THESIS

ASSESSING CHANNEL CHANGE AND BANK STABILITY

DOWNSTREAM OF A DAM, WYOMING

Submitted by

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ABSTRACT

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The Hog Park Creek watershed, in south-central Wyoming, has experienced several anthropogenic influences through time, the most notable in contemporary times being a reservoir in the upper extent of the watershed that was initially constructed in 1965 (Stage 1) and then later enlarged in 1985 (Stage 2). Flows released from the reservoir augment flows in Hog Park Creek. The existence of the channel-spanning dam creates a direct and identifiable disruption in the function of the two main drivers of geomorphic process: the water discharge, which has nearly doubled annually, and the concomitant disruption in the sediment transport regime. In order to assess channel responses, multiple analyses across a range of spatial and temporal scales were conducted. These include: a covariate hydrologic analysis relating three operational time periods using the Index of Hydrologic Alteration (IHA) software; an examination of the channel planform change from historical aerial photographs; analyses of annually repeated cross section survey data; and a study of bank erosion dynamics using the Bank Stability and Toe Erosion Model (BSTEM).

The timing, magnitude and duration of flows have been altered since the Stage 1 implementation of the reservoir in 1965. Following a Stage 2 enlargement in 1985, the

snowmelt-dominated hydrograph has most notably experienced a shift to bimodal high flows (an early spring, low-magnitude flow release from the reservoir and a late spring, high-magnitude flow release from the reservoir), a 550% increase in seasonal low flows, and a 10% reduction in peak discharges. The discharge historically corresponding to a 5-year recurrence interval now occurs annually under Stage 2 reservoir operations. Hence, formational flows for channel morphology have increased in both frequency and duration. The reduction in flow variability has ultimately altered the sediment transport regime, which is the base of the productivity and disturbance regimes that influence food web interactions, the composition of riparian vegetation and other ecological attributes of the pre-dam river ecosystem.

Aerial photographic analysis of 29 years prior to and 36 years following the construction of the dam indicates an adjustment of channel width both temporally and spatially through the system. Statistical analyses suggest that the overall rate of change corresponds significantly to both location in the watershed (distance downstream of the reservoir) and the operation of the reservoir (volume, timing, and duration of water released). Most notably, the channel has shifted to a single-thread channel with reduced morphologic heterogeneity. Responses are most abrupt immediately downstream of the dam following its construction in 1965, whereas responses are more muted and delayed in the furthest downstream study reach.

Cross section analyses indicate that each of the four study sites has experienced net erosion over the past five years. However, variation exists in erosion rates on the reach and site scales. Modeled erosion rates in BSTEM, corroborated with field data from bank erosion pins and repeated cross section surveys, suggest that the altered flow

regime enhances bank erosion. The enhanced duration of high flows directly lead to increased amounts of toe scour. Flow regulation has changed the forces acting on the banks, including subsurface flow fluxes related to water level fluctuations and increased shear forces. This in turn has created hydraulic conditions that increase preferential erosion of the finer bank materials. However, this response is partially offset as channel geometry changes with width increase relative to depth, which alters the shear stress acting on the banks.

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The completion of this thesis is not only to further my analytical skills, but a testament to my intrigue and awe regarding the processes continuing to shape our world, and that are so important to sustainability and conservation. I have many to thank for their support of me reaching this point. Without the guidance, wisdom and persistence of many, this simply would not have come to fruition.

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the wild places.

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1   INTRODUCTION

Hog Park Creek in the Medicine Bow National Forest of Wyoming was originally dammed in 1965 with the intent of regulating flow for water supply to the city of Cheyenne, Wyoming. The dam was modified and enlarged in 1985, nearly doubling the annual discharge in the channel through augmentation. Flow regulation has altered the natural, pre-dam flow, resulting in changes in bank erosion and channel stability. Other land uses, including 19th-century timber harvest and beaver removal and historical and contemporary cattle grazing, may also have altered channel dynamics along Hog Park Creek. The purpose of this project is to evaluate changes in hydrologic and planform characteristics subsequent to the installation of the dam and associated flow augmentation. An exciting opportunity is presented to discern anthropogenic drivers of channel change and to use a mechanistic approach to bank erosion research.

Following a review of the effects of flow regulation on channel dynamics and of streambank form and process, a chronological history of channel alteration at Hog Park Creek is presented. In order to assess channel response to altered flow and sediment discharge, I used multiple analyses across a range of spatial and temporal scales: multi-decadal planform change as recorded in aerial photographs; analyses of ecologically-based hydrologic parameters prior to and following flow regulation; and detailed bank analysis and erosion modeling. In the Hog Park Creek basin, an unregulated tributary, South Fork Hog Park Creek, joins the regulated main stem and divides the study reaches into two sections of varying extents of regulation. Upstream of this confluence exists a fully regulated section and downstream of this confluence a partially regulated section. The partially regulated section experiences a lesser footprint from regulation because of the input

of natural flow and sediment from South Fork Hog Park Creek. The presence of South Fork Hog

Park Creek as a reference stream enables the differentiation of the effects of land use and dam

operations on stream channel dynamics. The outcome is a multi-tiered analysis in the context of

basin-scale hierarchical controls, introducing a methodology for examining hydrogeomorphic

change in the setting of the Intermountain West.

1.1   BACKGROUND

Transbasin diversions and flow regulation play an important role in the complicated story of

water provision and channel adjustment in the arid and semi-arid West. Throughout the

Intermountain West, dams have provided multiple benefits including the mediation of water

scarcity through trans- and interbasin water transfers. Rivers play very important roles in society

by providing agricultural and municipal water supplies, ecological health (fisheries, riparian

species, and food webs), aesthetics and recreation, and dams can enhance or limit these roles. The

importance of water as a resource has prompted a broad range of studies, both in scale and

context, following the installation of dams (Willliams and Wolman, 1984; Graf, 1988). These

studies have shown that along with dams have come initially unforeseen geomorphic (Petts, 1979;

Williams and Wolman, 1984; Carling, 1987; Hadley and Emmett, 1998; Salant et al., 2005),

biotic (Ligon et al., 1995; Power et al., 1996; Orr et al., 2008) and societal impacts (Born et al.,

1998; Darby and Thorne, 2000; Doyle et al., 2000; Johnson and Graber, 2002). The studies are

diverse and have documented an equally diverse scope of dam-related changes.

The fact that many river systems experienced anthropogenic modifications prior to dam

construction adds another level of complexity to studies of the effects of dams on rivers (Wohl,

2006; Marston, 1994). For example, in south-central Wyoming, beaver removal by the early

pioneers altered the groundwater and flood hydrology concurrently with sediment deposition in

the channel (McKinstry et al., 2001; Naiman et al., 1988) Later, logging denuded hillsides, which enhanced overland flow and hillsope erosion, indirectly impacting the channel with excessive sedimentation (Haas, 1979). Channel scour also occurred when the river was used as a conduit for log transportation to nearby mills. Grazing occurred to various extents over several decades, and research has shown that impacts can range from soil compaction and reduction of infiltration capacity, to direct erosion from trampling and vegetation removal (Trimble and Mendel, 1995; Holland et al., 2005). Isolating dam-related effects from other natural and anthropogenic impacts to the channel has proven to be difficult, as has prediction of the channel response to damming. The combined inherent difficulty in predicting geomorphic response and the variety of anthropogenic impacts in most river basins necessitates an in-depth study of the complexity of the entire river system, both spatially and temporally, to determine whether a given change in control variables, such as those associated with the presence of a dam, is causing changes in channel morphology and process.

1.2   HYDROGEOMORPHIC CONTEXT

A river is a conveyor of water and sediment (Schumm, 1977). Sediment is produced in spatially varied rates across the watershed and transported downstream by a spatially and temporally variable hydrograph (Darby and Thorne, 1995). These sediments may be intermittently stored in deposits along the channel or on the floodplain and then reintroduced via bed and bank erosion. The hillslopes and channel evolve together through time, such that a change in one component is accommodated by the other (Hack, 1960). In the flux of the water and sediment regime, a central tendency about a mean exists, as described in the concept of dynamic equilibrium (Leopold and Maddock, 1953;;(Leopold and Maddock, 1953, Langbein and Leopold et al., 1964; Graf, 1988). An equilibrium condition means that the stream planform, geometry, and slope reflect an

approximate balance between the sediment load entering a reach of stream and the sediment load

leaving the same reach over a period of decades (Langbein and Leopold et al., 1964). Although

channel adjustment will occur in streams, the adjustment does not result in a net change in

channel dimensions over time if the stream is in dynamic equilibrium, so long as the hydrologic

and sediment regimes do not change. This can be qualitatively expressed as

$$Q_s \, D_{50} \sim \; Q_w \, S \qquad\qquad\qquad\qquad\qquad (1.1)$$

Where Q_w = water discharge, S = slope, QS = sediment yield, and D50 = size fraction of which

50% of the streambed sediment is finer (Lane, 1955; Bull, 1979).

When a disruption occurs in the flow and/or sediment regime, an alteration in channel

morphology is expected to occur. Lane's (1955) balance is a conceptual model aiding in the

prediction of changes likely to occur in response to an alteration of the hydrologic and sediment

regime (Figure 1.1). The proportionality of the scale can be used to illustrate the predicted effect

of a change in one parameter on one or more of the remaining parameters.

The volume on one pan represents sediment discharge, and the droplet on the other pan represents

water discharge. The balance arms represent the bed material size and the friction slope. If all are

in balance, the needle points downward to an equilibrium condition. If any of the four terms are

out of balance, degradation or aggradation occurs such that there is either a net gain or loss of

material moving through a reach. If the transport capacity exceeds the available supply, bed

and/or bank erosion can result. The river widens and/or deepens its channel as additional

sediment is transported. Erosion reduces the stream gradient and typically exposes coarser

material. If the transport capacity is less than the available sediment supply, aggradation or bed-

fining can result. Stream gradients lessen and bank angles decline.

Lane's balance provides a useful tool for conceptualizing how a channel responds to alterations in

water and sediment supply, but watersheds are much more complex than depicted with the four

variables of the balance. For example, the idea of a balance does not include complications such

as thresholds, lag time, and complex response. River systems experience shifts in climate and

topography through time. The channel can gradually adapt in a linear fashion to these external

changes, fluctuating about a given mean condition. The channel can also respond in a non-linear

fashion when a relatively small change in a driving variable triggers large changes in channel

characteristics; in this case, a threshold has been crossed (Schumm, 1977) (Figure 1.2).
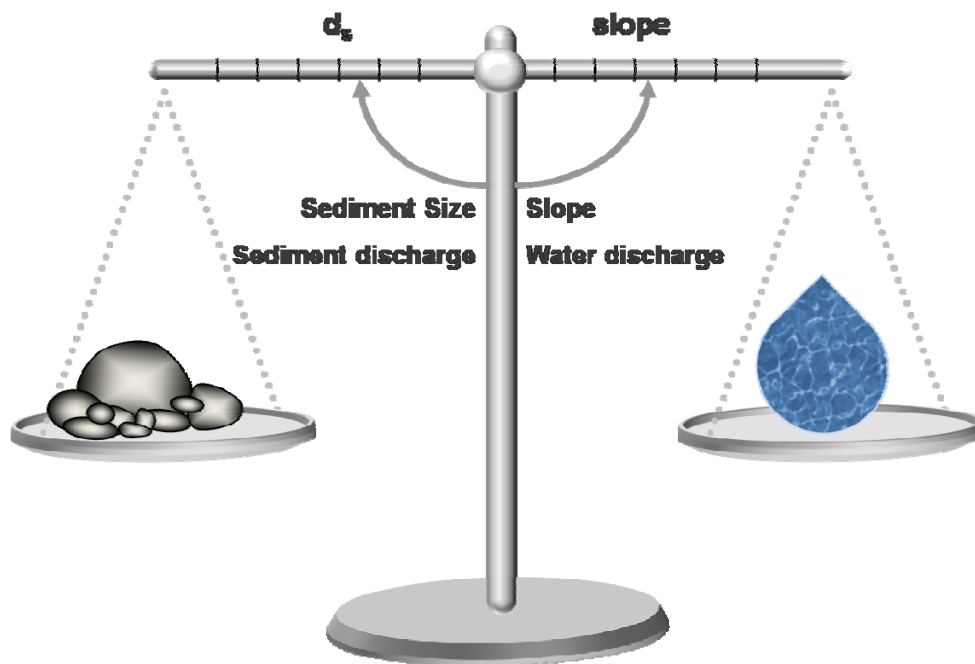
Figure 1.1: Schematic of Borland's depiction of Lane's Balance (1955).

Thresholds can be difficult to define because of the compounding effects of lag time and complex

response (Church, 2002). A delay in time between the occurrence of an antecedent perturbation

and the landscape response is considered lag time, and this can obscure interpretations of linkages

to perturbations (Chappell, 1983). Complex response describes the linkages between multiple

processes in such a way that the effect of one process may initiate the action of another (Petts,

1979; Phillips, 2006). One small event can cascade through a given system, creating new

components of change. This could include a series of responses to a single initial change,

resulting in a complex set of results, which could lead to more, and again possibly unforeseen,

changes. Hence, landforms exhibit simultaneous but spatially different responses to a

disturbance, depending on external controls.
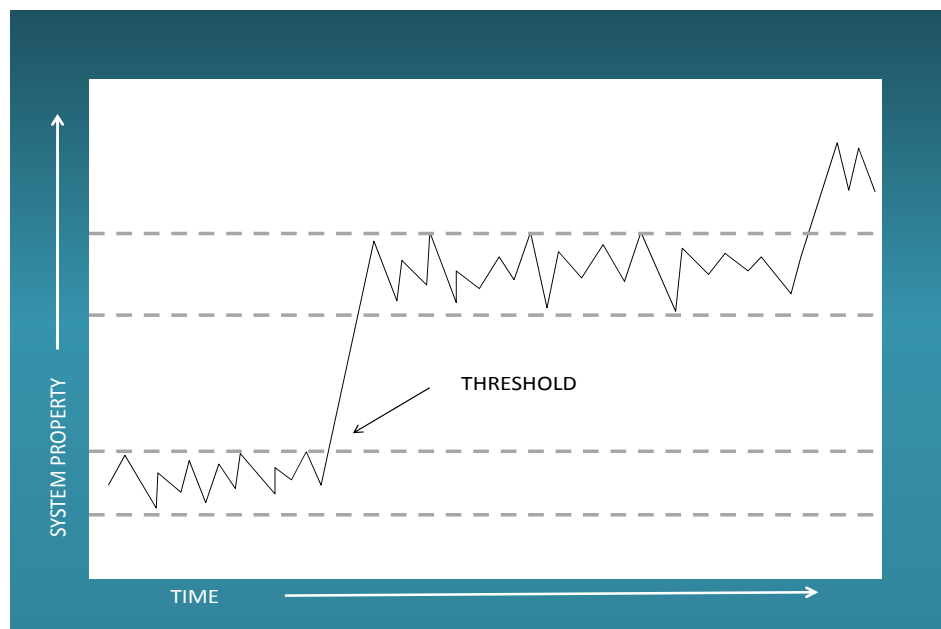
Figure 1.2: Illustration of threshold response.

Despite the complications discussed above, Lane's balance is useful in conceptualizing the

predicted effects of dams on channel dynamics. Dams influence the magnitude, frequency, timing

and duration of flows (Poff and Ward, 1989; Richter et al., 1996), and thus the ability of the river

to transport sediment, as well as the amount of sediment available for transport (Williams and

Wolman, 1984; Brandt, 2000). Stream flow alterations can also potentially alter the sediment

being supplied from channel banks, sediment transport relations, the morphological character of rivers and the ecological processes (Table 1.1)

Table 1.1: Components of the flow regime as depicted by Richter (1996) and geomorphic influence as provided by Graf (2006).

