the methodological dualisms that placed physical and critical human geographers at odds with one another. STMs are expansive enough to help move us beyond this qualitative–quantitative divide.

One strategy to dissolve this methodological antagonism is to recognize that different actors experience and narrate the landscape variably – numbers cannot tell the entire story. Leach et al. (2010), writing about zoonotic diseases, developed a pathways approach to unpack how different social, technological, and environmental variables influence the governance of emerging infectious diseases (see also Leach and Scoones, 2013; Wood et al., 2012). They observed: "the emergence of infectious diseases, and their spread and impact, relate to how pathogens interact with a complex of social, technological, and environmental processes" – these processes can interact with one another, sometimes nonlinearly and typically in context-specific ways (Leach et al., 2010:371). This framework accords a central role to narratives, seeing them as critical instruments for representing and framing the dynamics of social-ecological-technical systems. Here, narrative framings inform policies and the management response to infectious diseases. Narratives can originate from different perspectives, are often inflected with political motivations and power dynamics, and therefore are not neutral instruments. What this suggests is that an STM framework for socio-biophysical landscapes needs to account for (1) the impact different narratives have on framing landscapes and their effects on distributing – or rescinding – agency and power among human and non-human actors, and (2) a commitment to reflexive, composite narrative development that meshes quantitative and qualitative data so that tentative conclusions about what catalyzes state transitions can be ventured (see e.g. Bryant, 1998; Carr and McCusker, 2009; Forsyth, 2003; Knapp and Fernandez-Gimenez, 2008; Mitchell, 2002; Robbins, 2006, on issues of expert and lay knowledge production – a full consideration of knowledge politics is beyond this paper's scope).

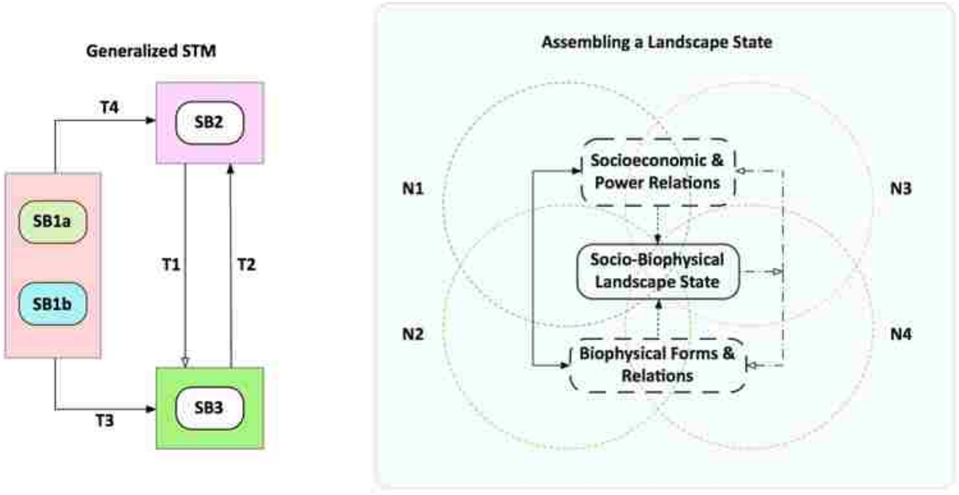


Figure 3.7. SB: socio-biophysical state; T: transition processes or drivers; N: narratives that frame perceptions of and interactions with the social and biophysical elements of landscapes. The left-hand side illustrates a generalized state-and-transition model (STM). Individual socio-biophysical states may have a single phase or multiple phases, as is the case with SB 1A/1B. On the right is a detailed representation of the drivers that interact to create socio-biophysical landscape states. The slight blue tinting around the right panel suggests that researchers' critical disposition influences their interpretations (i.e. critical reflexivity). Although represented as distinct, states are often characterized by blurry, indistinct boundaries – every state has a bleeding edge.

Bringing all of the conceptual frameworks I have discussed so far into conversation with one another has inched us toward a strategy to understand complex landscapes that has purchase for human and physical geographers alike. Figure 3.7 imagines what an integrated STM for socio-biophysical landscapes looks like. The left-hand side of Figure 3.7 generalizes the dynamics of state transitions. As with purely biophysical STMs, a landscape can occupy any number of states. Transitions emerge when significant changes impact the dominant process regimes – that is, process shifts can be materially transformative. Transitions may have a biophysical origin, a social origin, or in many cases, emerge from the complex interplay of social and biophysical processes. Taking a cue from ANT, this framework proposes that social and biophysical processes do not operate harmoniously – their scales of operation are varied, and function according to different temporal and spatial rhythms. A defined socio-biophysical landscape state is a space in which biophysical phenomena are exposed to and modified by a far-reaching relational network of social and biophysical processes. Some processes act directly upon the landscape. But if multiply-sited and -scaled political economic factors are at work, their effects may be materialized through a series of indirect translations (e.g. Law, 1992). For simplicity, the general framework retains the nested box-and-arrow diagrams to summarize states and landscape transitions. Although imperfect, this compartmentalization makes analysis tractable and emphasizes that social and biophysical objects are rarely on a completely symmetrical footing (Castree, 2002).

The right-hand side of Figure 3.7 decomposes individual states into their social and biophysical components. This is done for analytical concision. There are rarely neat demarcations between biophysically and socially networked processes. However, the underlying strategy in retaining these distinctions is to maintain a framework flexible enough to support analyses that consider biophysical processes or events in isolation – if the researcher choses to do so (see next section). Starting on the right-hand side and working outward, a socio-biophysical landscape state emerges out of the recursive and enfolded interactions between social and biophysical processes. The modification of landscapes drives changes in biophysical processes, which in turn creates new pressures that generate further landscape modifications. Socioeconomic and power relations is a category that encompasses human inputs and feedbacks – there may be varying levels of mediation and networking among social structures, humans, and the physical landscape (see Agrawal, 2001; Ostrom, 2007, 2009, for examples of metrics to describe socioeconomic relations). Relational – or topological – analysis aims to understand 1) how particular socio-biophysical relations emerge, 2) under what conditions landscape states remain resilient despite their constitutive relations being re-permutated continuously, 3) why threshold-crossing events take place, and 4) the role accorded to narratives in catalyzing material transitions (cf. Martin and Secor, 2014).

Human perception and narratives that frame landscapes shape their objective realities. Not all narratives exert commensurate influence, however, and the variable opacity of the dotted lines that represent narratives indicates that some stories wield more power than others in sculpting the material landscapes. Narrative is construed doubly, here – on the one hand, narratives are used to connect disparate strands of knowledge in the STM itself (during modeling); on the other hand, actors populating socio-biophysical landscapes frame their concepts of landscapes using narratives, which in turn structures the co-adjustment between social and biophysical processes (e.g. Carr and McCusker, 2009; McCusker and Carr, 2006). Landscape states have objective realities, and there are multiple ways to unpack these. Looking at how those realities are socially framed can reveal what the key social drivers of landscape change are (Leach et al., 2010; Wood et al., 2012). Future investigations should prioritize the role narratives play in catalyzing state transitions and how the spatially uneven mobilization of narratives by actors differently invested with power affects this process. When researchers write up analytical narratives to describe their findings, a pragmatic spirit should filter through their effort, one that privileges the scrutiny of empirical data, a commitment to open inquiry, and the acknowledgement that all knowledge claims are provisional (e.g. Koopman, 2013; Misak, 2013). Analytical narratives used to describe landscape states must also be attentive to multiple forms of knowledge production. This leaves room for researchers to experiment with and improvise multiple modes of critical biophysical or theoretical explanation that leverage quantitative methods and qualitative analyses. How these narratives are assembled and how methods are fused, is very much a contingent matter, dependent on the research goals and the landscape being studied. Blue tinting around the right-hand panel suggests that researchers' critical disposition influences their interpretations. Indeed, getting around issues of reflexivity is not possible. We need to remain attentive to how our theoretical prisms let us see – or not see – specific patterns on the landscape. Following Law, my intention is to encourage deeper, more pluralistic explanations by tracing the "webs of heterogeneous material and social practices" that coalesce through and are implicated in the emergence and transient stabilization of particular landscape states (2009:151; see also Fukami and Nakajima, 2011). Sometimes this means adopting a comprehensive view that places social and biophysical phenomena on an equal footing. But in other cases, it could mean being attentive to just the biophysical domain – for example, a river may be the node in a network of hydrogeomorphic process relations that lack the (consequential) imprint of social processes (cf. Inkpen, 2011).

3.5 Toward a Critical (Physical) Geography

Using STMs to represent how socio-biophysical settings are assembled and reassembled as biophysical and social processes interact with one another can push us toward a more critical physical geography. This paper responds to the issues raised by Tadaki et al. (2014) about nurturing critical practices in physical geography. Following their lead, this paper speaks to what it means to perform critical work. For them, "being critical is less about *opting in* to a particular subset of interests and more about *taking deeper responsibility* for the meaning of our practices…Cultivating critical practices is about making visible the invisible and exploring how steps can be taken to instigate substantive applications and outcomes" (Tadaki et al., 2014:10–11). STMs that direct critical attention toward the social framings and narrative descriptions of landscape states can illuminate the relationship between power-inflected narratives and policies and the materiality of landscape (Leach and Scoones, 2013). The relational work they perform can rematerialize the invisible. While this is vital, important work, I close by arguing that our reading of the term "critical" has profound implications for the future trajectory of CPG. "Critical," I suggest, should be read in a pluralistic and expansive light if we are to successfully engage a broad cross-section of physical and human geographers.

CPG promises an opportunity to fuse different explanatory modes. Yet it would be misleading to equate criticality with the integration of social theory, *tout court*, into narratives about socio-biophysical landscapes. Looking back at the past 100 years, for example, reveals a progressive effort on the part of scientists to understand and theorize the uncountable sources of complexity that influence landscape dynamics and evolution. Arguably, the shift away from reductionist tendencies in scientific investigations, which sought out inviolable physical laws and universal theories to explain physical landscapes, testifies to the fact biophysical scientists have reflexively analyzed their practices and now acknowledge the role complexity, contingency, and unexpected disturbances play in shaping the landscape *and* how epistemological shifts open up new modes of interpretation (e.g. Levin, 1999; Mitchell, 2009; Phillips, 2006, 2007; Scheffer, 2009; Stallins, 2006; Taylor, 2005). Successive refinements of theory and method like these qualify as critical interventions, and attest to the – ongoing – critical work of biophysical scientists. STMs provide a framework to grapple with biophysical processes *and* underlying political economic structures, power relations, and cultural struggles. As such, they can deepen environmental narratives and histories and demonstrate that our organization of data, knowledge, and stories is itself a task that amplifies our ability to develop critical insights into everyday landscapes.

That STMs have affinities with explanatory frameworks political ecologists have used suggests this approach could serve as a kind of meeting ground, an approach that yields a holistic yet critical explanatory mosaic. James's observation, which I opened up this paper with, that life is in the transitions signals the pragmatic underpinning of the framework described here. The relational work STMs perform lets researchers identify new connections between phenomena, and their variability across spatial and temporal scales. Their supplemental narratives can be used as experimental spaces in which researchers can work out more pluralistic explanations of environmental change. Because STMs open up a conversational space in which to understand socio-biophysical landscapes, they will ward off applications of social theory that can be hurried or superficial (Blomley, 2006). Moving forward, practitioners adopting STM frameworks will need to meld a *critical* awareness of social dynamics with a *critical* understanding of the practice of biophysical science and of biophysical processes. CPG can accommodate multiple forms of criticality – a sediment pulse may have just as much to do with purely biophysical dynamics (e.g. excess overland flow, erosion) as it does with contested social phenomena (e.g. clear-cutting in top-down development schemes that uproot and displace disempowered populations). Thinking like a critical physical geographer means figuring out how to weigh competing narratives and how to arrange them into an explanatory assemblage that judiciously weighs the biophysical and social contributions to landscape change, all while anticipating the most likely adjustment trajectories under a range of scenarios (e.g. Coreau et al., 2009). If used pragmatically, reflectively, and reflexively, STM frameworks can revitalize geography and re-energize it as a discipline characterized by a holistic outlook – that is, transitioning it back to what it has purported to be all along (Archer, 1995; Turner, 2002; see Malanson, 2014).

Table 3.1 List of Representative State-Transition Articles.

Fluvial geomorphology
Channel patterning/planform thresholds Beechie and Imaki (2014); Begin (1981); Bledsoe and Watson (2001); Burge and Lapointe (2005); Carson (1984); Chang (1979, 1986); Chitale (1973); Church (2002); Dust and Wohl (2010); Eaton et al. (2010); Ferguson (1987); Leopold and Wolman (1957); Lewin and Brewer (2001); Mueller and Pitlick (2013, 2014); Parker (1976); Podolak (2013); Van den Berg (1995); Van den Berg and Bledsoe (2003)
Qualitative state transitions (including dam and urbanization effects) Beechie et al. (2008); Benn and Erskine (1994); Bull (1979); Burchsted and Daniels (2014); Burge and Lapointe (2005); Burkham (1972); Cannatelli and Curran (2012); Chin (2006); Chin and Gregory (2001, 2005, 2009); Dean and Schmidt (2011); Doyle et al. (2000, 2002, 2003); Dust and Wohl (2010); Elliott et al. (1999); Erskine (1986); Fryirs et al. (2012); Graf (1977, 2001, 2005, 2006); Gurnell et al. (2007); Hawley et al. (2012); Nadler and Schumm (1981); Phillips (2013a, 2013b); Pizzuto (2002); Schumm (1969); Schumm et al. (1984); Simon (1989, 1992, 1995); Surian and Rinaldi (2003); Violin et al. (2011); Wolman (1967); Xu (1996); Ziliani and Surian (2012
Fluvial biogeomorphology Burkham (1972); Francis et al. (2009); Graf (1978); Gurnell and Petts (2002); Gurnell et al. (2001, 2012); Heffernan (2008); Heffernan et al. (2008); Kim and Phillips (2013); Perry et al. (2012); Rountree et al. (2000)
Limnology Carpenter (2005); Carpenter and Cottingham (1997); Carpenter and Pace (1997); Carpenter et al. (1999); Hansen et al. (2013); Petersen et al. (2008); Scheffer et al. (1993)
Coastal/aeolian geomorphology Austin and Masselink (2006); Barchyn and Hugenholtz (2013); Lippmann and Holman (1990); Loureiro et al. (2012, 2013); Masselink and Short (1993); McLachlan et al. (2012); Scott et al. (2011); Short (1979); Sonu (1973); Wright and Short (1984)
Soil geomorphology Phillips (2011, 2014)

Table 3.1 (continued)

Ecology (non-rangeland) Bagchi et al. (2012); Dublin et al. (1990); Fukami and Nakajima (2011); Hemstrom et al. (2007); Huggett (2005); Perry and Enright (2002); Quétier et al. (2007); Wainwright (1994); Zweig and Kitchens (2009)
Marine/aquatic ecosystems Bertness et al. (2002); Collie et al. (2004); de Young et al. (2008); Dudgeon et al. (2010); Knowlton (1992, 2004); Mumby (2009); Mumby et al. (2007); Nyström and Folke (2001); Perry and Smithers (2011); Perry et al. (2008); Petersen et al. (2008); Petraitis and Dudgeon (2004); Petraitis and Hoffman (2010); Smith et al. (1999); Steele (2004); Viaroli et al. (2008)
Overviews and Methodological Strategies Andersen et al. (2009); Groffman et al. (2006); Muradian (2001); Rietkerk et al. (2004); Scheffer (2009); Scheffer and Carpenter (2003); Scheffer et al. (2001); Scheffer et al. (2009) Schöder et al. (2005); Steele et al. (2012); van de Koppel et al. (2001)
Ice sheets Solgaard et al. (2013)
Restoration Grant 2006; Standish et al (2009); Yates and Hobbs (1997)

Chapter 4 – Landscape Memory in a Time of Amnesia: Recovering the Clark Fork River at Milltown, Montana

4.1 Introduction

One of the most fraught challenges of river restoration is selecting a channel design compatible with the ambient geomorphic conditions. Numerous case studies have recorded the disappointing or mixed outcomes of restoration projects that reconfigured stream alignment and geometry in an effort to improve the ecological and geomorphic resiliency of degraded channels (Kondolf, 1995; Kondolf et al. 2001, Miller and Kochel, 2010; Bernhard and Palmer, 2011; Doyle and Shields, 2012; see also Roni et al., 2008). Despite uncertainty over the long-term performance of “rehabilitated” channels, dam removal is a restoration technique that holds promise for reconnecting fragmented ecosystems and reestablishing natural hydrogeomorphic fluxes (Bendarek, 2001; Poff and Hart, 2002; Hart et al., 2002; Doyle et. al, 2005; Burroughs et al., 2010). Studies of post-dam removal channel responses have mostly focused on the upstream evacuation of reservoir sediments and morphological changes to upstream and downstream river segments (e.g., Doyle et al., 2003, 2004; Burroughs et al., 2009; Neave et al, 2009; Wilcox et al., 2014). But restoration projects combining dam removal, environmental remediation, and channel reconstruction remain understudied – in part because there are so few examples. Focusing on a 5 km stretch of Clark Fork River near Milltown, Montana, which as part of a broader restoration project combined remediation and dam removal with floodplain and channel construction, this paper explores debates surrounding channel design. It highlights the river’s short-term response after the river was restored following Milltown Dam’s removal in 2008.

Located just outside of Missoula, Montana (Figure 4.1), the study reach is part of the largest Superfund complex in the United States. Throughout the 20th century, the reservoir created by Milltown Dam was a sink for arsenic and other heavy metals, which contributed to groundwater contamination and motivated the decision to remove the structure. After the dam was taken out, a new meandering channel was built on the just-created floodplain, prompting criticism from geomorphologists, who argued the river design lacked a historical precedent, and elevated aesthetics over hydrogeomorphic functionality (Kondolf, 2006; Woelfle-Erskine, 2008; Woelfle-Erskine et al., 2012; see also Cluer and Thorne, 2014). Although typically cast as a single-threaded channel, the as-built design is more accurately termed a hybrid meandering planform, one that combines a sinuous main channel with branching secondary channels and distal wetlands (cf. Nanson and Knighton, 1996; Desloges and Church, 1989). Morphologically, a hybrid gravel-bed river falls between a single-threaded channel and a wandering planform. Critiques of the restoration prompt two questions. Does the chosen design stand as a justifiable baseline hypothesis – based on historical evidence – for the type of river that the valley setting could accommodate? Second, based on the morphological adjustments that have taken place since flow was diverted into the restored channel, what patterns of channel evolution are likely to occur?

Figure 4.1. Image of the restoration area. Taken in August 2011, this picture marks the location of two avulsions. The rectangles bound the extents of the upstream and downstream avulsions, respectively. Milltown Dam was located in the extreme upper-right portion of the image (Map Source: United States Department of Agriculture, ESRI).

Using historical evidence, I demonstrate that Clark Fork River was a predominantly single-threaded channel during the late-19th century in most of the study area, suggesting the implemented design falls within the historical range of variability (Wohl, 2011; cf. State of Montana, 2005, 2008; Woelfle-Erskine et al., 2012; see also Brierley and Fryirs, 2005; Fryirs et al., 2012). Having established this historical precedent, the river's post-restoration morphological adjustments are discussed. Using this as a springboard, a descriptive STM is developed to hypothesize possible channel evolution pathways the river may follow. STMs provide a framework to think through questions about river repair because they can account for the multiple contingencies that can influence rivers' future range of variability (cf. Brierley and Fryirs, 2008, 2009). They also encourage a relational method of landscape interpretation that blends historical analysis with scrutiny of contemporary dynamics. In asking what adjustment pathways are possible, they can inform new management strategies that focus on the spatial variability of channel evolution (Kondolf et al., 2001; cf. Montgomery, 2008;Steele et al. 2012). The Clark Fork River's hybrid meandering form is one possible (transient) state that could materialize and persist on the landscape (e.g., Fukami and Nakajima, 2011; Fryirs and Brierley, 2013; Beven, 2015). An STM-based framework sheds light not only on the Clark Fork River's evolution, it demonstrates that the application of state-transition thinking can assist environmental agencies in developing context-based management plans that lead to better river futures (Brierley and Fryirs, 2008; Brierley et al., 2013).

4.2 The Geomorphic Setting

The Clark Fork River's headwaters emerge near Butte, Montana as Silver Bow Creek. From Butte, the river flows north before turning to the west-northwest, eventually reaching its outlet at Lake Pend Orielle. Key tributaries emptying into the Clark Fork upstream of Milltown include Flint Creek and Warm Springs Creek. Another small tributary – Deer Creek – intersects the Clark Fork in the study area, which is located approximately 10 km upstream of Missoula and encompasses a stretch of river that is ≈ 5 km long. Milltown Dam was located immediately downstream of the confluence of the Clark Fork and Blackfoot Rivers. Above the study area, the Clark Fork Watershed drains

≈ 9,500 km^2. Characterized by a semi-arid climate, annual precipitation amounts vary little throughout the Upper Clark Fork Watershed. Butte receives ≈ 325 mm of precipitation each year, while Missoula receives ≈ 350 mm. The river's hydrograph peaks sharply – typically in May or June – owing to a combination of snowmelt and late-spring rainfall.

The Clark Fork is a gravel-bed river that exhibits considerable morphological diversity upstream of the study area. Interstate 90 runs parallel to the Clark Fork for much of its length. In many locations it, or railroad grades, provides a key structural control limiting the river's lateral movement. The planform varies considerably, with reaches alternating between straight, meandering, and wandering patterns (Desloges and Church, 1989; Church and Rice, 2009). With the exception of Butte, there is little urban development in upstream portions of the watershed. 65 percent of the watershed is covered by conifer forest, with another 20 percent of its area given over to agriculture, shrubland, and grasslands. Sediment loadings have fallen significantly since the late-19th and early-20th centuries. Near Butte, Evermann (1892) described the waters of Silver Bow Creek as having "the consistency of thick soup, made so by the tailings it receives from the mills at that city" (p. 18). As industrial activity diminished, the amount of tailings, sediment, and other mining byproducts conveyed by the river also waned.

In the study area, alluvial deposits occupy the valley floor. This alluvium is comprised of inter-bedded sand, gravel, and boulders, and clay lenses (Woessner, 1995). The most common rock type is quartzite derived from the Belt Supergroup. Flanked by the Sapphire Mountains to the south and the Garnett Mountains to the north, the ranges' exposed bedrock is also of the Belt Supergroup and is composed of siltite, argillite, quartzite and limestone metasediments (Woessner, 1995; Berg, 2006). Although the area was exposed to repeated episodes of glacial outburst flooding during the later Pleistocene (e.g. Baker, 2009; Alho et al, 2010), what few boulder deposits remain are situated downstream of the study area and exert no morphological control over the river (Berg, 2006).

4.3 The River's Architects – Historical Background

Word of the Milltown Dam's possible construction spread in early 1905 when agents of copper magnate William Clark began to explore whether Missoula, Montana, could support an electric streetcar system (Quivik, 1984; see also Swibold, 2006). Construction began later that year and wrapped up by the end of 1907, with the dam and its power plant first generating electricity on 9 January 1908. What emerged on the Clark Fork River was an intermediate-sized run-of-the-river dam that measured ≈ 12 m high and supplied power to local sawmills, Missoula, and an electric streetcar that ran between Missoula and Milltown (Brooks, 2012). Six months after the dam was completed, triggered by a wet spring and late-season snowfall, the flood of record swept through the Upper Clark Fork Watershed. The 1908 flood's discharge near Missoula approached 1,360 $m^3 s^{-1}$. Although unknown at the time, the 1908 flood washed immense quantities of arsenic, copper, lead, zinc, and other heavy metals – byproducts of upstream copper mining near Butte – into the dam's reservoir. Acting as a sink, contaminant deposition persisted in the reservoir during the 20th century, with between 590 and 740 MT of arsenic settling into its bottom sediments each year (Moore and Woessner, 2003). All told, 5.04 million cubic meters of polluted sediments accumulated in the reservoir and the river's adjacent floodplain. However, it was not until 1981 that environmental sampling revealed that arsenic had infiltrated into the aquifer that provided drinking water to the nearby community of Milltown.

Due to groundwater contamination, Milltown was designated a Superfund site in 1983 (EPA, 2004). The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) established the Superfund program; this vested the federal government with the authority to remediate abandoned and uncontrolled hazardous waste sites[6]. During the 1980s and early 1990s, the Environmental Protection Agency (EPA) investigated remediation options for Milltown. Initially, the EPA and the liable corporations (chiefly, the Atlantic Richfield Company [now a subsidiary of British Petroleum]) did not endorse dam removal. A 1996 ice scouring event, however, increased the urgency to find a permanent solution. In February of that year a sharp cold snap hit much of western Montana, prompting the formation of significant ice floes on the Blackfoot River. As ice traveled downstream, the reservoir level was lowered to avoid

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[6] The Upper Clark Fork Watershed stands as the largest Superfund complex in the U.S.

fracturing the dam's structure, releasing sediment-laden water downstream containing significant quantities of copper and other metals. Ultimately this produced large declines in multiple trout populations (EPA, 2002).

This event renewed conversations about how to address contamination, and was one of the catalysts behind the Clark Fork Coalition's – a Missoula-based environmental advocacy group – campaign for dam removal. Removing the dam, they argued, would remediate groundwater supplies and restore the habitat of the bull trout (*S. confluentus*), a species whose abundance had fallen sharply due to habitat fragmentation caused by the installation of multiple dams along the Clark Fork (Thompson, 2011; Brooks, 2012). Buoyed in part by increasingly vocal public support across the political spectrum, the EPA formally prescribed dam removal in 2003. The final record of decision released in 2004 outlined a comprehensive remediation and restoration plan for the Clark Fork River at Milltown. Although there are many facets of this story that are intriguing and have implications for how we understand the interplay of political, social, and economic drivers of restoration (see EPA 2003, 2004; DeSilvey, 2010; Gilbertz and Milburn, 2011; Brooks, 2012; and Tyer, 2013; which all contain accounts of the sociopolitical and economic issues related to dam removal), these lie outside my current focus on questions of channel design and restoration.

4.4 Materials and Methods

Unfortunately no photographic image of the study area before dam construction is known to exist. Piecing together the river's historical form hinges on the use of multiple written sources and artistic records. Previous attempts to determine river state before Milltown Dam was built have proven inconclusive (Woelfle-Erskine et al., 2012; State of Montana, 2005, 2008). My historical analysis centers on resources that have not been thoroughly examined, particularly Government Land Office survey notes and field maps dating from 1870 (GLO, 1870, 1883, 1884 1892, 1893, 1901, 1903). These notes and maps were the product of cadastral surveys that identified public land boundaries in the U.S. Their principal intent was to mark boundaries – as such, the quality of descriptions of the biophysical landscape varies considerably. The surveys encompass an area within 2-5 km of the confluence (in the upstream direction), and therefore offer a gauge of the river’s morphology during this period. To supplement this information, in July 2014 I mapped relic tree stumps throughout the lower restoration area (n = 662) using a Trimble GeoXH 6000. The postprocessed accuracy for horizontal and elevation data was < 50 cm for 97% of the positions. The unearthed tree stumps preserve a record of the pre-dam floodplain and were mapped to corroborate qualitative historical analysis and evaluate the suitability of the channel design (Thomas-Van Gundy and Strager, 2012). No formal dendrochronological analysis was performed; simple tree ring counts performed on site revealed trees 75-125 years old, with one specimen being ≈ 300 years old. Stumps were found across the entire surface of the excavated reservoir (Figure 4.2). Sedimentological data stems from cores taken in 2003–2005 (Envirocon, 2004, 2005). Sediment samples were collected using sonic drilling, a technique that entails using resonant energy, rotation, and minimal down force to push a core sample barrel into the soil profile and drill boreholes. The depth of retrieved cores ranged from ≈ 3.5 m to 17.5 m. The accuracy of sediment depths was +/- 0.6 m for all bores, irrespective of location. Cores were taken to describe and classify sediment, identify soil horizons, and perform chemical testing to determine levels of contamination. USGS maps and photographs taken during the early stages of the dam’s construction were used to validate interpretations.

To document the contemporary geomorphic adjustments along the restored channel, I rely on qualitative observation of channel response, planform mapping of primary and secondary channels, longitudinal profile analysis, and interviews with project stakeholders. For planform analysis, the bankfull channel boundaries in 2012 and 2014 were digitized. Channel boundaries were also digitized for 2011 and 2013 from images captured during baseflow. The 2011 aerial image had 1-m resolution, and was digitized at 1:500 scale. For the 2012-2014 images, channel lines were sketched at 1:500 scale; image resolution was 50 cm. Changes in water surface slope and thalweg gradient were assessed using longitudinal surveys performed in 2010 (representing the as-built condition) and June 2013, respectively. The June 2013 survey used a survey-grade GPS for above-water measurements and a single-beam echo sounder to perform underwater measurements (e.g., Flerner et al., 2012; Javernick et al., 2014). 2010 data are accurate to +/- 0.3 m, while 2013 data are accurate to +/- 0.1 m. The study area was broken into reaches according to construction phase (restoration moved from upstream to downstream). Reach-averaged slopes were calculated to identify significant adjustments. In 2013, cross sections (n = 62) were taken at various points on secondary channels to characterize channel geometry and gradient. All survey methods followed the procedures described by Harrelson et al. (1994).

Figure 4.2. (a) During remediation, excavation activities uncovered numerous trees beneath the former reservoir's surface, indicating where the historical floodplain previously resided. Trees identified included cottonwoods and ponderosa pine. (b) Over 600 relict tree stumps populate the lower portion of the restoration area today. Tree diameters range from <20 cm to > 1m.

4.5 Historical River Interpretation – What Kind of River Existed Here?

The confluence of the Clark Fork and Blackfoot Rivers was known to the Salish and Pend d'Oreille people as Naaycčstm – the "Place of the Large Bull Trout" (Smith, 2011). Before widespread industrialization and dam construction in the Clark Fork Watershed, the area was renowned for abundant bull trout and the fishing opportunities it offered Indigenous populations. The first written descriptions of the river came from the Lewis and Clark Expeditions (see State of Montana 2005; Woelfle-Erskine et al., 2012); the earliest preserved image of the confluence is a sketch by Gustav Sohon, the resident artist on the Mullan Expedition. Previous discussions focused on the stylized lithographic reproduction of this drawing, which overlooks the subtleties of the original rendering. Figure 4.3 shows Sohon's original drawing – the Clark Fork, portrayed as a single-threaded channel, occupies the right foreground, while upstream segments recede into the middle distance. A mix of trees drapes the floodplain's edges: cottonwoods, scattered pines, and an understory seemingly populated by willows. Terraces occupy the image's background, with fewer trees dotting the steeper slopes. While artistic representations can be unreliable and imperfect, later accounts and floodplain mapping confirm the verisimilitude of this illustration.

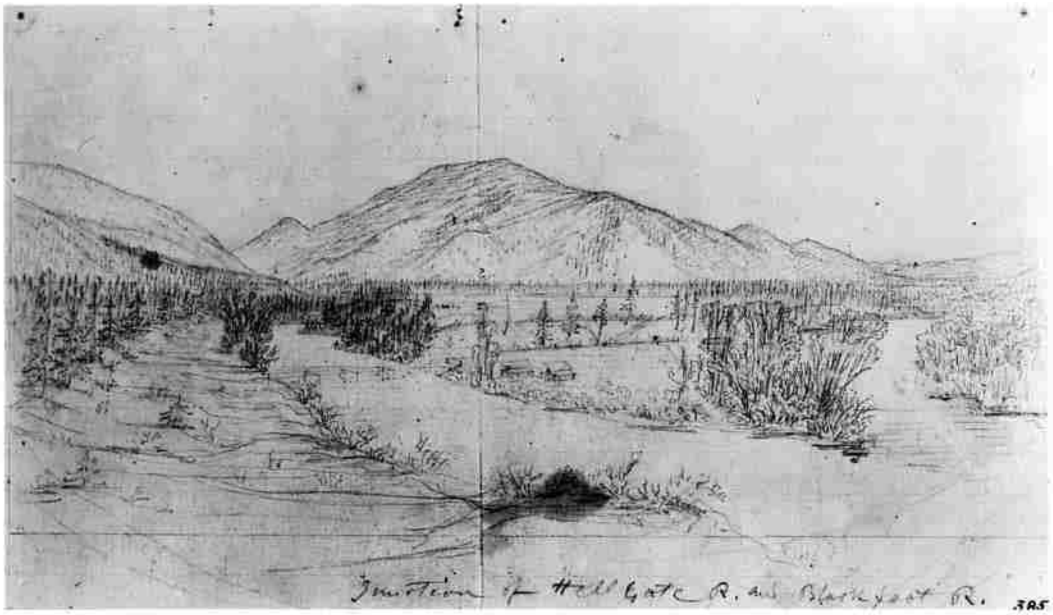

Figure 4.3. Gustav Sohon's Sketch of the Clark Fork River–Blackfoot River Confluence, c. 1862.

Table 1 summarizes information derived from GLO survey records. Based on surveyors' notes, it does not appear that significant morphological adjustments took place from the early 1880s into the early 1900s. The total width of a reach ≈ 5 km from the confluence was estimated at 225 m in 1901. However, this included two channels, ≈ 18 m and ≈ 60 m wide, respectively, with a gravel island with dense undergrowth between them. Previous surveys only made note of the 60-m wide channel. Riparian vegetation included willow (*Salix spp.*) in the understory and cottonwoods (*Populus spp.*) and pines (likely *P. ponderosa*) in the overstory. Survey notes of 1883 included the diameters of two cottonwood trees. One measured ≈ 35.5 cm in diameter, the other ≈ 76 cm. The 1901 notes were the first to mention sediment concentrations, with the surveyor noting, "The Hell Gate [Clark Fork] River crosses the township from east to west. The water in the river [is] heavily charged with sediment and tailings from the Butte and Anaconda smelters." Soil along the valley bottom was generally characterized as first and third rate. A designation of first-rate generally applied to soils suitable for agricultural production.

The 1892 and 1903 surveys described an area of the river ≈ 2 km upstream from the confluence, which is more proximate to the portions of floodplain and channels that underwent the most significant reconstruction. Here, the mainstem was ≈ 40 m wide, although the 1901 survey notes describe an area ≈ 160 m wide that was vulnerable to overbank flooding. Nearby, Deer Creek, a small tributary intercepted by the Clark Fork's left bank, measured ≈ 12 m across, with first- and third-rate soils throughout the area (notes remarked upon the presence of gravels and cobbles). Vegetation composition and community structure were similar to the upstream reach. The 1903 survey notes described a slough 75 links wide (≈ 15 m) adjacent to the Clark Fork's left bank, roughly along the line of township sections 21 and 28, near Deer Creek – this slough also appeared on the line dividing township sections 27 and 28 (Figure 3) [7]. Observation of this feature is critical for resolving the discrepancies between maps produced by the GLO and a 1903 map created by the U.S. Geological Survey (USGS).

Uncertainty over historical channel form have stemmed from the representational asymmetry of survey maps produced by the GLO and U.S. Geological Survey (USGS). The State of Montana's restoration documents noted that "maps surveyed by the [GLO] (1880s) and the U.S. Geological Survey (1903) provided differing interpretations of the Clark Fork River channel planform," with GLO maps depicting a single-threaded channel

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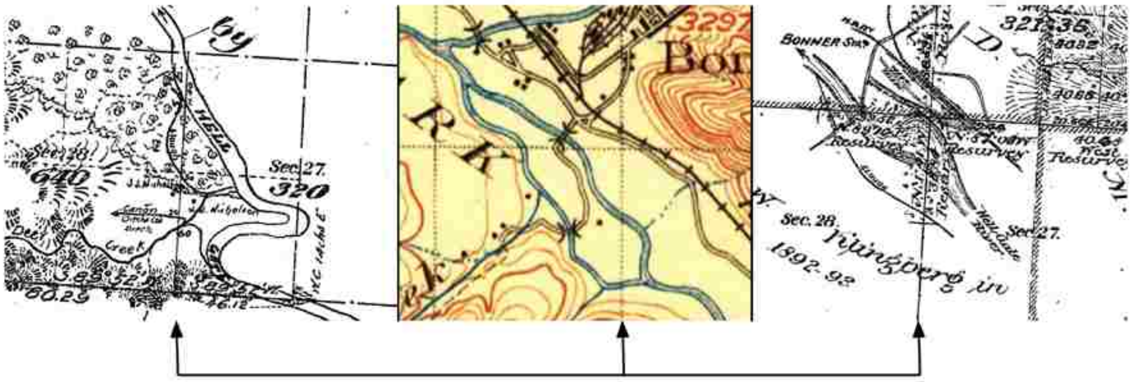
[7] The North American definition of "slough," which dates to the early-18th century, is "a side channel of a river, or a natural channel that is only sporadically filled with water" (Oxford English Dictionary). My interpretation of the historical morphology relies on this definition, and it assumes a surface connection between the main channel and features described as sloughs. Librarians with the Bureau of Land Management (BLM) verified that the survey notes invoked the term "slough" in this sense.

and USGS maps indicating an anabranching river (State of Montana, 2005, p. D-2). But a closer reading uncovers a slightly different story. Figure 4.4 places GLO and USGS maps side-by-side. Both GLO maps indicate that a secondary channel peeled away from the main channel's left bank (likely fed in part by Deer Creek). The 1893 map depicts a tortuous meander just upstream of the secondary channel's inlet, which is not present on the 1903 USGS map or 1905 GLO map. No other records mention this feature, so it is possible that an avulsion eliminated it and redirected flow toward the secondary channel during the late-19th century. The 1903 USGS map does not clearly show channel width or size. Nevertheless, its rendering of channel planform is consistent with GLO surveys and maps, with a secondary branch occupying the left side of the floodplain.



Arrows denote the boundaries between Township Sections 27 and 28

Figure 4.4. Comparison of 1893 GLO reconnaissance map (left panel), 1903 USGS topographical map (middle panel), and 1905 GLO reconnaissance map (right panel). Arrows point toward the line dividing Township Sections 21 and 28. This area is approximately 2-3 km upstream of the Clark Fork–Blackfoot confluence. A key reference point is Deer Creek, which enters the Clark Fork River along its south (left) bank. All maps indicate a hybrid planform, which is signified by the sloughs – intermittent secondary channels – that branch away from the mainstem. The 1893 GLO map depicts two sloughs along the river's left bank, both of which intersect Deer Creek. The 1903 USGS map shows a secondary channel intersecting and then taking on Deer Creek's flow; what is unclear is its size. Finally, the 1905 map shares affinities with the 1903 USGS map, with the slough represented as more elongated and running parallel to the mainstem. While it is not possible to entirely reconcile the maps due to uneven township section lines, these representations indicate there was some agreement between the two agencies' river surveys.

A final strategy to get a handle on pre-1905 channel morphology is to look for other markers that are suggestive of its form. Figure 4.5 maps relic tree stumps (n = 662) against the pre- and post-restoration channel (2004) and proposes a location for the historical channel. Most relic stumps were unearthed in the lower portion of the former reservoir, and are now situated on the left distal floodplain. Tree density diminishes from left to right and from downstream to upstream. Elevation data offered few clues for reconstructing the floodplain surface. Although the expected downstream elevation gradient is present, there is no cross-valley gradient. Sedimentological data were inconclusive with respect to channel location; although cores reached pre-dam alluvium

Figure 4.5. Distribution of tree stumps and proposed historical channel alignment. The large map plots relict tree stumps against the current channel as well as a hypothesized historical channel. For reference, the inset map depicts tree stumps against the river before dam removal. The proposed historical configuration is based on the distribution of tree stumps and sedimentological data collected from 2003 to 2005. Sediment cores obtained from the area between the eastbound and westbound lanes of Interstate 90 (immediately adjacent to the floodplain) did not contain any alluvium, suggesting it is unlikely the historical channel occupied that portion of the valley. The blue box indicates the presence of a bluff ≈ 15-20 m high. The historical channel – consistent with GLO and USGS maps – was likely straighter than today's river, but still exhibited hallmarks of a meandering planform (cf. Woessner, 1995).

they did not reveal a single surface that indicated exact location of the pre-dam channel. The proposed historical configuration is based on the distribution of tree stumps and sedimentological data collected from 2003 to 2005. Sediment cores obtained from the area between the eastbound and westbound lanes of Interstate 90 did not contain any alluvium, suggesting it is unlikely the historical channel occupied that portion of the valley. Deposits are consistent with a meandering or laterally active planform, with coarse basal deposits fining upwards into sands, silts, and clays. Sediment cores indicate that layers of historical alluvium rested atop of bedrock throughout the study area, suggesting that the river's lateral migrations has been inhibited by structural factors. The blue box indicates the presence of a bluff ≈ 15-20 m high. The historical channel – consistent with GLO and USGS maps – was likely straighter than today's river, but still exhibited hallmarks of a meandering planform (cf. Woessner, 1995).

What implications emerge from this? Foremost, it is unlikely that the pre-dam channel would have coincided with the position of the post-rehabilitation channel. The historical channel would have probably occupied a portion of the floodplain farther north, closer to present-day Interstate-90. For example, Woessner (1995, p. 18) located the historical channel – represented as single-threaded – in this position. And indeed, sedimentology data collected prior to dam removal underscored the presence of alluvial sediments on this portion of the floodplain (Envirocon, 2005, 2006). It does not appear that alluvial sediments were present in the stratigraphic record north of the I-90 boundary. Tree sizes (as noted), suggest a mature floodplain forest and relative stability – this is likely incompatible with a braided or a thoroughly anabranching planform given the lack of accommodation space on the floodplain (see Woelfle-Erskine, 2008). A 1905 photo snapped during the early phases of dam construction verifies that a mature floodplain forest existed upstream of the confluence. The photo, which looks upriver, reveals a floodplain stripped of trees – timber from this area was used in the dam's structure (Figure 4.6). Nestled into the background are well-developed forest patches with a mix of cottonwood (*Populus spp.*) and ponderosa pine (*P. ponderosa*). Based on ecological surveys of the exposed reservoir surface, before dam construction it is likely that willows and young cottonwoods were common in depositional settings, while mature cottonwoods, red osier dogwood (*C. stolonifera*), and ponderosa pine populated the distal floodplain and terraces (State of Montana, 2005).

Figure 4.6. Clark Fork River, Looking Upstream, c. 1905. Captured during the early stages of dam construction, this image shows the extent of floodplain forest cleared as well as mature forested areas farther upstream

Viewed cumulatively, historical records and images argue for a predominantly single-threaded mainstem before Milltown Dam was built. This indicates that a hybrid planform is one potential (and naturally occurring) river state the setting can accommodate – but not the only one. The historical reconstruction developed here is partial. But if landscapes are perfect (*sensu* Phillips, 2007a, b), our ability to reconstruct the past and make it transparent is also *imperfect* because we can never have knowledge of the entire constellation of form-process interactions responsible for their creation. To better grasp the appropriateness of a hybrid planform design in the restoration area, I examine the morphological adjustments that have occurred since the end of channel and floodplain construction in 2010.

4.6 The Contemporary Scene – Post-2010 Channel Response

By May 2011 the Clark Fork was in the midst of significant flooding that lasted for more than two months. Flows exceeded bankfull discharge (≈ 90 $m^3 s^{-1}$) for 75 days. Peak discharge at USGS Gage 12334550 (located near Turah, Montana, just upstream of the study area) was 360 $m^3 s^{-1}$. Flooding contributed to two significant avulsions – one at the upstream end the restoration zone, the other just upstream of the Clark Fork–Blackfoot confluence. Figure 4.7 illustrates the downstream avulsion site, including the main channel lines from 2011 and 2014 as well as secondary channel features from 2014. Here,

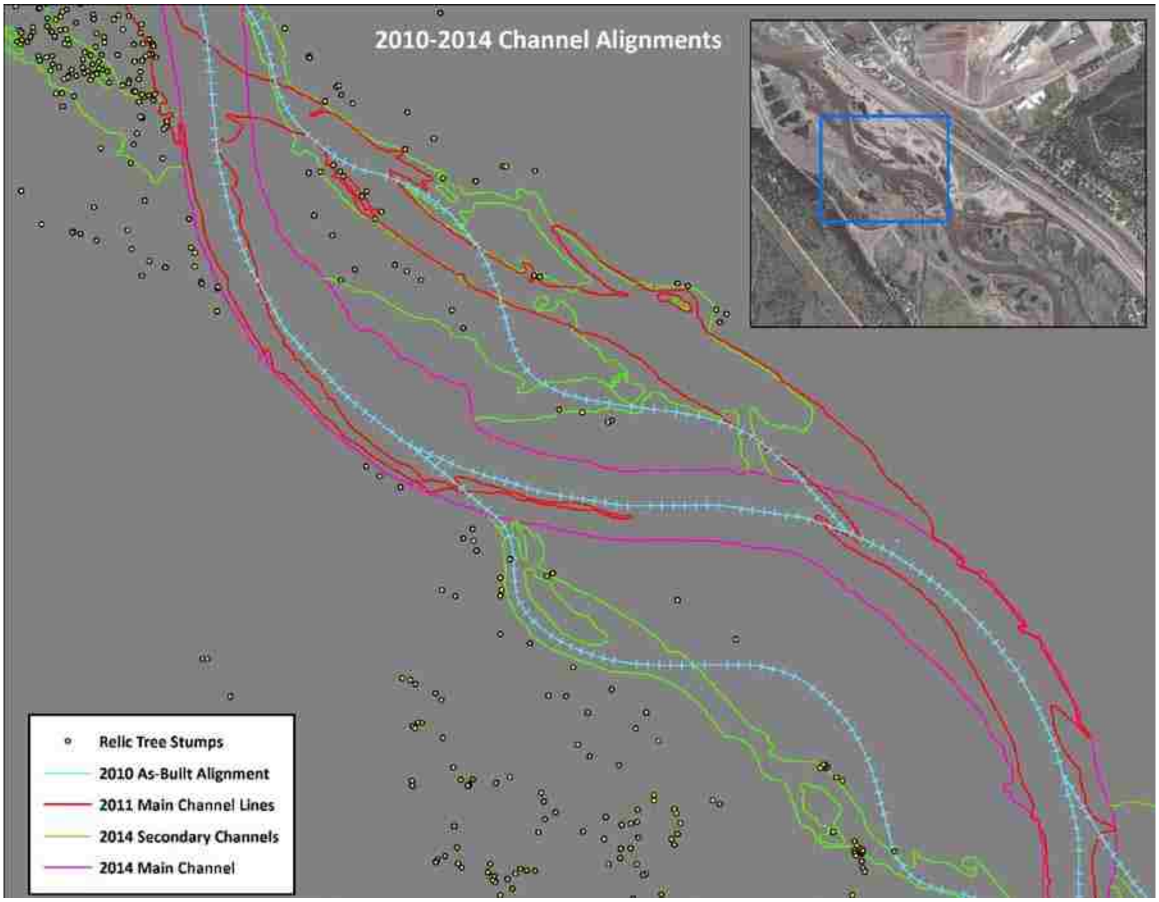


Figure 4.7. Mapping channel planform, 2010–2014. Relic tree stumps are included as a point of reference. Note that the avulsion sliced through the northern edge of the floodplain through a secondary channel. Positioning entrance of Secondary Channel 1 so near to the apex of the meander bend diverted excess water into it during the 2011 flooding. The avulsion produced a straighter channel, which was eventually repaired. Note that the current secondary channel (2014) occupies much of the space the avulsed channel previously did. Its entrance was also moved downstream slightly from its original position. Discharge was 130 $m^3 s^{-1}$ on the image-capture date 2014 channel lines were digitized from; it was 38 $m^3 s^{-1}$ for the 2011 image-capture date. The channel gradient of Secondary Channel 1 is ≈ 0.0041 m m^{-1} with localized values in the upper reaches exceeding 0.006 m m^{-1}, suggesting the possibility of future avulsive activity.

the mainstem cut a new path through Secondary Channel 1, straightening its planform and shifting the main channel toward the floodplain's northern edge. The avulsion opened up a crevasse channel through an area that experienced significant flood-induced erosion, with widespread scouring of ≈ 0.3 m and localized losses in excess of > 1 m near the avulsion node (Geum, 2012). Before undergoing repairs, the original (i.e., as-built) main channel was entirely abandoned. Floodwaters carved out a new secondary channel the south bank. The new channel had a complex planform. Near its downstream end, it is primarily a single thread; however, upstream areas feature a more braided planform, with abundant willows serving as a critical control on channel adjustment (e.g., Coulthard, 2005). High flows in 2014 (peak discharge, ≈ 185 $m^3 s^{-1}$) established a new entrance to this channel off of a small inlet.

Avulsion dynamics have been conceptualized using a setup-and-trigger framework – that is, multiple setup factors interacting with one another to prime the floodplain for avulsive activity; when high-magnitude floods or other disturbances occur avulsions often result because of these antecedent conditions (Slingerland and Smith, 1998, 2004; Smith et al, 1998; Phillips, 2011; see also Makaske, 2001; Makaske et al, 2002; Aslan et al., 2005). The Clark Fork's upstream avulsion was catalyzed primarily by high flows and in-channel aggradation, while the downstream avulsion resulted from the complex interaction of multiple factors. When high flows began, the recently constructed floodplain was still largely barren. Vegetation was immature and not developed enough to provide resistance against elevated flows (e.g. Simon and Collison, 2002). Another critical setup factor was the location of Secondary Channel 1's inlet, immediately downstream of a meander bend apex. Floodwaters from the main channel entered the secondary channel at an unexpectedly high rate, spreading across the unprotected surface of the adjoining floodplain. This dislodged large woody debris that had been used to create micro-topographic contours, which exposed underlying sediments and intensified scouring. Floodplain surfaces in upstream locations were also scoured, introducing excess sediment to portions of the channel near the avulsion site. High-magnitude flooding combined with sediment loading deformed the meander bend near the avulsion node and contributed to the water surface's super-elevation. A final driver of the avulsion was the main channel's bank and toe structures' lack of resiliency. They were engineered to protect banks from floods with a recurrence interval < 25 years, which this event (recurrence interval was ≈ 35–40 years) surpassed.

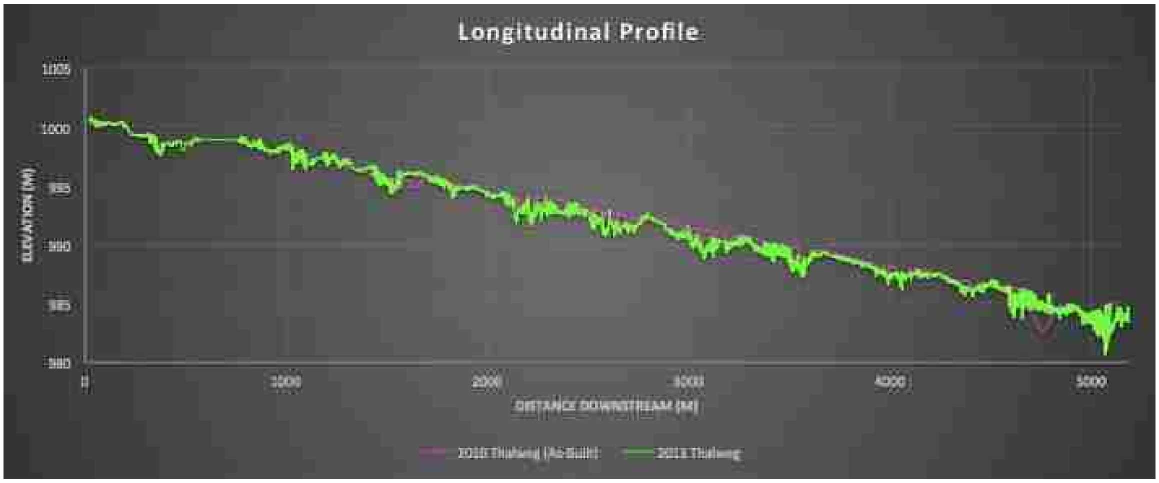


Figure 4.8. Comparison of the as-built longitudinal profile (2010) and the 2013 longitudinal profile. Table 2 includes reach-averaged slope changes.

Table 4.2 summarizes reach-averaged slope changes throughout the restoration area. Figure 4.8 captures finer-grained adjustments in the mainstem thalweg profile from 2010 to 2013. The bed's topography responded complexly, with bedform development unfolding in a spatially variable manner, especially in the middle reaches, which have experienced localized degradation and pool scouring (Carbonneau et al., 2012). Bookending the restoration zone are areas where pools have locally infilled. With the exception of Reach CF3B, there have only been minor changes in reach-averaged bed slope gradients. CF3B encompasses an area just downstream of the upstream avulsion site, and the adjustments likely stem from increases in base water levels along this reach and localized scouring of pools (Daniels, 2013). In lower portions of the study area, pools have deepened 1–2 m in several locations. There is currently no evidence of river-floodplain disconnection stemming from this degradation, nor of the thalweg migrating laterally. CF2, which includes areas repaired following the downstream avulsion, has channel gradients remarkably close to the as-built condition.

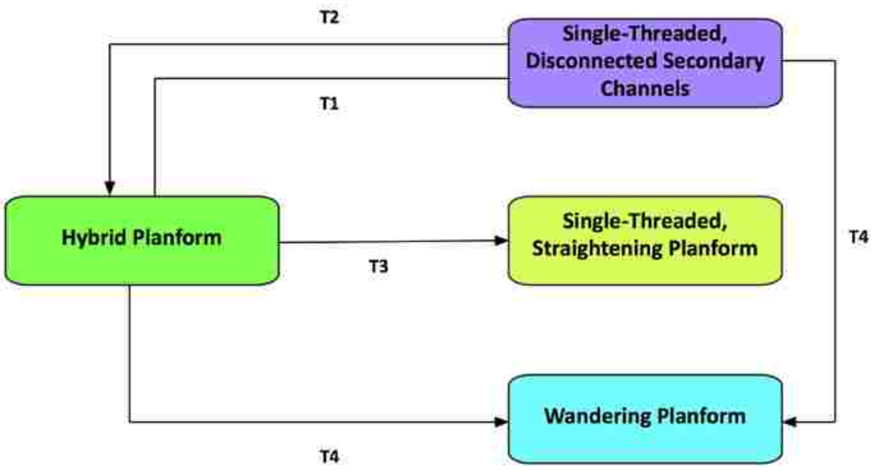
4.7 A Descriptive State-and-Transition Model for the Clark Fork River

Leveraging historical reconstruction and the brief record of post-restoration adjustments, this section describes a qualitative STM for the Clark Fork River. Rangeland ecologists originally devised STMs to document and narrate nonlinear vegetation dynamics in arid and semi-arid ecosystems (Westoby et al., 1989; Stringham et al., 2001, 2003; Bestelmeyer et al., 2003, 2006, 2011, 2015). Geomorphologists have recently mobilized state-transition thinking to capture the interplay of process regimes and morphological states in fluvial environments and their impact on river dynamics (Xu, 1996; Gurnell et al., 2001; Gurnell and Petts, 2002; Schumm, 2005; Hawley et al., 2012; Phillips, 2013, 2014; Wohl et al., 2014; Chin et al., 2014;). STMs consist of box-and-arrow diagrams that summarize potential states and the drivers of state transitions – qualitative changes in landscape state (Phillips, 2014). The detailed narratives that accompany these diagrams provide a finer-grained analysis of the landscape and the catalysts of state transitions. STMs organize information about landscapes and catalogue the possible states that may arise when new process regimes interact with established states (Caudle et al., 2013). They have proven well adapted to environmental management because they let practitioners identify managerial responses to multiple disturbance scenarios. Unlike traditional channel evolution models, STMs do not assume that landscape change is a linear or monotonic process (Schumm et al., 1984; Simon, 1992; Simon and Rinaldi, 2006). Eschewing theoretical commitments, STMs do not presuppose that river dynamics are deterministic (cf. Bestelmeyer et al., 2004). Instead, they establish baseline hypotheses about future landscape behavior. Section 5 demonstrated that the selected channel design did not fall outside the historical range of variability, however, it is imperative to recognize that the river's hybrid planform is only one possible state that could materialize and persist on the landscape.

Figure 4.10 presents a descriptive STM for the Clark Fork River. Four possible states have been identified: 1) a hybrid configuration (its current state); 2) a single-threaded channel, which may be either a) straight or b) meandering; and 3) a fully wandering channel. The 2011 downstream avulsion was repaired; however, Figure 4.11b reveals that the newly incised channel adopted a much straighter course once it cut off a meander bend. If future avulsions occur, it is likely they will exploit the weaknesses around meander apices (Smith et al., 1998; Slingerland and Smith, 2004). Figure 4.9 identifies a potential avulsion node at Secondary Channel 1. Along this segment, the main channel's gradient is 0.0033 m m^{-1}. Conversely, the slope gradient of Secondary

Channel 1 is 0.0041 m m^{-1}, y. In the upper reaches of Secondary Channel 1, slopes exceed 0.007 m m^{-1}. Secondary Channel 3a had a slope of 0.0043 in 2013, however, overbank flows deposited significant quantities of fine sediment (a mixture of sand, silt, and clay) near its outlet in 2014, reducing its slope to 0.0022 m m^{-1}, and temporarily mitigating the possibility of an avulsion. The presence of a gradient advantage is a critical avulsion setup. During floods this can promote flow diversion and the incision of a new channel (Phillips, 2011). Although an avulsion could lead to channel straightening, it could also be a precursor to a more wandering river. Figure 4.11c suggests what an early-stage wandering channel may look like, with the mainstem looping around a gravel island with sparse floodplain vegetation. This image was taken as the river was being rerouted back into its constructed channel; thus, it lacks the density and extent of vegetation usually associated with a wandering planform. The magnitude of an avulsion would influence the river's state – a full avulsion, which implies complete channel abandonment would likely produce a less sinuous channel, whereas a partial avulsion may support a wandering planform.

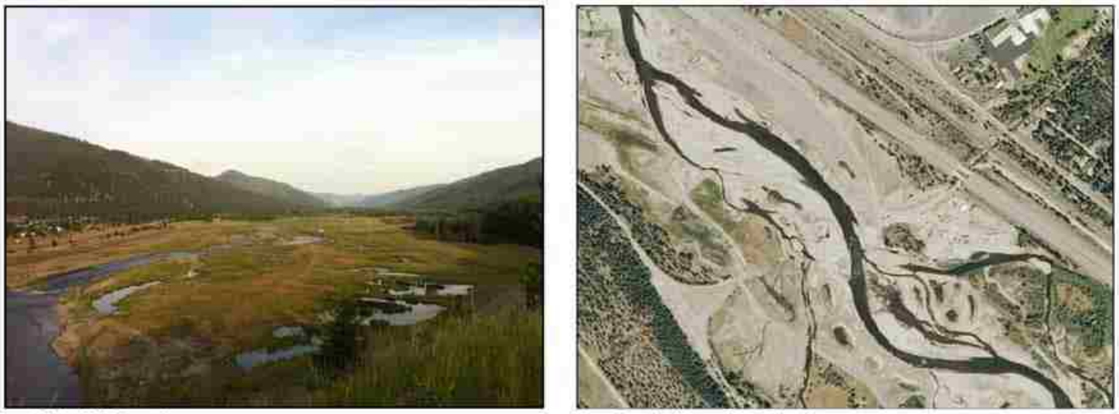
Figure 4.9. Restoration area with locations of key secondary channels indicated. The blue circle indicates a potential avulsion node, which is based on a comparison of bed slope gradients of the primary and secondary channels.



T1 – prolonged drought, sustained low discharges; vegetation recruitment and expansion in seconary channels and floodplain
T2 – drought effects releaxed through precipitation or management interventions, restoring flow to secondary channels
T3 – severe flooding and avulsions; increased sediment loading; widespread floodplain erosion, abandonment of secondary channels
T4 – severe flooding and avulsions; increased sediment loading; floodplain vegetation stripping and erosion; new vegetation recruiment on exposed islands; flow maintained in bifurcated channels

Figure 4.10. STM for the Clark Fork River – main channel. States are – principally – the outcome of variable inputs of water and sediment interacting with an established biogeomorphic template.

Several triggers could transition the river to a single-threaded meandering planform. Extended periods of low discharge may disconnect the main channel from secondary channels. Another potential trigger is the accumulation of large woody debris at secondary channel entrances, which can redirect incoming flow back toward the mainstem (Piégay and Gurnell, 1997). Secondary channels that originate in the upper reaches of the restoration area convey flow perennially, however, farther downstream, channels have intermittent streamflow. During the late-summer months these channels do not take on water from the mainstem. Under this scenario water-depleted channels would gradually blend into the floodplain with the expansion of grasses and woody plants – primarily *Salix spp*. This assumes that the water table does not fall to a level that desiccates vegetation. There have been management actions undertaken in response to the emergence of this state. For example, in 2013 the entrance of Secondary Channel 4 was lowered so that it would accept more water during bankfull- and high-flow events, though it continues to dry out early in the summer and fill with newly recruited vegetation (Figure 4.11d).



a. Hybrid Planform

b. Straightening Planform

c. Early-Stage Wandering

d. Infilling Secondary Channel

Figure 4.11. Observed landscape states along the Clark Fork River. See text for explanation.

In 2014, large woody debris was removed from the entrance of Secondary Channel 2 – the upper reaches of which have started blending into the floodplain, due in part to a downstream avulsion. Lastly, Figure 4.11a depicts the current hybrid planform. It is reasonable to expect this state would be self-maintaining if severe disturbances remain at bay. Keeping in mind that states represent transient assemblages, it is most accurate to view states not as discrete or mutually exclusive – for example, where secondary channels progressively disconnect, the river may gravitate toward a single-threaded state, but a hybrid planform may be simultaneously preserved in other locations given that channel adjustments often unfold in a spatially complex manner (Schumm, 1973; Gaeuman et al., 2005). Although this STM is based on a limited period of observation, it establishes preliminary hypotheses about the river's possible future. These can be used to assess landscape sensitivity as the cumulative effects of disturbance (or lack thereof) are etched in the landscape. With this knowledge, management strategies can be revised so that the likelihood of achieving project objectives remains high irrespective of disturbance regime.

4.8 Conclusion

Historical reconstructions provide strong evidence Clark Fork River was a predominantly single-threaded channel immediately upstream of its confluence of the Blackfoot River before Milltown Dam was built. Nonetheless, critics of the restoration project have seized on avulsive activity as evidence of the channel design being inappropriate for the hydrogeomorphic setting (Woelfle-Erskine et al., 2012). Is this a defensible argument? Probably not – riverine landscapes follow multiple adjustment pathways, which are contingent upon the combination of internal and external forcings that vary spatially and temporally. Rivers, like other landscapes, do not have inherent goal functions that compel evolution in a specific direction (e.g., Brierley, 1989; Schumm, 1991, 2005; Cullum et al., 2008; Phillips, 2009). Arguing that a particular channel state must necessarily abide in a particular landscape overlooks this fact. Had an alternative design been used, it is unclear whether the river would have responded differently. Woelfle-Erskine et al. (2012) noted that various planform indices suggest the valley would be most likely to support a transitional or wandering channel structure. However, planform indices rely on empirical discriminant functions, and while they often produce robust predictions about channel state there is considerable scatter in the data they are based on – they are not unimpeachable predictors of morphology (Métivier and Barrier, 2012). Given the circumstances, any design would have undergone extensive reorganization following high-magnitude flooding. That avulsions occurred does not indicate that restoration was a failure. It underscores the complexity associated with the project; no channel design can anticipate or withstand all contingencies that may arise.

In proposing that STMs be used to think through questions of channel adjustment and inform river management, my intent is to shift us away from the either/or logic that often sullies debates over restoration (Wilcock, 2012). My purpose in doing historical reconstruction is not to argue the Clark Fork River must adopt a hybrid meandering planform. It is to point out this is one possible state the river can occupy – we should not dismiss it arbitrarily based on theoretical dispositions. Thinking about what is possible, rather than being fixated on what is necessary (which we can never know for certain anyways), shifts us toward management strategies that are adaptive and improvisational. Although the hybrid planform is compatible with the geomorphic setting and the historical range of variability, two alternative states have emerged since 2010 – a straightening channel and a single-threaded channel disconnected from the adjoining floodplain and secondary channels. As Ferguson (1987) argued, “we should think in terms of *transitions* in channel pattern rather than sharp thresholds (p. 129). Using STM frameworks to organize our knowledge about rivers informs a diagnostic approach to management that contemplates multiple disturbance scenarios and hydrogeomorphic interactions to imagine the spectrum of possible channel responses (cf. Yates and Hobbs, 1997; Montgomery and MacDonald, 2002; Bestelmeyer et al., 2004; McDonald et al., 2004; Dufour and Piégay, 2009; Beechie et al., 2010).

State-transition thinking underscores that river states are not absolutely discrete. They are fluid and blend into one another, making it imperative that management strategies be pragmatic and cognizant of the full range of transitions that can materialize on a particular landscape (*sensu* Baker, 1999; Koopman, 2013). Accepting that rivers are characterized by blurry and unfixed transitional encourages management practices that recognize landscapes’ form-process relations are plastic and are constantly being remade. As such, what it means to work with a site – and not fight it – (*sensu* Brierley and Fryirs, 2009) is subject to ongoing negotiation. And that the means through which project objectives may be achieved are multiple – and the paths we can take to arrive at them are always changing.

Table 4.1. Summary of GLO Information

Observation Point Relative to Confluence	Years	River Width	Vegetation	Sediment Characteristics	Other Features
2 km Upstream	1892, 1903	40 m	- Dense undergrowth present near river on the left and right banks - Pine and cottonwood dominated in the overstory, willow in the understory	- Sandy loams and gravels	- Slough ≈ 15 m wide on mainstem left bank near Deer Creek - 1901 survey notes described a wide expanse, ≈ 150 m wide that was vulnerable to overbank flooding. The active channel remained consistent at 40 m.
3 km Upstream	1901	n/a	- Willow and alder in understory - Pine and cottonwood in the overstory	- n/a	- Slough ≈ 4 m wide on mainstem left bank
5 km Upstream	1883, 1892, 1901	60 m	- Ponderosa pine, firs, cottonwood - Dense undergrowth, but specific species not mentioned	- Sandy loams and gravels - 1901 survey notes mentioned that sediment inputs from upstream mining areas flowed into the reach	- 1901 survey notes described the presence two channels that were part of the mainstem, indicating a wandering planform may have been present.

Table 4.2. Reach-Averaged Slopes for the Clark Fork River[8]

Reach	Design Thalweg (m/m)	2013 Thalweg (m/m)	Change (%)	Design Water Surface (m/m)	2013 Water Surface (m/m)	Change (%)
Entrance	.0027	.0025	-7.4	.0027	.0024	-11.1
CF3B	.0027	.0039	44.4	.0027	.0032	18.5
CF3A	.0033	.0034	3.0	.0033	.0032	-3.0
CF2	.0033	.0034	3.0	.0033	.0035	6.1
CF1	.0033	.0035	6.1	.0033	.0024	-27.2

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[8] Slopes are calculated using reaches that were delineated based on construction phases. Construction proceeded from upstream to downstream, with upstream locations being completed first (i.e., Entrance, CF3B) and downstream reaches being the last portions of the restoration zone wrapped up.

Chapter 5 - Nature's Complex Flume – Using a Diagnostic State-and-Transition Framework to Understand Post-Restoration Channel Adjustment, Clark Fork River, Montana

5.1 Introduction

Experimental flume studies have contributed immeasurably to our knowledge of river channel dynamics and their response to imposed hydrogeomorphic fluxes (e.g., Friedkin, 1945; Schumm and Kahn, 1970; Ashmore, 1991; Tal and Paola, 2007, 2010). Flume experiments cannot, however, simulate the place-based contingencies that inevitably influence river channel evolution following a disturbance (Schumm, 1991, 2005; Beven, 2015; Brierley and Fryirs, 2005; Phillips, 2007, 2015a). What they can tell us about fluvial dynamics is influenced by the limitations inherent to laboratory settings, which includes the imaginations of scientists who decide what variables to manipulate. Some studies have manipulated bio-hydrogeomorphic variables in natural settings to induce particular forms of channel adjustment (see Nevins, 1969; Erskine, 1992), however, their performance has been uneven (Korpak, 2007).

Understanding the spatial variability of channel evolution requires close study of riverine landscapes to determine how the fine-grained variability of biogeomorphic interactions affects morphological adjustments (Gurnell and Petts, 2002; Gurnell, 2014; Toone et al., 2014; Corenblit et al., 2015). This means finding landscapes that approximate a flume-like condition in nature. Ideal landscapes to investigate channel evolution in would have two features: 1) a biogeomorphic template that has been reset to a known condition and 2) exposure to naturally variable hydrogeomorphic fluxes (cf. Schumm et al., 1984). Channel evolution models (CEMs) describe and anticipate the morphological responses of alluvial channels to fluctuating discharge, sediment inputs, and other perturbations. Pioneered to explain the process-form implications of channelization in the U.S. Southeast, they have served as a baseline to conceptualize adjustment trajectories in numerous hydrogeomorphic environments. But many rivers do not exhibit the sequence of morphological adjustments anticipated by classic CEMs, which propose an evolutionary template according to which a channel will undergo vertical and then lateral modifications as a channel progresses toward a pseudo-equilibrium state (Schumm et al., 1984 Simon and Hupp, 1987; Simon, 1992; Simon and

Rinaldi, 2006). Alternative explanatory frameworks equipped to account for the complex responses symptomatic of post-disturbance channel recovery are needed to improve the outcomes of river restoration and management (see Schumm, 1969; Huckleberry, 1994; Gaeuman et al., 2005; Hawley et al., 2012 on complex response).

Complex response has usually been defined as a single disturbance – e.g. high-magnitude flooding – producing channel adjustments that vary across space and time (Schumm, 1973; Schumm et al., 1984; Sherrard and Erskine, 1991). Complex responses emerge from spatially variable bio-hydrogeomorphic fluxes. As these fluxes interact with the landscape, they produce a mosaic of channel adjustment patterns on a single landscape. Multiple adjustment trajectories can occur on the same channel due to these fluxes being unevenly distributed, spatially (cf. Field, 2001). Disturbances (severe or minor, if the landscape is near a threshold) sometimes produce state transitions, which occur when there is shift to a qualitatively different landscape state (Phillips, 2014). States are transiently stabilized landscape configurations – resilient, yet contingent assemblages that arise from heterogeneous, networked spatial relations among water, sediment, and vegetation (cf. Fukami and Nakajima, 2011; see also Lane and Richards, 1997; cf. DeLanda, 2006).

This paper uses the remediation and restoration of the Clark Fork River near Missoula, Montana as its case study. It outlines a diagnostic state-and-transition model (STM) that can be adapted to study channel evolution (see Montgomery and MacDonald, 2002; Bestelmeyer et al., 2003, 2004, 2011; Steele et al., 2012). The study area encompasses an ≈ 3 km of stretch of river channel and floodplain. Following restoration, the as-built condition of the river and its floodplain were exhaustively documented. As such the result was akin to an experimental laboratory flume in which complex adjustment trajectories can be investigated, narrated, and predicted in a natural setting (Figure 5.1). Multiple complex responses have been observed on the Clark Fork River's floodplain and secondary channels since flow was introduced to the newly constructed main channel in December 2010. Like other gravel-bed rivers with patchy arrays of wetlands, active channels, and floodplain vegetation, channel evolution has not proceeded along a deterministic, linear path (e.g. Francis et al., 2009).

Figure 5.1 Multiple forms of fluvial adjustments observed on the Clark Fork River's restored floodplain and secondary channels. (a) illustrates a knickpoint migrating upstream into an area blanketed by grasses and weeds. This feature connects to well-defined channel that spans the floodplain and has its entrance 'along the mainstem. (b) shows the development of a channel that has emerged in fine sediments (sands and clays) that were deposited between two gravel-bed secondary channels. Evidence of multiple knickpoints indicated that channel evolution followed the classic model proposed by Schumm et al. (1984) and Simon and Hupp (1987). (c) reveals the widespread recruitment of grasses and woody shrubs (mainly *Salix spp*.) along a secondary channel, gradually erasing the distinction between it and the floodplain. (d) depicts an emergent pathway for channelized flow adjacent to a stand of willows. Note the downed willows parallel to the flow path – lateral erosion contributed to root exposure and uprooting and may facilitate bank erosion.

The diagnostic STM characterizes the spatial distribution of river states along the Clark Fork as well as the suite of interacting processes associated with either maintaining the landscape in its present condition or catalyzing a shift toward a qualitatively new condition (e.g. when an avulsion straightens a meandering planform). STMs generate narratives about cross-scale bio-hydrogeomorphic relationships and contextualize the multiple complex responses evident in river evolution (cf. Fryirs and Brierley, 2013). In doing so, they establish a foundation for management interventions.

5.2 Theoretical Background – State-and-Transition Models

The emergence of STMs in rangeland ecology stemmed from the recognition that vegetation communities did not always follow linear patterns of succession (e.g., Westoby et al., 1989; Stringham et al., 2003; Bestelmeyer et al. 2003). Combinations of equilibrium and non-equilibrium dynamics can lead to the production of multiple stable states in a particular setting. STMs consist of box-and-arrow diagrams accompanied by narratives that describe potential landscape adjustment trajectories. In rangeland ecology, state has a very specific meaning – it refers to different soil–vegetation assemblages that a possible on a site (Stringham et al., 2001; Bestelmeyer et al. 2012). Transitions are adjustment trajectories – precipitated by a change in process regime – that cannot be reversed without significant management interventions. Within individual states exist a suite of community phases, which are composed of plant groups with similar ecological functionality. STMs are developed to document what states are possible on a site and the catalysts responsible for transitions. As such, their primary function is to organize information and knowledge about landscapes and to help managers anticipate and respond to state transitions (Bestelmeyer et al., 2004). Recent studies have incorporated spatially explicit analysis to clarify the fine-grained patterning of states on the landscape and how differences in spatial configurations are implicated in transitions (e.g., Bestelmeyer et al., 2011; Steele et al., 2012).