Flow regime component	Definition	Geomorphic influence
Magnitude and duration	Describes daily conditions; describes extreme events and bankfull discharges; range of annual flows	Amount of available space for river forms, sediment and processes; overall channel morphology; sediment storage and mobility; geomorphic complexity; dominant particle size of bed materials; floodplain inundation; riparian species; groundwater recharge
Timing	Describes the seasonal nature of hydrologic components	Interaction between snowpack, vegetation and flows
Rate and Frequency	Describes the abruptness and number of intra-annual cycles; hydrologic variation within a year and provides measures of the direction rate and tendency of intra-annual change	Frequency of mobility of channel bed and bank materials; frequency of changes in functional surfaces. Likelihood of erosion of banks, bars. and islands; overall annual stability of channels and banks
Frequency and duration	Describes the pulsing behavior of high and low flows within a year and provides a measure of the shape of the pulses	Overall channel morphology; indicator of geomorphic complexity; limit on sediment transportation and channel maintenance

Dams located in the headwaters can be expected to have a different range of impacts than those in the lower portion of river systems (Grant et al., 2003) because the controls on channel morphology shift with distance downstream. Headwater reaches are characteristically directly coupled to the hillslope and dominate as a sediment transport system. Further down the channel, there is no longer direct channel-hillslope coupling and the stream transitions from a system dominated by sediment transport (supply limited) to one dominated by sediment accumulation (transport limited) (Figure 1.3:). In downstream reaches, a dam may cause a greater change in channel morphology related to changes in sediment transport rather than to changes in the hydrologic regime. The changes in channel morphology directly relate to control variables such

as sediment supply and flow regime, channel and valley morphology (especially channel gradients), the volume of sediment supplied to the river from hillslopes and channel banks, and the location within the river system.
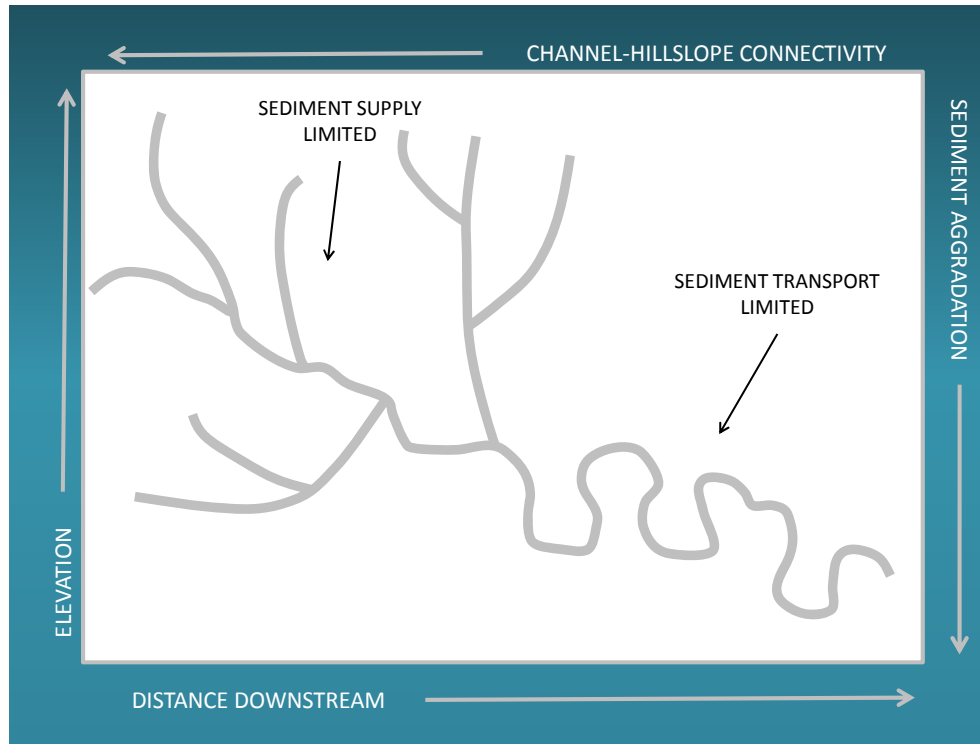
Figure 1.3: Illustration of river segments dominated by sediment supply versus transport-dominated regimes (partly derived from Schumm 1977 and Church 2002).

Streams respond to minor system alterations by modifying their size, shape and profile. There are many adjustable attributes of a channel, including width, depth, bed surface and subsurface material, boundary roughness, planform, and gradient, so the response of a channel to changes in sediment supply varies spatially and temporally (Petts, 1979; Williams and Wolman, 1984; Carling, 1988; Brandt, 1998). Other variables responding to the presence and operation of dams are sediment size and size distribution; type, extent and age of vegetation; and side channels and

backwater features. The aforementioned changes will vary in response due to the operation of the dam and the distance downstream.

Williams and Wolman (1984) found that each river may respond differently to similar adjustments in discharge and sediment regime, depending on the river's initial condition and on downstream influences such as tributary junctions or sediment supply from valley walls. Many subsequent studies have documented similar findings, and have expanded the documented impacts of dams to include features such as loss of floodplain connectedness (Sedell et al., 2006), water quality degradation (Simon et al., 2000), and increased vulnerability to the invasion of exotic riparian and aquatic species (Moyle and Mount, 2007; Miller et al., 1995). Some studies have shown that little change occurs following a dam (Williams and Wolman, 1984; Brandt, 2000). Over time, the nature and magnitude of response may change as well.

Grant et al. (2003) argue that the primary drivers of watershed processes are the geology, climate, and topography. Over geologic timescales, these are the major drivers of change and they largely influence morphologic adjustments to minor perturbations in shorter timescales as well. Feedbacks occur between geologic constraints and sediment supply, hydrologic events and topographic controls (see Figure 1.4). However, during shorter time periods of analysis, other drivers of considerable influence include riparian vegetation and bank strength. Numerous studies have shown that the impact of a dam can be directly related to the magnitude of alteration in the hydrograph and sediment flux of the river system from dam operation (Petts, 1979, 1982; Willams and Wolman, 1984; Carling, 1988; Brandt, 2000; Grant, 2003). In most river systems there are more controls than depicted with Lane's balance.
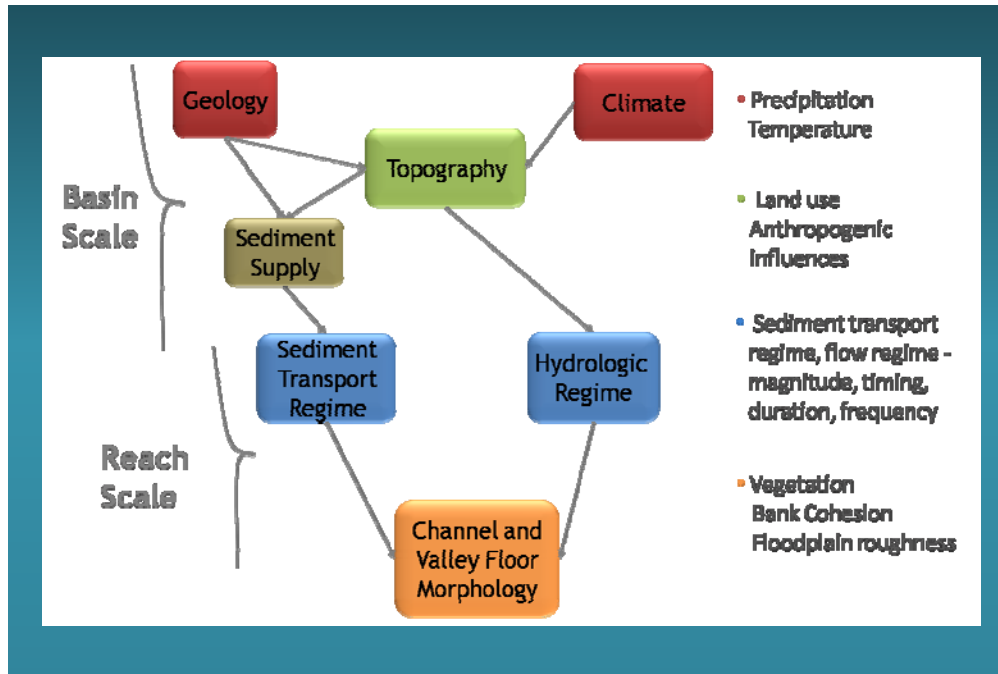
Figure 1.4: controls in a watershed as adapted from Grant et al., 2003 (Figure 1).

Vegetation type and distribution are influenced by climate and geographic location, as well as discharge regime and land use adjacent to the channel (Hupp and Simon, 1991). Locally, bank degradation can cause species shifts, changing availability to and storage of water by riparian species. Riparian vegetation in turn influences geomorphic processes by altering bank resistance, sediment deposition and hydraulic roughness along the channel boundaries (Simon et al., 2000; Simon and Collision, 2002; Pollen and Simon, 2005). Riparian species composition shifts throughout the watershed and the general influence of vegetation on bank stability decreases downstream. As emphasized previously, the relative influence of controls changes spatially through the river system and through timescale of analysis. For example, as the banks become progressively taller in higher-order streams, riparian vegetation roots become less effective as a stabilization tool because the ratio of root depth (added cohesion) to bank height decreases. In

the next section, the local mechanisms of bank erosion and stability will be described in detail to further document the complexities of bank analysis.

1.3   BANK EROSION

Bank instability is a form of adjustment to changes in factors that influence channel morphology. A brief overview of components of bank erosion is introduced here. First, I will discuss driving forces acting on the bank and the components of competing resistance. Following the discussion of these mechanisms, I will introduce elements which are considered preparatory, or which exacerbate erosion and are directly pertinent to the study area, specifically freeze-thaw cycles and grazing impacts. Two types of bank erosion will be defined; mass failure, which includes planar, rotational and cantilever failure types, and hydraulic scour, which addresses fluvial entrainment of particles at the toe of the bank. The intent of this section is to introduce bank erosion complexities relating to my analyses and to provide background for the discussion of the mechanisms and trends of bank erosion in the study area. Through the modeling of bank erosion and calibration to field-collected data, correlations with components of the flow regime are sought to explain trends in bank instability in Hog Park Creek following flow regulation.

1.3.1   GEOTECHNICAL CONSIDERATION

The type and amount of bank erosion are controlled by the underlying driving forces and substrate resistance. Bank mass failure is related to bank shear strength and gravitational forces, while hydraulic scour reflects bank erodibility and boundary shear stress. Stream bank erosion processes, although complex, are driven by two major components: stream bank characteristics (erodibility) and hydraulic forces (Leopold et al., 1964). Erosion is largely a gravitationally-related process, but the effects of bank composition, specifically related to cohesion and pore pressures, require a more complex view of bank shear strength than just that of gravitational

failure related to non-cohesive, or unconsolidated, banks. Stream bank characteristics that influence erodibility include grain-size distribution, stratigraphy, moisture content, bank shear strength, and riparian vegetation. Bank shear strength components include soil shear stress (the force exerted by soil shearing), cohesion (the electro-chemical force created by charged clay minerals), friction (the resisting force created by rough surfaces), friction angle (the rate of increasing strength with increasing normal force), and normal stress (the force created by a weight, acting normal (90°) to the shear surface) (Simon and Collison, 2002). In non-cohesive materials, gravity is a major component of erosion, but cohesive soils add complexity to the equation. Nanson and Hickin (1986) demonstrated that unsaturated banks are more difficult to erode than saturated banks. In their study, seasonal wetting of banks allowed for greater erosion during a flow in the winter with saturated banks versus a flow of similar magnitude in the summer with unsaturated bank conditions.

Hydraulic forces reflect hydrology (discharge magnitude, duration and frequency) and channel geometry (width/depth ratio, boundary roughness, cross-sectional and planform shape). Relatively infrequent flows which occur on the order of every 1.5 years to 2 years have the most influence in shaping the channel in most gravel-bedded streams (Wolman and Miller, 1960). These flows occur more regularly and do more work in the channel than infrequent extreme floods. In snowmelt-dominated streams such as those in the study area, catastrophic floods rarely occur. During high annual flows, confining pressures from flow generally do not exceed the driving force of fluid shear, resulting in bank erosion. Location in the channel is a major factor of river bank erosion. Most erosion occurs in the apices of meander bends, which is largely due to steep velocity gradients and high shear stresses associated with flow separation in these areas (Knighton, 1998). Failure occurs when hydraulic forces scour the bank toe, over-steepening the bank and allowing for gravitational forces to exceed the bank shear strength. The shear stresses

both erode the bank and preferentially scour the toe, leading to over-steepening. The shear stress

increases as the banks erode, enhancing protrusions to flow, in turn creating more susceptibility to

erosion and bank instability.

Flowing water exerts a shear stress on the toe and bank, as a function of water surface slope,

hydraulic radius and unit weight. Hydraulic shear force, the stream's ability to entrain a particle,

is represented by the equation:

$$\tau_o = \gamma \, R \, S \qquad\qquad\qquad (1.2)$$

Where τo = mean boundary shear stress, R = hydraulic radius = A / 2y + w, y = depth, w =

width, and S = channel gradient. The shear stress, or tractive force, is a fluid force per unit area

and represents the force acting on the boundary and hence will also be referred to as boundary

shear stress.

Shields (1936) developed a dimensionless critical shear stress which specifies the initial erosion

point of bank material, related to the shear stress and particle characteristics:

$$\tau^* = \tau_o \, / \, [\, (\gamma_s - \gamma_w) * d] \qquad\qquad\qquad (1.3)$$

Where τ^* = dimensionless shear stress, γs = unit weight of sediment, γw = unit weight of water,

and d = characteristic particle diameter (Knighton 1998). Resisting forces include soil strength

and reinforcement provided by vegetation. A simple resisting force can be considered in the

equation:

$$S_a = c \, L + \sigma \tan \phi \qquad\qquad\qquad (1.4)$$

where: $\sigma = W \cos \theta$, W = weight of the failure block, c = cohesion, L = failure plane length, ϕ =

friction angle and θ = failure plane angle (see Figure 1.5).

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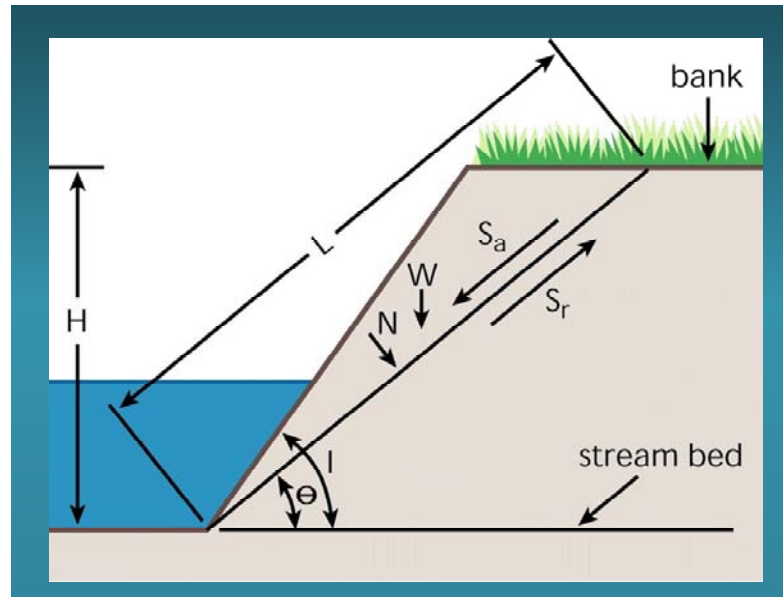
Figure 1.5: Components of bank shear strength: H represents bank height, I = bank angle, L = failure plane length, Sa = driving force, Sr = resisting force, θ = angle of the failure plane, N = normal component of weight, W, to the failure surface (FISRWG 2001, Figure 7-30).

Bed and bank material have the aforementioned resistance due to friction, cohesion and weight. A certain amount of shear stress, the critical shear stress τc, is required to overcome this resistance. The critical shear stress is the magnitude of shear stress required to move a given particle. The resistance of the particle to movement and thus its entrainment will vary depending on its size, its size relative to surrounding particles, how it is oriented and the degree to which it is embedded (Wohl, 2000). Packing or embeddedness will affect the amount of shear stress to which the particle is exposed. The difference between total boundary shear stress, τo, and critical shear stress, τc, is the excess shear stress, τe.

$\tau_e = \tau_o - \tau_c$ (1.5)

This is the shear stress that is available to cause erosion (Simon and Collison, 2002). When the flow conditions exceed the criteria for initial erosion, bank particles are entrained by the flow and removed from the bank. Unfortunately, attempts to calculate or measure shear stress values in mountain rivers are complicated by the channel bed roughness and the associated turbulence and velocity fluctuations (Wohl, 2000). Turbulence can lead to substantial variability in velocity and shear stress at a point during constant discharge. Heterogeneities caused by grains and bed forms may create substantial velocity and shear stress variations across the channel or downstream during a constant discharge.

Hanson and Cook described the amount of erosion (ε) that occurs as a function of the erodibility, k, and the excess shear stress, τe as:

$$\varepsilon = k (\tau_o - \tau_c) \tag{1.6}$$

where ε = erosion rate (m/s), k = erodibility coefficient (m3/N-s), τo = boundary shear stress, (Pa), and τc = critical shear stress (Pa). The term (τo-τc) = excess shear stress, or the force available to cause erosion (Figure 1.6).

From the relation between shear stress (τc) and erosion rate (ε), Simon et al. (2000) calculated erodibility (m3/N-s) as:

$$k = x \, \tau_c{}^y = 0.1 \, \tau_c{}^{-0.5} \tag{1.7}$$

Where k = erodibility, τc = critical shear stress (Pa), and x, y = empirical constants (see Figure 1.6). Erodibility of the banks varies significantly at the inter- and intra-reach scale (Parker, 2008), which substantially influences morphologic adjustments.
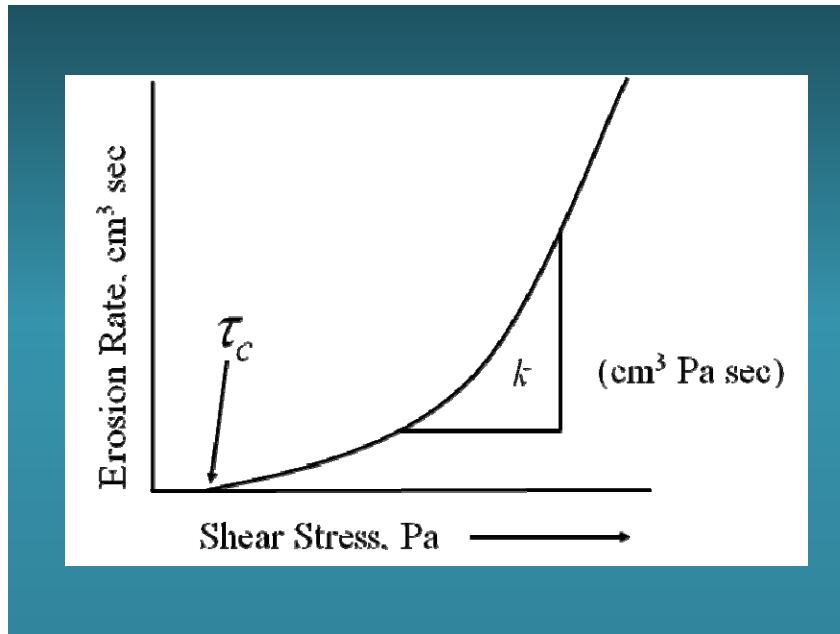
Figure 1.6: Derivation of erodibility coefficient (Simon and Collison 2002)

Driving gravitational forces are influenced by bank height, bank angle, water in the bank, and weight of the soil and may be represented by the equation:

$$S_r = W \sin \theta \qquad (1.8)$$

Where Sr = the driving (gravitational) force, W = weight of the failure block and θ = angle of the failure plane.

For the case of a planar failure of unit width and length, bank resistance is represented by shear strength. Soil shear strength can be quantified by the (revised) Coulomb equation summarizing soil cohesion, friction, and soil water pressure as:

$$\tau_f = c' + (\sigma - \mu_w) \tan \phi' \qquad (1.9)$$

where τf = shear strength (kPa); c' = effective cohesion (kPa); σ = normal stress (kPa); μw = pore

water pressure (kPa) and ϕ' = effective friction angle (degrees) (Simon et al., 2000). The normal

stress (σ) is represented by:

$$\sigma = W\cos\theta \qquad (1.10)$$

The Factor of Safety (Fs) summarizes the variables of bank erosion into a ratio of resisting forces

to driving forces:

$$Fs = \frac{Driving\ forces}{Resisting\ Forces} \qquad (1.11)$$

If the factor of safety equals one or greater, failure is expected to occur. This is the point at which

gravitational forces have overcome the resistance of the bank materials. The Factor of Safety is

an effective method of calculating or predicting erosion potential (Abernethy and Rutherfurd,

2000), and is commonly used in erosion studies.

An ubiquitous characteristic of gravel-bed alluvial channels is an upper layer composed of finer

silts and clays from overbank deposition and a gradation to a lower, coarser gravel and sand layer

from in-channel deposition. The finer layer is more resistant to erosion, while gravels are less

cohesive and experience preferential scour. However, cohesive materials tend to experience

inter-ped bonding, in which the finer bank material will aggregate into larger granules. These

granules represent an important consideration for the strength and hydraulic conductivity of the

soil. Ritter (1986) found that when a cohesive soil does not erode into individual particles, but

breaks off in peds, this influences bank cohesivity and hydraulic conductivity in the soil profile.

The flow regime is not only important because of the shear forces that entrain bank particles and cause over steepening and eventual failure of bank materials, but also because of the capacity to support banks when the flow is high or to induce failure during a rapid drop in stage. Saturated banks are more susceptible to failure than unsaturated, and banks have failed when the reinforcing weight of the water column is removed. A quick retreat in stage causes the groundwater to be higher relative to the stage in the channel, weakening the banks. The flow regime may have indirect impacts as well. In the case of a dam, peak flows are commonly reduced and of a shorter duration. This alteration fails to recharge groundwater and may ultimately result in a shift in riparian vegetation species (Wesche, 1988).

As fluvial processes are major components of bank erosion due to the shear forces and the influence on vegetation species, hydrology within the banks is also an important component in determining bank strength. In cohesive materials, the effectiveness of hydraulic scour is largely determined by the moisture content of the bank material. Groundwater, saturated pore water pressures and lateral movement of water within the soil profiles have a great capacity to weaken soil structure and prepare it for failure (Thorne, 1982). Bank hydrologic components have been shown to reduce bank shear strength by a reduction of matric suction and generation of excess pore-water pressure (Simon et al., 2000). Excess pore-water pressure can be an important component of bank erosion without fluvial action. Pore-water pressure reduces effective normal stress, increasing the weight of the bank, and weakening the soil. Even during moderate flows, the apparent cohesion can be strongly reduced as the soil approaches full saturation. Therefore, during a phase when the stage is quickly reduced, confining pressure of the water in the channel declines, and the excess pore water pressure leads to bank failure.

As previously mentioned, soil pore water pressure is a driving force enabling soil erosion. Unsaturated soils are subject to negative pore water pressures, which cause an apparent cohesion,

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and have been shown to increase bank resistance. A decline in the water table converts positive

pore water pressure to negative pressures, increasing overall bank strength. This is accomplished

by matric suction:

$$\psi = \mu_a - \mu_w, \tag{1.12}$$

Where μa = the air pressure and μw = pore water pressure. A negative value of pore water

pressure is a positive suction, incorporating added cohesion.

The Fredlund and Rahardlo (1993) approach incorporates matric suction as apparent (total)

cohesion into the apparent cohesion equation.

$$c_a = c' + (\mu_a - \mu_w) \tan \phi^b \tag{1.13}$$

Where c_a = apparent (total) cohesion, c'= effective cohesion, $(\mu a - \mu w)$ = suction on the failure

plane, and ϕb = angle representing the relation between the shear strength and the matric suction

(Simon and Collison, 2002). The latter value varies between all soils and generally ranges

between 10 and 20 degrees (as presented in Simon from Fredlund and Rahardlo, 1993). Soil

shear strength increases with increasing matric suction (Figure 1.7).
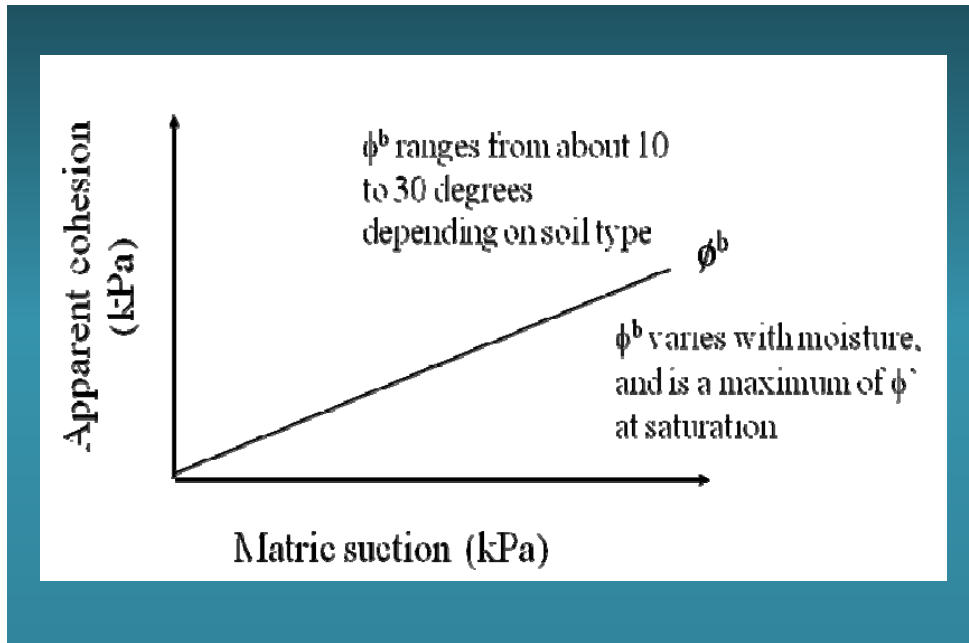
Figure 1.7: The effect of matric suction on apparent cohesion and bank strength. Note that negative pore-water pressures provide an apparent cohesion and greater shear resistance. Positive values of pore-water pressure reduce shear strength. (Derived from Andrew Simon, unpublished figure)

Incorporating these components of pore water pressure, matric suction and soil cohesion, Simon et al. (2000) derived an equation for Factor of Safety for cohesive streambanks, using the Mohr-Coulomb equation for saturated banks (excess pore water pressure) and the Fredlund approach for unsaturated streambanks (matric suction):

$$F_S = \frac{\Sigma\; c'Li \;+\; (Si \tan \phi\;ib) \;+\; [Wi \cos\beta - Ui + Pi \cos (\phi\; \beta)] \tan \phi'}{\Sigma\; Wi \sin \beta - Pi \sin (\phi-\beta)} \qquad (1.14)$$

c' = effective cohesion; Li = length of failure plane within the ith layer; S = force produced by matric suction on the unsaturated part of the failure surface; ϕ b = rate of increasing shear strength with increasing matric suction; W = weight of failure block; θ = failure-plane angle; U = hydrostatic-uplift force due to positive pore-water pressures on the saturated part of the failure

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plane; P = hydrostatic-confining force provided by the water in the channel; β = bank angle

(degrees from horizontal) and ϕ' = angle of internal friction (rate of increasing shear strength with

increasing normal force) (Simon et al., 2000).

Vegetation adds cohesion to the soil and increases flow resistance along the channel's boundaries.

Mechanical stabilizing effects of vegetation result from increased bank strength due to roots.

These effects are a function of the number and depth of roots, area of roots, and tensile strength of

roots and these vary with each vegetation species and age (Pollen and Simon 2006, Simon and

Collison, 2002). Riparian vegetation also influences channel adjustment processes by increasing

bank strength, altering failure modes, and enhancing floodplain sediment deposition (Friedman et

al., 1996; Micheli and Kirchner, 2001). Micheli and Kirchner (2002) quantified rates of stream

channel migration in a montane meadow and compared two types of meadow vegetation.

Streambanks colonized by wet graminoid meadow vegetation were five times stronger than those

colonized by dry xeric meadow species. Lateral migration rates were nearly 10 times higher

without wet meadow vegetation. And when banks were consistently higher than 1 m, the

meadow vegetation shifted from wet meadow to dry meadow communities. Small diameter roots

were shown by Easson and Yarbrough (2006) to have a higher tensile strength than large

diameter roots such as those from trees. The root tensile strength decreased with depth from the

top of bank and lateral distance from the bank edge. Banks with high root density have been

observed to be more resistant to lateral erosion (Gregory and Gurnell, 1988). Destabilizing

effects of vegetation can include increased infiltration capacity and destabilization due to added

weight on the bank, but the added cohesion provided by roots outweighs the destabilizing effects

(Easson and Yarbrough, 2006).

Wu et al. (1979) provide quantitative estimates of added shear strength provided by roots.

Assumptions of Wu et al.'s (1979) equation include the simultaneous breaking of roots, full

tensile strength of all the roots being mobilized at the time the soil fails, and the assumption that all the roots are well anchored and do not simply pull out of the soil when tensioned. Further research by Pollen and Simon (2005) found that bank stability models like those developed by Wu et al. overestimate the increase in the factor of safety for banks with root reinforcement. Pollen and Simon used a fiber bundle model to represent progressive breaking of the roots, as compared to a catastrophic failure event. As the roots progressively break in the fiber bundle model, the remaining shear stress is distributed to the intact roots, allowing for continued progressive breakage.

River systems generally increase in sediment transport with increasing drainage area. Thicker and more cohesive soils follow this trend as well. The factor of safety is always larger with vegetated banks versus no vegetation, but it decreases with bank height. Thus, the relative benefit that roots provide for added bank strength tends to decline from the upper to the lower reaches within a river system if the bank heights have a generally direct relationship with contributing drainage area.

Sub-aerial processes are those that affect soil moisture quantity, state or movement within a streambank (Thorne, 1982). Sub-aerial processes are considered preparatory as they increase soil erodibility (Wolman, 1959; Lawler, 1993; Couper and Maddock, 2001). Lawler's (1986, 1993, 1997, 2002) extensive research on freeze-thaw cycles in streambanks shows that winter flows may be much more effective at eroding banks compared to summer flows of the same magnitude because of the loosening and erosion of these weathered soil particles. Lawler (1993) estimated bank retreat from needle ice formation at 32-43% of the total bank retreat measured. Results showed that significant changes in the resistance of stream bank soils to fluvial erosion can be attributed to sub-aerial processes (Wynn et al., 2008). Regression analysis showed 80% of the variability in soil erodibility could be explained by freeze-thaw cycling alone. A further study by

Wynn and Mostagihimi (2006) on the relative impacts of soil properties, root density and sub-aerial processes on streambank erosion indicated both the erodibility coefficient (kd) and critical shear stress (τc) were influenced by freeze-thaw cycling, suggesting these parameters may vary seasonally. Studies have shown that kd and τc can vary by up to four and six orders of magnitude, respectively, along the same river reach (Hanson and Simon, 2001). The various types of mass failure generally dominate in different portions of the watershed. However, Lawler (1997) argues that sub-aerial processes are pervasive across the river system, indicating that they may be a significant component of erosion.

Another component of bank failure apart from fluvial processes is mechanical damage resulting from riparian grazing by cows. Results of grazing in riparian areas can be both direct modification of stream channels and banks and reduction of resistance to erosion by higher flows, which promotes channel erosion.

Within semi-arid rangelands, studies indicate that cattle favor riparian areas over uplands and use them heavily for forage and access to water (Trimble and Mendel, 1995). Grazing directly compacts soil particles, which reduces infiltration and creates unsaturated overland flow conditions (as compared to variable source) that tend to concentrate water (Trimble and Mendel, 1995). The concentrated flow areas may lead to rilling and eventual gullying. Severe compaction typically reduces the availability of water and air to the roots, sometimes reducing plant vitality (e.g., Reed and Peterson, 1961). Proportion of bare soil appears to correlate well with surface runoff and sediment yield (Copeland, 1965; Lusby, 1970; Branson et al., 1981). Low (< 0.5m), grass-covered, fine-textured banks are particularly vulnerable to trampling by cattle, especially when wet (Clary and Webster, 1990). The trampling further weakens biological resilience, changing its susceptibility to both water and wind erosion. Grazing animals also reduce resistance by removing protective vegetation and loosening soil. Trampling may loosen fragments

of soil and make them more erodible, at the same time reducing vegetation. Grazing of riparian areas can remove up to 80% of riparian vegetation (Platts and Nelson, 1985), thus usually lowering their resistance to erosive flows (Beschta and Platts, 1986). As banks degrade and cause morphological irregularities, several positive feedbacks are created at high stream flows. The increased hydraulic roughness creates turbulence, which accelerates bank erosion. Numerous studies have found that livestock access creates a combination of reduced channel boundary resistance and increased stream power such that bank erosion and subsequent mass failure occurs (Marston, 1994; USBLM, 1994). A review by Belsky et al. (1999) indicated that approximately 85% of riparian livestock studies concluded that livestock access negatively impacts stream morphology and aquatic habitat. However, McDowell and Magilligan (1997) found that significant changes occur within two decades if cattle are excluded from the riparian area, with reductions in bankfull dimensions and increases in pool area being the most common and identifiable changes.

1.3.2 FAILURE TYPES

A geotechnical failure occurs when gravitational forces acting on the bank material exceed the strength of the resisting forces, causing downward displacement of the soil mass. Three types of bank failure discussed herein include planar, rotational slump, and cantilever (Figure 1.8), as described by Thorne (1982) and FISRWG (2001). Rotational slumps are a deeper seated, graben-type failure with a less steep face and a center of rotation above the slope. With a planar slab failure, the top of the bank is in tension and tension cracks appear. The failures are almost planar, the center of rotation is below the slope, and usually failure occurs on bank slopes of 60 degrees, but this depends on soil, roots and the aforementioned bank characteristics. Tension cracks come from the presence of vertical planes of weakness due to cohesive materials and these will weaken soil structure and enhance failure potential.

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Most alluvial rivers are composed of a composite bank formation, with finer-grained and more cohesive soils overlying non-cohesive, gravel layers. Floodplain vegetation also creates a composite cut bank configuration (a cohesive layer overlying cohesionless materials). The typical cohesive upper bank and lower gravel deposit are particularly vulnerable to erosion by toe scour, which leads to undercut banks that are prone to cantilever failure. Cantilever failure occurs due to the preferential retreat of the more erodible basal layer at the toe, generating an overhang on the upper bank until gravity exceeds the shear strength of the bank.

An ubiquitous feature of bank erosion is that it is not equal along the perimeter of the channel, but rather is greatest at the juncture of the base and the toe, where shear stress is greatest (Knighton 1988). The material comprising the bank toe is generally less cohesive than the overlying layer as a result of differences in vegetation and bank composition.

Bank erosion occurs by fluvial entrainment of material from the lower, cohesionless bank at a much higher rate than wasting of material from the upper, cohesive bank (Lawler et al., 1993). Lawler describes fluvial entrainment as the process that leads to undermining of the bank, producing cantilevers of cohesive material. Upper bank retreat then takes place predominantly by the failure of these cantilevers. When a bank fails, the material can be entrained in the flow and removed from the site, deposited as bed material or deposited at the toe as intact slump blocks. These blocks of soil must be removed from the basal area by fluvial entrainment if rapid undermining and cantilever generation are to continue. Studies have shown that by increasing bank strength, wet meadow vegetation increases the thickness, width, and cohesiveness of a bank cantilever, which, in turn, increases the amount of time required to undercut, detach, and remove bank failure blocks (Micheli and Kirchner, 2002), when compared to banks with more xeric plant assemblage, which contributes less cohesion. Micheli and Kirchner observed that 60 % of an actively eroding bank was protected by failed slump blocks.
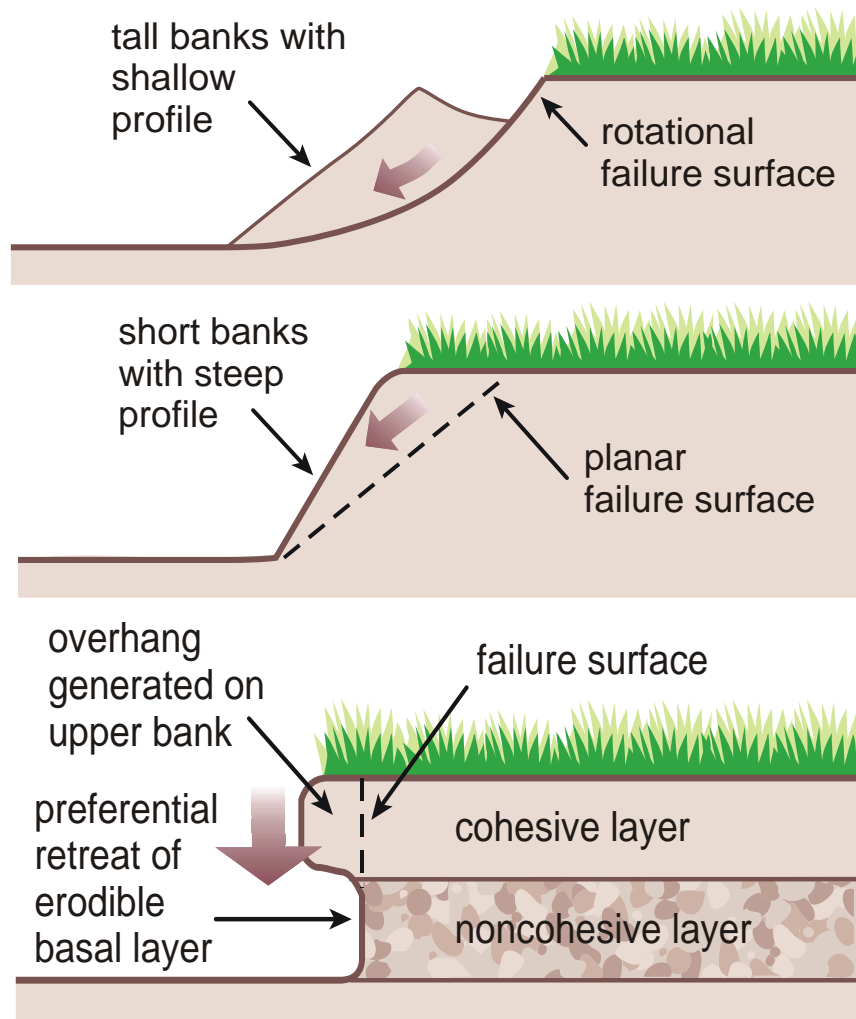
Figure 1.8: Modes of mass failure as depicted by FISRWG 2001, Figure 7-29.