River scientists have routinely used state-transition thinking, although the formalized application of STMs is a relatively new development (e.g., Phillips, 2011, 2013, 2014). In fluvial geomorphology, research on state transitions has often focused on river channel pattern. A number of empirical discriminant functions have been developed that relate changes in variables like channel gradient and characteristic discharge to planform (e.g. Leopold and Wolman, 1957; Parker, 1976; van den Berg, 1995; Church, 2002; Podolak, 2013). Other work has taken qualitative state changes as its focus. Schumm (1969) used semi-quantitative relations to explain the effects of changing discharge and sediment loading on morphological parameters such as river width, depth, and sinuosity. Xu (1996) partitioned the complex response exhibited by a wandering river downstream of a dam into three stages, each defined by multiple evolutionary pathways. The emergence of a state is contingent on discharge, sediment load, and the relative erosional resistance of the bank to the bed. Changing relationships among these parameters produce different channel forms. Similarly, Brandt (2000a, b) reviewed the influence of dams on downstream geomorphology and developed a generalized set of relations to describe the effects modified discharge regimes and sediment loads have on cross-sectional geometry, planform state, and bed state (see also Graf, 2001). These studies indicate that complex response is common, and that channels can follow multiple adjustment trajectories in response to one set of forcings due to antecedent conditions and place-based contingencies (see also Burkham, 1972; Nadler and Schumm, 1981; Gaeuman et al., 2005; Schumm, 2005; Phillips, 2006, 2007, Webb et al., 2014).

There are fewer examples of STMs developed for riverine landscapes that combine box-and-arrow diagrams with narrative explanations – as is common for rangeland STMs. Gurnell and Petts's (2002; see also Gurnell et al., 2001; Francis et al., 2009) state-and-transition framework, which summarizes the effects of bio-hydrogeomorphic interactions on the channel morphology of gravel-bed rivers, adopts this approach. It demonstrates how the complex interplay of allogenic and autogenic processes influence riparian vegetation and morphological structure to rework a river's structure (Francis, 2006; Corenblit et al., 2007, 2015). According to this model, the deposition of large woody debris and vegetation recruitment encourages sediment deposition and island building, increasing biogeomorphic patchiness. High-magnitude flooding events can reset channel morphology, uprooting vegetation and eliminating islands. Channel resetting events are uncommon (see Dean and Schmidt, 2011), with many disturbances reshaping instead of wiping clean rivers' biogeomorphic templates. Phillips (2013) explored the fitness of humid perennial channels using a flow channel fitness model. This model examines how stream power and shear stress influence a channel's tendency toward either fitness, overfitnees, or underfitness. The flow channel fitness model, unlike previous work on channel evolution, does not assume adjustment toward a steady-state or equilibrium condition (see also Phillips 2011). Whereas CEMs proposed that rivers evolve monotonically toward a fixed steady-state, more recent takes have attempted to capture the multiple adjustment trajectories that result from imposed bio-hydrogeomorphic fluxes (e.g. Makaske et al., 2002, Gurnell et al., 2002; Cannatelli et al., 2012; Halwey et al., 2013; Booth and Fischenich, 2015).

This raises a question about defining state transitions outside of rangeland contexts. Phillips (2014:208) suggested that "[a state transition] is a change that results in a qualitatively different landform, geomorphic environment, or landscape unit." This provides a useful starting point for defining "state" in the context of fluvial landscapes – a river state consists of a durable assemblage of form-process relations that has an identifiable morphological and spatial signature. Although broad, this definition underscores that researchers must define states in the manner most appropriate for a particular study. Numerous systems have been devised to classify or characterize river forms and processes (e.g., Schumm et al., 1984; Rosgen, 1994; Montgomery and Buffington, 1997; Montgomery, 1999; Brierley and Fryirs, 2005) that can provide guidance. Taking the original CEM proposed by Schumm et al., (1984), each stage in the evolutionary sequences could be seen as a state. Likewise, the River Styles framework pioneered by Brierley and Fryirs (2000, 2005; Brierley et al. 2013), could guide the identification of river states. Similar to Montgomery's process domains (1999), River Styles uses a nested hierarchical analysis of watershed conditions to characterize rivers (see also Frissell et al., 1986; Snelder and Biggs, 2002). Hawley et al.'s (2013) multi-pathway CEM defines states based on dominant processes and planform geometry. In some cases, defining states based on the channel planform may be sufficient if it is a strong enough indicator of river behavior.

This paper defines channel states based on their predominant river styles (Brierley and Fryirs, 2005). Like traditional STMs, this framework recognizes the difference between state transitions and within-state adjustments (cf. Fryirs et al. [2012] distinction between river change and river behavior). Channel states may be further partitioned into state phases. For example, imagine a meandering gravel bed state. That channel can withstand a specific level of internal adjustments – such as bank erosion or in-channel vegetation recruitment – without crossing a threshold, which prompts a state transition (e.g. Schumm, 1973). State phases are functionally analogous to the community phases found in rangeland STMs in the sense that shifts among different state phases do not place the river a new evolutionary trajectory. Once they have been defined, channel states' sensitivity to various disturbance regimes is assessed using a qualitative diagnostic matrix. Montgomery and MacDonald (2002) examined the sensitivity of different channel typologies to perturbations, with a focus on the response of channel dimension, bed material, reach morphology, and sediment transport. Although not included in their diagnostic approach, the influence of disturbance on riparian and in-channel vegetation should be assessed given its instrumental role in sculpting channel morphology (Gurnell, 2014; Corenblit et al., 2015). After evaluating each channel state, states can be mapped to identify spatial relationships determine what influence a state transition along one reach may have on others. Mapping states can assist environmental managers in identifying river segments that require attention and management intervention (Steele et al., 2012).

Quantifying the exact probability that a group of interacting factors will catalyze transitional behavior is a fraught task. The purpose of STMs is to improve river managers' ability to anticipate transitions – not deterministically predict their occurrence. Similar to Bestelmeyer et al. (2004), the diagnostic STM framework described below uses qualitative analysis to consider how numerous sources of variability influence channel response. Performing diagnostic evaluations for each state lets managers gauge the likelihood of transitional behavior and offers learning opportunities to anticipate how different combinations of process-form responses influence river morphology.

5.3 Geomorphic Context of the Study Area

With its headwaters rising near Butte, Montana, the Clark Fork River initially flows north before turning to the west-northwest, a course it maintains as it heads toward its outlet at Lake Pend Orielle. The river drains ≈ 9,500 km^2 above its confluence with the Blackfoot River, which is located downstream of the study reach (Figure 5.2). The study area encompasses a ≈ 1 km^2 area upstream of the confluence.

Alluvium blankets the valley floor, and is comprised of inter-bedded sand, gravel, and boulders, and clay lenses. The most common rock type is quartzite derived from the Belt Supergroup (Woessner, 1995; Berg, 2006). Western Montana is characterized by a semi-arid climate. Annual precipitation varies little in the Upper Clark Fork Watershed, with Butte receiving ≈ 325 mm of precipitation annually and Missoula ≈

350 mm. The river’s hydrograph peaks sharply – typically in May or June – owing to a combination of snowmelt and late-spring rainfall.

Figure 5.2 Aerial image of secondary channels and outline of the study area. The primary map illustrates and labels key features. The inset map in the lower left corner (a) magnifies middle portion of the study area. The inset map in the upper right corner (b) situates the study area in a more expansive geographic context.

Milltown Dam impounded the Clark Fork River and Blackfoot River from 1908 to 2008, creating a large reservoir downstream their confluence that trapped contaminated sediments washed down from upstream mining areas (EPA, 2004). After water testing revealed extensive groundwater and sediment contamination behind the dam in 1981, this segment of the river (along with the rest of the Upper Clark Fork Watershed) was designated as a Superfund site. As part of remediation, Milltown Dam was removed, ≈ 1.7 million m^3 of contaminated sediment were extracted from the drained reservoir, and ≈ 5 km of the main river channel and its adjoining floodplain were rebuilt (State of Montana, 2008). Flow was introduced to the constructed primary and secondary channels in late 2010.

Upstream of the study reach, the Clark Fork River exhibits considerable morphological diversity, with meandering, straight, and wandering segments (e.g. Desloges and Church, 1989; Church and Rice, 2009; see also Church, 2006, which refers to this planform as transitional) in evidence). The river's mainstem is characterized by a hybrid meandering channel – a transitional channel (Church, 2006) or plural system (Lewin and Ashworth, 2014). that combines a single-threaded meandering channel with secondary channels (anabranches) and off-channel wetlands. Like wandering rivers, the Clark Fork is vulnerable to avulsions, but unlike wandering rivers there is no evidence of active island construction within the study area (cf. Desloges and Church, 1989; Burge and Lapointe, 2005; Church, 2006). Secondary channels are connective links between the distal and proximate floodplain. Mainstem width-to-depth ratios range from 40 to 50 in both riffle and pool sections. The beds consist of cobbles and gravels, while banks have a mixture of cobbles, gravels, sands, and silts that are reinforced by geoengineered structures (coir logs) that been planted with willows (*Salix exigua*). Key tributaries emptying into the Clark Fork include Flint Creek and Warm Springs Creek. Another small tributary, Deer Creek, empties into the river along the study reach. Between Butte and Missoula, little urban development exists. Montane conifer forests, grasslands, shrublands, and agricultural occupy > 85% of land in the watershed.

This study focuses on seven secondary channels that were either constructed or have developed (since 2010) along the restoration area's lowermost reaches. Excluded from the study are three secondary channels originating in the upper reaches of the restored floodplain. Each of these channels was present before construction to varying degrees. While restoration activities enlarged these channels and improved their connection with the main channel, unlike the features discussed here, their biogeomorphic templates were neither created entirely anew following remediation nor emerged following disturbance. Channel lengths range from ≈ 180 m to 700 m. They are activated when discharge exceeds baseflow, and at bankfull flows they intercept up to 10% of the mainstem's water.

Previous restoration projects have used constructed secondary channels to improve habitat availability, especially during low flows, and enhance hydrological connectivity across floodplains (e.g., Schropp, 1995; Schopp and Bakker, 1998; Simons et al., 2001; Rodrigues et al., 2006, 2007). Most of these projects were focused on large rivers with discharges at least an order of magnitude larger than the Clark Fork. Flow is intermittent in five of the Clark Fork's channels. Downstream portions of Secondary Channel (SC) 2, which intercepts flow from Deer Creek, and SC 3, which SC 6 – a perennial anabranch – feeds, flow perenially. SC 1a and SC 1 retain water throughout the year, but during the summer months water is confined to pools and flow is stagnant. SC 4, SC 3a, and SC 6b empty completely during the late summer. Channel segments that experience seasonal drying have undergone the most significant vegetation recruitment, mainly grasses and willows (*Salix spp.*).

5.4 Methods

The primary and secondary channels were mapped using orthorectified aerial images that captured of the river each year since the reestablishment of flow – 2011–2014. Channel boundaries were delineated using conventional mapping techniques (Gurnell 1997; see also Marcus et al., 2012). The 2011 and 2013 images were taken when the river was at or near baseflow; the 2012 and 2014 images depict the river near or just above bankfull stage (≈ 90 m^3 s^{-1}). Each image was digitized at 1:350 scale. 2011 imagery had 1-m resolution, while images from 2012 to 2014 had 50-cm resolution.

In 2013, 62 cross sections were established and surveyed along the secondary channels. Repeat measurements were taken at select cross sections (n = 19) in 2014 to detect the magnitude of short-term adjustments. Surveying procedures followed the techniques described by Harrelson et al. (1994). Cross sections were measured with a Trimble R8 GNSS system, which yielded post-processed horizontal accuracy of +/- 10 mm and vertical accuracy of +/- 20 mm. In June 2013 a longitudinal survey of the main channel was performed using a single-beam echo sounder (Flerner et al., 2012; Javernick et al., 2014). Vertical accuracy of these data is +/- 10 cm. Reach-averaged slopes were calculated from the profile data and compared to slopes measured on the secondary channels. Cross-sectional geometry, field observations, and aerial images were used to identify the secondary channels' bankfull conditions.

Changes in the braiding index from 2012 to 2014 were calculated using imagery. Transects were spaced at 50-m intervals and the number of active branches that intersected each transect were counted. The braiding index equals the mean number of branches per transect (Howard et al., 1970; Ashmore 1991). This imagery, which was supplemented with ground observations, was used to estimate the vegetation cover (> 0.25 m in height) of each secondary channel (cf. VanLooy and Martin, 2005).

Surface material was characterized using pebble counts. Procedures followed the methods outlined in Wolman (1954) and Surian (2002). Homogeneous units of surface sediments were identified and transects were established perpendicular to the bed. At each site, approximately 120-130 particles were sampled to estimate the median particle size (D_{50}) as well as to characterize the overall distribution. Sampling of subsurface materials adhered to methods described by Church (1987) and Bunte and Abt (2001). At each site bed armoring was removed to the same depth as the thickness as the largest particle found in the armor. Sediments were then sampled to a depth slightly thicker than the armor layer. The samples were wet and dry sieved to determine the proportion of gravel, sand, and clay, respectively. The remaining unanalyzed fine-sediment fraction was then examined using a Mastersizer 2000, a laser diffraction particle size analyzer.

Combining field measurements, lab analysis, and qualitative observations, channel states were identified based on planform, vegetation, and sediment characteristics (Brierley and Fryirs, 2000, 2005; Brierley et al. 2014). Once states were identified and described, post-2010 channel adjustments were appraised to determine possible state transitions. Although some of these states have been observed, others have been inferred based on anticipated channel responses to bio-hydrogeomorphic fluxes (e.g., Schumm, 1969; Knighton, 1998; Brierley and Fryirs, 2005; Booth and Fischenich, 2015). This information was used to construct a diagnostic STM framework, which establishes qualitative relations that can be used to identify conditions likely motivate state transitions (Bestelmeyer et al., 2004).

5.5 Identifying States and Transitions in Secondary Channels

Table 5.1 summarizes morphometric data for the secondary channels. Three primary channel states have been identified – meandering gravel bed, straight gravel bed, and complex braiding-wandering gravel bed. SC3 was partitioned into two reaches because of the large difference in slope for the upstream and downstream segments (the downstream segment begins at its confluence with SC6). Channel slopes vary widely among the channels. The high and low ends of the range are found on SC 3, with a gradient of 0.0006 on its upper reach of SC3 and a slope of 0.0116 on its lower reach. The gradient along the mainstem within the study area is 0.0033. Also notable is SC 1a, the site of main channel avulsion in 2011. Its gradient is 0.0041, however, local slopes exceeding 0.006 in its upstream portions, adjacent to the main channel. Median width-to-depth ratios among the channels generally measure between 30 and 60. One exception is SC 3a. Originally part of the floodplain, its median width-to-depth ratio is 109.031. Although the channel has a well-defined entrance, as water moves downstream it spreads across a wide featureless area, before entering a constricted outlet.

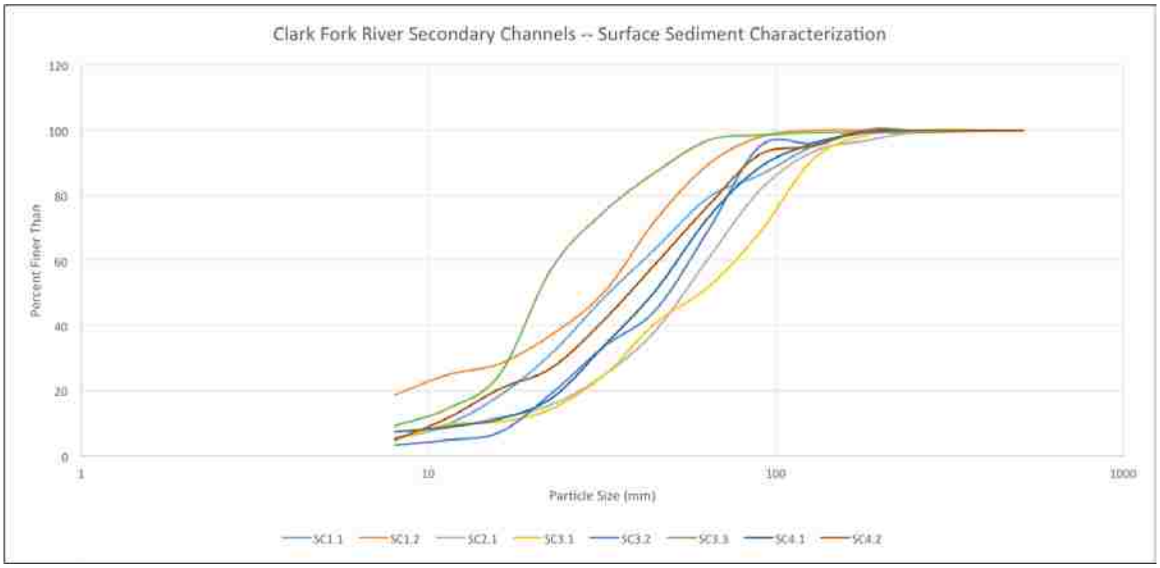


Figure 5.3 Pebble Count data for the Clark Fork River secondary channels.

With the exception of SC 3 and SC 4, median shear stress values are > 10 N m^{-2}. The low values on SC 3 are attributable to the very subtle channel gradient in its upstream segments and low average depth. SC 4 is also shallow, and it has experienced the highest rate of vegetation recruitment (see below). The diameter of surface particles ranges from 20 to 60 mm, with critical shear stresses falling between 15 and 45 N m^{-2}. Two channels are outliers, SC 2 and the downstream portion of SC 3. Larger median surface particle sizes contribute to this difference. Pebble counts on SC 2 were conducted near its upstream entrance, and larger-sized surface grains were incorporated into the design. The downstream portion of SC 3, which is oversteepened (slope = 0.0116) was likely constructed with coarser sediment in order to compensate for the sharper gradient. Subsurface sediment distributions are heavily weighted toward gravels. Material was sampled in 23 locations, and with the exception of several pools that had high silt fractions the proportion of gravel general exceeded 80% (n = 17). Although subsurface material can indicate the characteristics of bedload moved during previous disturbances (e.g. Parker et al., 1980), this material likely represents what was laid down during restoration. Braiding indices for SC 1 and SC 1a increased significantly between 2012 and 2014 due to the formation of newly channelizing features. Vegetation cover shows significant scatter. SC 1a has the highest percentage of in-channel vegetation (55%), and a significant portion of SC 4 is occupied as well. Although the general tendency is for braided-wandering channels to have the densest vegetation, SC 1's braiding tendencies are attributable to exposed gravel surfaces.

The following sections describe key stream channel states – 1) meandering; 2) straight; and 3) complex braided-wandering. The latter states tend to exhibit the greatest complexity, high rates of vegetation recruitment, spatially disjunctive planforms, and locally high width-to-depth rations in areas where braiding or wandering tendencies are pronounced. Meandering channels are generally narrower, however, in the case of SC 3a, which has an arcuate pattern, and is thus grouped here for the moment, high width-to-depth ratios and sediment deposition indicate that a more complex state is beginning to emerge. Interestingly, maximum shear stress values show a tight clustering for SC 1, SC 1a, SC 2, SC 3a, and SC 4. SC 4, although currently having a strong meandering signature, also significant vegetation recruitment (≈ 40%), and given the continued recruitment of vegetation it could trend toward a more complex planform.

5.5.1 Meandering Gravel Bed

SC 3, SC 3a and SC 4 are examples of the meandering gravel bed state. SC 3 and SC 4 have modestly sinuous planforms, whereas SC 3a lacks a regular meandering pattern. While SC 3 and SC 4 were constructed during restoration, SC 3a has materialized since 2010, gradually resolving a more definite channelized form. SC 3 and SC 4 are formally similar, characterized by pool-riffle morphologies that are structurally isomorphic to their as-built condition. Neither point bar construction nor thalweg shifting

Figure 5.4 Images from meandering gravel-bed channels. (a) depicts SC 3 and captures the bed, which is free of encroaching vegetation. The transverse channel gradient is subtle, particularly in riffle sections. (b), conversely, was taken in the lower reaches of SC 4, and indicates that the channel bed is gradually losing definition, becoming one continuous surface with the interior and exterior (distal) floodplain. (c) is looking downstream at the entrance of SC 3a, which is an opening on the left bank of SC 3. SC 3a has a gradient advantage over SC 3, contributing to its interception of flow – the bed in this channel segment is relatively free of vegetation, and there were spawning fish observed moving upstream toward SC 3 in 2014. (d) portrays the lower reaches of SC 3a (looking upstream). In 2014 high flows deposited significant quantities of sediment in the channel (sands and clays). The result was spatially uneven depositional surfaces that will likely influence flow and channel evolution in the coming years.

has occurred on either channel. Median shear stress values are ≤ 7.526 N m^{-2} for SC 4 and the upper segment of SC3. This value rises significantly on the lower portion of SC 3 due to the marked increase in bed slope (36. 713 N m^{-2}). Because SC 3's inlet is lower relative to the main channel than SC 4, it receives water later into the year. Along with the low shear stress values in SC 4, this accounts for the fact that SC 3 is relatively free of vegetation, whereas willows (*Salix spp.*), invasive weeds, and grasses, have overspread

SC 4. Vegetation is densest at the transitions into and out of pools, and at several locations there is no clear distinction between the SC 4 and the adjacent floodplain (Figure 5.4c). Despite three years of above-average spring flows, vegetation recruitment has not been impeded. Channel gradients for SC 3 and SC 4 have remained stable and roughly equivalent to the mainstem's slope.

SC 3a has a transitional form that falls between a defined channel and floodplain. Activated at above-bankfull flows, the channel takes on water from the mainstem as well as a small ≈ 10-m-wide entrance on SC 3's left bank. The channel has an arcuate shape, which explains its grouping here (Figure 5.4a), and it separates SC 3 from the main channel. In 2013 the channel gradient was 0.0043, locally higher than both SC 3 and the mainstem (each of which are ≈ 0.0033). SC 3a reconnects with SC 3 at a well-defined exit, however, during overbank flows, water diffuses back into the main channel. High flows in 2014 draped SC 3a with significant quantities of sediment – mainly sand and silt – in its lower reaches. Deposition approached 1 m in places, which flattened the bed's slope to 0.0026. Figure 5.4d illustrates the spatially uneven patterns of sediment deposition, which may be a precursor of early-stage island formation.

The most likely transition to occur on the meandering channels are switches to and from a floodplain state. On SC 4 in-channel vegetation expansion has occurred without increasing sediment retention, although as the existing plants mature and new propagules take root there is likely to be a positive feedback between sediment accumulation and vegetation growth (e.g., Dykaar and Wigington, 2000). Chronic below-average flows will magnify this dynamic, leading to recruitment in previously uncolonized channel locations. Another potential transition is to a vegetation-induced braiding state. This entails the plant matrix sculpting a braided planform, with multiple channels routed around increasingly resistant vegetation. SC 3a, with the appearance of new islands, may be susceptible to this transition. High-magnitude flooding could flush out SC 3a – resetting the channel. Periodic – low to moderate – overbank flows will reinforce current trends, with vegetation recruitment facilitating island building, producing a braided-wandering state (e.g. Gurnell et al., 2001, Gurnell and Petts, 2002).

Figure 5.5 The morphology of straight, gravel/cobble-bedded channels. (a) faces upstream along SC 6b and shows it pinned against an acutely sloped declivity. The hillside is mostly barren and is covered with a mixture of unconsolidated gravels and sands, which appear highly erodible. Exposed tree roots suggest further weathering and hillslope erosion could introduce large woody debris to the channel, potentially redefining flow pathways. (b) discloses small channelized features that have formed on the floodplain that separates SC 6b from SC 3. During overbank flows, the entire floodplain becomes inundated, which has opened up a number of small channels (< 1 m wide).

5.5.2 Straight Gravel/Cobble Bed

SC 6b opened up during the 2011 floods. Running parallel to a steep declivity, it diverts water away from SC 6. Although it has a clearly channelized form it lacks a well-defined inlet. Overbank flows spill onto the floodplain between it as the downstream segment of SC 3 and rework unconsolidated gravel. This has carved out several small rills that empty into SC 3 (Figure 5.5a). SC 6b is gently sloped (0.0012 m^{-1} m). Its right bank is pinned against a bluff that is 10–15 m high, and has no room for lateral adjustment along that margin. Accommodation space is available on the left bank for the channel to potentially migrate. Vegetation recruitment is most pronounced on upstream channel segments.

Likely transitions involve hillslope erosion and failure. Repeat cross sections indicate slight fluvial undercutting of the unconsolidated sediments of the unprotected slope along the channel’s right bank. Several large trees with exposed roots are precariously situated on this slope. As such, a wetter climate or even high-magnitude storms could initiate slope failures or tree throws (Figure 5.4b).Given the gentle channel gradient increased sediment inputs could lead to floodplain expansion. Introducing large woody debris could produce a similar response by deflecting flow toward SC 3, prompting additional floodplain dissection. Without severe perturbations, SC 6b is likely to retain its current form – channelized, but with oscillating levels of vegetation.

5.5.3 Braided-Wandering Gravel Bed

Before flooding in 2011, SC 1 had a meandering planform like SC 3 and SC4. After an avulsion shifted the main channel north on the floodplain, SC 1’s previous configuration was lost. Repairs maintained a significant portion of the geometry carved out by the avulsed main channel, leaving a spatially complex planform. Its entrance reach has been relocated farther downstream of a mainstem meander bend apex to reduce water intake at high flows. The entrance has a step pool configuration that empties into a broad, shallow expanse. Downstream of this area is an elevation break and flow moves across mid-channel braiding flats. Vegetation exerts some influence on flow direction and thread alignment, but gravel is mostly exposed, with surface and subsurface sediment vulnerable to reworking. The width-to-depth ratio through this area is > 100, which is consistent with a braiding morphology. Vegetation tends to be perched on local high points (Figure 5.6a). Flooding in 2012 and 2014 created two new exits roughly parallel to the braiding flats. While not thoroughly channelized, newly emergent plants indicate dominant flow paths (Figure 5.6b). The main portion of SC 1a converges toward a single-threaded state as it approaches its outlet. Relative to the mainstem, it has comparably high slopes, approaching 0.0007 along the upstream segments. This suggests that avulsive activity remain a possibility if flows reach a critical level.

SC 1a exhibits a spatially complex planform. Not built during as part of the restoration project, the channel emerged during the 2011 flooding through a partial avulsion of the mainstem. Before flooding opened up the channel, the area was low-elevation floodplain planted with willows (*Salix spp*.) and cottonwoods (*Populus spp*.). Today the channel’s upper and lower segments are single threaded. Near its midpoint a dense vegetation establishes a key structural control on channel form. Multiple channels loop around increasingly dense stands of willow that have undergone robust growth during the past three years, with many specimens exceeding 3–4 m in height. The middle segment has at least four distinctive branches, with one branch having an upstream-migrating knickpoint that is impeded by a stand of willows. Between 2012 and 2014 a new entrance opened up downstream of SC 1's exit (Figure 6c). Although willows exert strong influence over the branch's left bank, the right bank is exposed. Lateral erosion is pronounced, though there is some evidence of incision. At different points along the channel braiding results from vegetation-water interactions (e.g. Coulthard, 2005), while in others it is induced through the reworking coarse floodplain sediments alone. All of the branches eventually coalesce into a linear, shallow thread that empties into the mainstem.

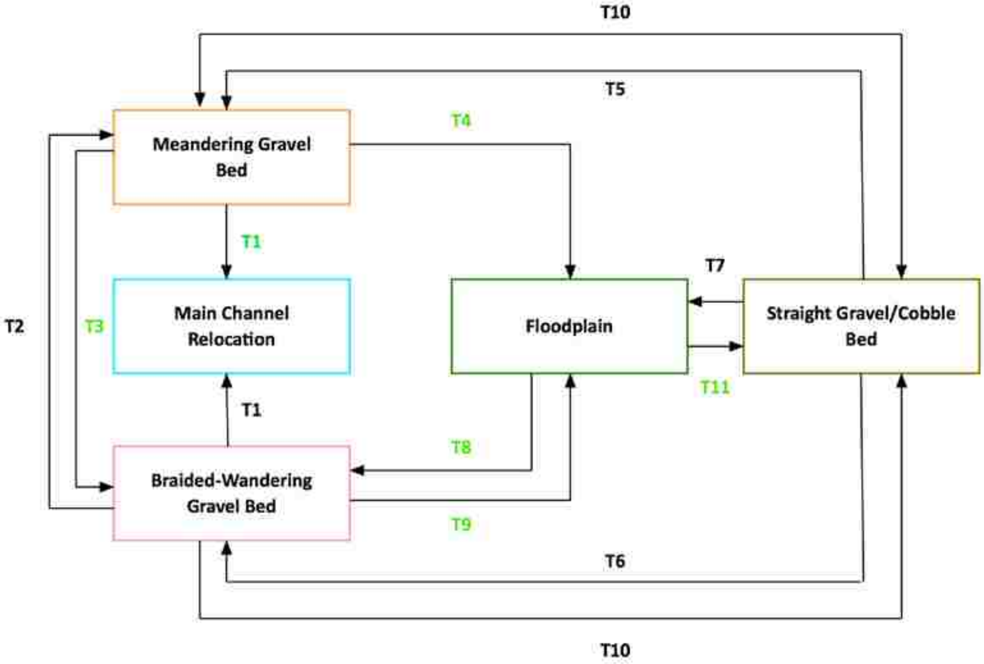
Figure 5.6 Characteristic patterns found on braided-wandering channels. Both (a) and (b) portray SC 1, and demonstrate that, compared to SC 1a (c and d) vegetation density is noticeably less. This allows for the reworking of gravel beds and banks without plants exerting significant structural influence. (b) shows an understated channelized feature that is part of the new exit that has opened up since 2012. There is a clear, nearly linear, bankline that is demarcated by newly recruited vegetation. (c) and (d) illustrate the newly forming entrance of SC 1a. Vegetation plays a critical role in shaping the amount of lateral migration and erosion that along the left bank. In both images, the largely unvegetated right bank is vulnerable to further erosion, and therefore lateral channel expansion is probably during high flows.

Figure 5.7 Transitions along SC 2. SC 2 experienced an avulsion shortly after flow was restored to the main channel. Designed as a meandering channel, it has adopted a straighter course and the lower two-thirds of SC 2 is perennially active due to water inputs from Deer Creek. (a) shows the abandoned channel, which has rapidly returned to a floodplain state. (b) is looking upstream toward the channel's entrance. A channel-spanning log jam blocking is located in the middle-background. Large woody debris that is recruited at channel inlets could significantly influence adjustment trajectories throughout the landscape. The upstream segment of SC 2 dries up while the river is at moderate flows; large woody debris has the potential to exacerbate this effect, and accelerate the conversion of channel to floodplain – causing a state transition. Disjunctive state transitions occur when one portion of the channel moves into a new state without affecting other reaches. (c) depicts a stable mid-channel island that is characteristic of a planform that falls toward the wandering end of the braided-wandering spectrum. (d) highlights a mid-channel bar that is anchored by large woody debris. Located just upstream of the exit reach, further growth of this bar has the potential to shift flow toward a secondary branch. A full avulsion could produce a much straighter channel.

Overall, SC 2 is relatively straight with a major semi-permanent island feature near its midpoint. Like other secondary channels, its original form was meandering, however an avulsion rerouted the it so it now directly intercepts water from Deer Creek. The abandoned channel has largely reverted to floodplain (Figure 7a), suggesting parallels with SC 4. The upper segments of the channel, because they lack perennial flow, have infilled with grasses and willows. A log jam that formed in 2014 facilitated this transition (Figure 7b). It has since been removed, but this indicates that large woody debris could potentially induce a state transition by limiting incoming flow, not only on SC 2, but on other channels also. Channels with entrances framed by debris jams could potentially snag debris floating downstream. SC 2’s vegetated island is better defined than the nascent islands on SCs 1 and 1a, and has proven resistant to high flows. The island’s footprint has expanded, with its left edge migrating to the channel’s left bank. Eventually flow in the left branch, which is already significantly diminished compared to the right branch, could graft onto the left bank, transforming it into a relatively straight channel (Figure 7c). The main exit reach is well defined, however, it appears a secondary branch has developed that conveys flow to the main channel. If an avulsion were to occur, transforming this into the main branch, the result would be a markedly straighter channel. A mid-channel bar, reinforced by woody debris partially impedes flow along the dominant flow path (Figure 7d). Bar growth could accelerate the diversion of flow to the new channel, resulting in a less sinuous planform.

5.6 A Descriptive STM for Secondary Channels on the Restored Clark Fork River Floodplain

Figure 5.8 is a qualitative STM for the Clark Fork that identifies possible state transitions and their drivers. Boxes indicate channel states and arrows the transitions between them. Table 5.2 is an a diagnostic matrix (Montgomery and MacDonald, 2002) that summarizes the effects of three disturbance scenarios – prolonged high discharge and chronically below-average flows, and chronic increases in bedload – on different morphological parameters. The diagnostic matrix can be used to anticipate the consequences of variable bio-hydrogeomorphic fluxes. Taken together, the diagnostic matrix and STM let us trace the etiology of state transitions. The previous section described the three primary channel states that have been observed– 1) meandering, 2) braided-wandering, and 3) straight gravel/cobble bed. Figure 5.8 includes two additional states – 4) floodplain and 5) main channel relocation. The first refers to a vegetated floodplain state that some secondary channels have transitioned toward. Main channel relocation is a mainstem avulsion that results in its occupying a secondary channel, eliminating the latter in the process.



T1 – Qw++, Qs+, V-, Ef ++, Ec++
T2 – Qw+, Qs-, V-, Ef+, Ec+
T3 – Qw n/c, -, Qs+, V+, Ef -, n/c, Ec-
T4 – Qw n/c, -, Qs +, V++, Ef--, Ec--
T5 – Qw+, Qs+, V n/c, -, Ef +, Ec +
T6 – Qw+, Qs+, V+, Ef +, Ec-
T7 – Qw--, Qs++, V++, Ef -, Ec--
T8 – Qw+, Qs n/c, - , V-, Ef +, Ec+
T9 – Qw-, Qs+, V++, Ef -, Ec--
T10 – Qw++, Qs-, V--, Ef-, Ec++
T11 – Qw++, Qs-, V-, Ef-, Ec+

Figure 5.8 A descriptive STM for the Clark Fork River's secondary channels, where Q*w* = discharge, Q*s* = bed-material load, V = vegetation cover and desnsity, E*f* = floodplain erosion, and E*c* = channel erosion (bed and bank). ++ = significant increase, + = increase, n/c = no change; -- = significant decrease, and - = decrease. Transitions highlighted in green have been observed since 2010.

Of the 11 proposed transitions, 7 have been observed since 2011. Comparable to Schumm's approach (1969; see also Knighton, 1998; Montgomery and MacDonald, 2002), each transition is related qualitatively to changes in five variables – water discharge; bed-material discharge; vegetation cover and density; floodplain erosion; and channel erosion (combined bed and bank). The remainder of this section highlights key transition possibilities, commenting on where they are most likely to happen and under what circumstances.

The state transition with the most far-reaching consequences for the entire landscape is a main channel relocation. This occurred in 2011 with the main channel avulsion through SC 1, and this remains the most probably location for future avulsion activity. In 2011 an extended period of high discharge, mainstem aggradation, and floodplain scour near the avulsion node were the principal catalysts of the avulsion. Channel repairs and the reworking of floodplain sediments have shifted SC 1 to its current complex state. Because its gradient is elevated relative to the main channel (0.0041 versus 0.0033 for the mainstem, and localized slopes exceeding 0.006 in upstream segments), avulsive activity is possible (e.g. Slingerland and Smith 1998, 2004). Unlike other secondary channels, the adjacent floodplain remains relatively unprotected, with spotty vegetation cover. The paucity of vegetation is not sufficient to trigger an avulsion, but it would be implicated. Arguably, slope advantages and high discharge would play the most significant role (cf. Anderson et al., 2004). A major avulsion would prompt a state transition in the main channel as well. This illustrates secondary channel dynamics influence main channel's fate, and that state transitions are contingent on process-form relationships unfolding across multiple scales.

SC 2 and SC 4 provide the clearest examples of channel-to-floodplain transitions. Although other channels (e.g. SC 1a) have exhibited significant gains in vegetation cover, it has not always been contiguous with the proximate and distal floodplains – rather, it has been largely confined to channel surfaces. On SC 2, an avulsion routed the secondary channel along a new path, depriving the original alignment of flow, leaving it overgrown with vegetation (primarily willows). SC 4, conversely, because of rapid drawdowns in water compared to the other channels, has undergone rapid vegetation recruitment even though it maintains its as-built form. Low width-to-depth ratios and mean shear stress contribute to this; there is little relief between the channel and floodplain surface, especially along riffles and runs. For some channels vegetation growth has reinforced the emergence of complex braided-wandering states (e.g. SC 1, SC 1a). While there is no evidence of this transition occurring on SC 4, it remains a possibility. Yet this is unlikely absent of sediment pulses that deposit material on the channel and adjacent floodplain (Ashmore, 1991). While high-magnitude flooding could reset channel form to its as-built meandering state – clear of vegetation – the flows required to uproot vegetation would likely have to exceed those of 2011.