1.4 BANK EROSION, FLOW REGULATION, AND STUDY PERTINENCE

Dams inherently alter components of the natural flow and sediment regime and this change

subsequently impacts channel dynamics. The location of the dam is important because of

sediment dynamics both upstream and downstream of the reservoir, especially since flow

magnitude, sediment supply, and stream competency vary spatially throughout river systems and

over time. Erosion rates are not equal throughout the watershed. They tend to be higher in the

middle reaches where stream power tends to be highest (Abernethy and Rutherfurd, 1998). Local

site characteristics influence the spatial distribution of erosion, including channel gradient, channel planform, bank geometry, and bank composition. Riparian vegetation contributes an additional component of cohesion to the locations of the soil profile containing roots and greatly influences erosion rate and failure mechanism. The uneven distribution of erosion along reach- and system-scales attests to the complexity of erosion. The changes to flow and sediment input have the capacity to affect vegetation and floodplain dynamics, which then affect ecological processes.

Although dams play a large role in stream channel processes, human land use can also be influential. When studying bank erosion it is difficult to isolate causes because most watersheds have experienced a suite of natural and anthropogenic impacts over time. For example, heavy grazing directly affects riparian vegetation from livestock trampling the plants and soil, indirectly impacting the vegetation by allowing shifts in the types of species, and potentially weakening the bank structure because of reduced bank strength. Beaver dams create wide, shallow channels which cause sediment deposition and reduce flood velocities. The streamflow detention encourages groundwater recharge and the viability of mesic floodplain plant species. Removal of beaver can change groundwater and flood hydrology, also potentially causing a shift from mesic to xeric plants. Logging can indirectly impact streams by increasing hillslope runoff and causing excessive erosion, while also directly scouring channels when used as a conduit to move logs downstream to the mill.

Channel responses to land use activities and natural climatic disturbances are compounding and difficult to predict or interpret due to geomorphic thresholds, lag times, and complex responses. Differences in bank geometry and geotechnical properties along a river introduce reach- and basin-scale spatial variability in bank stability, while temporal and spatial variations in bank stability at individual sites are also present (Knighton, 1973; Hooke, 1979; Lawler, 1992). The

presence of multiple potential drivers of water and sediment yield, combined with natural channel

variability, can make it very difficult to conclusively demonstrate that observed changes in

channel dynamics are greater than those in reference systems or are primarily attributable to flow

regulation. This study attempts to discern the interacting effects of land use and dam operations

on channel dynamics in Hog Park Creek. Spatial and temporal changes in channel morphology

are measured at multiple sites from a sequence of aerial photographs over a 29-year period prior

to dam installation in 1965 and over a 35-year period following operation of the dam. Changes

associated with the dam are also examined in relation to distance downstream of the dam and are

compared to an adjacent reference stream with similar climate, geomorphic, and land use

attributes.

1.5   OBJECTIVES

This research is designed to study the effects of dam operations and land use on flow hydrology

and sediment processes, channel dynamics and morphology, and channel bank stability

downstream of a reservoir. The primary goals of this project are to determine the location and

mechanisms of channel change, and to investigate potential correlations between observed

channel changes and current dam operations and previous land use.

Hypotheses are set up to test whether (i) there is a detectable change in channel geometry and

dynamics between pre- and post-dam periods, (ii) detected channel change can be attributed to

dam operations, and (iii) the mechanisms driving channel change can be identified. Bank stability

and geomorphic stability are assessed through multiple means, including aerial photographic

analyses, field data collection, and statistical analyses. This study has four primary objectives:

1) Determine changes in flow regime characteristics (e.g., timing, duration and magnitude of

peak discharge; base flow discharge and duration; rise and fall rates of hydrograph) following

regulation. I will identify the contemporary dam hydrologic regime characteristics and compare

them to pre-dam conditions to determine whether there is a significant difference following regulation.

2) Document historical and contemporary characteristics of channel planform and morphology using a series of historical photographs. Planform characteristics of Hog Park Creek will be compared to an unregulated reference reach, South Fork Hog Park Creek, and observed changes will be related to characteristics of the flow regime, sediment supply, and land use through time.

3) Determine the primary bank erosion mechanisms driving the observed bank erosion using a bank stability model. Erosion predicted by the bank stability model will be calibrated using direct field measurements of bank erosion and channel geometry.

4) Predict potential bank erosion during different reservoir operation flow scenarios using the calibrated bank erosion model. For example, the calibrated model can be used to examine which hydrologic parameters bank erosion is more sensitive to.

1.6 HYPOTHESES

1.6.1 HYPOTHESIS 1

(Ho(1)): Dam operations have not significantly altered flow regime characteristics when compared to an unregulated time period.

Five alternate hypotheses examine whether specific components of the flow regime have changed; these are magnitude and duration (H1A1), timing (H1A2), duration and frequency (H1A3), frequency (H1A4), and flashiness (H1A5). These five components are as described in Table 3.4 of the results section.

The current flow regime will be examined to determine whether and how it varies from conditions prior to dam installation. Multiple tools and indices currently exist to describe hydrologic characteristics and temporal alteration. In this study, I use a small subset of the

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available tools, including flood frequency analyses and the Index of Hydrologic Alteration (IHA).

IHA generates indicators of hydraulic alteration associated with activities such as dam operations

using sixty-four metrics that are assessed by comparing measures of central tendency and

dispersion between pre-impact and post-impact time frames (Richter et al., 1996).

1.6.2   HYPOTHESES 2-4

Each of the following null hypotheses proposes that a specific channel form parameter has not

changed as a result of flow regulation. Each associated alternate hypothesis proposes that this

parameter has changed.

($H_{o(2)}$): No detectable temporal changes in channel mean width have occurred since installation
or changes to the dam.

 ($H_{o(3)}$): No detectable temporal changes in lateral migration rates have occurred since installation
or changes to the dam.

($H_{o(4)}$): No detectable temporal changes in channel complexity have occurred since installation or
changes to the dam.

The rate of channel change through time will be analyzed using aerial photographs and by (i)

determining the range of average values of various channel characteristics on a decadal time

scale, (ii) assessing deviations from these values during specified time intervals, (iii) comparing

deviations during the pre-dam flow regulation to post-regulation, and (iv) testing whether there is

a significant difference between values prior to regulation, following initial dam installation

(Stage 1), and post-dam enlargement (Stage 2).

Trends in channel adjustment will be statistically compared with historical rates obtained using

ortho-rectified aerial photographs in GIS. With aerial photo analysis I will quantitatively assess

the spatial and temporal changes of physical attributes; spatially as a function of proximity to the

dam and geologic controls and temporally in reference to land-use patterns, decadal precipitation

trends, and pre- and post- dam time frames.

1.6.3 HYPOTHESES 5-7

Each of the following null hypotheses proposes that a specific parameter does not significantly affect bank erosion rates. Each associated alternate hypothesis proposes that this parameter is a significant control.

$(H_{o(5)})$: Bank erosion rates, as simulated by the Bank Stability and Toe Erosion Model (BSTEM), are not significantly elevated under the current hydrologic regime.

$(H_{o(6)})$: Bank erosion rates are not correlated to inter-reach characteristics.

$(H_{o(7)})$: Bank erosion rates are not correlated to intra-reach characteristics.

Bank erosion will be assessed at varying spatial scales along the reaches, as well as varying temporal scales, from annual cross section surveys and erosion pins (fine scale) to aerial photographic analysis (coarse scale). Segments of the streams are delineated into reaches using confluences with major channels, relative degrees of confinement and channel slope. Inter-reach characteristics such as hydrology (relative levels of regulation) and land-use are tested for significant relations with erosion amounts between reaches. Intra-reach characteristics including near-bank hydraulic characteristics, location within the channel and bank morphologic characteristics are tested for significant relations at a site.

Fine-scale bank stability will be assessed using multiple methods, expanding on the data the USDA Forest Service (USFS) began collecting in 2004. Repeat cross section and erosion pin surveys over several years provide an indication of current bank retreat and bed incision and are compared with long-term trends observed in aerial photographs. The Bank Stability and Toe Erosion Model (BSTEM version 5.2)(Simon et. al., 2000) is used to determine bank stability and failure mechanisms at different stages, with consideration of multiple soil compositional layers, varying flow characteristics, vegetation types, and locations in the channel at a representative

cross section in site 2. As the model of bank erosion is compared to an annual hydrograph,

specific components of the flow regime are indicated as major drivers of erosion.

2   WATERSHED DESCRIPTION

Hog Park Creek is located in the Medicine Bow National Forest in southeastern Wyoming, and

within the Southern Rockies ecoroegion (Omernik and Gallant, 1987) (Figure 2.1). The creek

flows into the Encampment River, a tributary to the North Platte River. The watershed comprises

76 km2, with the major tributary South Fork Hog Park Creek contributing 32 km2. At the

location of the dam, Hog Park Creek similarly drains 32 km2. The catchment lies roughly at

2,545 m elevation, and the headwaters of Hog Park Creek constitute the Continental Divide. The

watershed experiences a high alpine climate characterized by cold winters and mild summers.

Precipitation averages 100 cm annually, with the majority falling as snow. Thunderstorms occur

mid-summer but have a minimal effect on the hydrograph. The hydrograph peak results from

snowmelt in early to mid June. Resistant crystalline rocks dominate the geology of the basin, and

the area is underlain by intrusive and metamorphic rock types (Mast et. al., 1999), specifically by

Precambrian granitic rocks (Lowry et al., 1973; USGS, 1985).

The Encampment River watershed and Hog Park watershed were glaciated in the Pleistocene,

which is reflected in the broad valleys and scoured peaks of both watersheds. The Encampment

River and Hog Park Creek transported considerable quantities of water and sediment from their

respective watersheds during this period (Atwood, 1937).

The study reaches are sinuous, pool-riffle sequences composed of cobbles, gravels and sands. The

relatively low gradient reaches are located in wide valley bottoms that allow the streams to

migrate laterally, whereas the steeper reaches are located in narrow valleys underlain by bedrock

that limits channel migration. Abandoned channels and small floodplain pools adjacent to Hog

Park and South Fork Hog Park contain streamflow during higher discharges.
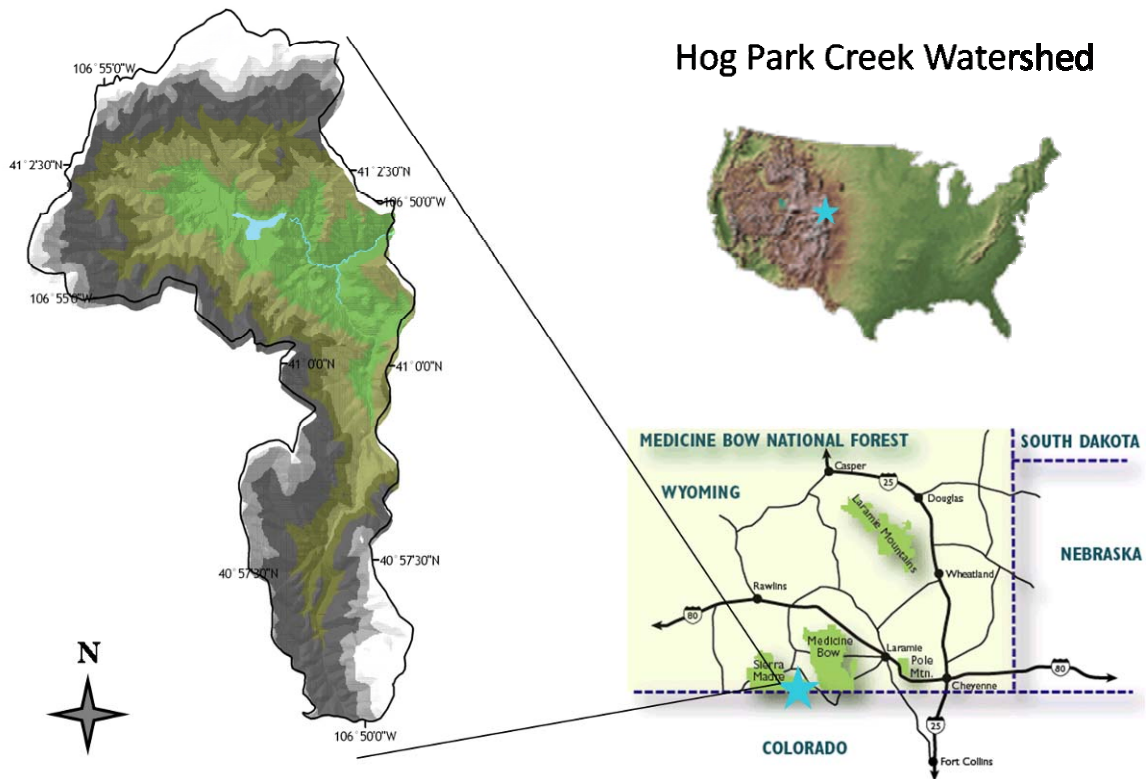
Figure 2.1: Geographical location of the Hog Park Creek watershed.

Vegetation communities include steppe, open woodland, coniferous forest, and alpine meadow

plant types. Montane and subalpine forest types, including spruce and subalpine fir, lodgepole

pine, and minor amounts of aspen, cover much of the area. Vegetation of the alpine meadows and

valleys includes grasses, sedges, forbs, wildflowers, and small shrubs, including willow, but

lacking riparian trees. It remains uncertain whether trees initially existed in these high alpine

meadows, or parks, prior to intensive grazing in the early 1900's. Kendall Johnson retraced the

route of William Henry Jackson, a landscape photographer who had accompanied an 1870

expedition across southern Wyoming prior to the cattle boom (Johnson, 1987). Johnson was able

to locate and re-photograph fifty-six scenes approximately 100 years later. He found that

vegetation had been affected since the initial photos, but subalpine meadows did not have

abundant riparian tree species. Thybony et al. (2001) propose that aspects of the soil prevent the

success of tree species in mountain meadows and allow for the riparian domination of willow and

sedges. Johnson's book also illustrates that river bottoms have changed dramatically due to

impoundments, irrigation, cultivation, livestock grazing, and settlements

Historical land use in the Hog Park Creek watershed and the adjacent watersheds have included

beaver trapping, logging (including tie driving), and grazing of sheep and cattle. A Wyoming

Department of Environmental Quality/Water Quality Division (2002) report states that 'It was

reported by the USFS that bank de-stabilization as a result of intensive grazing in the

riparian/upland areas and gravel mining in the watershed were responsible for the large sediment

load in SFHP [South Fork Hog Park] Creek'. The report further states that tree revetments were

placed in Hog Park Creek and SFHP Creek in the 1980's and 1990's to stabilize the banks and

'help the stream restore a more natural shape and to improve the fishery'. Current land uses in

the Hog Park Basin include logging operations, primarily at lower elevations, cattle grazing, and

recreational use.

2.1   HISTORICAL AND CURRENT LAND USE

Wendy Haas, Rangeland Management Specialist for the Medicine Bow National Forest, provided

a robust historical account of land use in the Hog Park watershed and the Medicine Bow National

Forest. Much of the historical information provided in this chapter comes from the work of Haas

(1979). Land use of what is now the Medicine Bow National Forest began in the mid-1800's and

remained unregulated until 1906 when the national forest was established. Initially, beaver pelts

led many 'mountain men' to the Hog Park Creek area. As emigrants traveled westward in the

1860's, sheep and cattle followed, causing watershed, channel and riparian degradation. Later, logging, mining and ranching exploited those resources. Fire prevention also began in the early 1900's with the earliest forest rangers overseeing the new national forest lands. The dam for Hog Park Reservoir was initially constructed in 1965 and later enlarged in 1985. Following the initial dam installation, stream enhancement in the form of wood pieces and large rock were placed throughout Hog Park Creek. These structures are discussed in the current land use section of this chapter. Currently, the main land uses in the Hog Park Creek basin are recreation, flow augmentation, timber removal and minimal grazing.

2.1.1 BEAVER TRAPPING

Historic accounts indicate that beaver activity was likely high in the Hog Park Creek area. The history of beaver trapping and resource extraction in the region of Hog Park and the Medicine Bow Mountains is summarized by Scott Thybony et al. (2001) in the book 'The Medicine Bows: Wyoming's Mountain Country'. As noted in trapper memoirs, the Medicine Bow area was a prized trapping location. The first Euro-Americans may have been in the Medicine Bow area by 1808, when beaver trapping appears to have begun. Trappers were not present in Carbon County until the 1840's, when the trapping era was diminishing. Many trappers came to south-central Wyoming because it had not yet been heavily trapped; they found an abundance of beaver. Trapping during the 1840's through the 1860's was heavy in the Hog Park area. More trapping parties were brought to the area in the 1850's via the Overland Trail. Trapping continued into the 1860's and was supported by the Union Pacific Railroad. The development of the Overland Trail brought in more trapping parties in the 1850's, and the construction of the Union Pacific Railroad increased trapping activities in the 1860's. Many large game hunters also followed the railroad

and Overland Trail to provide meat to emigrants, Overland Trail stations, railroad builders, and tie hackers.

Beaver have been an important landscape-forming feature, influencing riparian landscapes. Their dam building broadens floodplains and reduces channel gradients. Beaver dam construction on small and mid-sized streams causes water to pond over large areas, retain sediment, form meadows, and enhance riparian vegetation development (Ives, 1942; Butler and Malanson 1995, 2005; Gurnell 1998; Westbrook et al., 2006). Although individual dams fail, the dense network of beaver dams serves as a buffer to high spring runoff that would otherwise dismantle individual lodges. The sedimentation allows for broader surface water storage, greatly enhanced bank storage, and leads to sustained stream flow throughout the summer. The ponded water alters water chemistry downstream, which improves conditions for riparian plants (Parker, 1986; Naiman et al., 1988).

When the beaver are removed, the stored sediments may be eroded. The reduction in dams reduces energy dissipation during spring runoff, causing channel incision. Channel incision lowers the water table, which may create a shift from willows and mesic meadow vegetation to more xeric grasslands and shrublands.

Occasional beaver dams are built in Hog Park Creek, but not on the order of the numbers present prior to the mid-1800s. In 1999, rangeland managers on the Brush Creek/Hayden District initiated a 3-year experimental program to increase beaver ponds on South Fork Hog Park (SFHP) Creek, between the State Section and Hog Park Creek (WDEQ, 2001). Three loads of freshly cut aspen trees were unloaded on the banks of SFHP Creek. Beavers built two substantial dams with these materials that autumn. Aspen was again deposited along this reach in 2000-2002, with four dams eventually constructed. By spring 2003 the dams were washed out.

Without the resupply of aspen and larger willows and a network of dams throughout these creeks, successful reestablishment of beavers has proven to be difficult.

2.1.2 TIMBER HARVEST

Knight (1994) provided a detailed account of logging history in Hog Park Creek in his book 'Mountains and Plains: The Ecology of Wyoming Landscapes'. Timber harvest has occurred in the general area of Hog Park Creek from the early 1900's to the present (Knight, 1994). The first major logging operations were established to provide railroad ties for the industrious expansion of the Union Pacific Railroad, which reached Wyoming in 1867. Along the Encampment River, in Commissary Meadows, a large camp of 500 men was established in 1902. The camp consisted of a sawmill plant, company store and lumber camp. By the spring of 1903, the company had 500,000 ties ready to drive to the North Platte River. Logging occurred through the winter months to take advantage of high spring flows for log shipment. Horse teams were used to sled the loaded ties out to tie landings along drivable streams. In the headwaters of smaller channels, splash dams were commonly constructed to impound water near tie landings. These were catastrophically broken, sending a surge of water and logs downstream. Historical accounts indicate that railroad ties were floated or driven down tributaries of the Encampment River between 1910 and 1920 (Young et al., 1994). Frequently used tie-drive streams were periodically cleaned to remove deadfall and large rocks. In some instances, log jams became so severe that people had to dynamite the jams. In the Hog Park watershed, the prime years of logging for the railroad were 1900 to 1906.

The tie drives and associated stream clearing reduced channel complexity and decreased the amount of wood in streams. Historical documentation states that tie drives may have occurred in Hog Park Creek between 1910 and 1924, although the extent and exact location of the tie drives are unknown. It is likely that streams draining to the area now inundated by Hog Park Reservoir

experienced splash damming, but splash damming is unlikely to have occurred in the meadow section of Hog Park Creek below the current dam location since this section lacks the necessary gradient for successful log transport.

The tie camp in the Hog Park Creek area was abandoned in 1912, although logging for the railroad continued until the 1920's in nearby areas. The heyday of logging in the Medicine Bow National Forest was 1925, which combined supplies for the railroad as well as telephone poles. In 1940, tie drives for the railroad were discontinued in the national forest.

Due to the reduction of timber harvest, forests in the Hog Park Creek area began to recover by the mid-1900's. Aerial photographs of Hog Park Creek depict denuded hillsides in 1936 and tree regeneration occurring by 1955. Timber harvest has been minimal in the Encampment River Basin during the period between 1960 and 1990. Limited timber harvest was allowed in these basins during 1990–96; a total of about 620 km2 was harvested during this period. Best management practices, including limiting clear-cut size and tractor logging harvesting, are presently used to minimize impact to forest resources. Prior to the heavy logging, forest fires were noted as common (Dorn, 1986), but both logging and the presence of forest rangers reduced the fire interval once the national forest became established.

2.1.3   GRAZING

Human influences on the Hog Park Creek region prior to the mid-1800's were relatively minor. A substantial impact to the ranges of Wyoming occurred between 1841 and 1868, with the arrival of more than 35,000 emigrants who traveled through the Wyoming territory along the Oregon Trail (Knight, 1994). Along with the wagon trains came thousands of livestock, both sheep and cattle. The railroad tie camps also kept horses and mules for hauling ties and other supplies and for general transportation, so livestock grazing in the high alpine meadows was possibly heavy beginning in the late 1800's.

After the completion of the railroad in 1869, the effects of livestock in Wyoming became even more widespread as the railroad created a larger market for beef, lamb, and wool raised on the rangelands. Sheep herds numbering tens of thousands of animals were not uncommon (Wentworth, 1948). Because no regulations were in place to mitigate resource impacts until government regulation began in the late 1880's, extensive overgrazing occurred even in unsuitable terrain.

The livestock boom ended in 1887, following a crash in the beef market that coincided with the dry summer of 1886 and the devastating winter of 1886-1887, which killed 40-60% of the cattle in Wyoming (Haas, 1979). By 1906, when the Sierra Madre Forest Reserve was officially established, the range condition was extremely poor on most rangelands. Once grazing was brought under the administration of the federal government in the early 1900's, three sheep allotments were established in the Hog Park area, each of which was granted a high number of sheep. Because historic use levels were so high, range condition was very poor for many years on the allotments. Old inspection notes describe accelerated soil erosion in the Hog Park Creek watershed (most of which has since been inundated by Hog Park Reservoir) and on the burned slopes around the park (Haas, 1979).

A 1906 report on the condition of the Reserve in that year stated:

> "The grazing industry of this section is nearly extinct, brought on by overstocking. In fact, with the exception of that portion which is protected by the long period that snow lies on the ground, the short summer season, and the early advent of winter, it may be said that the country is destitute of all forage necessary to support animal life… A comparison of results can be detected along the state line of Colorado and Wyoming. Across the line in Colorado where sheep are not allowed under any circumstances, the forage grasses are luxuriant, knee high all over the open prairies and parks extending far into the forests, but on the Wyoming side, one would think that a cyclone had passed by, leaving nothing but bare land where the continuous winds drive and blow the sand in all directions" (as quoted in Bruce, 1959 from a 1906 report on the state of the Forest Reserve).

From 1949 through 1959, the permitted number of sheep was reduced. In 1962, official sheep grazing ended on the Hog Park Allotment, but some unauthorized use likely occurred in the Hog Park Creek area (Haas, 1979). Construction of Hog Park Reservoir began in 1962, which inundated much of the largest open park; the allotment was therefore left vacant.

In 1978, measures were put in place in the South Fork Hog Park Creek and part of Hog Park Creek area to relieve overstocking by cattle. At that time the permits for Wood Mountain Allotment, which includes the study area (Figure 2.2), included a limited number of animals and a limited grazing season, between July 1 and September 15. Cattle used the portion of Hog Park Creek below the dam, in addition to reaches 2, 3, and 4 that are within the Wood Mountain Allotment. A fence completed in 1989 curtailed livestock movement into the portion of Hog Park Creek below the dam (reach 1). Forage utilization and bank trampling have mostly been light and intermittent along that reach since 1989. Along the sections of Hog Park Creek and South Fork Hog Park Creek that have continually experienced grazing (reaches 2, 3, and 4), livestock use has mostly been moderate since 1982, although there have been some years with higher use levels.

Figure 2.2: Depiction of current grazing allotments in Hog Park Creek. Note that reaches 2, 3 and 4 of this study are in a current allotment, while reach 1 is excluded. Image courtesy of W. Haas, Rangeland Management Specialist, Medicine Bow National Forest.

2.1.4   RESERVOIR CONSTRUCTION AND FLOW AUGMENTATION

The construction of Hog Park Dam occurred between 1963 and 1965. A diversion was built in 1964, Stage 1, to pipe water from multiple tributaries of the North Fork of the Little Snake River on the west side of the Continental Divide (125 collection structures in several tributaries) to Hog Park Reservoir on the east, running 1,067 m (3,500 ft). Because of increasing water demands for the City of Cheyenne, enlargement of Hog Park Reservoir began in 1983 and was completed in 1985 (Stage 2). The impoundment was raised from 21 to 36 m, with a water storage increase from 3.7 million m3 to 27.9 million m3. The estimated water yield in Hog Park Reservoir at 100% snow pack is 25.9 million m3 (21,000 ac-ft) annually (City of Cheyenne Board of Public Utilities, unpublished report, 2007).

2.1.5 CHANNEL STABILIZATION

In an apparent response to what was perceived as increased erosion rates throughout Hog Park Creek below the dam, boulder and log structures were constructed in the early-mid 1980's at various locations along reach 1 and reach 3 to stabilize channel banks and improve aquatic habitat (Figure 2.3). The placement of many of these structures have actually increased bank erosion and widened the channel as flows are directed toward the banks. Little documentation exists, however, of channel characteristics prior to the installation of the structures and the design specifications of the structures. Although these structures have locally influenced channel morphology, these changes are not readily apparent on aerial photographs or quantified in the planform analysis of channel change.

Figure 2.3: Photos taken in 2008 of instream structures placed throughout Hog Park Creek in the 1970's. The picture is taken adjacent to and just upstream of Site 3.

2.2   PRIOR DATA COLLECTION

Hog Park Dam will undergo a re-authorization of the permit to operate a water storage facility on the national forest in 2011. As part of this process, the USFS began monitoring channel form in Hog Park Creek in 2004, installing 11 cross sections and six photo point monitoring sites, and collecting stream bed particle distribution data in seven locations. This monitoring was continued in 2005 with the exception of the pebble counts. In 2006, 37 additional cross sections were installed and surveyed (Table 2.1) and 90 erosion pins were placed in banks with slopes greater than 20 degrees in the cross sections. The USFS began field studies in 2004 by establishing cross sections in four sites in Hog Park Creek below Hog Park Dam (Figure 2.4 and Figure 2.5). For clarity, the length of channel containing adjacent cross sections is a site, while greater lengths of channel have been designated reaches. The reaches are segmented by either bedrock canyon or stream confluences and contain sites (the four sites are located within four reaches) Four study reaches currently exist in the area. Site 1 is 900 m downstream of the dam in reach 1; site 2 is in reach 2 and located downstream of a relatively confined section of channel; site 4 is a control site in reach 4 in South Fork Hog Park Creek; and site 3 is in reach 3 situated between the confluence of Hog Park Creek with South Fork Hog Park Creek, and the confluence of Hog Park Creek with the Encampment River (Table 2.2 and Figure 2.6 through Figure 2.9). Hog Park Creek runs a total of 6.1 km from the site of the dam to the confluence with the Encampment River.

Table 2.1: Previous data collection in Hog Park Creek by the US Forest Service (Purchase, 2007)

Monitoring Site	Cross Sections				Pebble Counts		Bank Erosion Pins	
	2004	2005	2006	2007	2004	2005	2006	2007
Site 1	3	3	12	12	2	6	13	15
Site 2	3	3	14	14	2	6	27	26
Site 3	2	2	12	12	1	8	31	33
Site 4	3	3	10	10	2	6	19	23
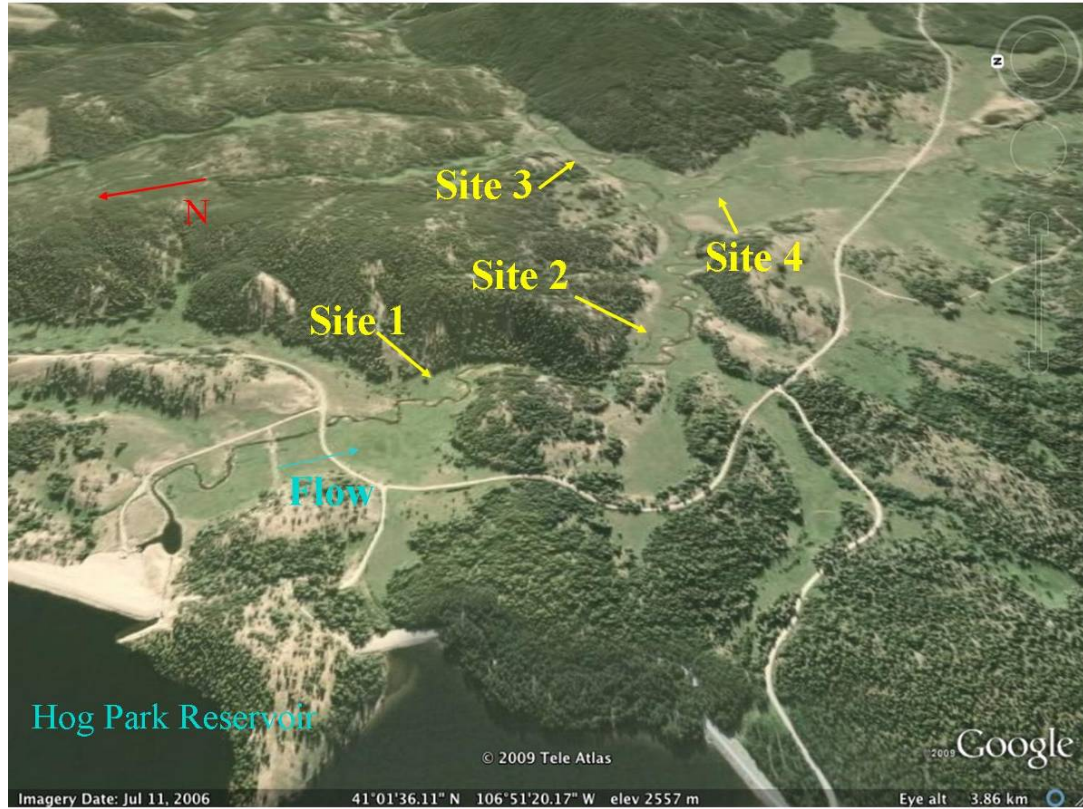
Figure 2.4: Overview of Hog Park Creek and the four study sites. Photo courtesy of Google Earth, no scale available, but sites 1 and 2 are approximately 0.4 km apart.

Table 2.2. Charateristics of Monitoring Sites

	Gradient[2]	Length (m)[1]	Average Channel Width[1] (m)	Average Channel Depth[2] (m)	Average Sinuosity[1]	Bed Material (D$_{50}$ mm)[2]
Reach 1	.005	90	10	.40	1.5	34
Reach 2	.004	190	13	.46	1.6	30
Reach 3	.002	160	15	.55	1.3	20
Reach 4	.006	140	9	0.3	1.6	39

1- **Values determined in GIS**

2- **Determined from on-site measurements (channel depth during low flow)**

South Fork Hog Park Creek is a naturally flowing system (unregulated), which flows into Hog

Park Creek approximately 1.6 km upstream of the confluence with the Encampment River. South

Fork Hog Park Creek was chosen as a reference reach because the geology, vegetation, elevation,

gradient, and land-use activities are similar to those of Hog Park Creek.