SC 1a, which has flipped from floodplain to a complex braided-wandering state, poses an interpretive problem because of its spatially disjunctive planform. Transitions could be localized or the product of interactions with other channels. SC 1a’s midpoint consists of a gravel plain and multiple small channelized features that loop around willow stands. This area is bookended by relatively linear, single-threaded channel configurations. As vegetation matures, it will continue to exert considerable influence over the channel. Extremely high flows could eliminate much of this vegetation and produce a dominant flow path that connects the upper and lower reaches. Recall that SC 1a has a new entrance reach that is an unprotected gravel bed. Any flow significant enough to eliminate vegetation would be sufficient to produce incision and lateral erosion on this stretch, potentially opening up a wide braiding plain. But another complication would arise with high-magnitude flooding occurs – the possibility of a main channel avulsion through SC 1. If an avulsion cut through SC 1, the river would be routed away from SC 1a’s main entrance toward its secondary inlet (assuming a path comparable to the one opened in 2011). The flow-starved upper reaches of SC 1a would transition then to a floodplain state, while the upper portion of the new channel would likely exhibit some degree of braiding. Downstream areas would likely be unaffected. This attests to the immense complexity of state transitions – a transition in one portion of the landscape can resonate significantly elsewhere.

Although I have not discussed every transition possibility exhaustively, I have highlighted likely adjustment pathways and illustrated the type of iterative and stepwise thinking needed to work through the implications of state transitions. Some transitions are relatively uncomplicated and would not produce changes throughout the landscape. Others, especially those that couple state transitions on the mainstem and secondary channels, could instigate a complex sequence of adjustments that produce a new mosaic of channel states. The overwhelming complexity of the landscape suggests the number of possible evolutionary trajectories is very large (e.g. Phillips, 2007). Management strategies, however, must focus on what is probable, not attempt to plan for every contingency, and identifiable undesirable transitions that would prevent the attainment of project objectives. Generalized STMs, combined with close observation of the landscape, can highlight the possibilities that merit the closest scrutiny.

5.7 Conclusion

The Clark Fork River offers a rare opportunity to study early-stage bio-hydrogeomorphic adjustments in a landscape reset by environmental remediation and restoration. This approximated a flume-like condition that lets us investigate and document channel response in a natural yet experimental setting. Unlike controlled laboratory environments, where simulating the contingent interplay of water, vegetation, and sediment fluxes is exceedingly difficult (cf. Lane and Richards, 1997), the Clark Fork magnifies spatial variability and complexity of channel evolution. Long-term study of the restoration site promises to open up new theoretical horizons and to refine our ability replicate the natural dynamics of matter and energy fluxes in laboratory settings.

The descriptive STM presented here stands as a baseline hypothesis to inform future monitoring and management activities. In accentuating the importance of complexity and plurality in riverine landscapes, the paper has adopted an expansive view of what adjustment trajectories are possible along the Clark Fork River. Given that a number of channels have seen portions of their beds and banks transition to a floodplain state, it appears this is likely to be the most common state shift in the absence of severe perturbations (i.e. prolonged high discharges). This does not necessarily imply the floodplain state operates as an attractor state toward which most channelized features converge, especially given the patchiness of recruitment. Vegetation coverage has grown on most channels, but not isotropically.

Although they are models, STMs are more profitably viewed as frameworks to organize information about rivers – or other landscapes – so that environmental management agencies can design better policy frameworks to guide adaptive management. STMs are more about *anticipating* possibilities than offering deterministic or mechanistic predictions. The secondary channels on the Clark Fork River reveal patterns of complex adjustment. Channels starting from identical states can undergo spatially and temporally divergent evolution. Even within the same channel, multiple adjustment trajectories are possible that are contingent on micro-scale hydrogeomorphic fluxes that impact areas with dissimilar biogeomorphic spatial signatures in multiple ways (e.g. Curran and Hession, 2013). Diagnostic STMs are valuable for appraising how river states will undergo morphological transformations caused by impermanent form-process relations, which can inform pragmatic management interventions, particularly in restored landscapes.

Table 5.1 Morphometric Data Summary for Secondary Channels

Secondary Channel	Flow Regime	Length (m)	Slope (m/m)	Median w:d	Minimum w:d	Maximum w:d	Median Shear Stress	Maximum Shear Stress	Minimum Shear Stress
SC1	Perenial	536	0.0041	59.254	18.795	122.590	21.015	27.292	9.242
SC1a	Intermittent	490	0.0036	31.021	18.942	166.176	12.563	28.083	4.371
SC2	Perenial	499	0.0031	45.611	17.620	95.788	13.178	24.904	5.985
SC3 - Upper	Intermittent	348	0.0006	46.546	13.909	82.654	1.214	4.242	1.062
SC3 - Lower	Perenial	151	0.0116	47.138	16.625	69.654	36.713	65.493	20.112
SC3a	Intermittent	360	0.0043	109.031	65.353	154.765	15.191	23.505	6.289
SC4	Intermittent	678	0.0032	33.617	13.596	92.609	7.526	22.834	2.705
SC6b	Intermittent	184	0.0115	54.924	20.365	114.684	22.581	65.959	10.957

Secondary Channel	Sinuosity	Braiding Index 2012 (2014)	% In-Channel Vegetation Coverage	Channel State
SC1	1.152	1.40 (2.00)	55%	Complex Braided-Wandering
SC1a	1.044	1.30 (1.90)	15%	Complex Braided-Wandering
SC2	1.077	1.30 (1.30)	25%	Complex Braided-Wandering
SC3 - Upper	1.120	n/a	<5%	Meandering
SC3 - Lower	1.056	n/a	<5%	Meandering
SC3a	1.133	n/a	35%	Meandering (Arcuate)
SC4	1.240	n/a	40%	Meandering
SC6b	1.060	n/a	20%	Striaght

Table 5.2 Diagnostic Matrix for Secondary Channels

	Chronically High Discharge			Chronic Below-Normal Flows			Chronic Increases in Bedload Material		
Response Variables	MGB	SGB	BWGB	MGB	SGB	BWGB	MGB	SGB	BWGB
Bankfull Width	+	+	+	-	-	o	+	+	o,+
Bankfull Depth	+	+	+	o,-	o,-	o,-	+	+	+
Median Surface Particle Size	+	+	+	o,-	o,-	o,-	o,+	o,+	o,+
Embeddedness	-	-	-	+	+	+	-	-	-
Bedload Transport	+	+	+	-	-	-	+	+	+
Suspended Load Transport	+	+	+	-	-	-	o,+	o,+	o,+
In-Channel Geomorphic Unit Construction (e.g., point bars; mid-channel bars)	-	-	-	-	o,-	-	+	+	+
Vegetation Cover and Density -- In-channel	-	-	o,-	+	+	+	o,-	o,-	o,+
Vegetation Cover and Density -- Riparian	o,-	-	o,-	o,+	o,+	o,+	o,+	o,+	o,+
Sinuosity	o,+	+	o,+	o,-	o	-	+	o,+	o,+
Braiding Intensity	o,+	o,+	+	o	o	-	o,+	o,+	+

+ = increase; - = decrease; and n/c = no appreciable change

Chapter 6 – Conclusion

Writing a conclusion for a dissertation that consists of four self-contained articles poses challenges. The first thought that comes to mind is – what can I write that does not repeat the findings that were described in each chapter? Certainly, I could lifelessly repeat the conclusions of those chapters, but this formality hardly seems necessary. A reflection on river restoration seems more appropriate. During much of my time writing this document I was insistent on *not* invoking the concept of river restoration because of the ontological baggage it carries. Very simply, restoring anything is impossible. Recovering a past landscape in a place that history has already exacted its toll on seems misguided and hints at an effort to step outside of…history itself and into a place governed by invariant universal laws reacting entirely as expected to our interventions.

Various terms have been offered as alternatives to river restoration – rehabilitation and recovery spring to mind first. Eventually I decided the semantic battle was pointless. Pretty much anyone involved in projects like those executed on the Clark Fork River will refer to them as restoration. And this is fine. Taking a page from my discussion about what it means to be a critical (physical) geographer, applying the word restoration to projects that attempt to improve degraded river landscapes should not worry anyone. It seems more important to focus our energies on the material environments that we seek to transform. Restored landscapes will adjust, and ultimately waves of biophysical change may erase any record of that restoration.

Most of the people involved in the Clark Fork project acknowledge that the river will do what it wants to over the long run. The principal design engineer admitted to me that if they were to attempt the project again there would be less effort to make things function perfectly. Indeed, what is actually perfect is probably a great deal messier-seeming than our minds would like to admit. And so it is with battles over what to call restoration. Language is imperfect and there is really no good term to describe what restoration projects actually do, so we might as well just stick with "restoration[9]." Improvement, melioration, betterment – all of these words could be used to describe the

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[9] A lesser writer, at this point, would probably make some kind of clever observation about how when you say "restore" aloud the second syllable pretty much forces you to contemplate "order." And certainly, restoration, in many cases, attempts to install order.

intentions that underwrite our ambitions to restore the landscape, especially in places like Milltown where the source of environmental damage is transparently obvious – if not so easily fixed.

Readers will have noticed that I used the words "potential" and "possibility" many times, perhaps too many, in this document. The main reason for this is that my goal has been to think through what is possible and how the Clark Fork may – potentially – evolve in the coming years. Perhaps, restoration more than anything is bound up with our inclination to imagine a different future. The purpose of using state-transition thinking to consider the evolution of landscapes is to demonstrate that the future is unfixed, that betterment may be achieved in multiple ways, that how the river adjusts can only be anticipated and never deterministically predicted. What most of the heated debates over river restoration (the Rosgen Wars) overlook is the essential role that chance plays in reshaping our rivers and landscapes, and that it is something that can never fully be accounted for. Talking about possible trajectories of changes attempts to cope with this reality somewhat, although it can quickly become exhausting to consider all of the potential scenarios. While it is fine to pursue short-term goals – at engineering time scales – we should recognize that this slice of time is vanishingly small, and that it is perfectly appropriate to think about river restoration with much longer time frames in mind. In all likelihood the Clark Fork River will continue to flow for hundreds or even thousands of years.

Although we might have a reasonably good handle on how hydrogeomorphic processes will affect fluvial dynamics in the near future, no model can account for chance events, and the compounded effects of chance. Restoration does not eliminate the possibility of chance and the environmental orderings that are produced by chance. This is what is so fascinating about some strands of restoration – the attempts to exactly recreate a past environment. Yes, this speaks to the desire for a past order, but this is an order that arose at least partially due to chance events. Whether we consciously recognize this is unclear, but it places into pretty stark relief the paradox of associating past landscape with necessarily having a better order (obviously this does not consider the issue of restoration attempting to improve ecological or hydrogeomorphic functionality, and treats chance in isolation – abstractly). Which is to say that being pragmatic about restoration and recognizing that whatever enhancements made to the landscape will be temporary should be at the forefront of our minds. And this means thinking about what is possible, not what is necessary. Restoration is thus about temporarily restoring a set of possibilities that otherwise would have eluded us, and that had it eluded us permanently our landscapes would have been the poorer for it. But the possibilities we imagine now do not reflect what is possible 10 or 100 years from now. Potential states need to be remapped all the time to account for what has taken place, and even then we can only account for a fraction of what we see or what may be.

Dwelling on the semantics and the progressive erasure of restored landscapes, however, does little to improve our current practices. One reason why STMs appeal to me is they force reflection upon many different states that may abide in the landscapes. While STMs can be used to great effect in planning, their downside is that they can sanction agnosticism or indifference toward environmental deterioration, precisely because their entire purpose is to look for multiple adjustment trajectories to infer the reaction of landscapes under varying biophysical process regimes. That is, if we are aware of potential state transitions, and see the landscape sliding into a new and intransigent state that could not be easily reversed, it would be easy to adopt a fatalistic or resigned attitude, one that would justify not intervening because it is seemingly a lost cause – after all, we could say this is just one possible state among many. Certainly, with money for environmental management and protection vanishing everyday because of competing policy demands, it is all the more plausible to imagine this scenario.

However, STM frameworks and state-transition thinking more broadly can perhaps alert us to the early signs of degradation so that we might attempt to forestall decline before it is too far gone. What is the utility of STMs, then? Other than being a conceptual space that is used to store knowledge about landscapes? So far, despite, my just-stated misgivings, I have argued STMs are tools for thinking about potential and possibility. But this seems inadequate, and this suggestion – alone – will hardly benefit the people who are responsible for managing natural resources on a day-to-day basis. What is to be done with that knowledge? The pragmatic answer, I suppose, is that we can use STMs, and scenario planning more generally, to develop short- and medium-term management goals (on the order of 1–50 years). When setting goals, STMs provide us with a way to ask questions and set hypotheses about landscape adjustment.

Suppose our intent is to reestablish connectivity between a river and its floodplain so that a more vibrant ecological community can flourish. It we were to map out the future using STMs, we would begin with very simple questions. For example, what hard and soft engineering solutions could we implement to fuse river and floodplain more intimately? Perhaps the decision is made to install log jams to encourage floodplain sedimentation and generate microtopographic contours that will open up space for vegetation recruitment (e.g. Montgomery and Abbe, 2006). Of course, hydrogeomorphic fluxes vary, and it is probable that our river will experience a flood at some point. At this point out state-transition thinking kicks into gear, and we could ask what would happen if high-magnitude floods occurred one year after completing restoration. Then we could ask the same question, but at different time intervals (five years, twenty years, and so forth). The idea is to look at one type of disturbance, spaced at different points in time, and think about what the consequences would be for the landscape. Would a state transition occur? Would flooding remove woody debris and the incipient floodplain? What would the magnitude of the changes be? And perhaps most importantly, how would we respond? Exhaustively mapping out every contingency is beyond the reach of any natural resources agency, but anticipating future disturbances, landscape responses, and management interventions even in their broadest outlines can prevent us from being caught off guard. This kind of visioning exercise would also give us the opportunity to decide when preserving the current management is warranted and when it may be time to rethink our goals and how we achieve them, because to do otherwise would engage us in an impossible fight against the landscape (Brierley and Fryirs, 2009).

But what does all of this mean for the Clark Fork River? Chapters 4 and 5 described the adjustment trajectories we can expect under different circumstance. What can we do with this knowledge? What does it tell us about management in the future? These questions are more difficult to answer, in part because the money available for management interventions is limited. Moving forward, the state’s primary objective is to ensure biogeomorphic succession continues apace on the floodplain while maintaining the morphological resiliency of the main channel. For example, as my discussion in

Chapter 5 highlighted, large portions of some secondary channels that have become indistinguishable from the floodplain topography. Is this problematic? Not necessarily.

Observations and the STM developed for the secondary channels indicate this is one evolutionary trajectory among others. If the state wanted to increase the amount of flow captured by these channels, and consequently restore their channel-like features, this would be possible with minor adjustments (e.g. lower the secondary channels' bed levels). These adjustments could support flows at lower discharges. Similarly, large woody debris has collected at the inlets of at least two secondary channels. Although none of the jams observed so far have spanned the entire length of an entrance, thus diverting flow back to the mainstem, this is a possibility. Knowing that log jams could 1) transition secondary channels to a floodplain condition and 2) increase flows in the main channel could influence management decisions. Although a secondary channel reverting to floodplain may be inconsequential, adding more flow to the mainstem could potentially introduce instabilities that would have transformational consequences during high-magnitude flows (e.g. mainstem avulsion). It is probable that – barring a new injection of money into the project – that management will focus on tweaking small elements of channel design and floodplain condition, such as repairing degraded geoengineered structures, opening up secondary channel entrances, and eliminating weeds and other invasive species from the floodplain. This summer new trails will be constructed on the floodplain to improve access. The area is now a state park. And while the plan is to construct most of these trails on terraces or the distal floodplain, it is probably worth studying whether their development could negatively impact the area's recovery. Creating STMs to forecast the possible impacts of trail development would be a useful exercise.

None of this, I recognize, sounds grandly inspirational (or transformational). The examples and interventions highlighted are modest, but thinking about what state transitions that are possible can better prepare us to manage routine biophysical fluxes and equip us with the knowledge to improvise responses if a catastrophic disturbance were to occur. Looking to the programs and strategies used by the NRCS, specifically their attempts to design STMs for managerial purposes, can improve our ability to develop STMs for a wide range of biophysical (or socio-biophysical) environments.

Certainly, I have attempted to demonstrate their usefulness for the Clark Fork River. But the intractable reality is that the Clark Fork restoration has already achieved what it set out to accomplish. Milltown Dam was removed and the most harmful and contaminated sediments were excavated and hauled from the floodplain, leaving a landscape that, if nothing else, is significantly less toxic than it once was. It is understandable that the State of Montana – now renowned for its restoration economy – plans to direct most of its resources toward other injured landscapes. The ideas described in this dissertation are as much about the Clark Fork River as they are about our natural environments more generally. More specifically, their purpose is to pragmatically and imaginatively (although the two are not mutually exclusive) reconsider how we talk and think about biophysical landscapes. Whether these ideas will gain a foothold is unclear. Like any set of concepts, the ones I have described are *idealized* to a certain extent, and probably spring from an overly romantic and even naive view of what environmental management sets out to accomplish – although my recognition that possibilities are limited and money and time are always in short supply inserts a bit of realism. Nevertheless, some of the fundamental ideas I talk about would prove beneficial if adopted in practice – even if the day never arrives when natural resource agencies preserve meticulously curated records overflowing with state-and-transition frameworks for every landscape imaginable.

If nothing else, scholarship is mostly about instigating or participating in conversations. Like the landscape itself, how we talk about the landscape is ephemeral. Perhaps in advocating for state-transition thinking my contributions situate me as another "fashion dude" attempting to interject new strands of thought into geomorphology (Sherman, 1996). In some ways, this is true, although introducing new concepts into is valuable because it lets us envision landscapes in a manner that was not previously possible. And this is often the first step toward producing new and innovative knowledge. Even ostensibly outdated fashions exert an influence well beyond their heyday. Undeniably, other frameworks will supersede STMs – but those frameworks will be redolent with the minor contributions of myself and others. No ideas are ever lost permanently, they just pass in and out of focus depending on the fashion of the time. Everything in this dissertation, when taken together, stands as a snapshot of how we think about environmental transformation and the Clark Fork River at this moment (at least from my perspective as the one snapping the picture). Some of the ideas and predictions will prove more resilient and accurate than others. But if scholarship is about conversation, the most important thing is to keep the conversation going, even it is by venturing guesses that will be revealed as unfounded by the future. Taking part in this conversation is meaningful and yet oddly insufficient. But then it is hard to imagine it being any other way.

Appendices

Appendix A – Methods in a Nutshell

This table summarizes the methods used to perform field measurements and – if applicable – academic references from which I obtained information on their execution. For more detailed explanations, see Chapters 4 and 5.

Table A.1 (Methods)

Activity	Approach/Notes	Academic References
Surface Sediment Characterization (Pebble Counts)	- Locations with homogenous bed material were selected and a transect was placed perpendicular to the channel at each sampling location - Particles were randomly selected at 50-cm intervals - Each particle's intermediate axis was measured and recorded - Sampling continued until 125-150 particles had been measured	- Wolman (1954) - Kondolf (1997) - Bunte and Abt (2001) - Surian (2002)
Subsurface Sediment Analysis	- At 2-6 locations along each channel subsurface sediment was sampled - The surface (armor) layer was removed and a conical hole was dug into the exposed surface. - Sediments were sampled to the thickness of the largest particle in the armor layer -Samples were wet and dry sieved to assess the fraction of gravels, sands, and clays - A Mastersizer 3000 was used to analyze the fraction of fine sediment that was not captured by dry sieving - Sand and clay fractions were corrected based on analysis of these samples	- Church (1987) - Bunte and Abt (2001)

Table A.1 (continued)

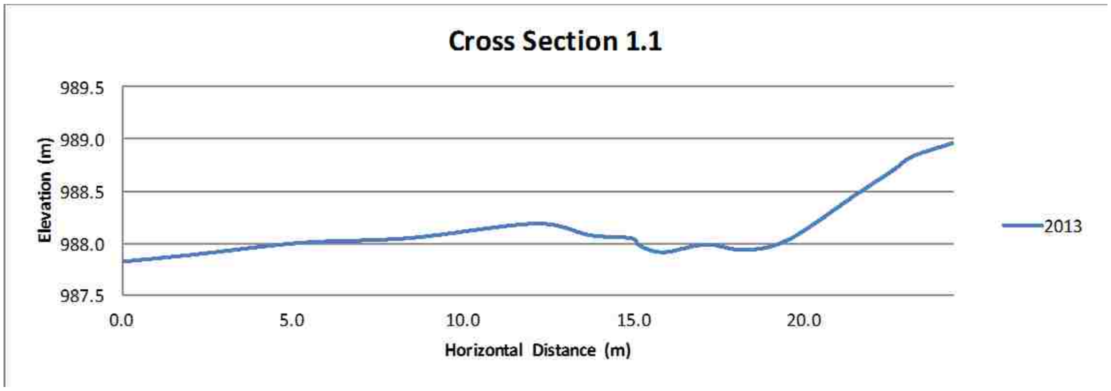
Channel Cross Sections	**- In 2013, for each secondary channel, 10-17 locations were selected to obtain a representative sample of channel geometry** **- Repeat cross sections were performed in 2014 on a subsample** **- A Trimble R8 GNSS was used for measurements** **- Horizontal accuracy of the R8 is +/- 10 cm; vertical accuracy is +/- 20 cm** **- With the exception of Secondary Channel 3 (for which a longitudinal profile was measured), channel gradients were calculated using cross-sectional data and channel's center lines (approximation of the thalweg)**	**- Harrelson et al. (1994)**
Main Channel Longitudinal Survey	- In 2013, a survey of the main channel's slope gradient and water surface slope were performed - Above-water measurements were taken with a survey-grade GPS unit - A single-beam echo sounder was used for underwater measurements (i.e. bed topography) - Three passes were made with the single-beam echo sounder to ensure the precision and accuracy of the measurements - Slopes were calculated on a reach-averaged basis	- Flerner et al. (2012) - Javernick et al. (2014)
Floodplain Mapping	- Relic tree stumps were mapped using a Trimble GeoXH 6000 - The post-processed accuracy – horizontal and vertical – was +/- 50 cm for 97% of the points (n= 662)	- n/a
Sedimentological Data	- From 2003-2005, sediment cores were taken from the reservoir and adjacent portions of the floodplain - Samples were collected using sonic drilling to retrieve cores - Core depths ranged from 3.5 m to 17.5 m - The accuracy of estimated sediment depths was +/- 0.6 m	- n/a

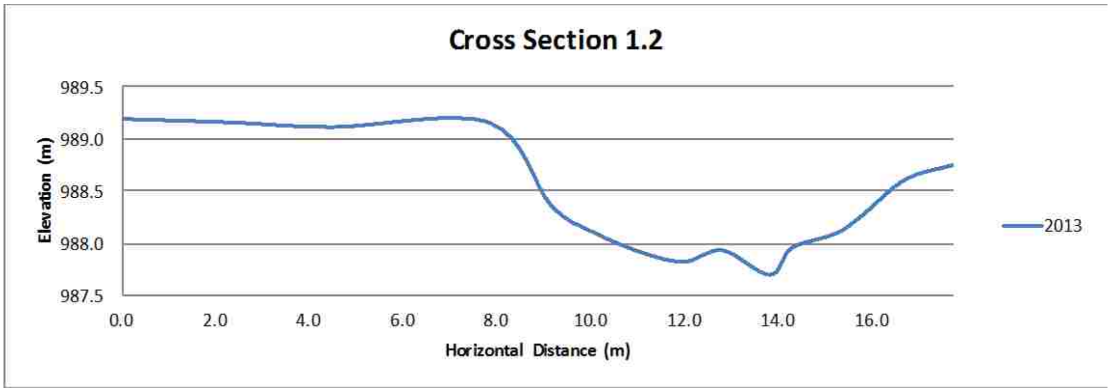
Table A.1 (continued)

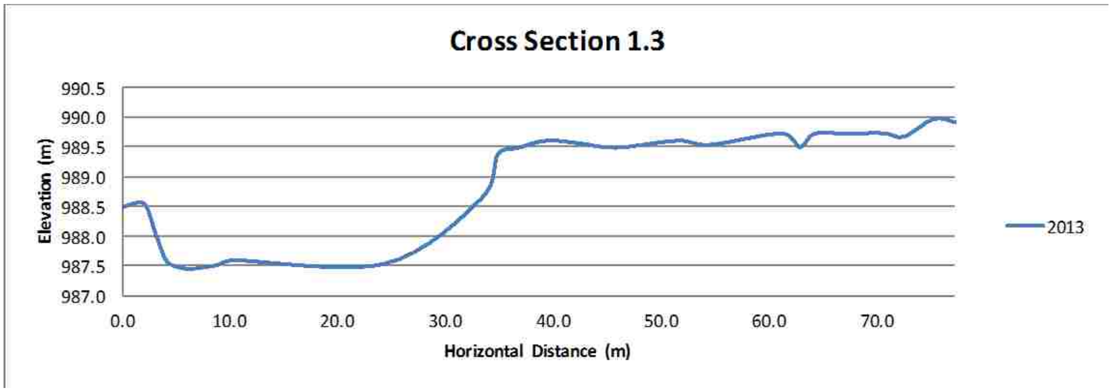
Channel Planform Mapping	**- Remotely sensed images were obtained for each year, 2011-2014** **- The images were orthorectified and channel boundaries were digitized at 1:500 scale. Resolution for the 2011 images was 1 m; for the 2012-2014 photos, it was 50 cm** **- 2011 and 2013 images captured the river near baseflow, with the 2011 data illustrating post-flooding adjustments** **- 2012 and 2014 images were acquired near or slightly over the estimated bankfull flow** **- Vegetation cover was estimated from 2013 photos, comparing the extend of coverage against the area of the active channel**	**- Gurnell (1997)** **- Fonstad et al. (2012)**
Historical and Qualitative Assessments	- For GLO survey notes, maps, and other historical material I performed close readings to identify the pre-dam condition of the river - In other words, I sat around and thought about this material. Sorry – it does not get any more interesting, nor is their a deeper story to tell.	- n/a

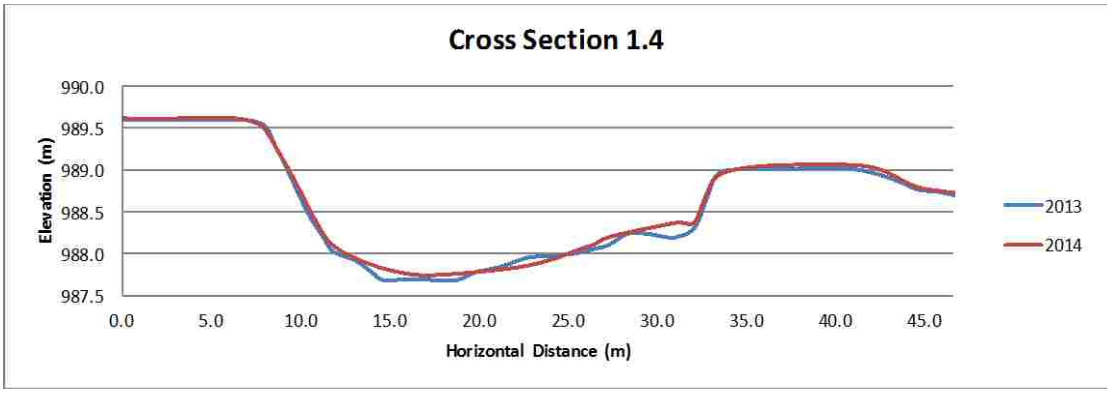
Appendix B – Secondary Channel Maps and Cross Section Locations

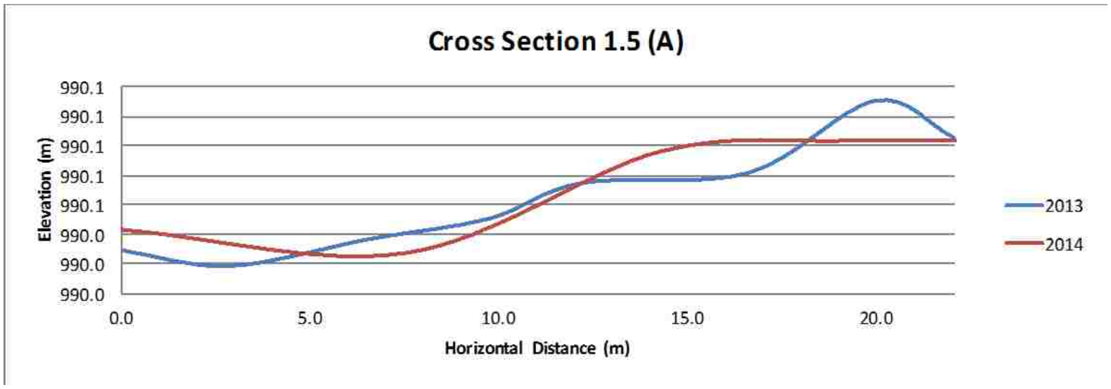
Secondary Channel 1

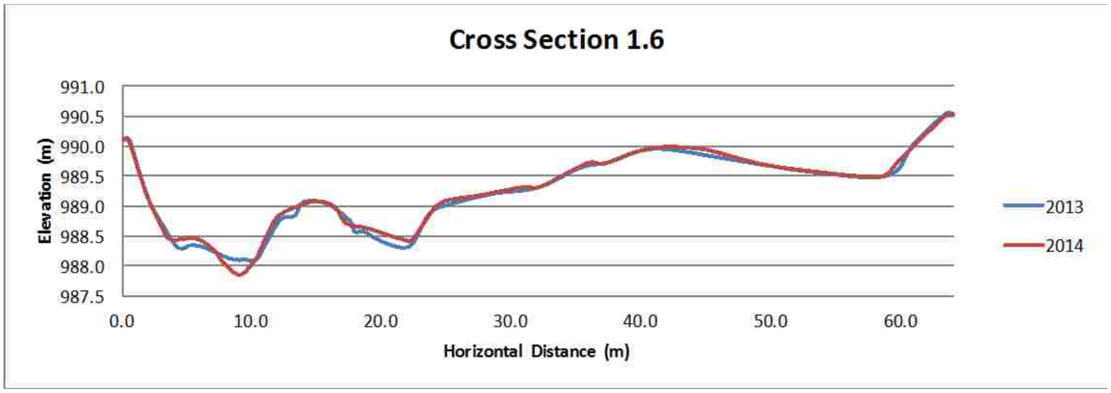


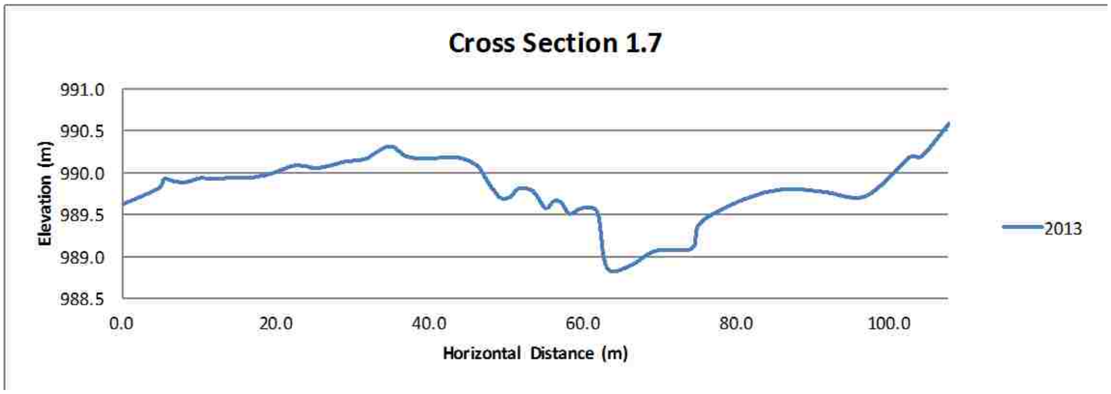

Cross Section 1.2

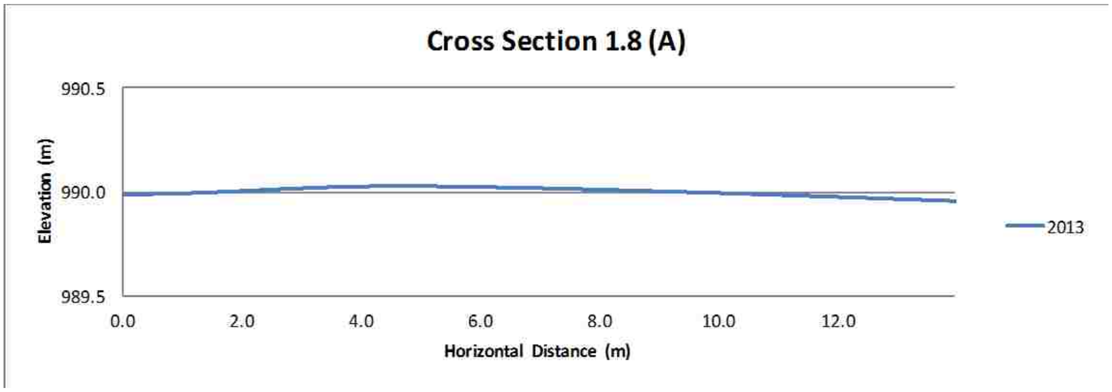

Cross Section 1.3

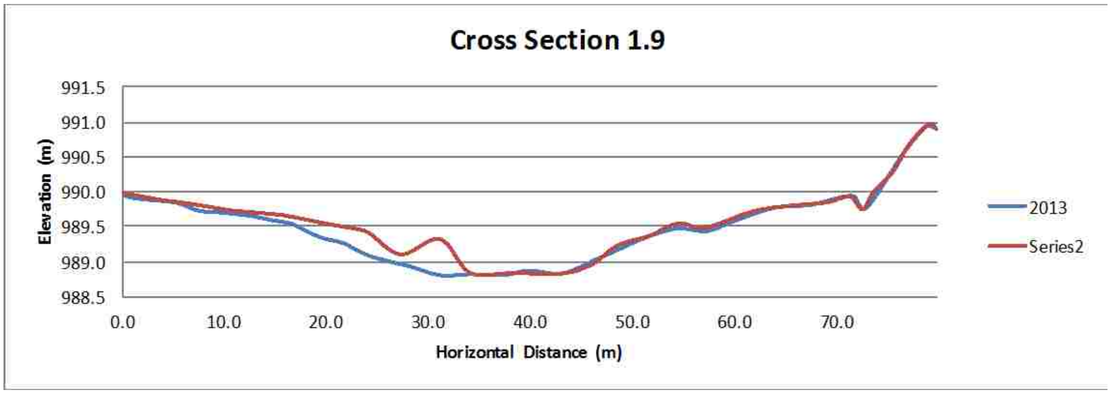

Cross Section 1.4

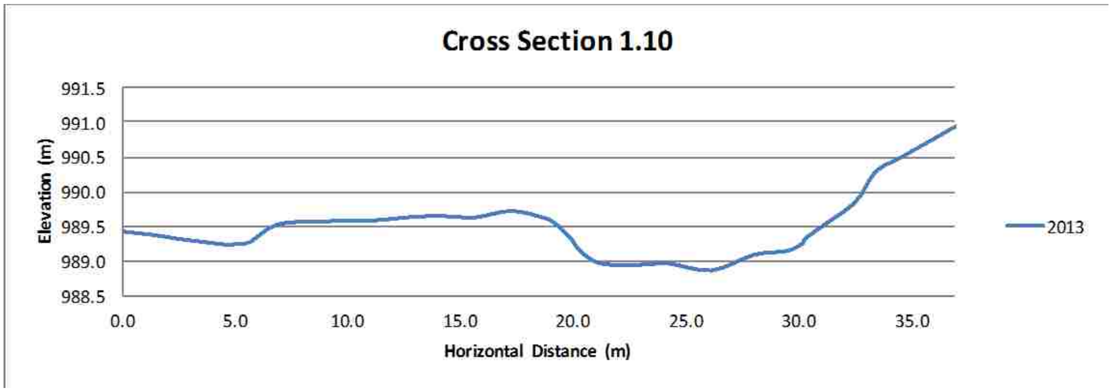

Cross Section 1.5 (A)