Two Global Water Model WL16 pressure transducers were installed at site 2 and site 3 along Hog

Park Creek in October of 2007, to quantify flow stage at 15-minute intervals (Figure 2.5). A

crest-stage gauge was installed at site 1 just below Hog Park Dam and at site 4 along South Fork

Hog Park Creek. Daily mean discharge release data from the dam outlet since 1970 were obtained

from the Cheyenne Board of Public Utilities.
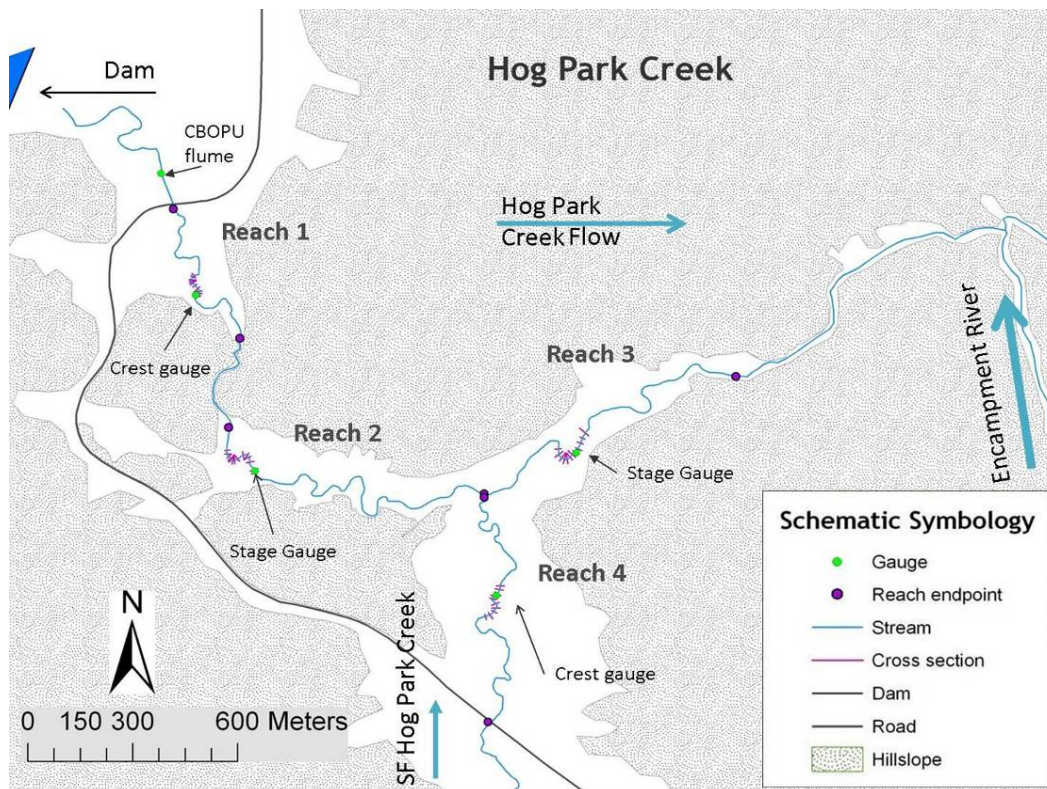
Figure 2.5: Schematic of the area of study, indicating locations of crest gauges (reaches 1 and 4) and stage gauges (reaches 2 and 3). The cross sections delineate individual sites within each reach.

Figure 2.6: Photo of Site 1, mainstem Hog Park Creek. The photo is looking upstream at Hog Park Dam.

Figure 2.7: Photo of Site 2, main stem Hog Park Creek. The photo is looking downstream from the top of the Site.

Figure 2.8: Photo of Site 3, main stem Hog Park Creek. The photo is looking downstream from the top of the Site (D. Cenderelli, 2006).

Figure 2.9: Photo of Site 4, South Fork Hog Park Creek. The photo is taken looking upstream from the bottom of the Site.

3   METHODS

In order to assess channel response to altered flow and sediment discharge, I used multiple analyses across a range of spatial and temporal scales: repeat surveys of channel cross sections and longitudinal profiles over multiple years; analyses of ecologically-based hydrologic parameters prior to and following flow regulation; multi-decadal planform change as recorded in aerial photographs; and detailed bank analysis and erosion modeling with a bank stability and erosion model.

3.1   FIELD METHODS

The USFS began field studies in 2004 by establishing cross sections at three sites along Hog Park Creek below Hog Park Dam and one site along South Fork Hog Park Creek, a tributary to Hog Park Creek not affected by regulation. For clarity, the length of channel containing adjacent cross sections is a site, while lengths of channel segmented by either bedrock canyon or stream confluences, and containing sites, are called reaches throughout this report (the four sites are located within four reaches) (Figure 2.5).The cross sections were established in 2005, and additional cross sections and bank erosion pins were placed in 2006. Cross sections and bank pins were surveyed again in 2007, 2008 and 2009. To support detailed bank composition and erosion analyses, additional bank composition, bank stratigraphy, and mass wasting and fluvial erosion data were gathered in 2008.

3.1.1   CROSS SECTION AND LONGITUDINAL PROFILE SURVEYS

The resurvey of established cross sections was done using a Topcon GTS 212 total station in 2008 and 2009 (Table 3.1). The cross sections, originally placed in 2004 and 2006, are identified by rebar pins on both the right and left margins of the floodplain or terrace (Figure 3.1). The total station location is benchmarked by a cemented rebar pin. A tape was strung from left bank to right bank, with most cross sections extending 5 meters or more onto the floodplain. A range of 20 to 40 survey points were taken at each cross section, indicating surface gradient changes, shifts in dominant substrate composition, erosion pin locations, vegetation shifts, the top and bottom of the bank and bank toe, the left bank and right bank wetted edge perimeter, thalweg, and the top and bottom of the benchmarked cross section endpoint pins. In this study, bankfull flow was identified by obvious topographic indicators adjacent to the channel; specifically, a topographic break in the bank from vertical or nearly vertical bank walls to a horizontal floodplain. Bankfull flow in this study represents the point at which flow spills over onto the floodplain.

Hog Park Creek Site 1

Legend
- Gauge
- Cross section

0 25 50 100 Meters

Hog Park Creek Site 2

0 25 50 100 Meters
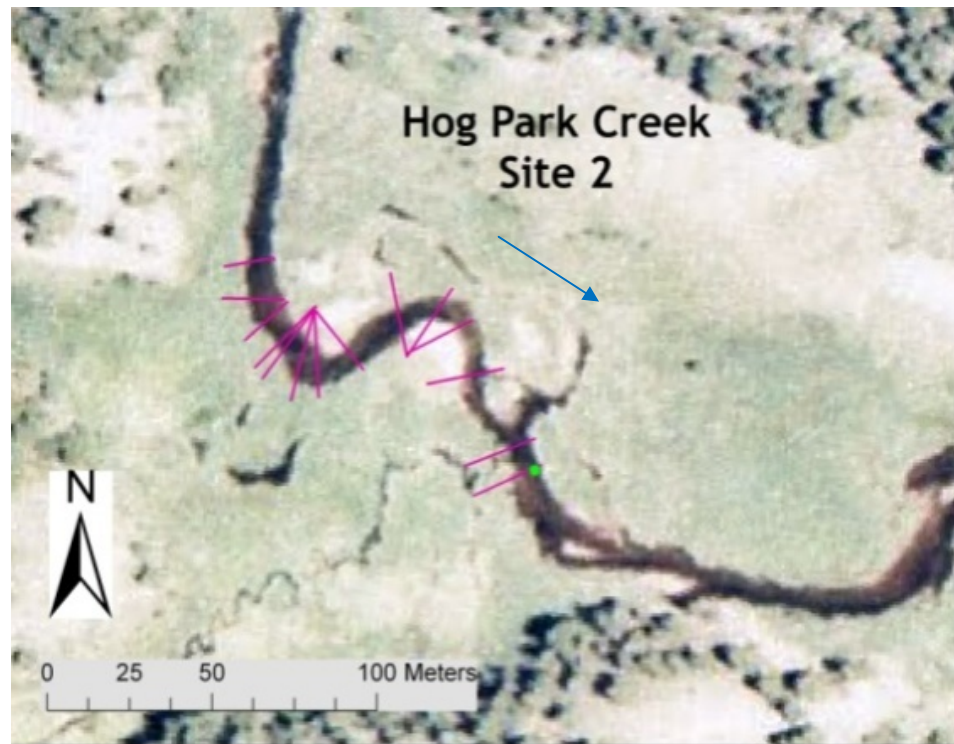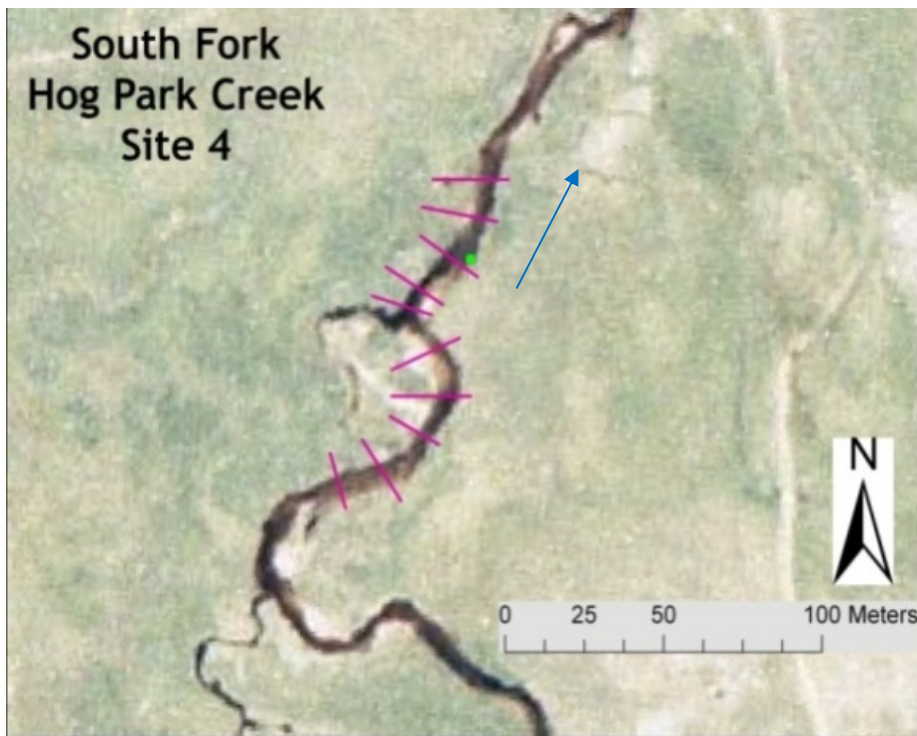
Figure 3.1: Site and cross section characteristics for sites 1-4. Direction of flow is indicated by the blue arrows. Green dots indicate the location of a pressure transducer (Site 2, 3) or crest gauge (Site 1 - 4).

Table 3.1: Data collection in each reach during 2008

Monitoring Site	Cross Sections 2008	Bank Erosion Pins 2008	Pebble Counts 2008	Velocity Profiles 2008	Discharge Measurements 2008	Gauge Type
Site 1	12	13	2	16	2	Crest
Site 2	14	27	2	31	2	Pressure Transducer
Site 3	12	31	2	23	2	Pressure Transducer
Site 4	10	19	2	24	2	Crest

Longitudinal profiles documenting channel bed and water surface slope along the established sites in Hog Park Creek and South Fork Hog Park Creek were surveyed, as well as outlining projections and concavities of the top bank along erosional zones in each site.

3.1.2   VELOCITY AND DISCHARGE DATA COLLECTION

Two Global Water Model WL16 pressure transducers installed in October 2007 provide stage data in reach 2 and reach 3, with reach 4 data resulting from the difference calculated between these two records. Reach 1 data are provided by the Cheyenne Board of Public Utilities (CBOPU) from a flume located downstream of the dam and 100 m upstream of reach 1. The dataloggers record both water stage and temperature every 0.5 hour. Both dataloggers were placed in the lower sections of the study site. A crest gauge was installed in site 1 just below Hog Park Dam and another at site 4 in South Fork Hog Park Creek to record annual high discharge. These consist of a PVC pipe fitted with a wooden stick and placed in the channel with cork shavings placed inside. The shavings adhere to the spool, which is demarcated with height measurements (in), and record the highest stage experienced at that site.

A Marsh-McBirney Flow Mate, which considers only one-dimensional velocities, was used to collect an average velocity measured over 20 seconds. Velocity (m/s) was recorded at 5 m increments longitudinally in each site (as measured from a tape strung along the right bank) at a location approximately 0.5 m perpendicular from the right bank, providing near-bank velocities relating to bank erosion. This method allowed for the collection of data during high flows that reduced access to the channel. In relatively shallow locations, the distance from the bank was increased to 1.0 or 1.5 m to ensure location replicability during lower flows. The locations were flagged, with specific notes to ensure replication of placement during subsequent field efforts. At each velocity profile location, velocities were collected in 20% increments in the vertical profile, with at least five measurements for each profile. The first measurement was recorded at a depth of 3 cm (the closest proximity to the bed feasible with the flow meter), then four more measurements at 20, 40, 60, and 80 percent of the flow depth, respectively. In the cross section profiles, another measurement was recorded within 3 cm of the water surface (the highest point which provided a consistent reading).

For each profile, absolute heights were standardized by converting them into a fractional height relative to the total depth of the water column. I then determined the relative heights of maximum velocity in each profile and the average velocity, using an equally-weighted average of all the point measurements. Other observations at the profile site include water depth (thalweg), wetted width, a substrate classification composed of four categories identifying the dominant and subdominant particles at the base of the toe and determined visually (sand/gravel, gravel/sand, gravel/cobble, cobble/gravel), the presence/absence of an eddy current or a partial eddy current (flow dissipation where flow is still irregular but only negative at some of the depths), meander location (inside, outside, straight) and whether there was a noticeable obstruction to the flow, such as a slump block or large rock.

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Velocity profile data were collected in each of the three regulated study reaches and the reference reach on South Fork Hog Park Creek. The sampling method was repeated both at high and low flow stages. The high flows were captured during spring snowmelt (as soon as access was feasible) and low flows were captured in late summer and autumn. Discharges were calculated adjacent to the two established pressure transducer locations (site 2 and site 3), the two crest gauge locations (site 1 and site 4), and at the flume at the outlet of Hog Park Reservoir (upstream of site 1), at least twice during the field season at a high and low flow (Table 3.1).

3.1.3 EROSION PIN MONITORING

Ninety erosion pins were established in 2006 by USFS personnel in each of the four study sites. Rebar pins (0.8 m length) were placed at points one-third and two-thirds of the bank height in the cross section line of banks with slopes greater than 20 degrees (Figure 3.2). The pins were driven perpendicular into the bank until protruding approximately 1- 2 cm from the bank. Erosion pins were installed in banks experiencing active erosion and displaying no evidence of erosion in 2006. These were measured, surveyed, and reset following high flows in 2007, 2008 and 2009. Each pin was measured on the downstream side of the pin from the end of the pin to the point where it intersects the bank. Both the distance below the top of the bank and the extent of undercut were recorded. Erosion rates were derived from sequential cross section surveys, but the extent of bank erosion may not be captured at undercut banks. Erosion pins and undercut profiles are assumed to provide a more accurate measurement of the annual extent of erosion.

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Figure 3.2: Example of the placement of two erosion pins in a vertical bank. The bank is located in a meander bend in Site 4, pins are indicated by orange flagging.

3.1.4   BANK COMPOSITION SURVEYS

To quantify the type and extent of erosion and intra-site bank compositional changes within the sites, an extensive bank survey was undertaken in 2008 to document percentage of banks failing, mode of failure, and current bank characteristics. A bank failure classification at each site was delineated by geomorphic process as fluvial erosion, mass wasting, or depositional. Banks eroded by fluvial action were visually indentified by undercutting at the toe and an overhanging upper bank, whereas banks experiencing mass wasting were expressed as vertical banks with exposed soil and roots, and tension cracks at the surface. A representative location within each section of mode of failure was used to collect detailed undercut profile measurements. At these locations the bank height was measured from top of the bank to the base of the toe. Soil layer transitions were identified based on the depth from the top of the bank. The depth of 95% of the root mass from the top of the bank was also identified. To determine the geometry and depth of

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undercut banks, a five-point undercut profile was measured. Water surface elevation, bank top

elevation, bank angle, toe angle, tension crack lengths (if present), and vegetation at the top of the

bank, and adjacent channel bed substrate size were noted as well. Soil samples for each unique

layer in a site were collected and dry sieved in the laboratory to determine grain-size

distributions.

The Wolman (1954) pebble count procedure, using the step-toe method, was used at multiple

locations in each site to sample the gravel-bed surface and quantify the grain size-distribution

(Wolman, 1954).

3.2   HYPOTHESIS 1: HYDROLOGIC ANALYSIS METHODS

Discharge data at the reservoir outlet, USGS gauge data, discharge-stage relations and regional

regression equations are used to characterize flow regime characteristics under regulated

conditions and pre-flow regulation conditions. Records of mean daily discharge released from

the Hog Park Dam are available from 1970 to present. Handwritten records from 1970 to 2007

were entered into an Excel spreadsheet by the USFS. The City of Cheyenne automated records

are available to present. An anomalous event occurred on August 9th, 1973, recorded as "…36"

valve opened, losing 1472 acre feet over two week period." This event of 1472 acre-feet (21

m3/s) is assumed to have occurred over the previous two-week period, not a single day, with the

valve then closed on August 10th, returning flows to 10 acre feet/day. The value of 1472 is

considered anomalous and is edited as 95 acre-feet (1.3 m3/s) on August 9th. A similar event is

recorded on January 24th, 1970. During this event the flow below Hog Park increased from 10

acre feet/ day (0.14 m3/s) on the 23rd to 30 acre feet/ day (0.43 m3/s) on the 24th, and then

declined back to 10 acre feet/ day on the 25th. These are the only two anomalous records in the

log provided by the City of Cheyenne. Other errors such as illegible records are interpolated in

IHA and long spans of missing data are excluded from analysis.

3.2.1   FREQUENCY ANALYSES

In the absence of gauge data, common methodologies to obtain estimates of flow frequency and

magnitude include the use of time series data from gauged rivers outside of the basin but

consisting of similar basin characteristics (climate, geology, topography, elevation, size); or from

the use of regression formulae (Ries and Crouse, 2002). Three procedures of frequency analysis

are described in this section and results are presented in Section 4.1.1. A recurrence interval

analysis is used to provide a first indication of hydrographic changes due to regulation by

comparing calculated discharges of various recurrence intervals with data representing the three

flow eras. Recurrence intervals for Stage 1 and the current Stage 2 operations are calculated

using a Log-Pearson Type III analysis. These results are compared with unregulated recurrence

intervals derived from regional regression equations using empirical calculations. In support,

frequency and duration of the regulated flow eras are compared using a flow duration curve

analytical procedure.