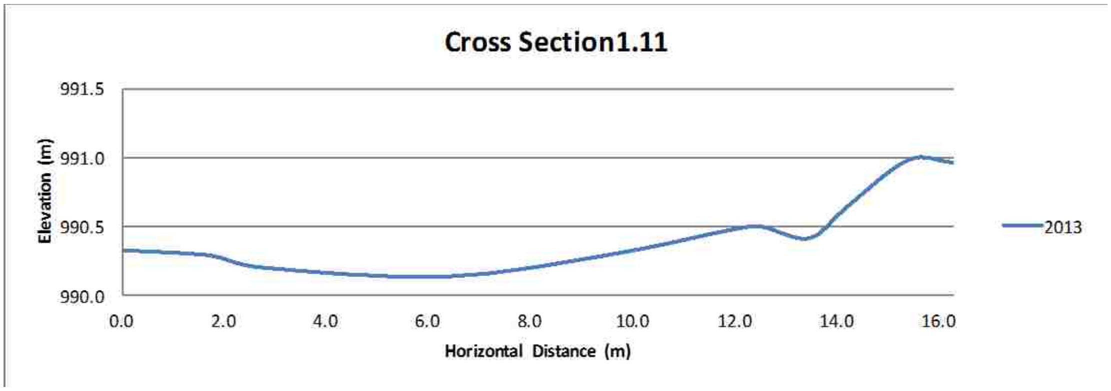

Cross Section 1.6
991.0
990.5
990.0
989.5
989.0
988.5
988.0
987.5
Elevation (m)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
Horizontal Distance (m)
2013
2014


Cross Section 1.7
991.0
990.5
990.0
989.5
989.0
988.5
Elevation (m)
0.0
20.0
40.0
60.0
80.0
100.0
Horizontal Distance (m)
2013

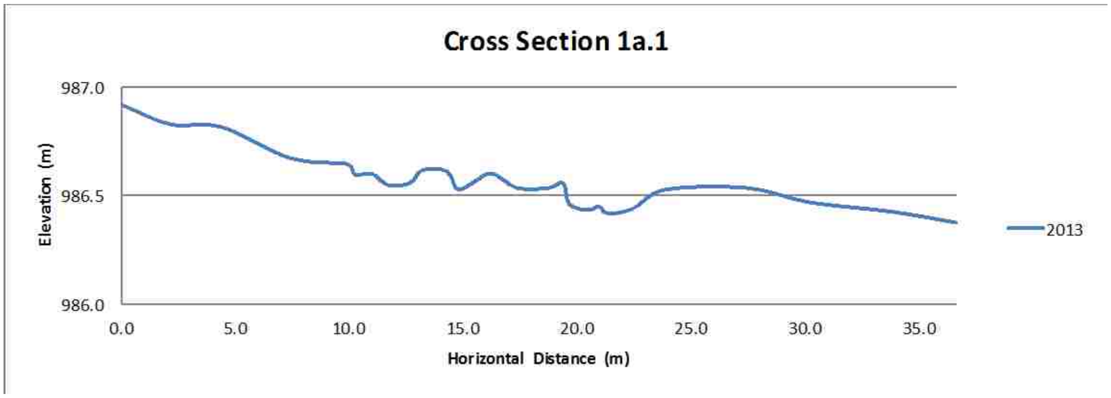

Cross Section 1.8 (A)
990.5
990.0
989.5
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Horizontal Distance (m)
2013

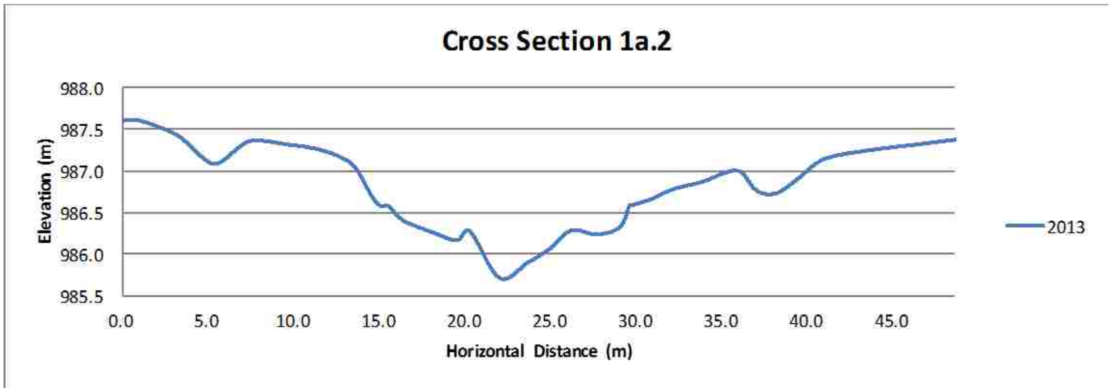

Cross Section 1.9
991.5
991.0
990.5
990.0
989.5
989.0
988.5
Elevation (m)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
Horizontal Distance (m)
2013
Series2

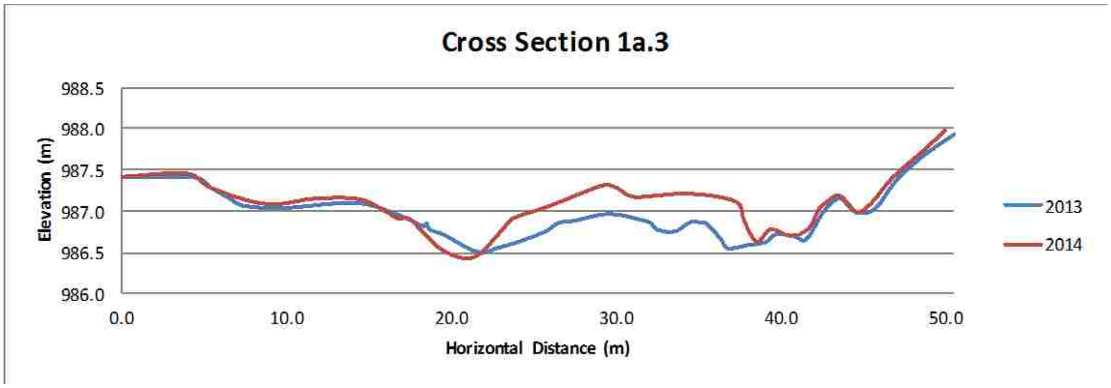

Cross Section 1.10
991.5
991.0
990.5
990.0
989.5
989.0
988.5
Elevation (m)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
Horizontal Distance (m)
2013

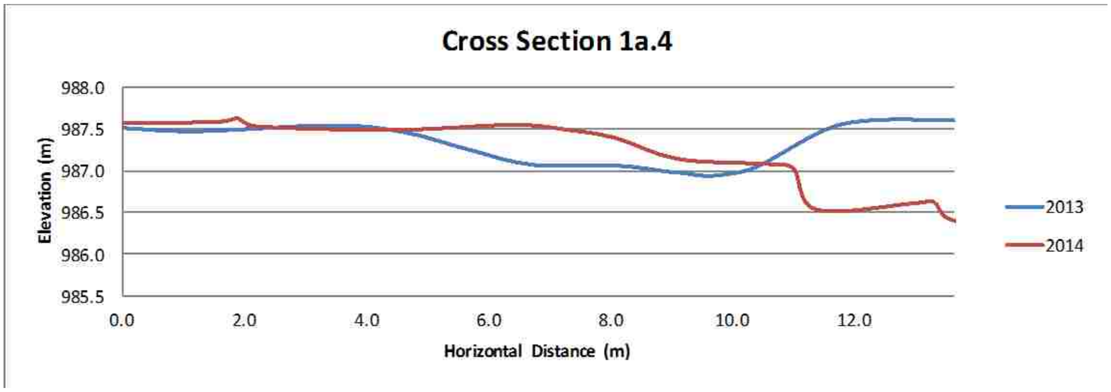

Cross Section1.11
991.5
991.0
990.5
990.0
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Horizontal Distance (m)
2013

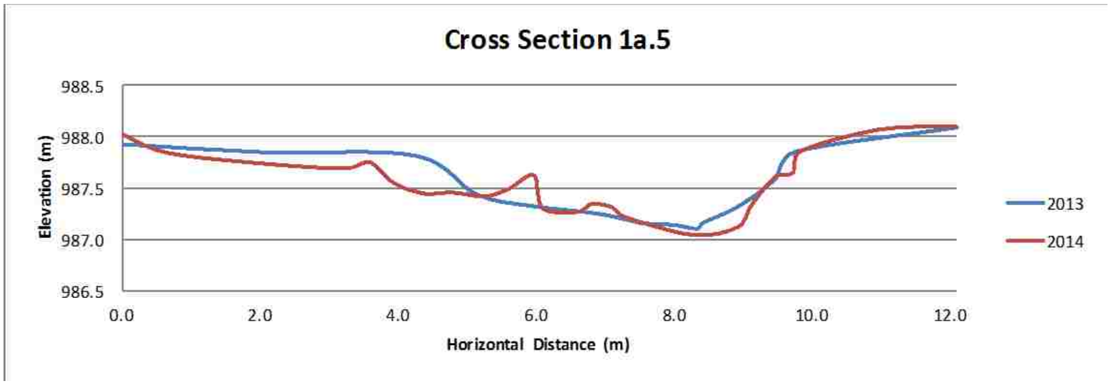
Secondary Channel 1a

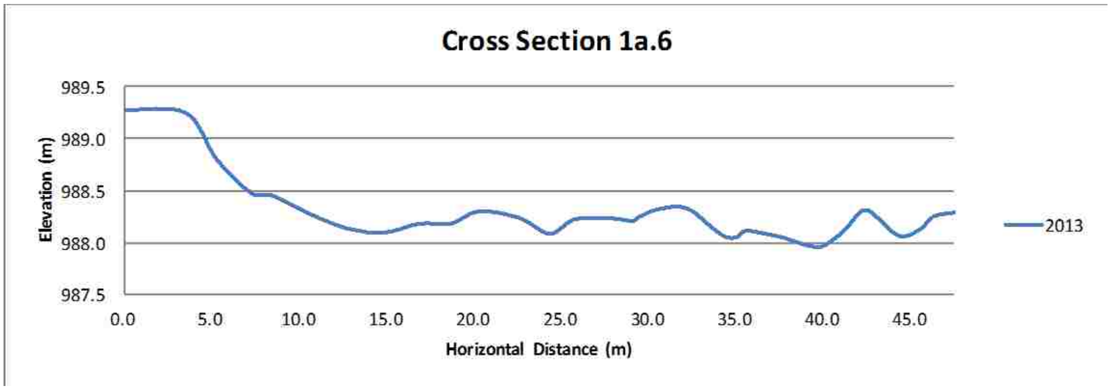



Cross Section 1a.2
988.0
987.5
987.0
986.5
986.0
985.5
Elevation (m)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
Horizontal Distance (m)
2013

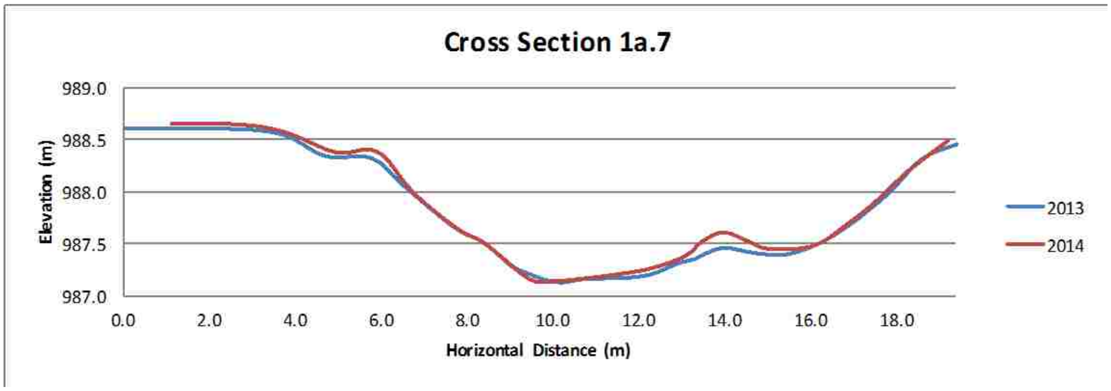

Cross Section 1a.3
988.5
988.0
987.5
987.0
986.5
986.0
Elevation (m)
0.0
10.0
20.0
30.0
40.0
50.0
Horizontal Distance (m)
2013
2014


Cross Section 1a.4
988.0
987.5
987.0
986.5
986.0
985.5
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Horizontal Distance (m)
2013
2014

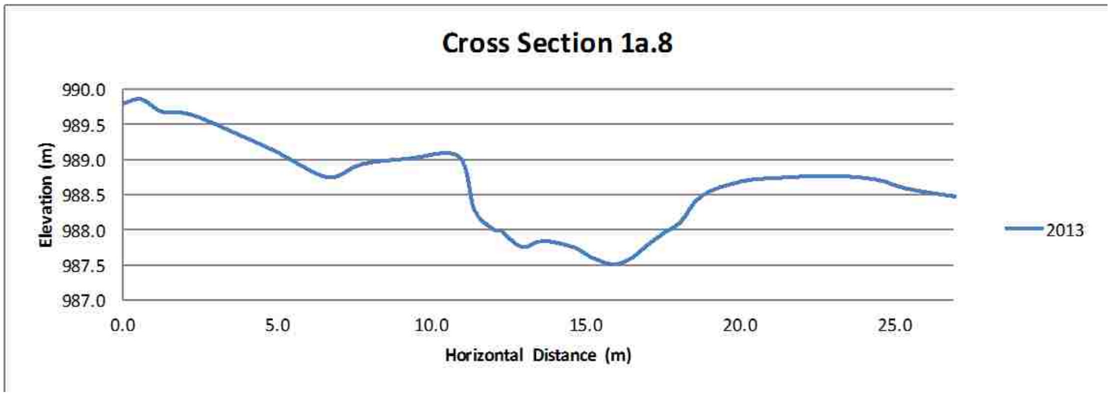

Cross Section 1a.5
988.5
988.0
987.5
987.0
986.5
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Horizontal Distance (m)
2013
2014



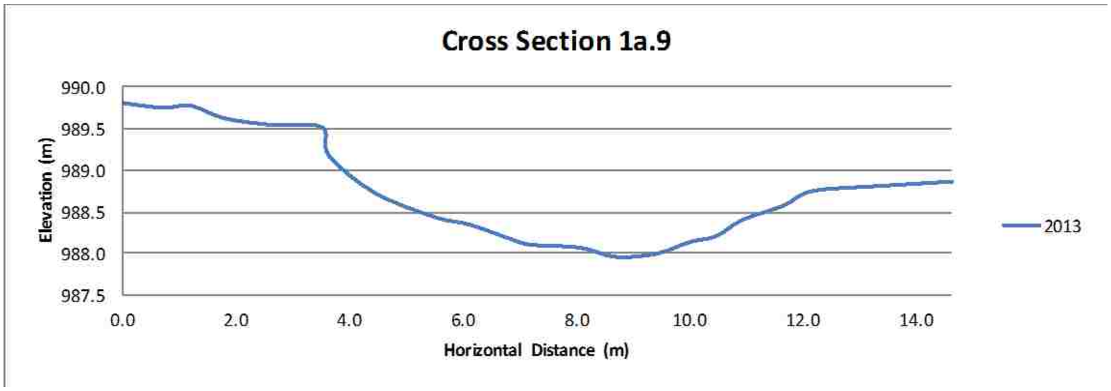
Cross Section 1a.6
Elevation (m)
989.5
989.0
988.5
988.0
987.5
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
Horizontal Distance (m)
2013



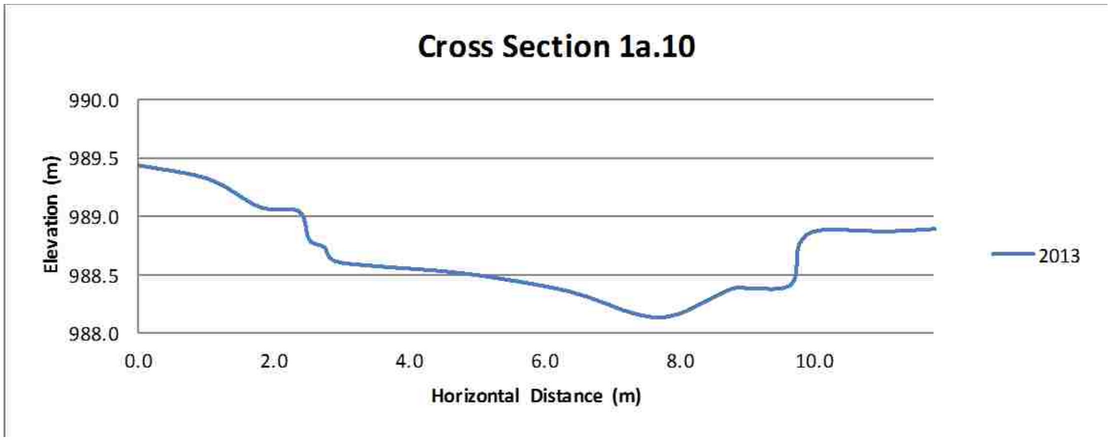
Cross Section 1a.7
Elevation (m)
989.0
988.5
988.0
987.5
987.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
Horizontal Distance (m)
2013
2014



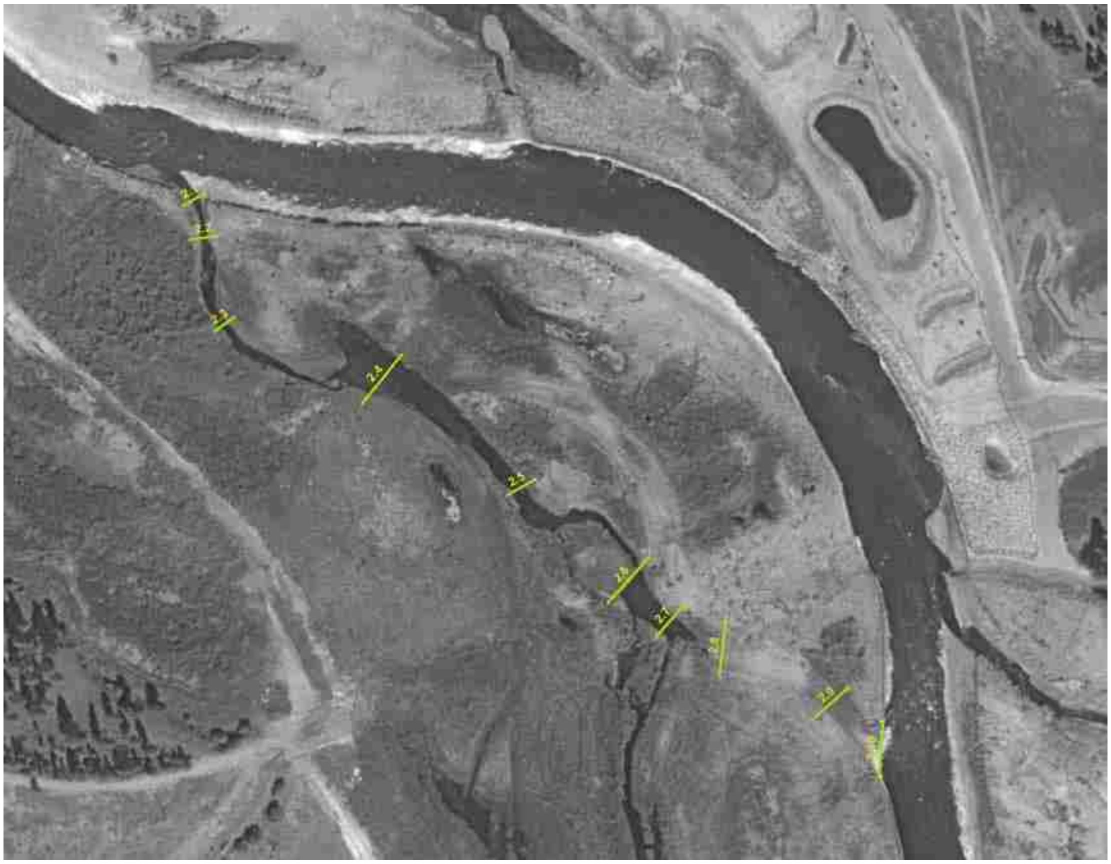
Cross Section 1a.8
Elevation (m)
990.0
989.5
989.0
988.5
988.0
987.5
987.0
0.0
5.0
10.0
15.0
20.0
25.0
Horizontal Distance (m)
2013

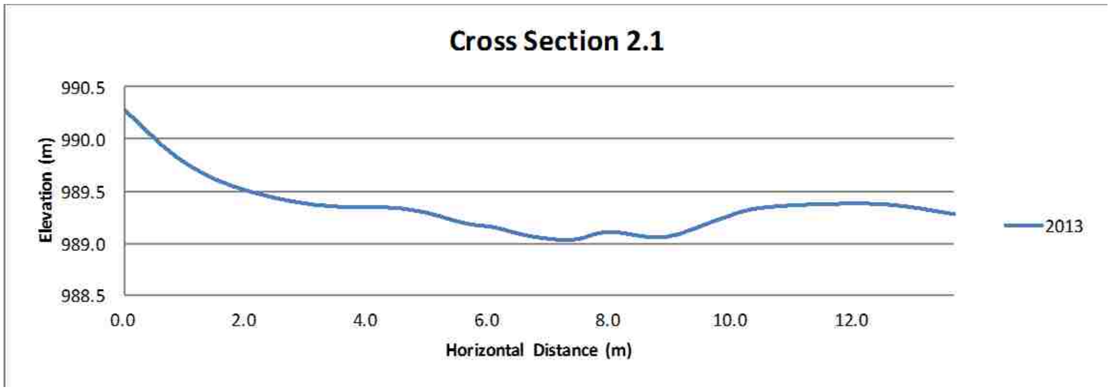


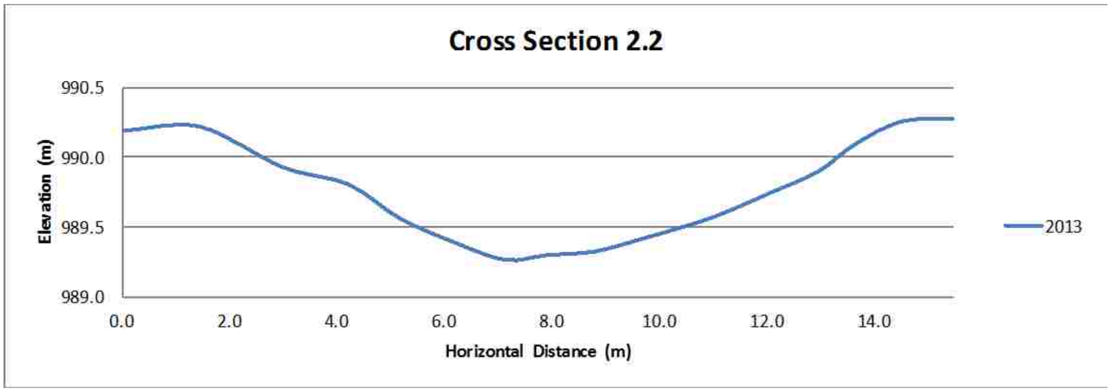
Cross Section 1a.9
Elevation (m)
990.0
989.5
989.0
988.5
988.0
987.5
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Horizontal Distance (m)
2013

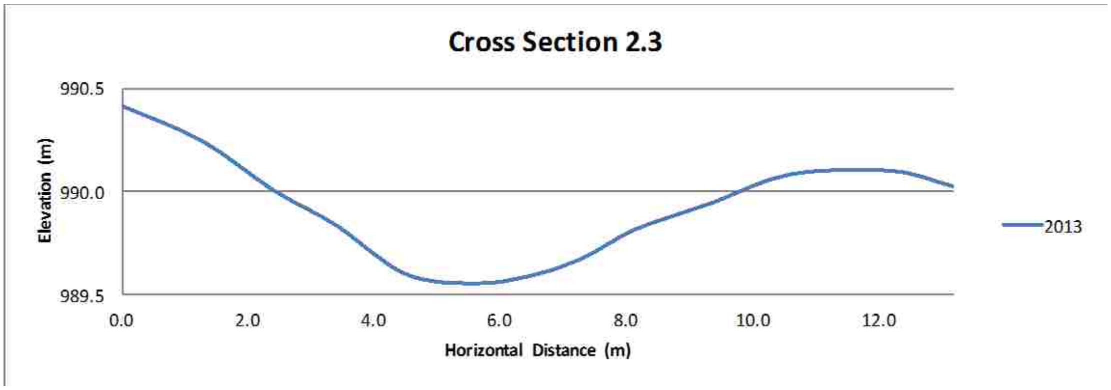

Cross Section 1a.10
990.0
989.5
989.0
988.5
988.0
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
Horizontal Distance (m)
2013

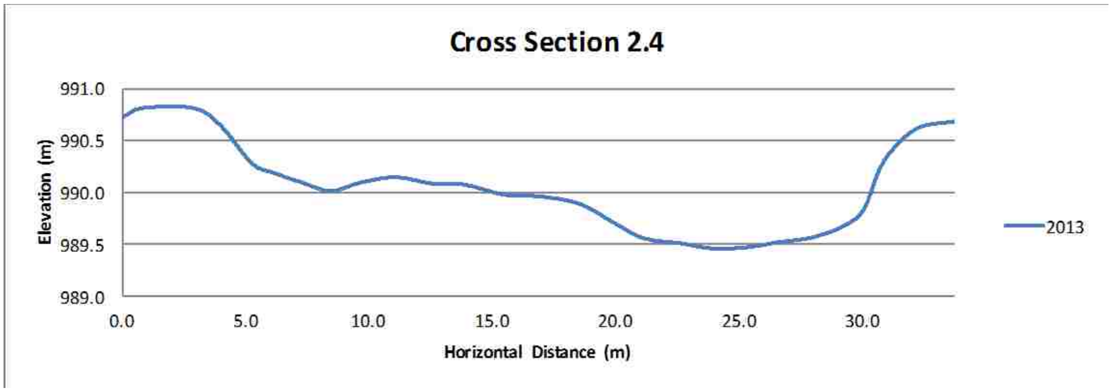
Secondary Channel 2

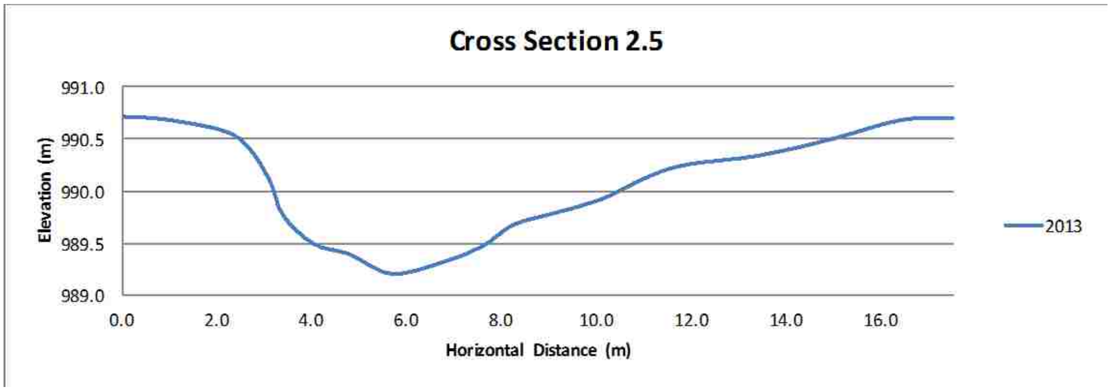


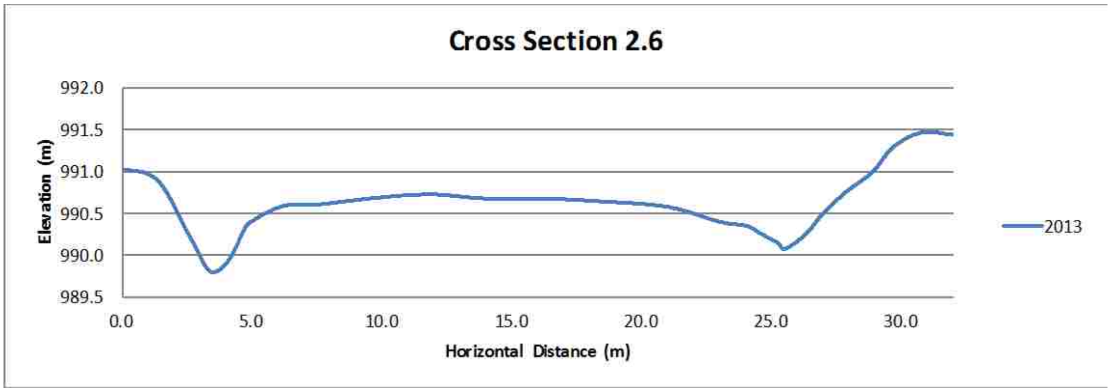


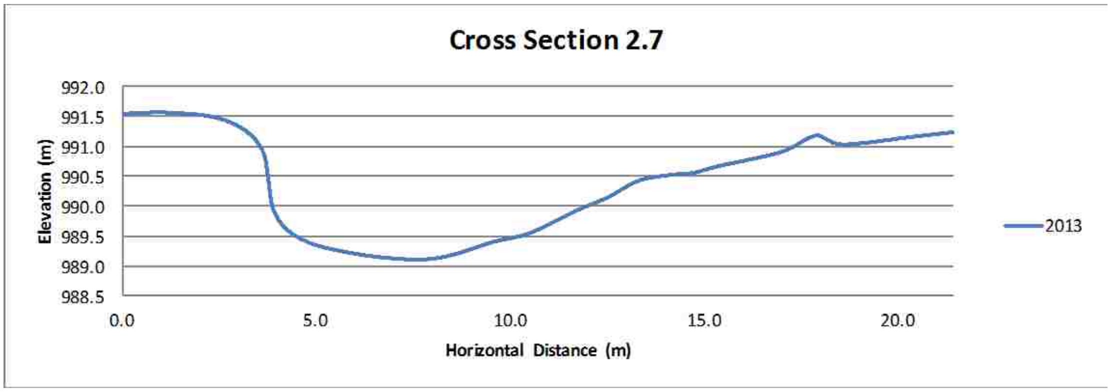

Cross Section 2.2
990.5
990.0
989.5
989.0
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Horizontal Distance (m)
2013

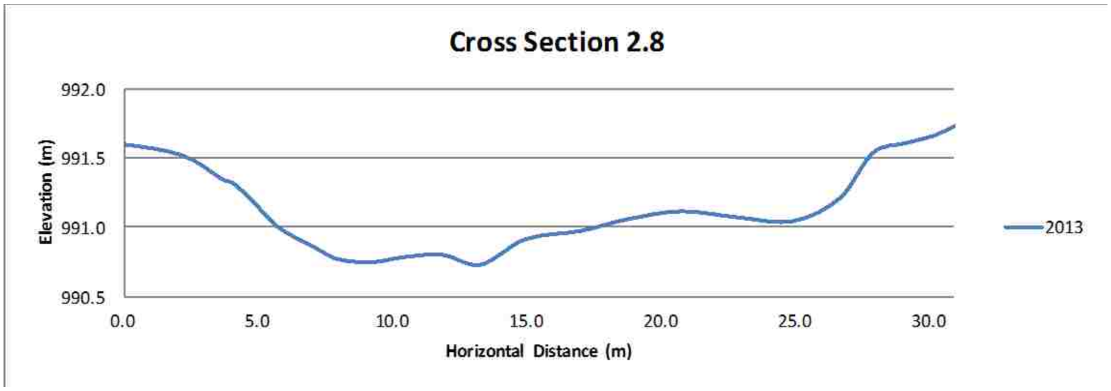

Cross Section 2.3
990.5
990.0
989.5
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Horizontal Distance (m)
2013

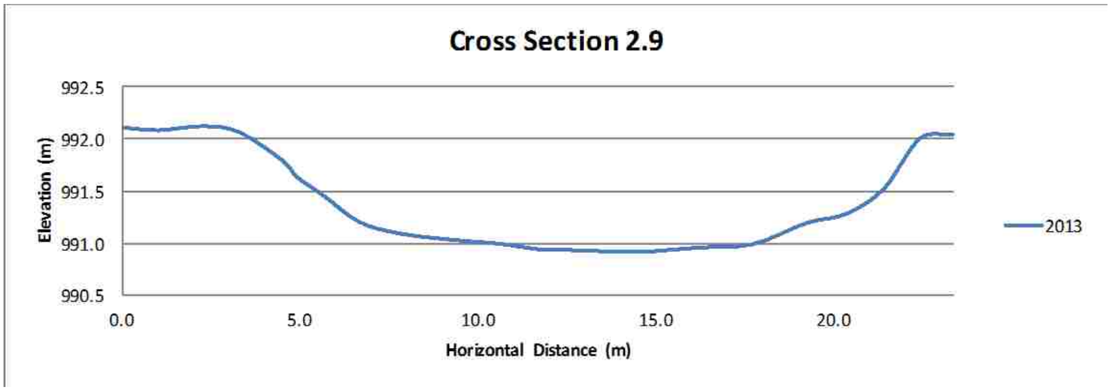

Cross Section 2.4
991.0
990.5
990.0
989.5
989.0
Elevation (m)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Horizontal Distance (m)
2013

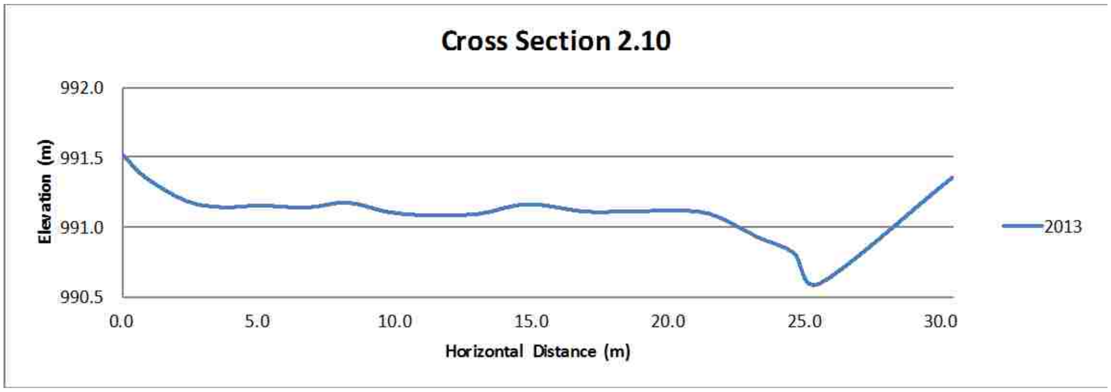

Cross Section 2.5
991.0
990.5
990.0
989.5
989.0
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Horizontal Distance (m)
2013


Cross Section 2.6
992.0
991.5
991.0
990.5
990.0
989.5
Elevation (m)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Horizontal Distance (m)
2013

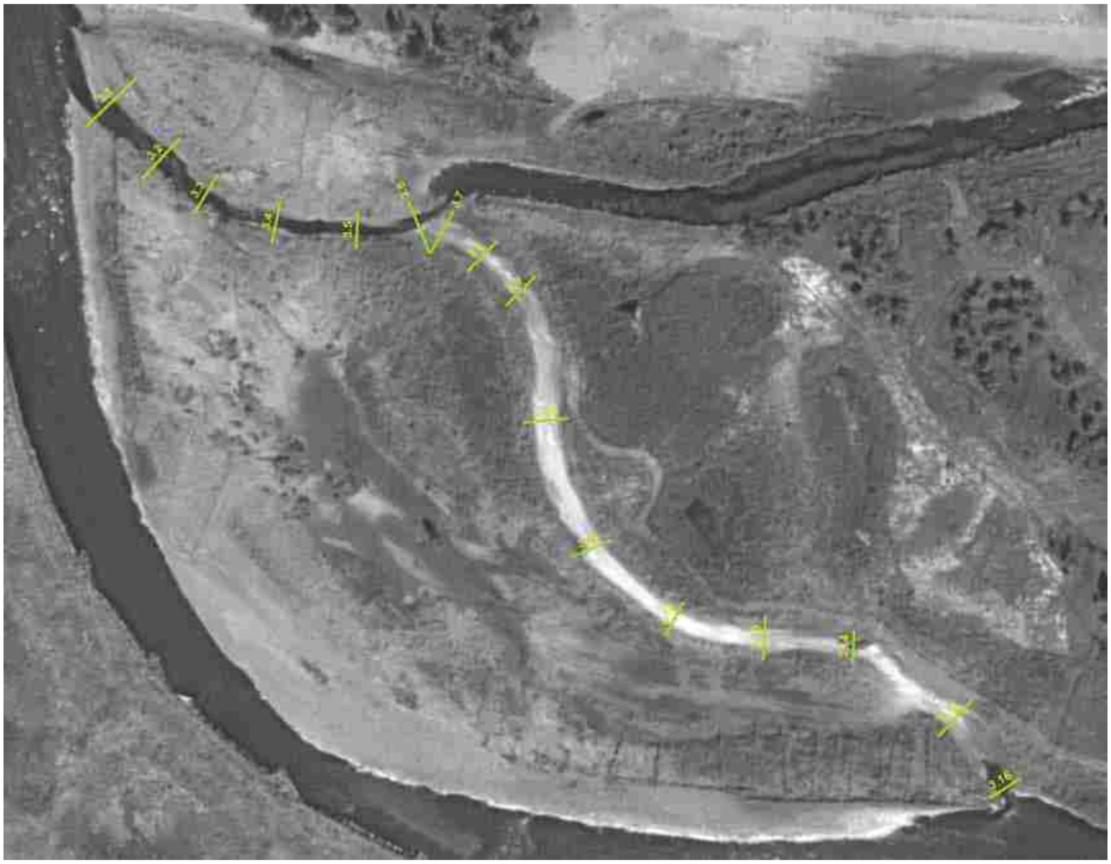

Cross Section 2.7
992.0
991.5
991.0
990.5
990.0
989.5
989.0
988.5
Elevation (m)
0.0
5.0
10.0
15.0
20.0
Horizontal Distance (m)
2013