The Log-Pearson Type III distribution is a statistical technique for fitting frequency distribution

data to predict and interpret flow magnitudes and is presented by the USGS Water Resources

Committee Bulletin 17B (1982). This method provides the estimated average time interval within

which a flood of a given size will occur as an annual maximum. A frequency distribution is

constructed from the computed data, producing the probabilities of various discharges. The

advantage of using the Log Pearson methodology to construct a frequency distribution curve is

the ability to extrapolate return events beyond the extent of gauge records. The available data set

spans over 20 years, which is appropriate to extrapolate to a frequency of a 100 year event. The

use of mean daily discharge values is employed for all gauges in the Log-Pearson Type III

calculations. The resultant estimates of peak discharge values may be underestimated if

instantaneous peak values are employed. Mean daily values are the highest frequency of data

available for the CBOPU flume data and were used in all calculations for consistency. This

application of the Log-Pearson Type III violates the stipulation that no regulation nor

augmentation exist and these analyses must be used as general trend analyses and do not

represent actual frequencies of Hog Park Creek currently or historically. Additionally, the

underestimation of peak discharges as a result of using daily mean discharge instead of

instantaneous discharge measurements results in inaccurate predictions. These peak discharge

results do have large inherent errors and most likely underestimate flood flows. These analyses

are intended to provide insight for trends and magnitudes of change, whereas reliance on

quantitative results should be avoided, especially as larger magnitude flood discharges are

predicted.

The peak record data were first checked for outliers and anomalies. A low flow record in 1984

was removed from analysis. This was during the period of construction for the dam enlargement

and likely resulted from non-natural influence. No high flow outliers were discovered. The Log-

Pearson Type III distribution is calculated using the equation:

$$\log x = \overline{\log x} + k\sigma$$

(3.1)

where x is the flood discharge value of a specified probability, logx is the average of the logx

discharge values, K is a frequency factor, and σ is the standard deviation of the logx values. The

frequency factor K is a function of the skewness coefficient and return period. The flood

magnitudes for the various return periods are found by solving equation (3.1). The mean,

variance, and standard deviation are calculated and then used to calculate the skewness

coefficient Cs as:

$$Cs = \frac{n\Sigma(\log x - \overline{\log x})^3}{(n-1)(n-2)(\sigma_{\log x})^3}$$

(3.2)

where n is the number of entries, x the flood of some specified probability and σlogx is the

standard deviation. The skewness estimate (Cs), computed using the equation above,

incorporates data only from the gauging station of interest. Error and bias in the skewness

estimate increase as the number of observations (n) decreases. A generalized estimate of the

coefficient of skewness, Cw (for instantaneous peak flow data only), is based on the skewness of

sample data and regional skewness and is calculated by:

$C_w = WC_s + (1-W)C_m$

(3.3)

where W is a weighting factor, Cs is the coefficient of skewness computed using the sample data,

and Cm is a regional skewness factor. The coefficient K is then found using tabulated values

according to Cw and the return period for each discharge (USWRC, 1982).

Regionalized regression techniques are a method of developing hydrologic characteristics for

ungauged basins (Watson et al., 1997) and are used in this study to describe pre-dam flow

frequencies. Peak-flow characteristics for unregulated streams in Wyoming are described by

Miller (2003). His analysis resulted in the creation of frequency relations for annual peak flows

through water year 2000 at 364 stream gauging stations in and near Wyoming.

 The physical and climatic characteristics of the various basins were used in multiple correlation

and those with similar peak-flow and basin characteristics were grouped into six hydrologic

regions, reducing the standard error of the estimates. Dominant physical characteristics were used

to develop equations for the discharges associated with each quantile of recurrence interval, 1, 2,

2.33, 5, 10, 25 and 50 years. The equations developed for Hydrologic Region 1, encompassing

Hog Park and Battle Creeks, are listed in Table 3.2. Miller (2003) employed instantaneous peak

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discharge values in the derivation of regression equations and mean daily discharges are employed in the Hog Park Creek analysis. As a result, peak discharge values are underestimated and should be used with caution. The weakness with regional regression equations in general lies in the fact that they are purely empirical and assume that future hydrology will be similar to past. However, regional regression equations have been shown to be most reliable in snowmelt-dominated hydrology as an estimate of high frequency, low magnitude events (Doyle et al., 2005). These flows are important to understand because of the great geomorphic influence in a river system (Dunne and Leopold 1978).

Table 3.2: Equations for estimating peak flow characteristics, Rocky Mountains, Wyoming (Miller, 2003).

EQUATIONS	SE$_P$ (percent)
$Q_{1.2} = 0.126(AREA^{0.893})((\frac{ELEV-3,000}{1,000})^{2.36})((LNG - 100)^{0.082})$	56
$Q_2 = 0.313(AREA^{0.866})((\frac{ELEV-3,000}{1,000})^{2.32})((LNG - 100)^{-0.066})$	50
$Q_{2.33} = 0.458(AREA^{0.858})((\frac{ELEV-3,000}{1,000})^{2.22})((LNG - 100)^{-0.110})$	47
$Q_5 = 1.89(AREA^{0.828})((\frac{ELEV-3,000}{1,000})^{1.83})((LNG - 100)^{-0.262})$	39
$Q_{10} = 4.71(AREA^{0.810})((\frac{ELEV-3,000}{1,000})^{1.6})((LNG - 100)^{-0.357})$	36
$Q_{25} = 12.1(AREA^{0.790})((\frac{ELEV-3,000}{1,000})^{1.34})((LNG - 100)^{-0.431})$	35
$Q_{50} = 22.3(AREA^{0.778})((\frac{ELEV-3,000}{1,000})^{1.16})((LNG - 100)^{-0.310})$	36

Q$_T$, estimated peak flow in cubic feet per second for recurrence interval of T years, AREA, total drainage area in square miles, ELEV, mean basin elevation in feet, LNG, longitude of basin outlet location, in decimal degrees) SE$_p$, standard error of prediction, includes the average sampling error and the average model error.

In this third section of frequency analyses, a flow duration curve is used to differentiate the duration of various discharges between the flow eras. A flow duration curve shows the percentage of time that a given flow is equaled or exceeded. Daily mean data from the CBOPU records and the unregulated proxy are solved for the probability (P) that a given flow will be equaled or exceeded by the equation

$$P\ 100\ *[M/\ (n + 1)] \tag{3.4}$$

Where M is a rank given by the highest mean daily flow in a given era (and sequentially ordered to the lowest flow), and n is the number of records in the given dataset. The flow duration curve is a plot of the probability that a given discharge is equaled or exceeded.

No historical gauge records are available in the Hog Park Basin prior to the extent of the City of Cheyenne record keeping beginning in 1970. Therefore, characteristics of the hydrologic regime are estimated using nearby gauges. This historical information will provide context to analyze changes in the hydrologic regime during the different flow eras; pre-dam, (1956-1963), Stage 1 (1965-1985) and Stage 2 (1985-present). Due to a lack of pre-dam hydrologic data for Hog Park Creek, nearby relatively unimpacted streams with extensive records pre-dating 1965 are used as a proxy for Hog Park Creek's pre-dam hydrologic characteristics. Following peer-reviewed protocol (USWRC, 1982), the gauged systems are located in similar hydrologic units, which are identified by the USGS as being located at a similar elevation with similar geologic and climatic characteristics. The system used as a proxy will be unregulated and lacking significant diversions upstream of the gauge location. Gauge data from Battle Creek, North Fork Little Snake River, USGS Encampment River Gauge below Hog Park Creek, and USGS Encampment Gauge above Hog Park Creek are compared to determine the most appropriate representation of the pre-dam hydrology in Hog Park Creek.

3.2.2   PRE- AND POST-REGULATION HYDROLOGIC ANALYSIS

The Indicator of Hydrologic Alteration (IHA) software created by The Nature Conservancy's

BioHydrology Group is a software package useful for computing hydrologic regime

characteristics and analyzing the change in these characteristics over time (Richter et al., 1996).

The model was developed to analyze components of the flow regime; in this case, the analysis of

three different time periods corresponding to potential ecologic and, primarily, geomorphic

impacts. The three time periods include Pre-dam (1956-1963), Stage 1 (1970-1983; post

construction of the dam in 1965 but prior to the enlargement of the dam in 1985), and Stage 2

(following enlargement). The three flow eras of interest are modeled and contrasted using

specific variables determined a priori. For these hydrologic analyses involving multiple gauging

stations, the discharge records are reduced to a common base in order to minimize the effect of

drainage basin size by expressing the discharge (m3/s) as a ratio to the drainage basin size (km2).

Once reduced, the flows are multiplied by the drainage area to represent results appropriately.

The IHA program is based upon an analysis of mean daily flow data, and uses 32 parameters to

statistically characterize hydrologic variation within a year. The 32 indices (Table 3.3) are

divided into five major hydrologic regime components of i) magnitude, ii) magnitude and

duration of extreme annual conditions (high and low flows), iii) annual timing of high and low

flows, iv) frequency and duration of high and low flow pulses, and v) rate and frequency of

changes in discharge. Measures of central tendency and deviations are compared for each

parameter. This provides a statistical method for analysis of alterations in the flow regime in

relation to specific perturbances. A proxy gauge is identified for historical records pre-dating

available Hog Park Creek gauge data and is explained in more detail in Section 4.1. Statistical

analyses testing the hydrologic differences between unregulated and regulated time frames

included non-parametric tests of the differences of medians of flow data. A difference of medians

test reveals whether the observed differences between unregulated and regulated and time frames are statistically significant. The IHA statistics are tested for significant differences between the three flow eras for this report. A subset of the 64 parameters has been chosen due to geomorphic significance. The terminology for the subset of the parameters discussed in this report is presented in Table 3.3.

The median value for each annual time series (October 1st to September 30th) is tested in Group 1 for statistically significant differences between pre- and post-impoundment flow regimes using a non-parametric test of the medians (Helsel and Hirsch, 1992). Medians respond less to extreme events and are a more conservative approach; a change in the median is less likely than a change in the mean and might be a true indicator of change in central tendency. The Group 2 statistic characterizes the magnitude and duration of extreme flow conditions. The maximum and minimum 1-, 3-, 7-, and 30-day means are computed from a moving average over the period of record. Group 3 tests the variation in timing of extreme flow events and Group 4 is a measure of the frequency and duration of extreme flows, in this report presented as a flow duration curve. Group 5 parameters assess the variation in the rate of change and number of reversals.

Table 3.3: Summary of attributes used in the Index of Hydrologic Alteration and their characteristics.

IHA Statistics Group	Regime Characteristics	Hydrologic Attributes
Group 1: Magnitude of monthly water conditions	Magnitude Timing	Median for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual minima of 1-day medians Annual maximum of 1-day medians Annual minima of 3-day medians Annual maximum of 3-day medians Annual minima of 7-day medians Annual maximum of 7-day medians Annual minima of 30-day medians Annual maximum of 30-day medians Annual minima of 90-day medians Annual maximum of 90-day medians Base flow index- annual 1-day minimum flow/ annual median flow

Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual 1-day minimum Julian date of each annual 1-day maximum
Group 4: Frequency and duration of high- and low-flow pulses	Magnitude Frequency Duration	Number of high- flow pulses each year Number of low- flow pulses each year Duration of high-flow pulses in each year Duration of low-flow pulses in each year
Group 5: Rate and frequency of water condition changes	Frequency Rate of change	Means of all positive differences between consecutive daily means Means of all negative differences between consecutive daily means Number of rises Number of falls Number of reversals

Table adapted from Richter and others 1996

IHA computes a "significance count" for the deviation values for each parameter. To calculate this, the software program randomly shuffles all years of input data and recalculates (fictitious) pre- and post-impact medians 1000 times. The significance count is the fraction of trials for which the deviation values for the medians are greater than for the real case. A low significance count (minimum value is 0) indicates that the difference between the pre- and post-impact periods is highly significant, and a high significance count (maximum value is 1) means that there is little difference between the pre- and post-impact periods. The significance count can be interpreted similarly to a p-value in parametric statistics.

IHA can be a first approximation of relative risk to the extent of biologically relevant hydrologic alteration; statistically significant changes in IHA statistics between flow eras indicate that hydrology has been altered. In terms of potential biological importance, the size of detectable changes in IHA statistics over time might be more important than whether the changes are statistically significant (Richter et al., 1996).

Because flow data do not exist for Hog Park Creek prior to the construction of the dam, I used gauge data to characterize pre-regulation data for Hog Park Creek. Although the data from Battle

Creek are weighted by drainage area, there are limitations to this approach. Trends and size of detectable differences should be given most weight, rather than the precise numbers. Limitations do exist with the interpretation of the results and those limitations are discussed herein.

1) A nearby undammed channel with gauge data pre-dating the dam installation in Hog Park Creek is used as a proxy for pre-dam data in the IHA analysis. Battle Creek is nearby and similarly sized, but on the western side of the Continental Divide, and therefore a less than ideal analog for a stream on the drier, eastern side of the divide.

2) Not all of the statistics can be relied upon because of the limited pre-dam data set, but trends and directions may be inferred because all of these lie in snowmelt systems and respond similarly.

3) The available time record for analysis, particularly the pre-dam data set, only comprises 7 years of data. Many statisticians recommend 15 to 20 year data sets for reliable results and thus the analyses may be compromised by both on-site data for the pre-dam hydrology and a limited data set for nearby gauges used in the analysis. Again, these analyses are intended to be a measure of the general direction and magnitude of change, not the specific statistical significance.

3.3   HYPOTHESES 2-4: PLANFORM ANALYSIS METHODS

Spatial and temporal changes in planform channel morphology were measured at the four reaches from a sequence of historical aerial photographs over a 28-yr period prior to operation of Hog Park Dam in 1965, and over a 29-yr period after dam operation. The photographs were taken on a nearly decadal basis, with the most recent shot in 2001.These photos were imported and ortho-rectified into GIS by USFS staff. Lateral channel migration rates, channel width and a measure of complexity are evaluated in GIS. Complexity is qualitatively derived as the standard deviation of the channel widths through each reach, and qualitatively derived by visual observation of side channels and ponded areas within a reach. Results of the width analysis are presented in section

4.2.1. The temporal changes in planform attributes are quantitatively assessed in reference to land-use patterns, decadal precipitation trends, and pre- and post-dam time frames using multiple regression in section 4.2.4. Changes associated with the dam are examined in relation to distance downstream of the dam and statistically compared to a nearby undammed reference stream with similar climatic, geomorphic, and land use features (gauge detail is presented in Section 4.1). Lateral migration analyses are presented in Section 4.2.2 and the complexity parameter in 4.2.3.

3.3.1   WIDTH

The extent of changes in channel width was measured in GIS from a series of aerial photographs and changes in the pattern are described. Right bank and the left bank of the channel were digitized on all sets of aerial photographs (1937, 1955, 1966, 1973, 1983, 1991, and 2001) at each study reach. The water line rather than the vegetation line was digitized to represent the width of the channel because the photo quality complicated the ability to correctly identify the presence of gravel versus vegetation on the bank. In all photo series with the exception of 2001, the photos were taken in September and October, reducing the variability in the wetted width between photo series. Using a GIS module (Planform Statistics Tool) developed by the National Center for Earth Surface Dynamics (NCED), a centerline was interpolated from the bank lines using an algorithm that defines a point as being on the centerline if it is equidistant from both bank lines and a specified horizontal distance from the previous centerline coordinate (Figure 3.3). The procedure results in a relatively smooth representation of the centerline, with output of width, angle of deflection and radius of curvature at a user-identified point spacing. For this study, point-to-point spacing ranged from 3 to 5 m longitudinally along each reach.

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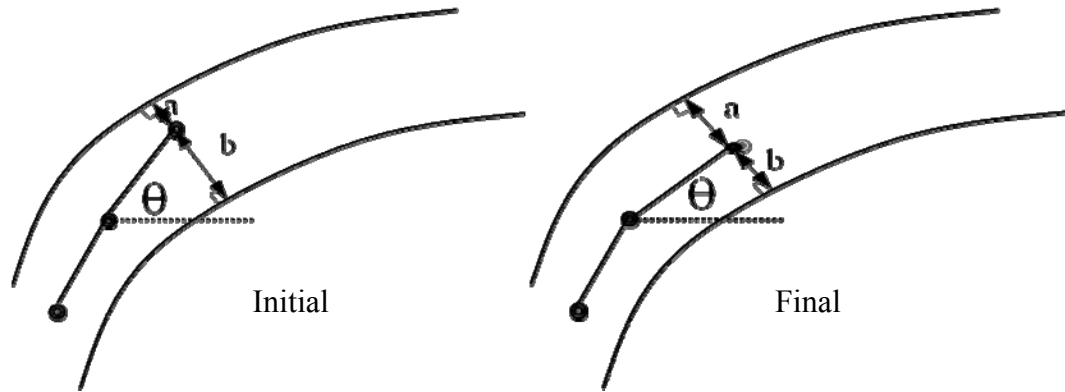
Figure 3.3: Schematic of the planform diagnostics tool. The model interpolates equidistant centerline points from digitized bank lines (a, b), then outputs a spreadsheet containing width, angle of deflection (θ) and radius of curvature at each node of the interpolated centerline. Drawing from NCED website.