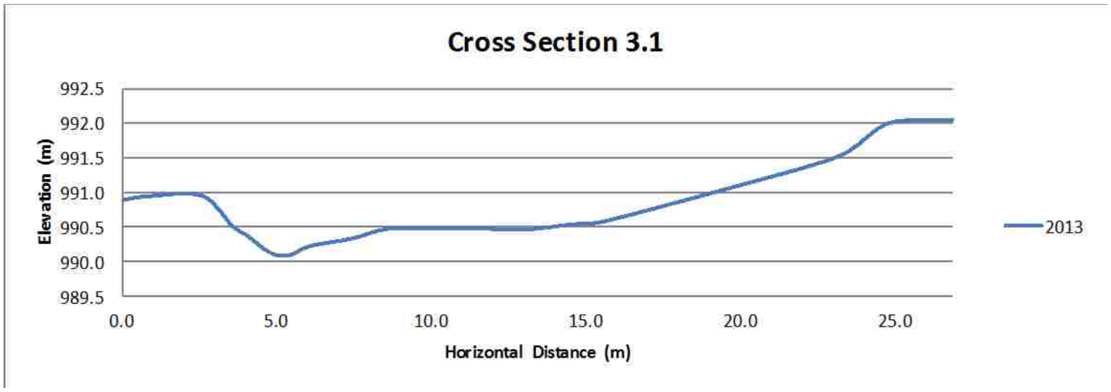

Cross Section 2.8
992.0
991.5
991.0
990.5
Elevation (m)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Horizontal Distance (m)
2013

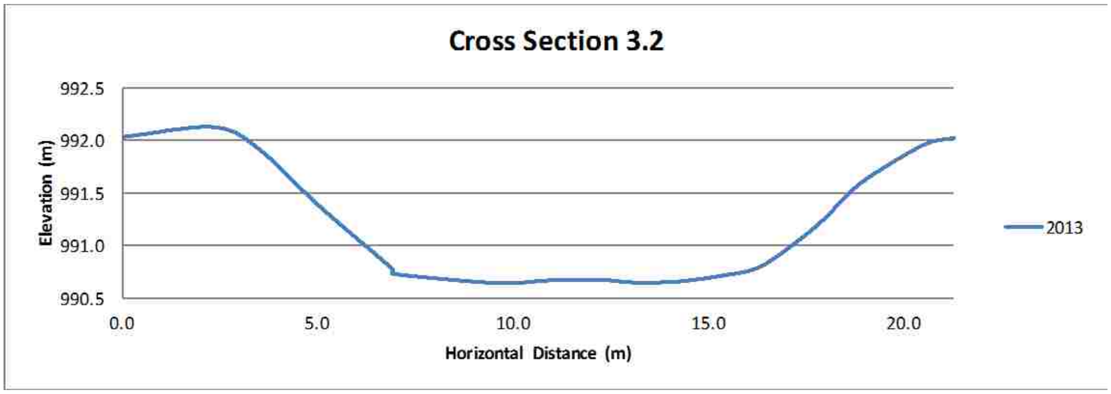

Cross Section 2.9
992.5
992.0
991.5
991.0
990.5
Elevation (m)
0.0
5.0
10.0
15.0
20.0
Horizontal Distance (m)
2013

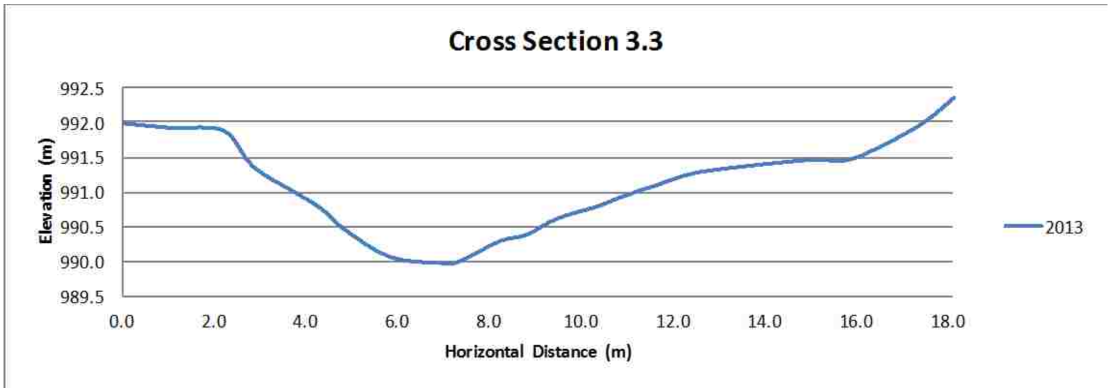

Cross Section 2.10
992.0
991.5
991.0
990.5
Elevation (m)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Horizontal Distance (m)
2013

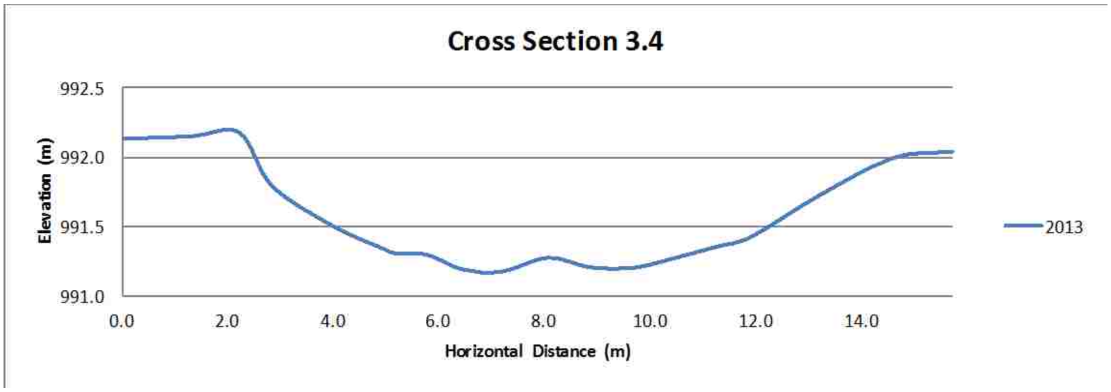
Secondary Channel 3

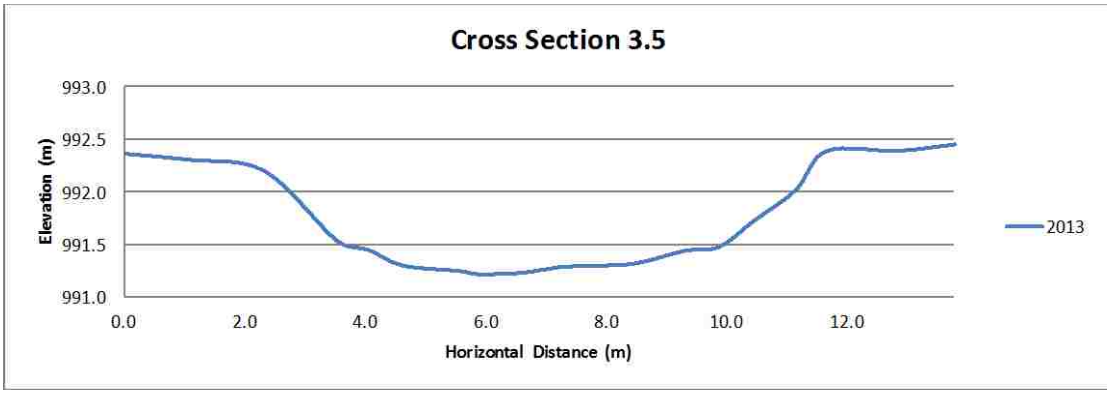


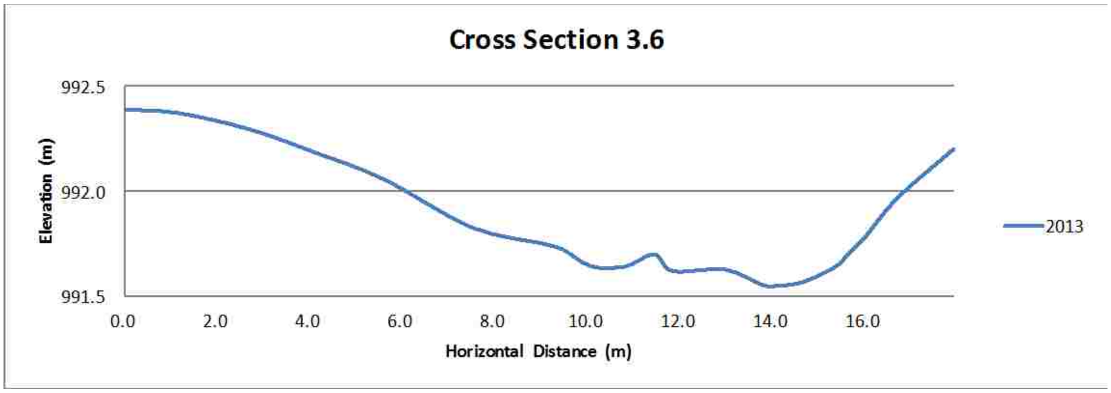


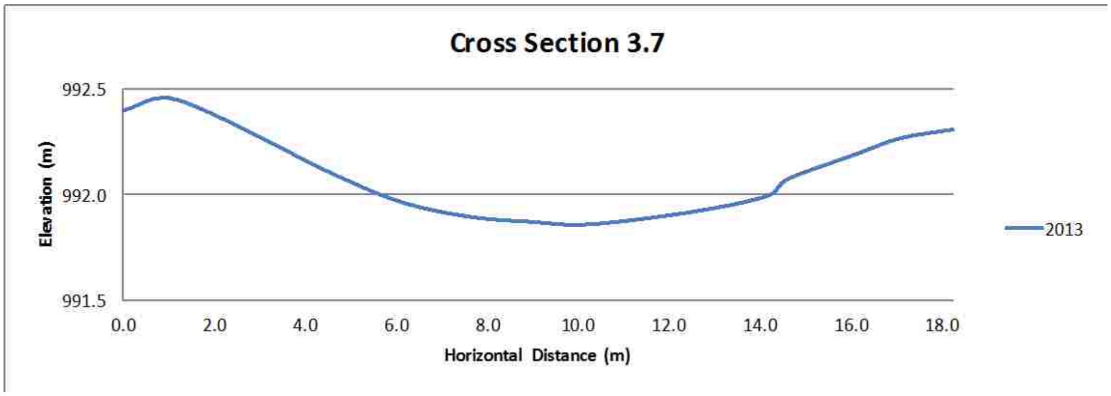

Cross Section 3.2
992.5
992.0
991.5
991.0
990.5
Elevation (m)
0.0
5.0
10.0
15.0
20.0
Horizontal Distance (m)
2013

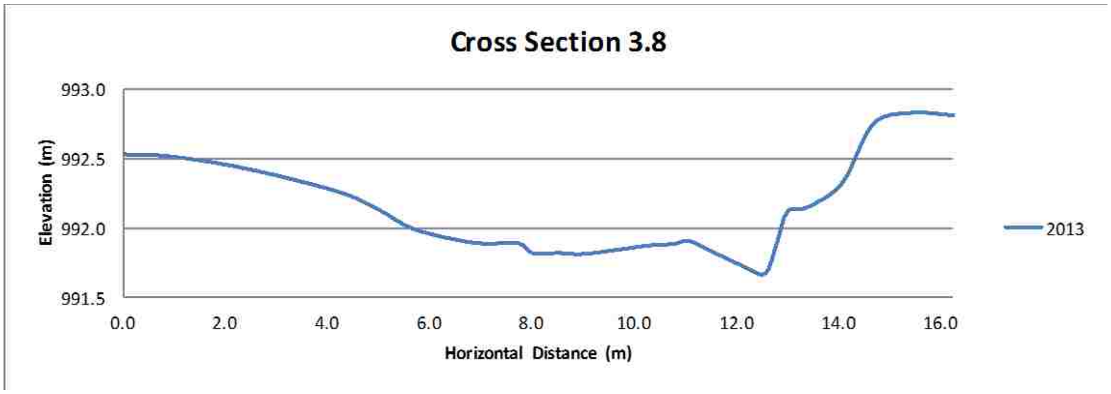

Cross Section 3.3
992.5
992.0
991.5
991.0
990.5
990.0
989.5
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
Horizontal Distance (m)
2013

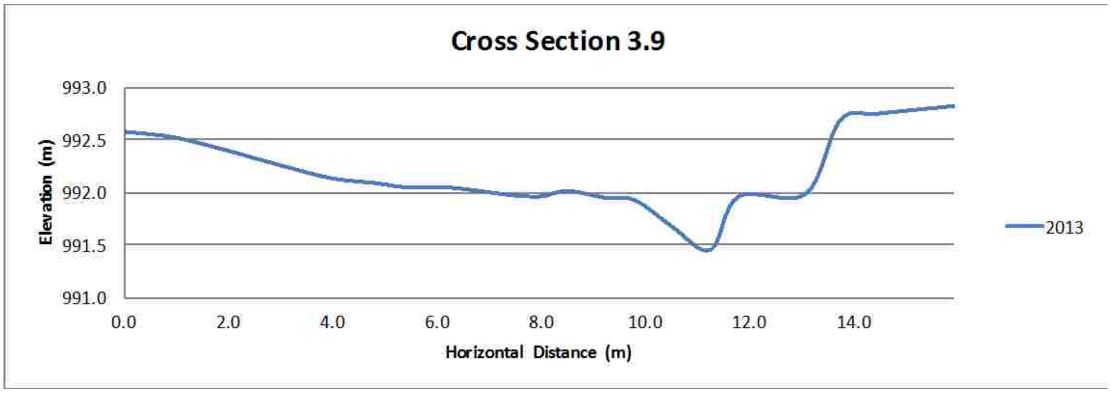

Cross Section 3.4
992.5
992.0
991.5
991.0
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Horizontal Distance (m)
2013

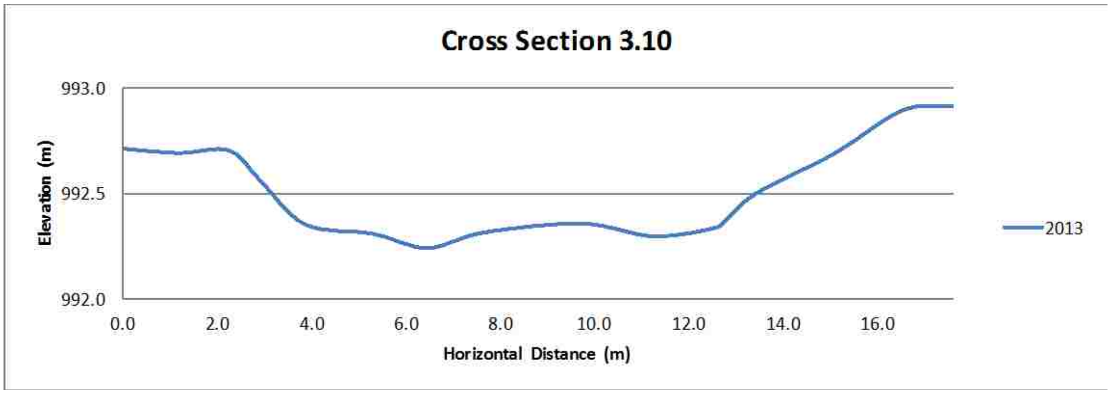

Cross Section 3.5
993.0
992.5
992.0
991.5
991.0
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Horizontal Distance (m)
2013

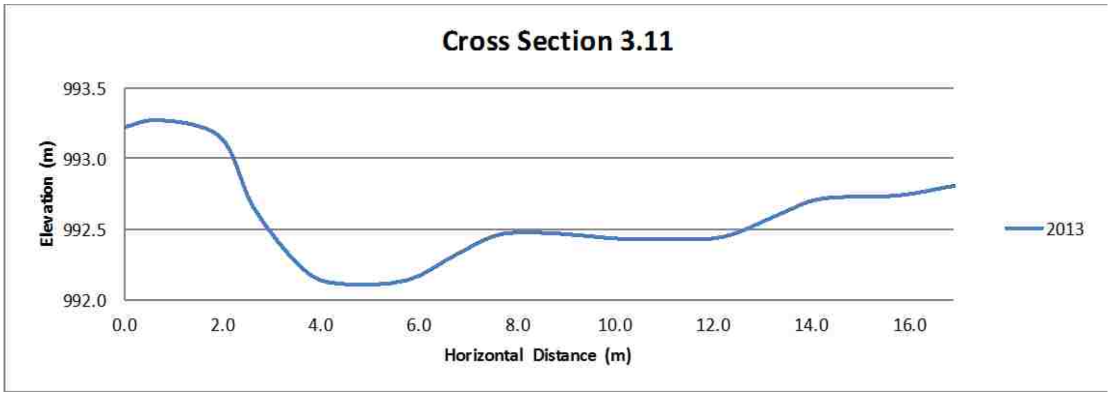

Cross Section 3.6

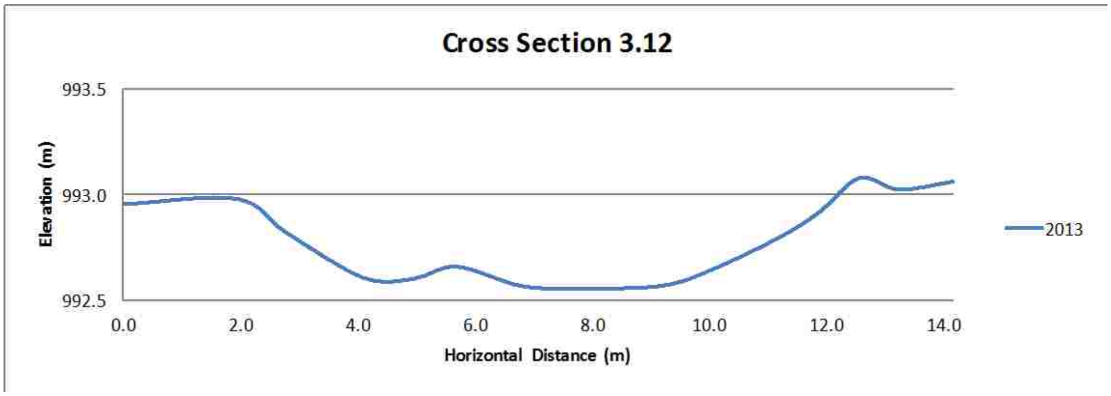

Cross Section 3.7

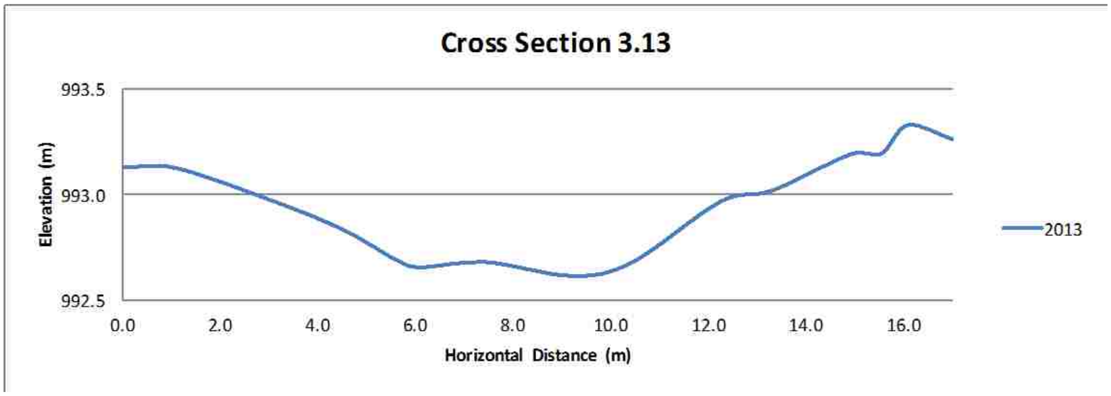

Cross Section 3.8

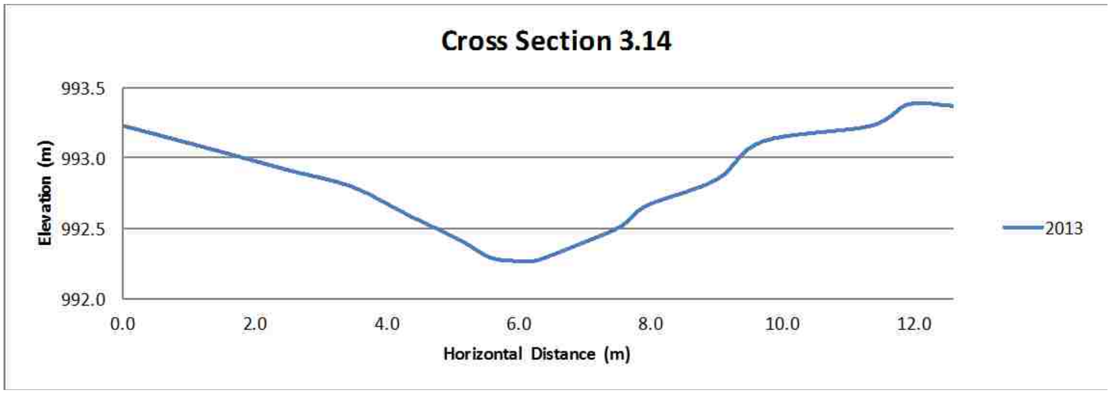

Cross Section 3.9

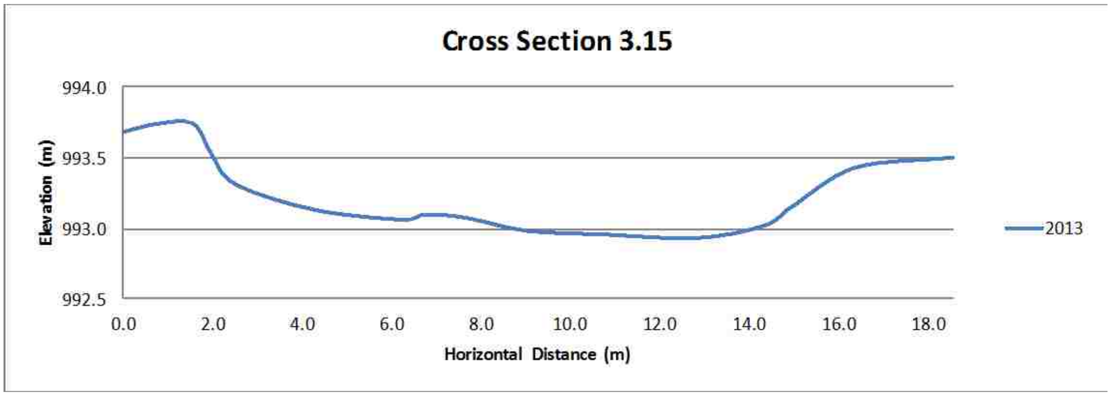

Cross Section 3.10
993.0
992.5
992.0
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Horizontal Distance (m)
2013

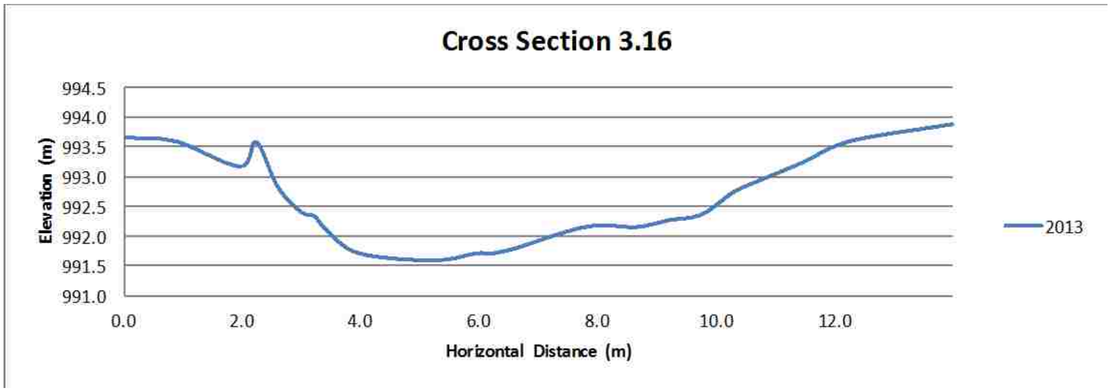

Cross Section 3.11
993.5
993.0
992.5
992.0
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Horizontal Distance (m)
2013


Cross Section 3.12
993.5
993.0
992.5
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Horizontal Distance (m)
2013


Cross Section 3.13
993.5
993.0
992.5
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Horizontal Distance (m)
2013


Cross Section 3.14
993.5
993.0
992.5
992.0
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Horizontal Distance (m)
2013


Cross Section 3.15
994.0
993.5
993.0
992.5
Elevation (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
Horizontal Distance (m)
2013


Cross Section 3.16
994.5
994.0
993.5
993.0
992.5
992.0
991.5
991.0
Elevation (m)
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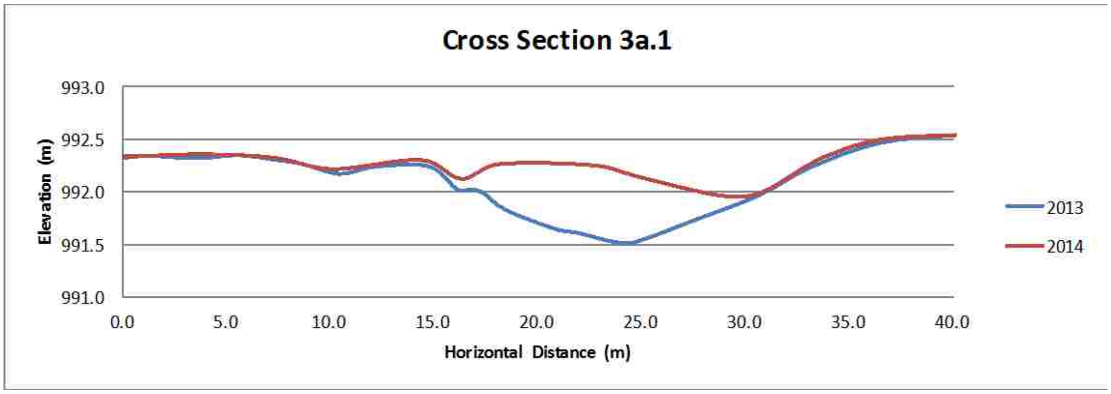
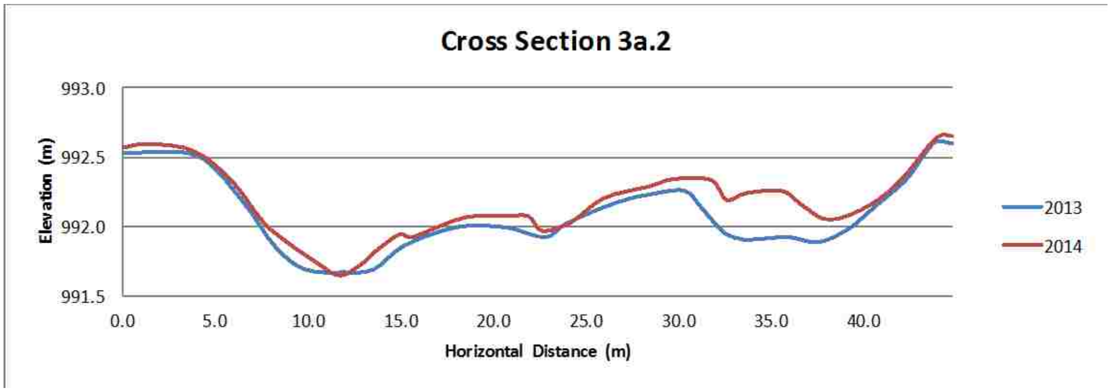
2.0
4.0
6.0
8.0
10.0
12.0
Horizontal Distance (m)
2013

Secondary Channel 3a




Cross Section 3a.2
993.0
992.5
992.0
991.5
Elevation (m)
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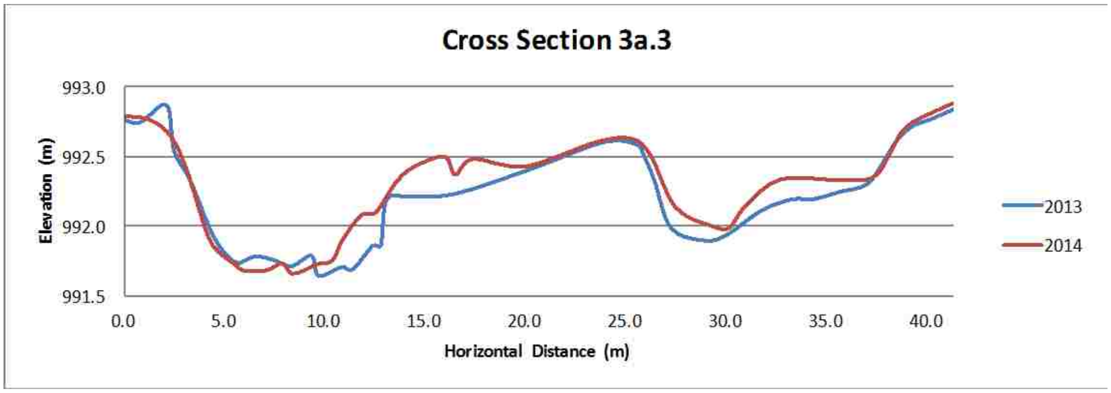
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
Horizontal Distance (m)
2013
2014


Cross Section 3a.3
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992.5
992.0
991.5
Elevation (m)
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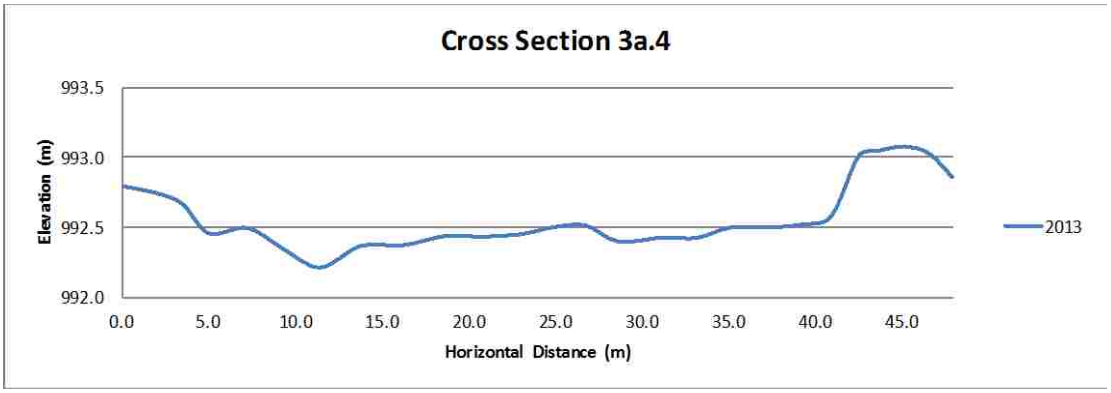
10.0
15.0
20.0
25.0
30.0
35.0
40.0
Horizontal Distance (m)
2013
2014


Cross Section 3a.4
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993.0
992.5
992.0
Elevation (m)
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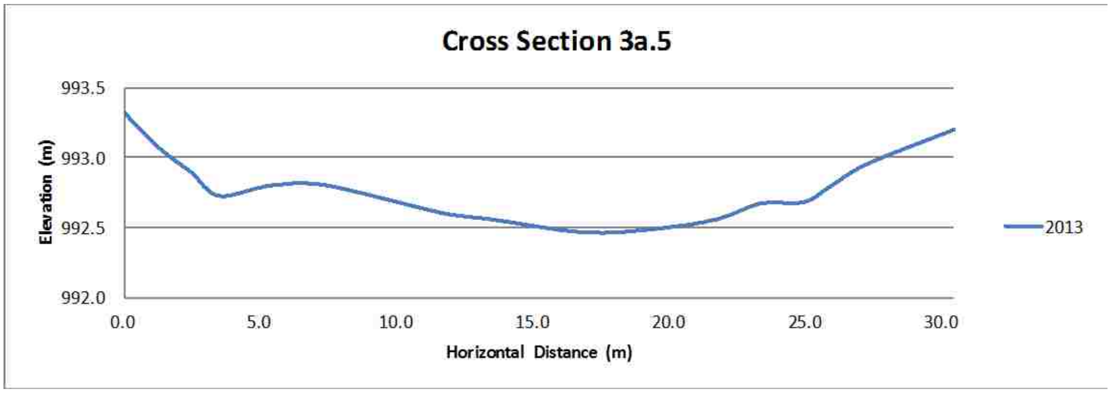
20.0
25.0
30.0
35.0
40.0
45.0
Horizontal Distance (m)
2013


Cross Section 3a.5
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Elevation (m)
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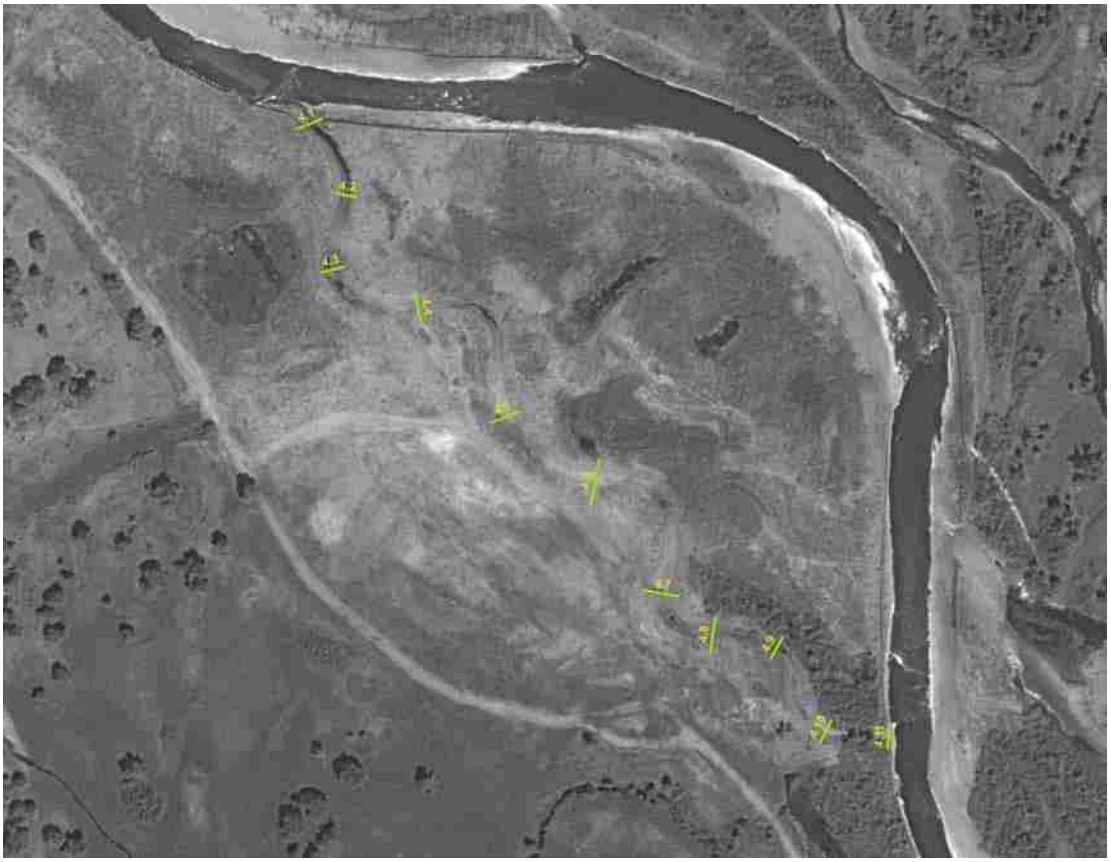
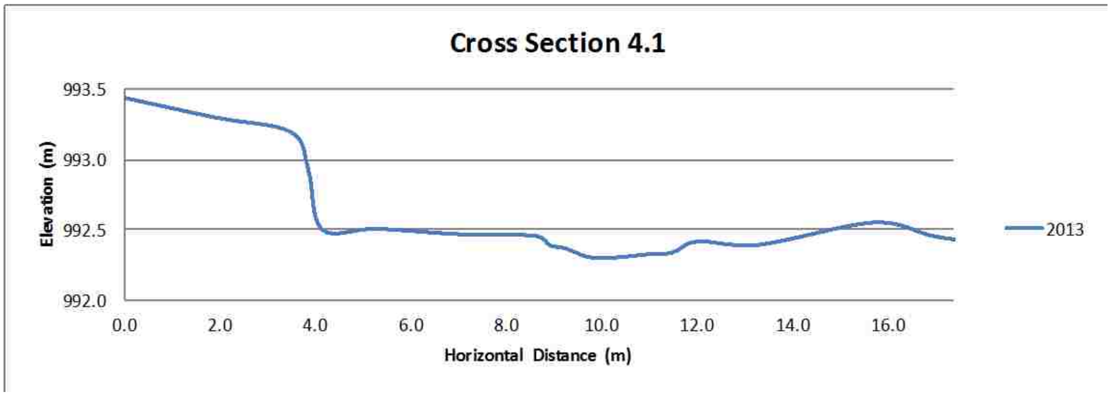
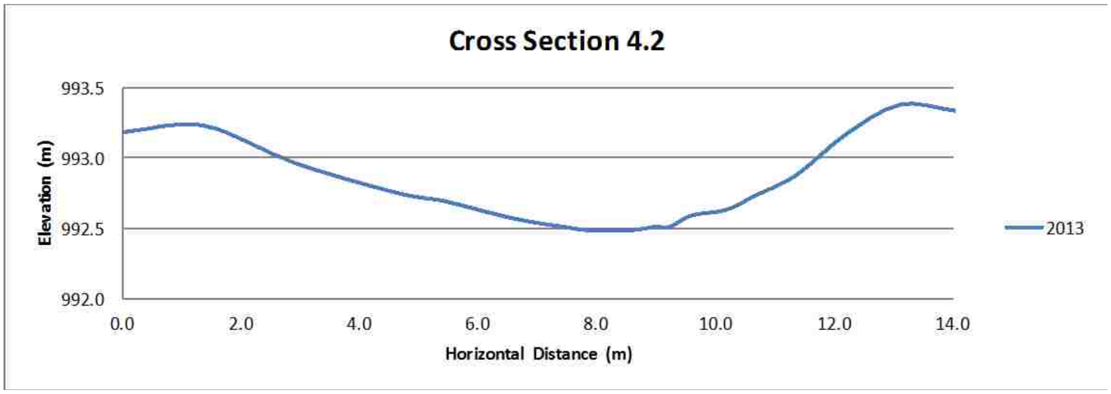
15.0
20.0
25.0
30.0
Horizontal Distance (m)
2013

Secondary Channel 4






Cross Section 4.2
993.5
993.0
992.5
992.0
Elevation (m)
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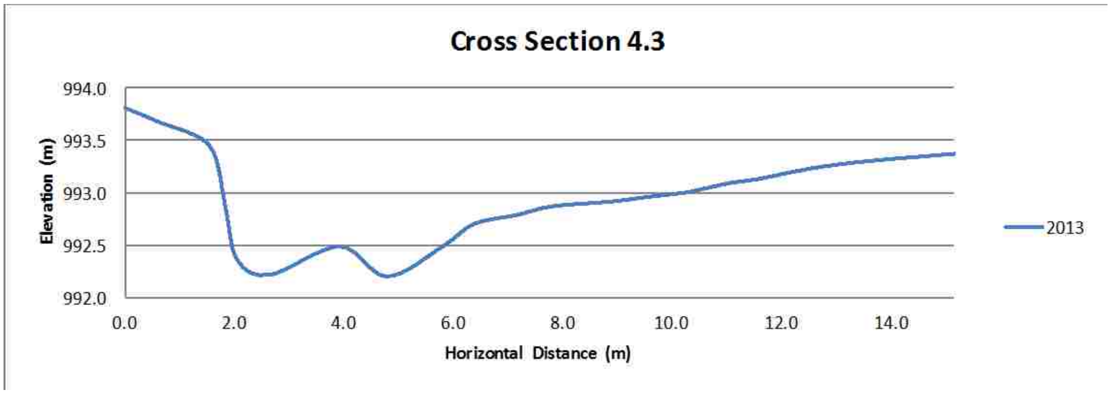
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Horizontal Distance (m)
2013


Cross Section 4.3
994.0
993.5
993.0
992.5
992.0
Elevation (m)
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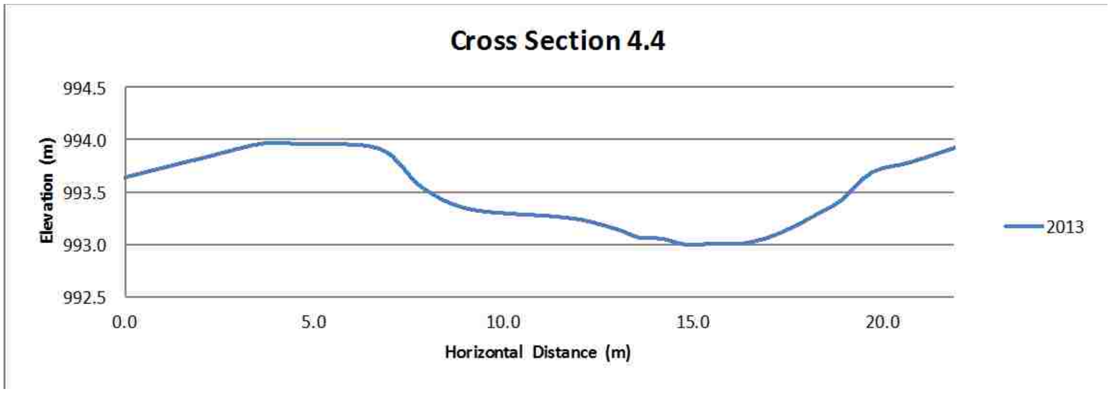
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Horizontal Distance (m)
2013


Cross Section 4.4
994.5
994.0
993.5
993.0
992.5
Elevation (m)
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5.0
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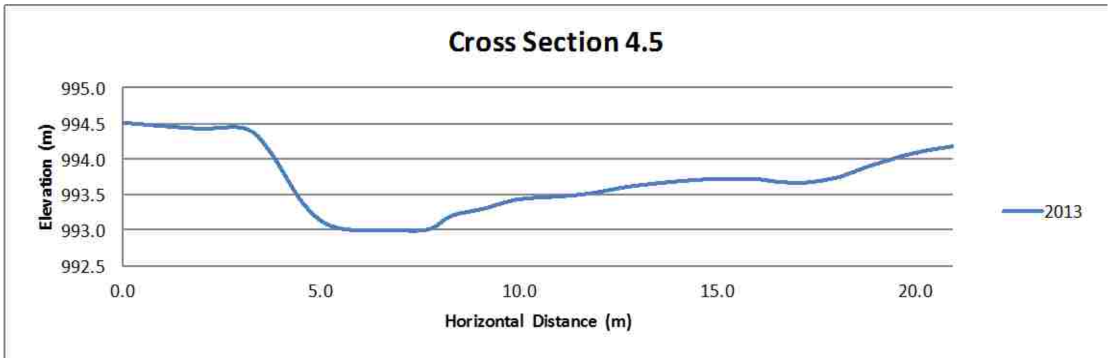
15.0
20.0
Horizontal Distance (m)
2013


Cross Section 4.5
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994.5
994.0
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992.5
Elevation (m)
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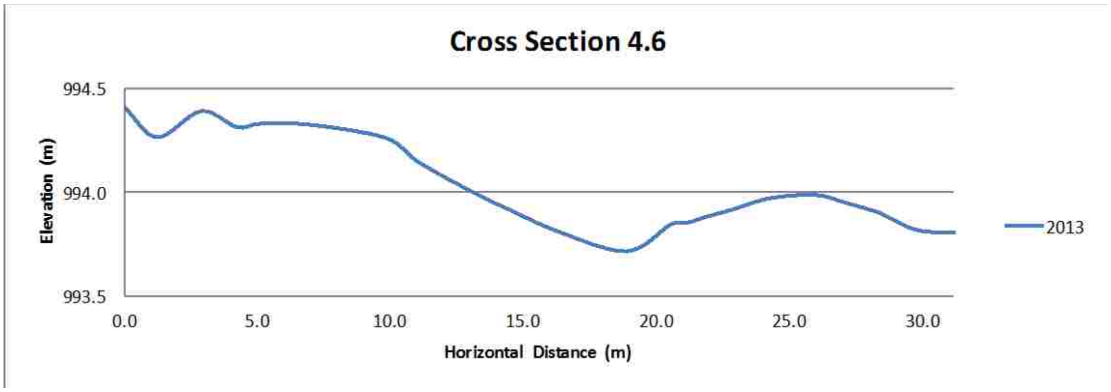
5.0
10.0
15.0
20.0
Horizontal Distance (m)
2013


Cross Section 4.6
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Elevation (m)
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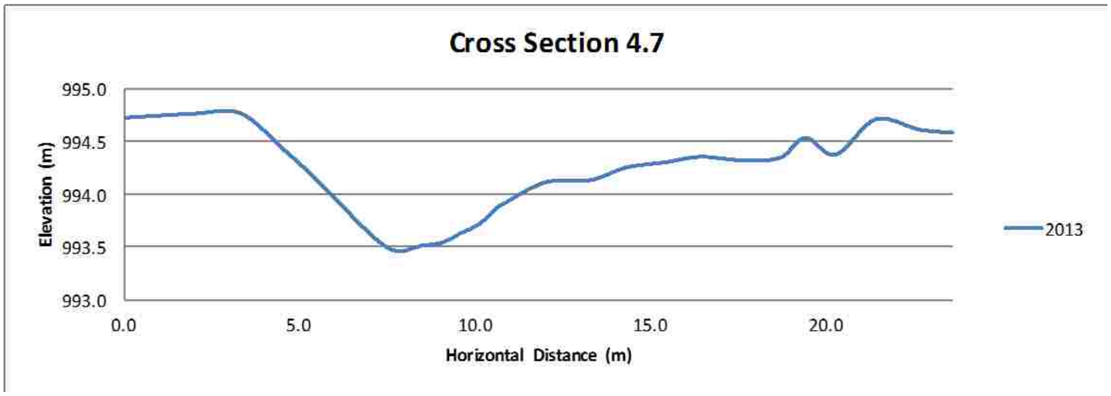
5.0
10.0
15.0
20.0
25.0
30.0
Horizontal Distance (m)
2013


Cross Section 4.7
995.0
994.5
994.0
993.5
993.0
Elevation (m)
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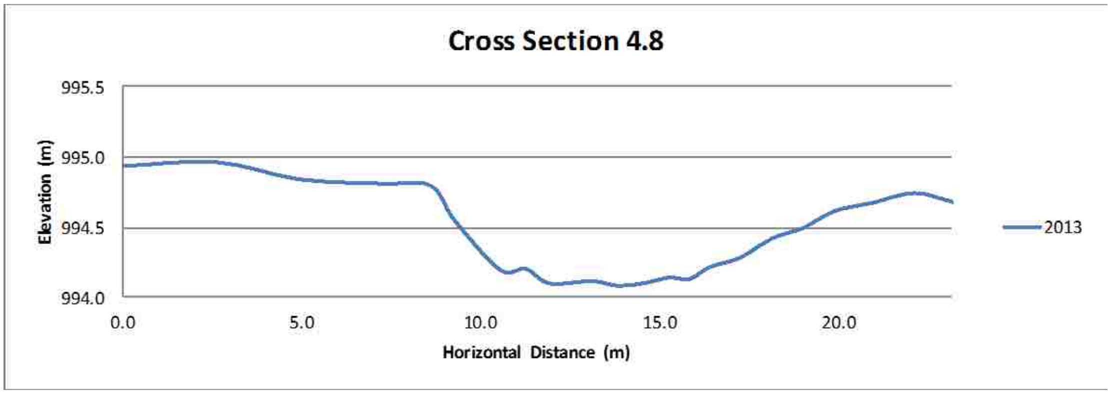
5.0
10.0
15.0
20.0
Horizontal Distance (m)
2013


Cross Section 4.8
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995.0
994.5
994.0
Elevation (m)
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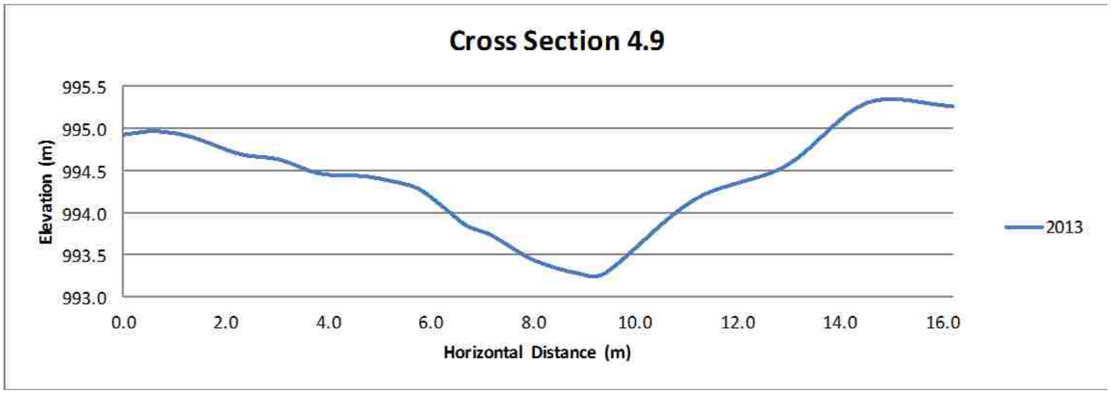
5.0
10.0
15.0
20.0
Horizontal Distance (m)
2013


Cross Section 4.9
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995.0
994.5
994.0
993.5
993.0
Elevation (m)
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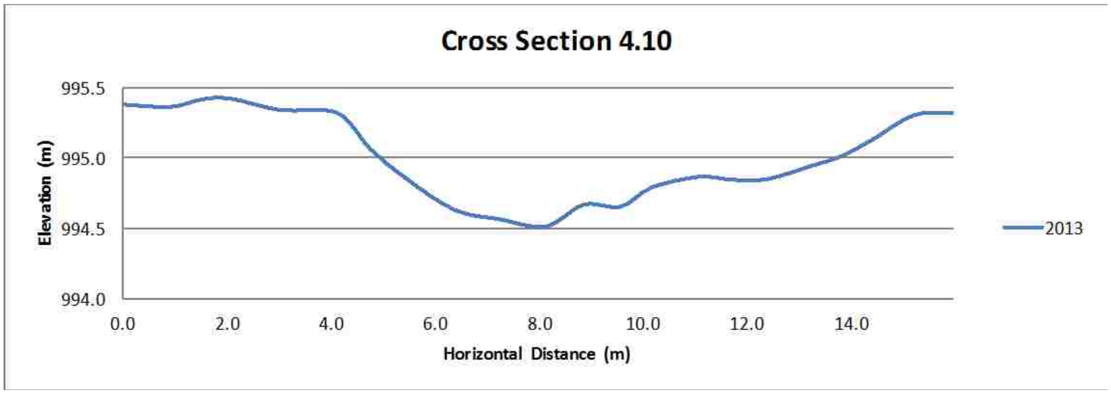
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Horizontal Distance (m)
2013


Cross Section 4.10
995.5
995.0
994.5
994.0
Elevation (m)
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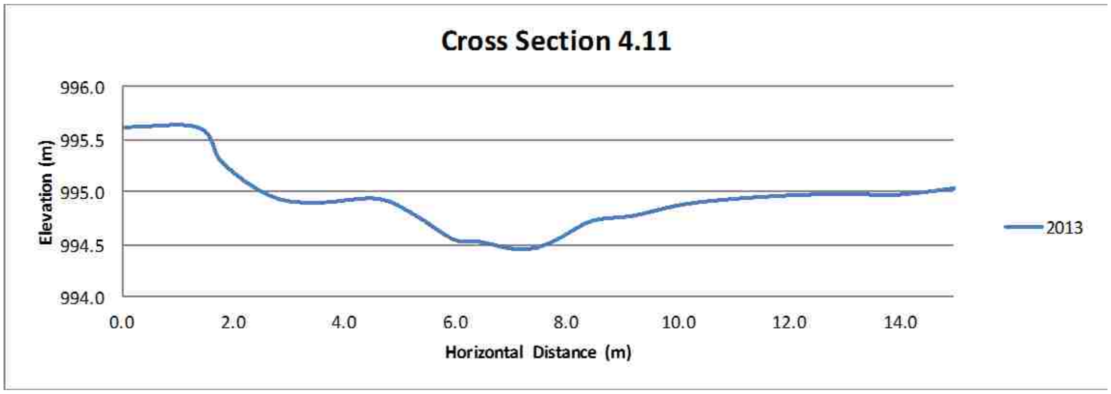
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Horizontal Distance (m)
2013


Cross Section 4.11
996.0
995.5
995.0
994.5
994.0
Elevation (m)
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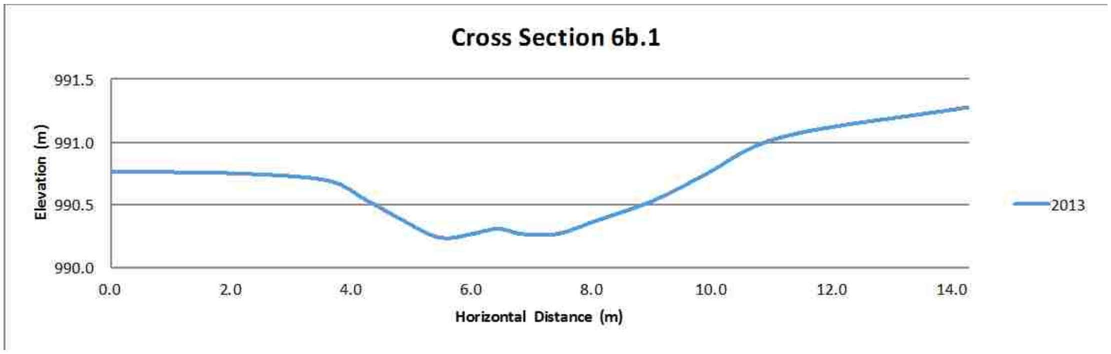
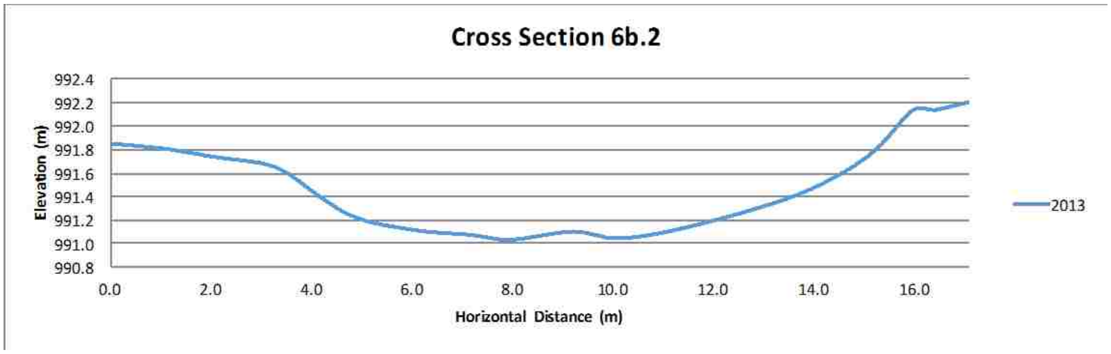
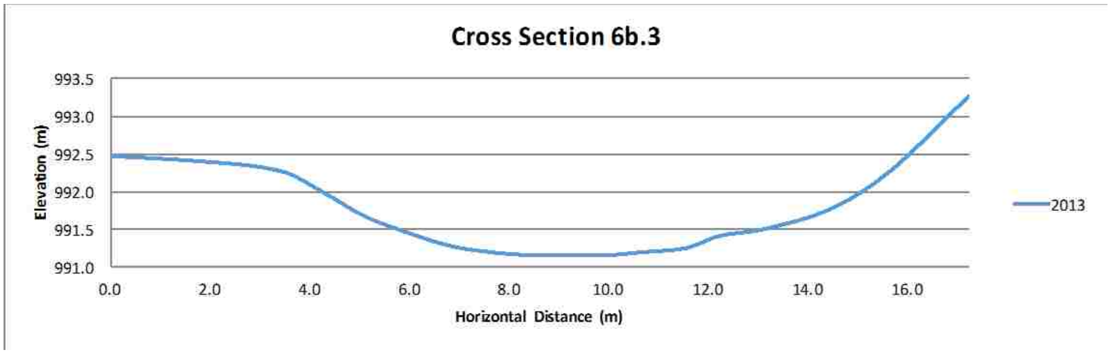
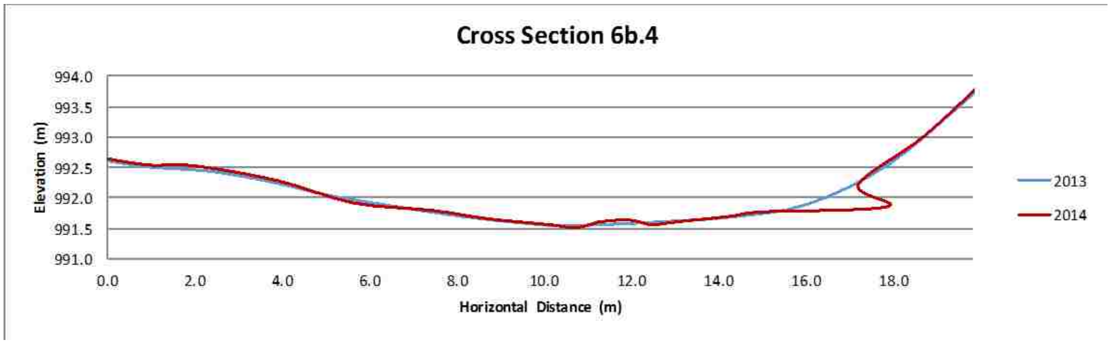
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Horizontal Distance (m)
2013

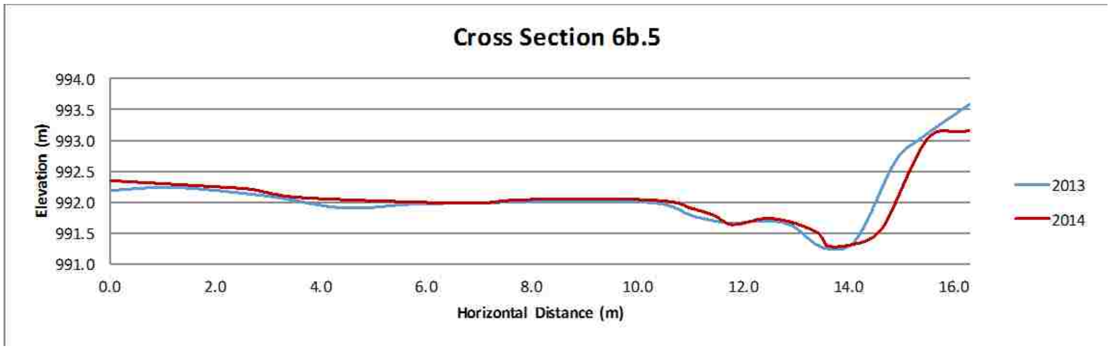
Secondary Channel 6b






Cross Section 6b.3


Cross Section 6b.4


Cross Section 6b.5

Appendix C – Surface Particle Data

- SC1 (Middle)

Size Class	**Number of Rocks**	**Number Embedded**	**Proportion Embedded**	**Percent of Total**	**Cumulative Percent**
<8	8	0	0.000	5.48	5.48
8	6	0	0.000	4.11	9.59
11.3	13	1	0.077	8.90	18.49
16	19	4	0.211	13.01	31.51
22.6	25	5	0.200	17.12	48.63
32	22	4	0.182	15.07	63.70
45	23	4	0.174	15.75	79.45
64	10	6	0.600	6.85	86.30
90	13	4	0.308	8.90	95.21
128	7	4	0.571	4.79	100.00
180	0	0	0.000	0.00	100.00
256	0	0	0.000	0.00	100.00
Total Number	146				

- SC1a (Middle)

Size Class	**Number of Rocks**	**Number Embedded**	**Proportion Embedded**	**Percent of Total**	**Cumulative Percent**
<8	27	0	0.000	18.62	18.62
8	9	0	0.000	6.21	24.83
11.3	5	0	0.000	3.45	28.28
16	13	0	0.000	8.97	37.24
22.6	19	3	0.158	13.10	50.34
32	32	4	0.125	22.07	72.41
45	25	4	0.160	17.24	89.66
64	12	2	0.167	8.28	97.93
90	3	3	1.000	2.07	100.00
128	0	0	0.000	0.00	100.00
180	0	0	0.000	0.00	100.00
256	0	0	0.000	0.00	100.00
Total Number	145				

- SC2 (Upstream)

Size Class	**Number of Rocks**	**Number Embedded**	**Proportion Embedded**	**Percent of Total**	**Cumulative Percent**
<8	8	1	0.125	5.23	5.23
8	5	0	0.000	3.27	8.50
11.3	5	1	0.200	3.27	11.76
16	6	2	0.333	3.92	15.69
22.6	14	4	0.286	9.15	24.84
32	21	7	0.333	13.73	38.56
45	34	6	0.176	22.22	60.78
64	32	6	0.188	20.92	81.70
90	18	9	0.500	11.76	93.46
128	5	3	0.600	3.27	96.73
180	4	4	1.000	2.61	99.35
256	1	1	1.000	0.65	100.00
Total Number	153				

- SC3 (Upstream)

Size Class	**Number of Rocks**	**Number Embedded**	**Proportion Embedded**	**Percent of Total**	**Cumulative Percent**
<8	6	0	0.000	4.80	4.80
8	6	0	0.000	4.80	9.60
11.3	1	0	0.000	0.80	10.40
16	5	1	0.200	4.00	14.40
22.6	13	2	0.154	10.40	24.80
32	20	2	0.100	16.00	40.80
45	14	1	0.071	11.20	52.00
64	21	8	0.381	16.80	68.80
90	28	8	0.286	22.40	91.20
128	9	2	0.222	7.20	98.40
180	2	2	1.000	1.60	100.00
256	0	0	0.000	0.00	100.00
Total Number	125				

- SC3 (Middle)

Number Embedded	Proportion Embedded	Percent of Total	Cumulative Percent
1	0.250	3.20	3.20
0	0.000	1.60	4.80
2	0.667	2.40	7.20
1	0.067	12.00	19.20
1	0.056	14.40	33.60
4	0.286	11.20	44.80
6	0.194	24.80	69.60
11	0.344	25.60	95.20
1	1.000	0.80	96.00
3	0.600	4.00	100.00
0	0.000	0.00	100.00
0	0.000	0.00	100.00

- SC3 (Exit)

Size Class	**Number of Rocks**	**Number Embedded**	**Proportion Embedded**	**Percent of Total**	**Cumulative Percentage**
<8	12	0	0.000	9.09	9.09
8	7	0	0.000	5.30	14.39
11.3	14	2	0.143	10.61	25.00
16	43	11	0.256	32.58	57.58
22.6	23	5	0.217	17.42	75.00
32	16	1	0.063	12.12	87.12
45	13	6	0.462	9.85	96.97
64	2	0	0.000	1.52	98.48
90	1	1	1.000	0.76	99.24
128	0	0	0.000	0.00	99.24
180	0	0	0.000	0.00	99.24
256	1	1	1.000	0.76	100.00
Total Number	132				

- SC4 (Downstream)

Size Class	**Number of Rocks**	**Number Embedded**	**Proportion Embedded**	**Percent of Total**	**Cumulative Percentage**
<8	12	0	0.000	9.09	9.09
8	7	0	0.000	5.30	14.39
11.3	14	2	0.143	10.61	25.00
16	43	11	0.256	32.58	57.58
22.6	23	5	0.217	17.42	75.00
32	16	1	0.063	12.12	87.12
45	13	6	0.462	9.85	96.97
64	2	0	0.000	1.52	98.48
90	1	1	1.000	0.76	99.24
128	0	0	0.000	0.00	99.24
180	0	0	0.000	0.00	99.24
256	1	1	1.000	0.76	100.00
Total Number	132				

- SC4 (Middle)

Size Class	**Number of Rocks**	**Number Embedded**	**Proportion Embedded**	**Percent of Total**	**Cumulative Percent**
<8	6	0	0.000	4.92	4.92
8	8	0	0.000	6.56	11.48
11.3	11	0	0.000	9.02	20.49
16	8	1	0.125	6.56	27.05
22.6	18	2	0.111	14.75	41.80
32	21	3	0.143	17.21	59.02
45	22	4	0.182	18.03	77.05
64	19	9	0.474	15.57	92.62
90	3	3	1.000	2.46	95.08
128	6	5	0.833	4.92	100.00
180	0	0	0.000	0.00	100.00
256	0	0	0.000	0.00	100.00

Appendix D – Subsurface Sediment Data Analysis

Pre-Processing			
Sample	**Tin (g)**	**Wet (g)**	**Dry (g)**
SC1 #1	4.14	100.35	100.01
SC1 #2	4.16	344.62	483.67
SC1 #3	4.13	229.06	228.10
SC1a #1	4.15	141.30	140.01
SC1a #2	4.15	558.90	455.83
SC1a #3	4.17	494.07	455.83
SC1a #4	4.17	81.32	79.44
SC1a #6 OGA	4.14	194.53	193.87
SC1a #6 P	4.15	171.32	124.68
SC1a #7	4.16	204.81	204.09
SC2 #1	4.17	187.90	187.40
SC2 #2	4.17	86.27	86.07
SC2 #3	4.14	415.24	378.93
SC2 #4	4.20	582.62	570.97
SC3 #1	4.15	171.30	169.31
SC3 #2	4.18	91.76	91.59
SC3 #3	4.17	114.44	113.78
SC3 #4	4.18	803.51	781.40
SC3 #5	4.14	228.22	226.93
SC3 #6	4.15	514.83	500.52
SC3/6 #1	4.16	871.81	857.77
SC4 #1	4.16	425.99	415.76
SC4 #2	4.21	169.73	168.12

						Dry Sed		Beaker
Sample	**250ml Beaker**	**Sediment (g)**		**Sample**	**Sand Tin (g)**	**+ Tin (g)**	**Sand (g)**	**+ Silt/Clay (g)**
SC1 #1	104.47	231.20		SC1 #1	4.19	233.21	229.02	106.82
SC1 #2	105.04	107.83		SC1 #2	4.23	105.55	101.32	11.92
SC1 #3	115.86	277.53		SC1 #3	4.20	277.23	273.03	120.57
SC1a #1	105.61	127.53		SC1a #1	4.18	129.54	125.36	107.59
SC1a #2	98.22	119.52		SC1a #2	4.19	102.14	97.95	119.64
SC1a #3	104.63	133.74		SC1a #3	4.21	113.45	109.24	129.13
SC1a #4	110.10	122.62		SC1a #4	4.18	124.60	120.42	112.02
SC1a #6 OGA	103.91	173.35		SC1a #6 OGA	4.21	175.89	171.68	106.10
SC1a #6 P	103.85	92.01		SC1a #6 P	4.22	4.63	0.41	113.32
SC1a #7	116.18	145.63		SC1a #7	4.19	145.79	141.60	120.53
SC2 #1	97.55	103.46	99.27	99.00				
SC2 #4	103.96	136.28		SC2 #4	4.21	139.03	134.82	105.84
SC3 #1	105.62	144.81		SC3 #1	4.19	147.14	142.95	107.68
SC3 #2	109.16	91.51		SC3 #2	4.16	95.32	91.16	110.18
SC3 #3	104.76	194.71		SC3 #3	4.19	201.51	197.32	112.38
SC3 #4	111.90	123.89		SC3 #4	4.21	127.23	123.02	113.07
SC3 #5	109.45	149.45		SC3 #5	4.23	152.58	148.35	110.86
SC3 #6	109.88	137.01		SC3 #6	4.22	138.80	134.58	112.72
SC3/6 #1	103.37	113.91		SC3/6 #1	4.22	117.54	113.32	104.37
SC4 #1	108.06	99.28		SC4 #1	4.21	100.96	96.75	111.03
SC4 #2	109.67	197.30						

Sample	**Sieve**	**Empty weight boat (g)**	**Weigh boat + Sed (g)**	**Sed (g)**
SC1 #1	# 5	2.36	201.74	199.38
	# 7	2.39	5.71	3.32
	# 10	2.34	5.92	3.58
	# 14	2.43	5.18	2.75
	# 18	2.35	4.41	2.06
	# 20	2.46	3.36	0.90
	# 35	2.43	5.25	2.82
	# 45	2.32	3.82	1.50
	# 60	2.32	4.90	2.58
	# 80	2.37	5.68	3.31
	# 120	2.44	5.74	3.30
	# 170	2.37	4.44	2.07
	# 230	2.41	3.31	0.90
	# 270	2.36	2.43	0.07
	Catch Pan	2.37	2.40	0.03

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC1 #2	# 5	2.36	98.91	96.55
	# 7	2.39	2.94	0.55
	# 10	2.34	2.80	0.46
	# 14	2.43	2.87	0.44
	# 18	2.35	2.69	0.34
	# 20	2.46	2.58	0.12
	# 35	2.43	2.97	0.54
	# 45	2.32	2.43	0.11
	# 60	2.37	2.68	0.31
	# 80	2.44	2.59	0.15
	# 120	2.37	2.51	0.14
	# 170	2.37	2.70	0.33
	# 230	2.33	3.05	0.72
	# 270	2.35	2.41	0.06
	Catch Pan	2.39	2.43	0.04

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC1 #3	# 5	2.36	233.46	231.10
	# 7	2.39	7.06	4.67
	# 10	2.34	5.51	3.17
	# 14	2.43	5.38	2.95
	# 18	2.35	4.76	2.41
	# 20	2.46	3.62	1.16
	# 35	2.43	9.73	7.30
	# 45	2.32	9.06	6.74
	# 60	2.37	8.36	5.99
	# 80	2.44	5.49	3.05
	# 120	2.37	4.34	1.97
	# 170	2.23	3.46	1.23
	# 230	2.39	3.12	0.73
	# 270	2.29	2.34	0.05
	Catch Pan	2.28	2.33	0.05

Sample	**Sieve**	**Empty weight boat (g)**	**Weigh boat + Sed (g)**	**Sed (g)**
SC1a #1	# 5	2.36	99.39	97.03
	# 7	2.39	9.44	7.05
	# 10	2.34	8.38	6.04
	# 14	2.43	7.46	5.03
	# 18	2.35	5.32	2.97
	# 20	2.46	3.44	0.98
	# 35	2.43	5.64	3.21
	# 45	2.32	3.43	1.11
	# 60	2.37	3.15	0.78
	# 80	2.44	2.84	0.40
	# 120	2.37	2.65	0.28
	# 170	2.28	2.31	0.03
	# 230	2.38	2.53	0.15
	# 270	2.26	2.28	0.02
	Catch Pan	2.36	2.40	0.04

Sample	**Sieve**	**Empty weight boat (g)**	**Weigh boat + Sed (g)**	**Sed (g)**
SC1a #2	# 5	2.36	26.53	24.17
	# 7	2.39	3.29	0.90
	# 10	2.34	2.86	0.52
	# 14	2.43	2.94	0.51
	# 18	2.35	3.31	0.96
	# 20	2.46	3.27	0.81
	# 35	2.43	8.65	6.22
	# 45	2.32	10.12	7.80
	# 60	2.37	17.36	14.99
	# 80	2.44	15.96	13.52
	# 120	2.37	13.39	11.02
	# 170	2.28	10.87	8.59
	# 230	2.38	8.18	5.80
	# 270	2.26	3.02	0.76
	Catch Pan	2.29	2.48	0.19

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC1a #3	# 5	2.36	51.55	49.19
	# 7	2.39	7.59	5.20
	# 10	2.34	6.73	4.39
	# 14	2.43	6.87	4.44
	# 18	2.35	5.68	3.33
	# 20	2.46	3.83	1.37
	# 35	2.43	10.21	7.78
	# 45	2.32	8.85	6.53
	# 60	2.37	7.93	5.56
	# 80	2.44	6.54	4.10
	# 120	2.37	7.98	5.61
	# 170	2.34	8.62	6.28
	# 230	2.31	7.27	4.96
	# 270	2.37	7.88	5.51
	Catch Pan	2.39	2.50	0.11

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC1a #4	# 5	2.36	115.23	112.87
	# 7	2.39	6.04	3.65
	# 10	2.34	3.89	1.55
	# 14	2.43	3.12	0.69
	# 18	2.35	2.78	0.43
	# 20	2.46	2.59	0.13
	# 35	2.43	2.85	0.42
	# 45	2.32	2.53	0.21
	# 60	2.37	2.55	0.18
	# 80	2.44	2.55	0.11
	# 120	2.37	2.48	0.11
	# 170	2.34	2.49	0.15
	# 230	2.31	2.46	0.15
	# 270	2.37	2.41	0.04
	Catch Pan	2.32	2.34	0.02

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC1a #6	# 5	2.36	151.18	148.82
OGA	# 7	2.39	5.08	2.69
	# 10	2.34	4.69	2.35
	# 14	2.43	4.71	2.28
	# 18	2.35	4.35	2.00
	# 20	2.46	3.29	0.83
	# 35	2.43	6.43	4.00
	# 45	2.32	5.61	3.29
	# 60	2.37	5.01	2.64
	# 80	2.44	3.65	1.21
	# 120	2.37	3.13	0.76
	# 170	2.34	2.78	0.44
	# 230	2.31	2.55	0.24
	# 270	2.37	2.41	0.04
	Catch Pan	2.30	2.35	0.05

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC1a #6	# 5			
P	# 7			
	# 10			
	# 14			
	# 18			
	# 20			
	# 35	2.43	2.47	0.04
	# 45	2.32	2.36	0.04
	# 60	2.37	2.43	0.06
	# 80	2.44	2.49	0.05
	# 120	2.37	2.44	0.07
	# 170	2.34	2.42	0.08
	# 230	2.31	2.38	0.07
	# 270	2.37	2.39	0.02
	Catch Pan	2.40	2.42	0.02

Sample	**Sieve**	**Empty weight boat (g)**	**Weigh boat + Sed (g)**	**Sed (g)**
SC1a #7	# 5	2.36	84.77	82.41
	# 7	2.39	15.55	13.16
	# 10	2.34	14.19	11.85
	# 14	2.43	9.81	7.38
	# 18	2.35	6.21	3.86
	# 20	2.46	3.74	1.28
	# 35	2.43	8.58	6.15
	# 45	2.32	8.00	5.68
	# 60	2.37	7.20	4.83
	# 80	2.44	4.94	2.50
	# 120	2.37	3.83	1.46
	# 170	2.34	3.24	0.90
	# 230	2.31	2.87	0.56
	# 270	2.37	2.43	0.06
	Catch Pan	2.39	2.42	0.03

Sample	**Sieve**	**Empty weight boat (g)**	**Weigh boat + Sed (g)**	**Sed (g)**
SC2 #1	# 5	2.36	169.63	167.27
	# 7	2.39	10.71	8.32
	# 10	2.34	8.40	6.06
	# 14	2.43	7.12	4.69
	# 18	2.35	5.71	3.36
	# 20	2.46	3.69	1.23
	# 35	2.43	9.01	6.58
	# 45	2.32	8.95	6.63
	# 60	2.37	8.16	5.79
	# 80	2.44	4.87	2.43
	# 120	2.37	3.61	1.24
	# 170	2.34	2.86	0.52
	# 230	2.31	2.49	0.18
	# 270	2.37	2.39	0.02
	Catch Pan	2.35	2.37	0.02

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC2 #2	# 5	2.36	180.63	178.27
	# 7	2.39	5.08	2.69
	# 10	2.34	3.44	1.10
	# 14	2.43	4.10	1.67
	# 18	2.35	3.48	1.13
	# 20	2.46	2.79	0.33
	# 35	2.43	3.71	1.28
	# 45	2.32	3.56	1.24
	# 60	2.37	3.98	1.61
	# 80	2.44	3.31	0.87
	# 120	2.37	3.03	0.66
	# 170	2.34	2.75	0.41
	# 230	2.31	2.51	0.20
	# 270	2.37	2.40	0.03
	Catch Pan	2.34	2.39	0.05

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC2 #3	# 5	2.36	47.28	44.92
	# 7	2.39	6.12	3.73
	# 10	2.34	4.63	2.29
	# 14	2.43	4.99	2.56
	# 18	2.35	4.00	1.65
	# 20	2.46	3.15	0.69
	# 35	2.43	6.28	3.85
	# 45	2.32	6.30	3.98
	# 60	2.37	12.01	9.64
	# 80	2.44	14.91	12.47
	# 120	2.37	10.66	8.29
	# 170	2.34	5.89	3.55
	# 230	2.31	3.92	1.61
	# 270	2.37	2.47	0.10
	Catch Pan	2.26	2.29	0.03

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC2 #4	# 5	2.36	114.09	111.73
	# 7	2.39	7.06	4.67
	# 10	2.34	5.79	3.45
	# 14	2.43	5.25	2.82
	# 18	2.35	4.17	1.82
	# 20	2.46	3.21	0.75
	# 35	2.43	5.31	2.88
	# 45	2.32	4.40	2.08
	# 60	2.37	4.52	2.15
	# 80	2.44	3.65	1.21
	# 120	2.37	3.14	0.77
	# 170	2.34	2.77	0.43
	# 230	2.31	2.50	0.19
	# 270	2.37	2.39	0.02
	Catch Pan	2.27	2.28	0.01

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC3 #1	# 5	2.36	114.66	112.30
	# 7	2.39	11.20	8.81
	# 10	2.34	10.07	7.73
	# 14	2.43	7.25	4.82
	# 18	2.35	5.35	3.00
	# 20	2.46	3.46	1.00
	# 35	2.43	4.72	2.29
	# 45	2.32	3.00	0.68
	# 60	2.37	3.07	0.70
	# 80	2.44	2.71	0.27
	# 120	2.37	2.92	0.55
	# 170	2.34	2.69	0.35
	# 230	2.31	2.49	0.18
	# 270	2.37	2.42	0.05
	Catch Pan	2.27	2.30	0.03

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC3 #2	# 5	2.36	77.16	74.80
	# 7	2.39	7.02	4.63
	# 10	2.34	6.15	3.81
	# 14	2.43	5.46	3.03
	# 18	2.35	3.93	1.58
	# 20	2.46	2.87	0.41
	# 35	2.43	3.45	1.02
	# 45	2.32	2.66	0.34
	# 60	2.37	2.67	0.30
	# 80	2.44	2.69	0.25
	# 120	2.37	2.58	0.21
	# 170	2.34	2.49	0.15
	# 230	2.31	2.39	0.08
	# 270	2.37	2.39	0.02
	Catch Pan	2.41	2.43	0.02

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC3 #3	# 5	2.36	177.31	174.95
	# 7	2.39	7.21	4.82
	# 10	2.34	5.49	3.15
	# 14	2.43	5.02	2.59
	# 18	2.35	4.00	1.65
	# 20	2.46	3.08	0.62
	# 35	2.43	5.63	3.20
	# 45	2.32	4.78	2.46
	# 60	2.37	4.45	2.08
	# 80	2.44	3.39	0.95
	# 120	2.37	2.94	0.57
	# 170	2.34	2.70	0.36
	# 230	2.31	2.55	0.24
	# 270	2.37	2.41	0.04
	Catch Pan	2.30	2.34	0.04

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC3 #4	# 5	2.36	107.11	104.75
	# 7	2.39	7.41	5.02
	# 10	2.34	5.95	3.61
	# 14	2.43	4.94	2.51
	# 18	2.35	3.98	1.63
	# 20	2.46	3.00	0.54
	# 35	2.43	4.01	1.58
	# 45	2.32	3.22	0.90
	# 60	2.37	3.45	1.08
	# 80	2.44	3.22	0.78
	# 120	2.37	2.89	0.52
	# 170	2.34	2.60	0.26
	# 230	2.31	2.43	0.12
	# 270	2.37	2.40	0.03
	Catch Pan	2.42	2.45	0.03

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC3 #5	# 5	2.36	106.64	104.28
	# 7	2.39	10.67	8.28
	# 10	2.34	9.93	7.59
	# 14	2.43	8.74	6.31
	# 18	2.35	7.42	5.07
	# 20	2.46	4.50	2.04
	# 35	2.43	9.90	7.47
	# 45	2.32	5.69	3.37
	# 60	2.37	4.42	2.05
	# 80	2.44	3.38	0.94
	# 120	2.37	2.91	0.54
	# 170	2.34	2.62	0.28
	# 230	2.31	2.47	0.16
	# 270	2.37	2.41	0.04
	Catch Pan	2.30	2.34	0.04

Sample	**Sieve**	**Empty weight boat (g)**	**Weigh boat + Sed (g)**	**Sed (g)**
SC3 #6	# 5	2.36	119.65	117.29
	# 7	2.39	5.72	3.33
	# 10	2.34	4.54	2.20
	# 14	2.43	3.88	1.45
	# 18	2.35	3.32	0.97
	# 20	2.46	2.86	0.40
	# 35	2.43	4.15	1.72
	# 45	2.32	4.20	1.88
	# 60	2.37	4.62	2.25
	# 80	2.44	3.76	1.32
	# 120	2.37	3.19	0.82
	# 170	2.28	2.83	0.55
	# 230	2.31	2.63	0.32
	# 270	2.37	2.41	0.04
	Catch Pan	2.27	2.32	0.05

Sample	**Sieve**	**Empty weight boat (g)**	**Weigh boat + Sed (g)**	**Sed (g)**
SC3/6 #1	# 5	2.36	95.97	93.61
	# 7	2.39	12.26	9.87
	# 10	2.34	7.76	5.42
	# 14	2.43	4.89	2.46
	# 18	2.35	3.21	0.86
	# 20	2.46	2.67	0.21
	# 35	2.43	2.96	0.53
	# 45	2.32	2.45	0.13
	# 60	2.37	2.46	0.09
	# 80	2.44	2.52	0.08
	# 120	2.37	2.41	0.04
	# 170	2.28	2.43	0.15
	# 230	2.31	2.38	0.07
	# 270	2.37	2.40	0.03
	Catch Pan	2.32	2.34	0.02

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC4 #1	# 5	2.36	52.24	49.88
	# 7	2.39	7.83	5.44
	# 10	2.34	6.68	4.34
	# 14	2.43	7.21	4.78
	# 18	2.35	5.74	3.39
	# 20	2.46	3.62	1.16
	# 35	2.43	8.68	6.25
	# 45	2.32	8.00	5.68
	# 60	2.37	8.82	6.45
	# 80	2.44	5.67	3.23
	# 120	2.37	4.61	2.24
	# 170	2.28	3.69	1.41
	# 230	2.31	2.96	0.65
	# 270	2.37	2.43	0.06
	Catch Pan	2.37	2.40	0.03

Sample	Sieve	Empty weight boat (g)	Weigh boat + Sed (g)	Sed (g)
SC4 #2	# 5	2.36	163.24	160.88
	# 7	2.39	7.15	4.76
	# 10	2.34	5.95	3.61
	# 14	2.43	5.56	3.13
	# 18	2.35	3.98	1.63
	# 20	2.46	2.98	0.52
	# 35	2.43	5.30	2.87
	# 45	2.32	7.18	4.86
	# 60	2.37	8.87	6.50
	# 80	2.44	6.34	3.90
	# 120	2.37	4.61	2.24
	# 170	2.28	3.30	1.02
	# 230	2.31	2.64	0.33
	# 270	2.37	2.41	0.04
	Catch Pan	2.31	2.37	0.06

Corrected Grain Proportions

Core	Sediment Full (s+c)	Ro-tap sand	>=2 mm	Calculated sed weight	Total Sediment
SC 1.1	2.35	22.29	206.28	230.92	231.20
SC 1.2	6.88	3.3	97.56	107.74	107.83
SC 1.3	4.71	33.63	238.94	277.28	277.53
SC 1A.1	1.98	15	110.12	127.10	127.53
SC 1A.2	21.42	71.17	25.59	118.18	119.52
SC 1A.3	24.50	55.58	58.78	138.86	133.74
SC 1A.4	1.92	2.64	118.07	122.63	122.62
SC 1A.6OGA	2.19	17.78	153.86	173.83	173.35
SC 1A.6P	9.47	0.45	0.00	9.92	9.20
SC 1A.7	4.35	34.69	107.42	146.46	145.63
SC 2.1	2.17	32.69	181.65	216.51	216.11
SC 2.2	1.75	9.48	182.06	193.29	192.58
SC 2.3	9.39	48.42	50.94	108.75	108.32
SC 2.4	1.88	15.13	119.85	136.86	136.28
SC 3.1	2.06	13.92	128.84	144.82	144.81
SC 3.2	1.02	7.41	83.24	91.67	91.67
SC 3.3	7.62	14.8	182.92	205.34	199.71
SC 3.4	1.17	9.98	113.38	124.53	123.89
SC 3.5	1.41	28.31	120.15	149.87	149.45
SC 3.6	2.84	11.77	122.82	137.43	137.01
SC 3/6.1	1.00	4.67	108.90	114.57	113.71
SC 4.1	2.97	35.33	59.66	97.96	99.28
SC 4.2	1.52	27.1	169.25	197.87	197.3

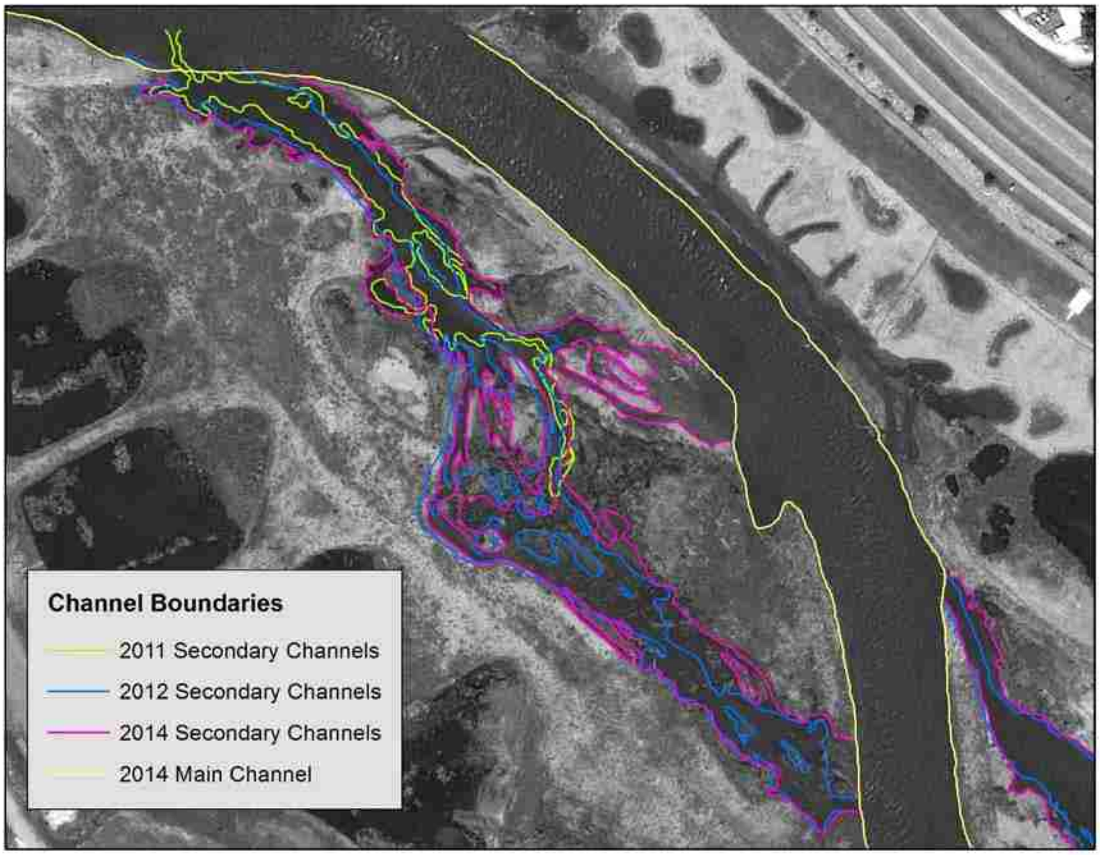
Core	**Percent >=2 mm**
SC 1.1	89.22
SC 1.2	90.48
SC 1.3	86.10
SC 1A.1	86.35
SC 1A.2	21.41
SC 1A.3	43.95
SC 1A.4	96.29
SC 1A.6OGA	88.76
SC 1A.6P	0.00
SC 1A.7	73.76
SC 2.1	84.05
SC 2.2	94.54
SC 2.3	47.03
SC 2.4	87.94
SC 3.1	88.97
SC 3.2	90.80
SC 3.3	91.59
SC 3.4	91.52
SC 3.5	80.39
SC 3.6	89.64
SC 3/6.1	95.77
SC 4.1	60.09
SC 4.2	85.78

Core	% Sand	% Silt	% Clay
SC 1.1	18.53	73.07	8.41
SC 1.2	9.22	80.90	9.88
SC 1.3	9.77	82.06	8.17
SC 1A.1	10.08	80.38	9.54
SC 1A.2	17.18	75.26	7.56
SC 1A.3	13.65	81.43	4.92
SC 1A.4	6.42	85.78	7.80
SC 1A.6OGA	7.84	86.04	6.12
SC 1A.6P	8.32	86.18	5.49
SC 1A.7	7.19	85.10	7.71
SC 2.1	6.73	88.04	5.23
SC 2.2	10.26	84.97	4.77
SC 2.3	18.59	75.97	5.44
SC 2.4	9.39	85.92	4.69
SC 3.1	18.18	77.56	4.26
SC 3.2	7.99	87.80	4.21
SC 3.3	8.53	82.09	9.39
SC 3.4	12.81	82.66	4.53
SC 3.5	6.21	88.33	5.46
SC 3.6	8.60	83.43	7.97
SC 3/6.1	5.46	84.88	9.66
SC 4.1	9.60	80.48	9.91
SC 4.2	12.82	82.69	4.48

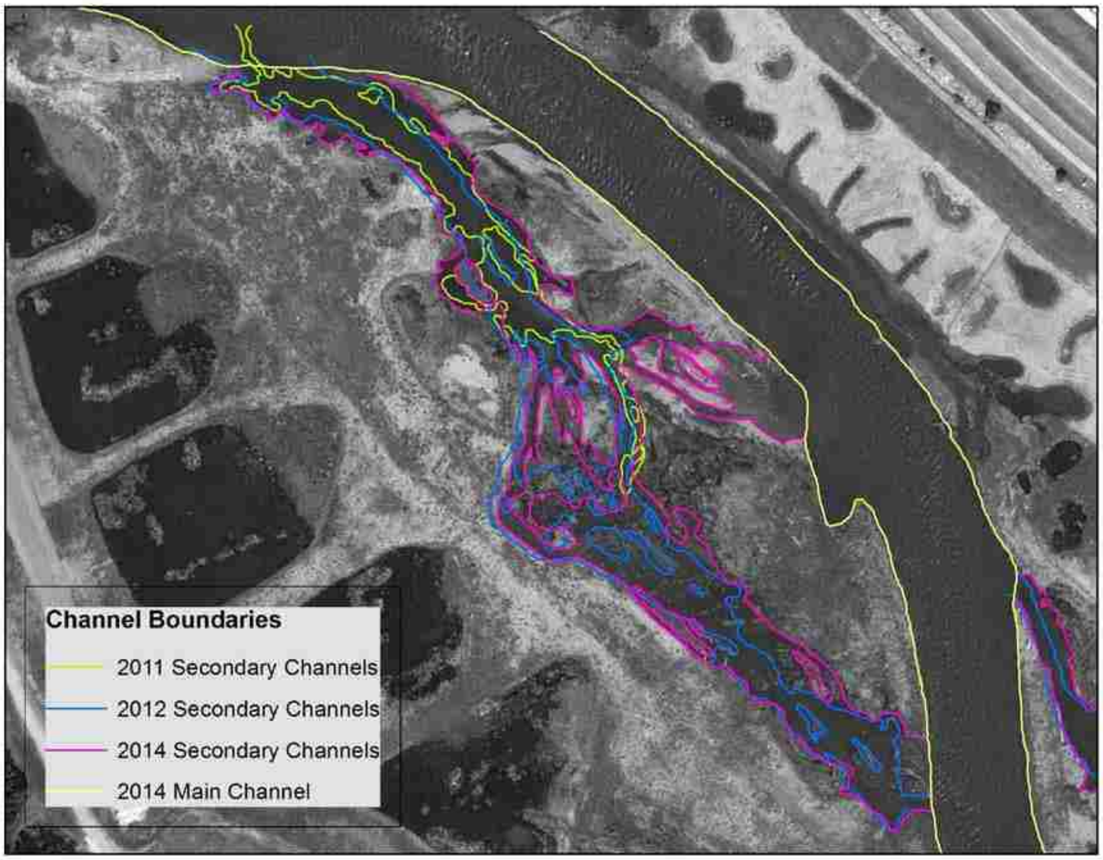
Core	**Corrected % Gravel**	**Corrected % Sand**	**Corrected % Silt**	**Corrected % Clay**
SC 1.1	89.22	2.00	7.88	0.91
SC 1.2	90.48	0.88	7.71	0.94
SC 1.3	86.10	1.36	11.41	1.14
SC 1A.1	86.35	1.38	10.97	1.30
SC 1A.2	21.41	13.50	59.15	5.94
SC 1A.3	43.95	7.65	45.64	2.76
SC 1A.4	96.29	0.24	3.18	0.29
SC 1A.6OGA	88.76	0.88	9.67	0.69
SC 1A.6P	-	8.32	86.18	5.49
SC 1A.7	73.76	1.89	22.33	2.02
SC 2.1	84.05	1.07	14.04	0.83
SC 2.2	94.54	0.56	4.64	0.26
SC 2.3	47.03	9.85	40.24	2.88
SC 2.4	87.94	1.13	10.36	0.57
SC 3.1	88.97	2.00	8.55	0.47
SC 3.2	90.80	0.73	8.07	0.39
SC 3.3	91.59	0.72	6.90	0.79
SC 3.4	91.52	1.09	7.01	0.38
SC 3.5	80.39	1.22	17.32	1.07
SC 3.6	89.64	0.89	8.64	0.83
SC 3/6.1	95.77	0.23	3.59	0.41
SC 4.1	60.09	3.83	32.12	3.95
SC 4.2	85.78	1.82	11.76	0.64

Appendix E – Channel Planform Maps

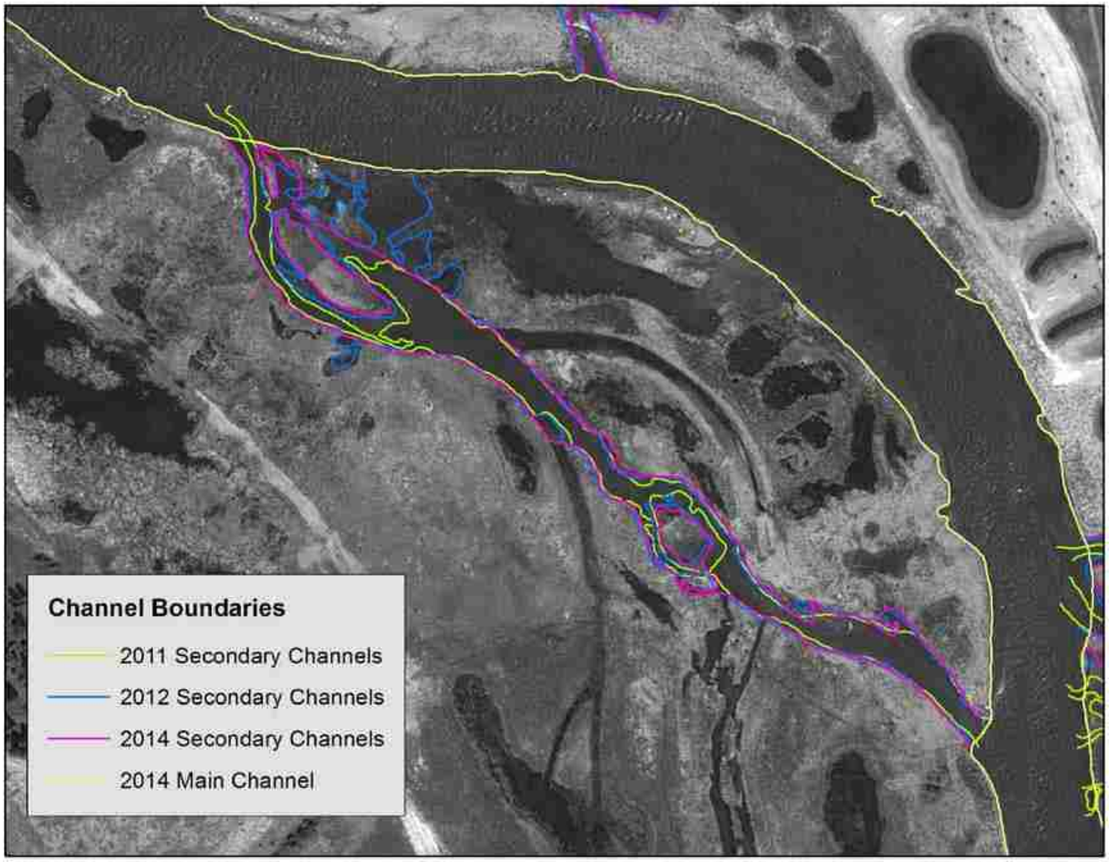
- Secondary Channel 1



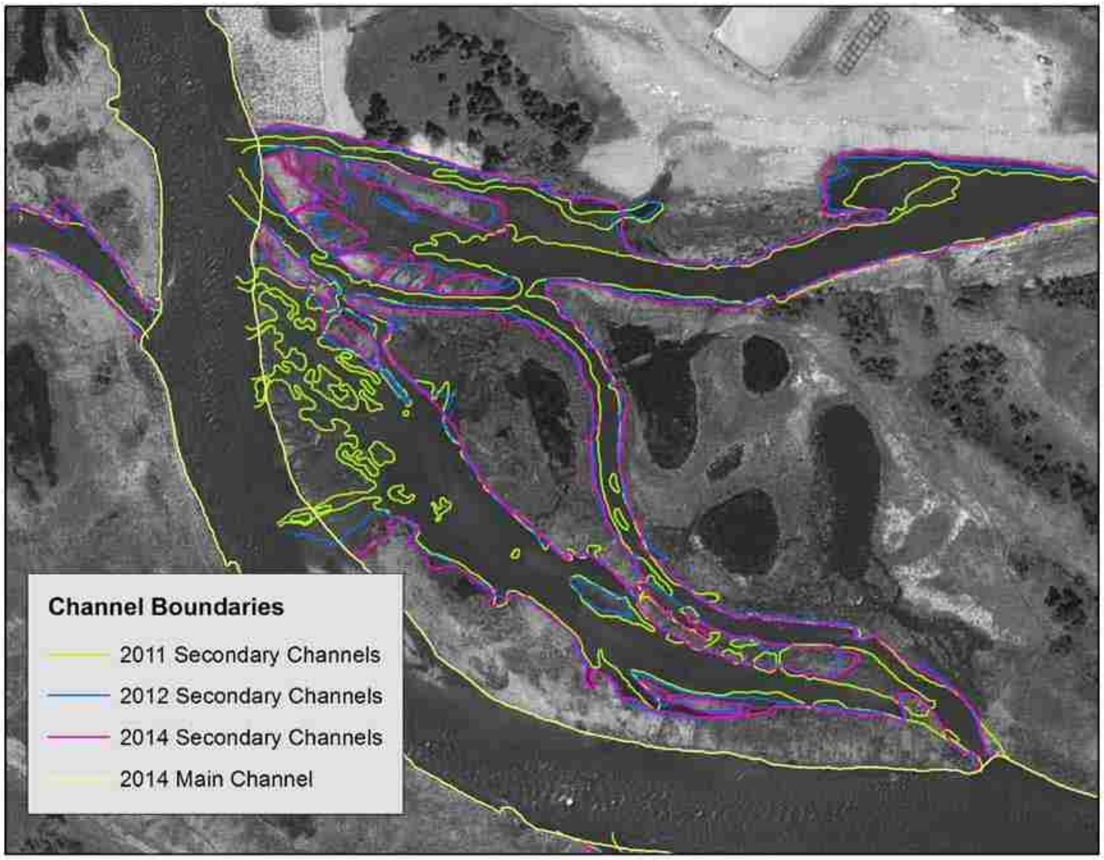
- Secondary Channel 1a



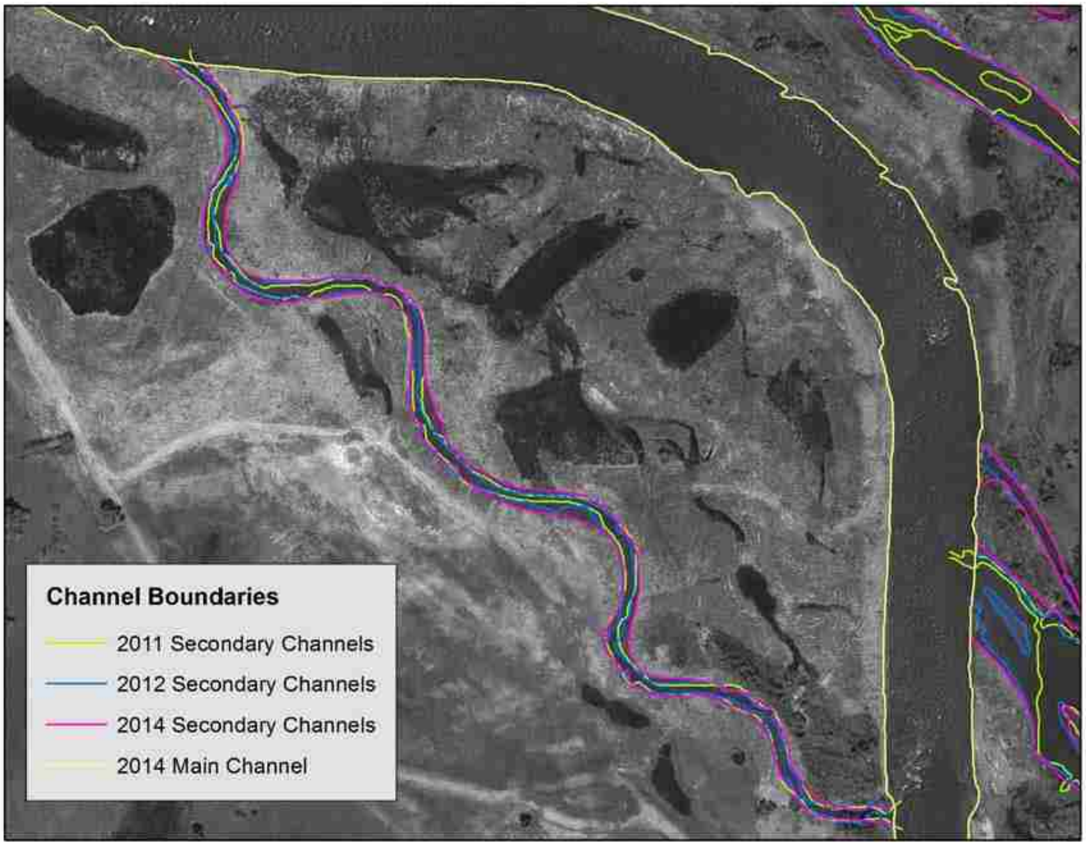
- Secondary Channel 2



- Secondary Channels 3, 3a, and 6b



- Secondary Channel 4



Appendix F – Sediment Sampling Locations

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Chris Van Dyke – Curriculum Vita

Education

- **Graduate Certificate**, Applied Statistics, University of Kentucky, 2011
- **MA**, Geography, University of South Carolina, 2009
  Advisor: Amy Mills
  Thesis Project: “How Far to the Nearest Arsonist?” Representing a National Landscape in Great Smoky Mountains National Park
- **BA**, English and American Literature (Minor: Geography), *summa cum laude,* University of South Florida, 2006

Research Publications

- Van Dyke, C. 2015 . Boxing Daze—Using a State-and-Transition Models to Explore the Evolution Socio-Biophysical Landscapes. *Progress in Physical Geography* (Forthcoming; Published Online 5.2015).
- Lave, R., Wilson, M., Barron, Biermann, C., Carey, M., Duvall, C., Johnson, L., Lane, K., McClintock, N., Munroe, D., Pain, R., Proctor, J., Rhoads, B., Robertson, M., Rossi, J., Sayre, N., Simon, G. Tadaki, M., Van Dyke C. 2014. Intervention: Critical Physical Geography. *The Canadian Geographer*, 58, 1-10.
- Smith, M., Stallins, J.A., Maxwell, J.T., Van Dyke, C. 2013. The Complex Nature of Hydrological Shifts and Tree Growth Responses to River Modification Along the Apalachicola River, Florida. *Physical Geography* 34, 491-511.
- Van Dyke, C. 2013. Channels in the Making – An Appraisal of Channel Evolution Models. *Geography Compass* 7/11, 759-777.
- Van Dyke, C. 2013. Plastic Eternities and the Mosaic of Landscape. *Environment and Planning D: Society and Space* 31, 400-415.
- Van Dyke, C. 2009. Losing My *Dasein* in the Penny Slots: An Impressionistic Deconstruction of Las Vegas. *Human Geography* 2, 96-100.

Book Reviews

Van Dyke, C. 2013. Review of *Fields and Streams: Stream Restoration, Neoliberalism, and the Future of Environmental Science*. *Progress in Physical Geography* 37, 567-570.

Submitted Manuscripts

- Van Dyke, C. Nature’s Complex Flume – Adjustment Trajectories of Secondary Channels on a Reconstructed Floodplain, Clark Fork River, Montana. Submitted to *Geomorphology* 5/15
- Van Dyke, C. Landscape Memory in a Time of Amnesia – Recovering the Clark Fork River at Milltown, Montana. Submitted to *Physical Geography* 3/15.
- Phillips, J.D., Van Dyke, C. Principles of Geomorphic Disturbance and Recovery in Response to Storms. Submitted to *Earth Surface Processes and Landforms* 1/15.

Conference Presentations

- Sturgill, R., McCormack, S., Van Dyke, C., Howell, B., Kreis, S.D. 2015. Case Analysis of Inherent Programmatic Sustainability Resulting from Application of Context-Sensitive Design Principles. Transportation Research Board 94th Annual Meeting, Washington, D.C., 14 January 2015.

- Van Dyke, C., McCormack, S., Gibson, J.B., Kreis, S.D. 2015. Developing a Sustainability Audit Template for Small Inland Port Facilities. Transportation Research Board 94th Annual Meeting, Washington, D.C., 12 January 2015.

- Van Dyke, C. 2014. Landscape Memory in a Time of Amnesia – Recovering the Clark Fork River at Milltown, Montana. Association of American Geographers 110th Annual Meeting, Tampa, FL, 9 April 2014

- Sturgill, R., Howell, B.K., Kreis, D., Van Dyke, C., McCormack, S. 2013. Structured Analysis/Predictive Model for Inland Waterway Systems. Transportation Research Board 92nd Annual Meeting, Washington, D.C., 16, January, 2013.

- Van Dyke, C. Changing States: Applying State-and-Transition Models to Understand Channel Evolution. Southeast Division of the Association of American Geographers 67th Annual Meeting, Asheville, NC, 19 November 2012.

- Van Dyke, C. Radicle Pebble Counting: A Place for Critical Physical Geography. Association of American Geographers, 108th Annual Meeting, New York, NY, 27 February 2012.

- Van Dyke, C. Panelist. Critical Physical Geography. Association of American Geographers, 108th Annual Meeting, New York, NY, 26 February 2012.

- Van Dyke, C. A Moveable Democracy? Rethinking Bruno Latour's The Politics of Nature. Association of American Geographers, 107th Annual Meeting, Seattle, WA, 15 April 2012.

- Van Dyke, C. An Ecological Democracy Without Nature? University of Kentucky Dimensions of Political Ecology Conference, Lexington, KY, 19 February 2011.

- Van Dyke, C. The Exhaustion of Landscape Studies? Association of American Geographers, 106th Annual Meeting, Washington, D.C., 17 April 2010.

- Van Dyke, C. How Far to the Nearest Arsonist? Protecting the State Through Culture in Great Smoky Mountains National Park. Southeastern Division of the Association of American Geographers, 64th Annual Meeting, Knoxville, TN, 23 November 2009.

- Van Dyke, C. “How Far to the Nearest Arsonist? Frontier Nationalism and the Construction of Great Smoky Mountains National Park,” PLACE Group, University of South Carolina, 9 April 2009.

- Van Dyke, C. Irony and the Politics of Scale. Association of American Geographers, 105th Annual Meeting, Las Vegas, NV, 26 March 2009.

Technical Research Reports

- McCormack, S., Sturgill, R., Howell, B., Van Dyke, C., Kreis, D., 2014 Green Infrastructure. Kentucky Transportation Center Research Report.
- Gibson, B., Van Dyke, C., Kreis, D. 2014 Inland Waterways Funding Mechanisms Synthesis. Kentucky Transportation Research Report.
- McCormack, S., Van Dyke, C., Deaner, H., Kreis, D. 2014. Targeting Inland Port Sustainability. Kentucky Transportation Research Report.
- McCormack, S., Van Dyke, C., Deaner, H., Blackden C., Kreis, D., 2013. Jurisdictional Roadside Ditch Replacement. Kentucky Transportation Center Research Report.
- McCormack, S., Howell, B., Sturgill, R., Van Dyke, C., Blackden, C., Kreis, D. 2013. Green Initiatives. Kentucky Transportation Research Report.
- McCormack, S., Van Dyke, C., Souza, A., Kreis, D. 2012, Temporary Flood Barriers. Kentucky
Transportation Center Research Report.

Awards and Fellowships

- **2013-2014**
  - Dissertation Year Fellowship, Graduate School, University of Kentucky
- **2013**
  - MTIC (Multimodal Transportation and Infrastructure Consortium) Student of the Year
- **2009-2012**
  - Daniel R. Reedy Quality Achievement Award, Graduate School, University of Kentucky
- **2009-2010**
  - Kentucky Opportunity Fellowship, Graduate School, University of Kentucky
- **2002-2006**
  - Presidential Scholars Award and Honors College Scholarship University of South Florida