3.3.2   LATERAL MIGRATION

Using the Planform Statistics Tool, the lateral migration rate between subsequent years of aerial photographic series was measured between the older and newer interpolated centerlines. The planform statistics tool, as described by Lauer and Parker (2008), finds the average lateral normal distance between the nodes from the interpolated centerline and a second (time successional) centerline (

Figure 3.4). For bends that translate primarily downstream without changing form, the program computes the outward normal migration rate for the new centerline by fitting a Bezier curve between a user-defined bend apex trajectory rather than the historic centerline. The program prompts the user for a Shapefile representing a set of apex trajectories for bends that translated downstream and uses a best-fit Bezier curve that is assumed to represent the most likely path of migration for a particular point. (Lauer and Parker, 2008).The model reports distance of migration, (d), as

$$d = c_i * \Delta t \tag{3.5}$$

where d is the length of the fit Bezier curve, ci is the migration rate and

$$\Delta t' = (\ell/D)\, \Delta t \qquad\qquad\qquad\qquad (3.6)$$

is a modified time step defined by the distance D between the older and newer apex positions (Figure 3.5) and the distance ℓ between the end of the fit Bezier curve and the newer apex position. Conceptually, $\Delta t'$ represents an approximation of the time that a given channel coordinate would take to migrate between the apex translation line and its current position. The length of each curve represents the approximate migration distance and, when divided by Δt, provides the approximate local migration rate. The absolute lateral migration distance was summed through each reach, and a rate was derived by dividing this sum by the number of years between airphotos. The reaches were normalized for comparison by reducing the reaches to a base of respective channel length.
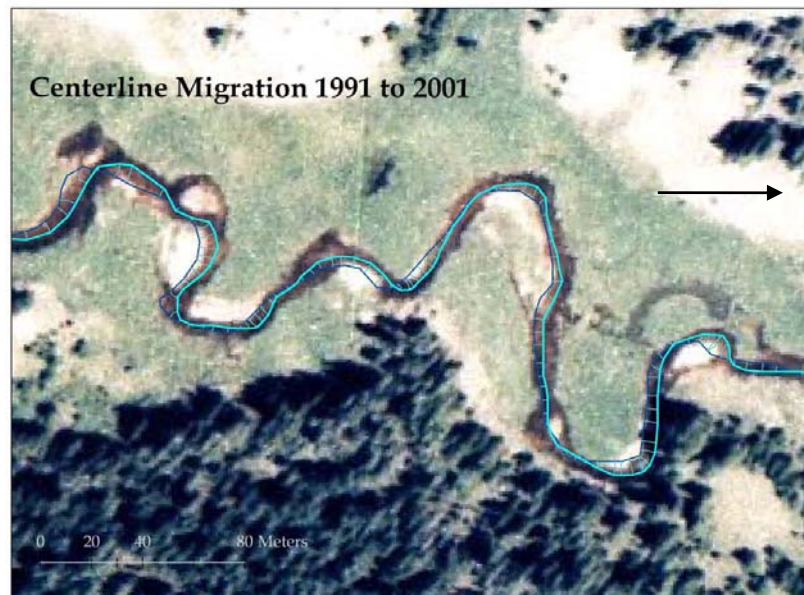
Figure 3.4: A schematic of the centerline lateral migration in reach 2 in Hog Park Creek between the years 1991 (light blue) and 1983 (darker blue) on a 2001 aerial photograph. Flow direction is indicated by the black arrow.

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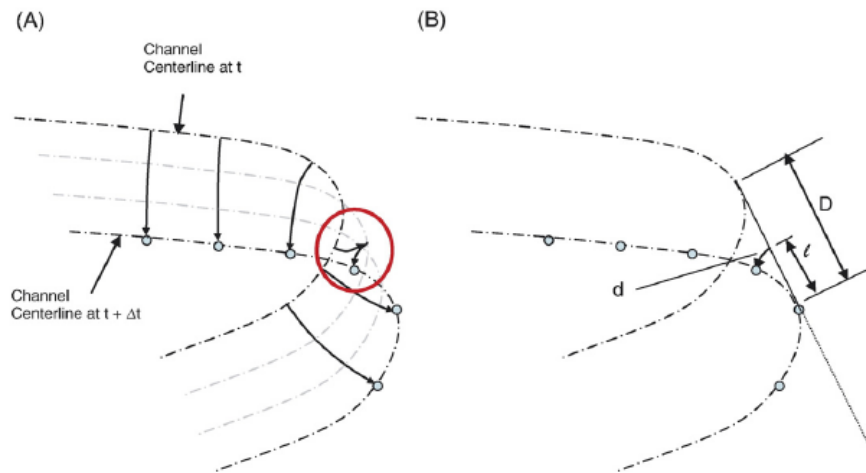
Figure 3.5: Representation of algorithms for the Planform Statistics tool developed by the National Center for Earth Surface Dynamics. (A) Outward normal migration trajectory near the apex of a downstream translating bend. (B) Definition of terms used in approximating migration distance near the apex of a translational bend. Figure copied directly from Lauer and Parker (2008, Figure 8).

3.3.3 COMPLEXITY

Complex channels are thought to contain a diversity of geomorphic surfaces and habitat types. In this study, the sample variance of width is derived from the width measurements in Section 4.2.1 and used as a measure of complexity. Visual observations also guided the complexity analysis through time indicating the relative abundance of side channels, and also the presence of ponded areas created by beaver activity.

3.3.4 LIMITATIONS AND ASSUMPTIONS OF PLANFORM ANALYSIS METHODS

Variation in planform variables can be explained by numerous factors, as discussed in the introductory section regarding the complexity of geomorphic analyses, including delays in responses to perturbations and complex responses. Additional topics to be considered that are lightly discussed in this thesis include the role of local base level controls throughout the study

area and the role of proximity to the dam. Both of these have the ability to largely influence river

dynamics and thus planform characteristics through time. The statistics in this study are a

subsample of potential parameters to quantify planform changes through time and space. The

precision of the airphoto analysis is limited by the availability and quality of airphotos through

time and the interpretation of the results are mindful of this inherent limitation.

The baseline, or existing, condition from the beginning of this study (1937) is not necessarily

representative of an unimpacted system in equilibrium. As mentioned in the Introduction

(Section 2.1.3), grazing began in the early 1900's and was quite heavy around the time period of

the initial series of aerial photographs in 1937. Likewise, Thybony et al. (2001) reference a

Cheyenne newspaper article that suggests that the dam was initially constructed to reduce the

extent of erosion in Hog Park Creek. This statement must be qualified as a potential commercial

campaign for the dam because overwhelming motivation for construction of the dam was not to

reduce erosion but to mitigate for the City of Cheyenne's water supply. However, the article does

suggest that the channel may have been experiencing a legacy effect, in the form of bank erosion,

due to previous land use at that point. As another indication of bank erosion already existing

during the 1960's and 1970's, field surveys conducted in the mid-1970s and 1980's focused on

indicating restoration opportunities along the river corridor. Undoubtedly, the most extensive

erosion in the Hog Park area subsided following the high grazing era of the 1940's to 1960's.

Given that grazing allotments were reduced in HP and SFHP in 1978, the system may be

undergoing recovery and tending toward a more equilibrated state.

A major limitation in this analysis is the pixilation of the scanned aerial photographs, either due

to the quality of the actual photograph or the scanning process. The inherent difficulty of

distinguishing bank vegetation from gravel bars resulted in the use of the wetted width to

delineate channel width instead of bank lines (active channel area). Throughout the series of

photographs, all but the most recent (2001) were taken during the low flow months of late

summer and fall, with flows ranging from 0.057-0.44 m3/s. Discharge data are not available

specific to Hog Park Creek prior to 1970, but the photos are dated from the months of September

and October in 1937, 1955 and 1966. The latest series was flown in June of 2001 when the

discharge in Hog Park Creek was 0.85 m3/s, an order of magnitude larger than the previous

photos.

Table 3.4: Available date and discharge information coinciding with aerial photograph series
for Hog Park Creek.

Photographic series	Month of Photography	Discharge in Hog Park Creek (m^3/s)
1937	7 September	* Not available
1955	7 October	* Not available
1966	28 September	* Not available
1973	17 Oct	.09
1991	25 Sept	0.44
2001	17 June	0.85
* Flow data are not available for this date as it pre-dates available gauge data.		

The pictures also experience deformation from curvature of the land surface. Where possible,

photos are used where the area of interest is located in the center of the photo. Also, the root

mean square error (RMSE) ranged from 0.6 to 6.7, which is a great deal of variation and possibly

extends beyond the error of some of the statistical ranges. A more appropriate measure may be

active channel width in place of low flow width. Active channel width is difficult to discern in

many of the photos due to pixilation issues mentioned previously.

3.4   HYPOTHESES 5 - 7: BANK EROSION ANALYSIS METHODS

The assessment of bank erosion and stability is covered in three subsections analyzing bank

erosion at three different spatial scales. A quantitative analysis of erosion and deposition as

measured from surveyed cross section profiles is presented in Section 3.4.1. These analyses

provide detailed information of location and nature of erosion and deposition in individual cross

sections using annually collected total survey data. Additional site-specific physical and hydraulic

data are statistically correlated with bank erosion rates in Section 3.4.2 using correlation and

linear regression with field-derived bank erosion data. The statistical analysis identifies variables

that explain the occurrence and amount of erosion at a total of 48 cross sections over three years.

In Section 3.4.3 a bank erosion model is employed, using site and regional-specific data and

stepped through stages and duration of a complete annual hydrograph, to identify thresholds of

erosion.

3.4.1   REPEATED CROSS SECTION ANALYSIS

Cross sections in all reaches were evaluated for net changes in channel cross-sectional area

through time. The repeated cross section measurements (2004 – 2008) are assessed for annual

changes using WinXSPro, developed by the Stream Systems Technology Center of the USFS

(Hardy et al., 2005). Survey data were used in the model, overlaying two consecutive years, and

quantifying the net change in cross sectional area between years. Cross sections were established

in 2006 and 2007 and re-surveyed annually. In total, 48 cross sections are compared between

years and reach-scale trends in channel aggradation and/or degradation are determined.

3.4.2   FIELD SURVEY AND HYDRAULIC DATA ANALYSIS

To determine the amount of correlation between lateral bank erosion, bank properties and near-

bank hydraulics, scatter plots are created and a correlation model applied to the data. Bank

properties and near-bank hydraulic data were collected at each site in 2008. Continuous and

categorical variables were used to test significant relations between and within sites to lateral

bank erosion. Those variables are listed in Table 3.5 and include velocity profiles and derivation

of near-bank hydraulic characteristics; bank profiles and bank morphology. Twenty variables are

regressed with the lateral erosion distance. The resulting correlation coefficient (R^2) is 1 or -1 for

perfect correlation and 0 for no correlation. The significance of each correlation is tested using

an F-statistic and a corresponding p-value indicating the confidence level. A Bonferroni

adjustment for multiple comparisons is used for testing 10 variables at a level of significance of α

= 0 .10, so α = 0.10/20 = 0.005 results in a positive test of significance. All statistical analyses are

performed using the SAS software package (SAS Institute, 2001).

Table 3.5: Continuous and categorical variables used in covariate analysis

Continuous variables	Explanation
width of channel	relative height of maximum velocity
total depth	near bank velocity
thalweg depth (m)	unit stream power
average depth (ft)	depth of roots to bank height ratio
velocity (m/s)	height of bank
width/depth ratio	bank angle
average velocity (ft/s)	relative depth
Categorical variables	**Explanation**
eddy or edge of eddy	yes or no
location in reach	straight segment , inside of bend, outside of bend
near-bank boulder	yes or no
vegetation type on bank	grass, willow, both, none
bank composition	cohesive, non-cohesive, multiple layers

The response variable (lateral bank erosion, m) was measured over three years at approximately

98 erosion pins in the four sites. The erosion pins were placed in the 48 established cross sections

where the bank slope is greater than 20 degrees. Predictor variables were collected in 2008

during bank morphology, velocity profile, and total station survey efforts. In four extreme cases, differences in annual lateral bank erosion over sequential years at a site ranged between 0.46 and 0.52 m, which is assumed to coincide with mass wasting of the bank. For the other cross sections where lateral bank erosion does not exceed 0.40 m, differences in lateral bank erosion between sequential years at a site averaged 0.09 m. Since erosion at a site does not vary significantly between years, results were compiled into an Excel database and each of the three years of erosion pin data are linearly regressed with the parameters listed in Table 3.5 that were collected in 2008. Comparisons are made to determine erosion mechanisms, initially testing for reach-scale trends, followed by within-reach, site-specific analyses.

3.4.3 BANK STABILITY AND EROSION MODELING

Streambank erosion reflects a variety of factors that include hydrologic influences, location of a stream reach within a watershed, and bank structural characteristics (Lawler, 1993; Lawler et al., 1997). The varying temporal and spatial scales of streambank erosion make identifying the specific causes of retreat difficult. Commonly, multiple processes are at work and are difficult to separate. In this study, fine-scale bank stability is assessed using various methods. Expanding on the data the USFS collected beginning in 2004, bank composition and stratigraphy data were collected in each of the 48 cross sections in the study area comprised of three sites in Hog Park Creek and one in South Fork Hog Park Creek.

The Bank Stability and Toe Erosion Model (BSTEM), version 5.2, developed by Simon et al. (2002) is employed to identify erosion mechanisms along Hog Park Creek throughout the annual 1971 and 2008 hydrograph. The erosion events are identified at stream stage thresholds. Characteristics of soil composition, bank structure and root strength are modeled with different flow stages and corresponding shear stresses, to determine the conditions at which erosion is predicted to occur.

As a tool for analysis of bank erosion and potential instability, this model estimates bank erosion in multi-layered soils. The model will account for spatial and temporal variations in soil shear strength and riparian root characteristics and their effect on streambank stability. Site-specific data are used when possible, and literature reviews of similar studies were conducted for model parameterization where site-specific information is not available; this is discussed in detail later in this section. Sensitivity analyses are used to determine each parameter's influence on bank erosion rates. Model calibration included adjustments of model parameters using erosion rates between 2007 and 2008 and validated with erosion pin data. Timing and extent of erosion was then modeled during the annual hydrograph for a cross section in each reach. To determine differences in erosion rates due to dam operations, a similar bank structure was modeled for water year 1971 and 2008. The years had similar snowpack conditions in May, indicating similar water year types, except that 2008 is operated under Stage 2 conditions and 1971 is operated under Stage 1 conditions. No flow data are available for pre-dam flows.

Field data are used where available and values from literature are used where necessary. Erosion is modeled in individual cross sections through the duration of 2008. The annual hydrograph (October 1st through September 29th) is broken into steps. Steps were delineated by a daily flux in discharge of 1 m3/s per day, and the stage is averaged within each step. Erosion is modeled for the stage and duration (hours) of each step. Results include the volume and depth of erosion at each cross section, as well as the computed Factor of Safety at each step in the hydrograph. Field reconnaissance determined that two main types of erosion are occurring in Hog Park Creek; fluvial scour at the toe and cantilever failure. The BSTEM model can simulate both of these erosion mechanisms. Using a combination of data sources including i) field-collected data (cross section and longitudinal profile, bank composition and structure, Wolman bed and sieved bank particle size distributions), ii) hydrologic records (local pressure transducer and stage-discharge

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relations), and iii) published values in the literature (soil hydraulic conductivities, geotechnical

bank properties, vegetation root structure and cohesion), the BSTEM model is run under various

scenarios to test the site-specific sensitivities of the banks to these parameters. An erodibility

coefficient is built into the model when assigning bank materials and the model also considers

additional root shear strength using a fiber bundle model. The greater resistance a bank has to

failure, the greater its Factor of Safety (FS).

The first step in the analysis using BSTEM is to test the sensitivity of the model to the various

parameters comprising the model. Input parameters for soil composition include friction angle,

cohesion, saturated unit weight (kN/m3), and shear angle of the bank. Due to a lack of

geotechnical data, published values from a bank stability study by Simon and Mahacek (2009)

undertaken in Tahoe, Nevada (similar elevation, geology, glacial history) are used. The median,

25th and 75th percentiles of the critical shear stress and erodibility coefficient set the boundaries

of what may be likely to occur given the variability in soil characteristics between sites and also

variability at a site, both of which are significant (Parker et al., 2008).

The RipRoot component of the BSTEM model has incorporated root cohesion and surcharge

values for 22 vegetation species from sites across the United States. In the RipRoot model, the

woody vegetation species use a mean growth curve to estimate root numbers (Pollen-Bankhead

and Simon, 2008). The user can adjust the age and composition of species, indicating percentage

of different species composition to the total covering the bank. Geyers willow (Salix geyeriana),

represented in the RipRoot model by Pollen and Simon (2005, 2006), is documented in Knight

(1994) to occur in the subalpine meadows in Wyoming. Two vegetation scenarios are modeled

during the sensitivity analysis: dry meadow vegetation comprises 100% of the bank top, while in

the second scenario, a combination of 85% wet meadow vegetation and 15% willow is modeled.

Both of these relate to vegetation characteristics observed in Hog Park Creek. Anecdotal

observations suggest that locations of relatively more grazing (e.g., Site 3 and 4) also supported more xeric bank top vegetation species (sage and grasses as compared to brushy plants in other reaches), while the majority of the bank consisted of sedges, willows and other wet meadow plant species.

Two banks are simulated in BSTEM, with composition and geometry derived from field data; one with a single loam soil, and one with a gravel toe, a bottom soil layer comprised of gravel in a sand matrix and overlain by a loam top bank. In both scenarios banks are vertical with no undercut present. Soil cohesion, saturated unit weight, friction angle and erodibility coefficient are derived from unpublished data collected in the Lake Tahoe region (Simon et al., 2009) provided by Andrew Simon (pers. communication, 2009).

Two flow stages are modeled. One represents a near-bankfull stage and the other represents a low flow stage. The bankfull stage is modeled with two relative conditions of surface water height (SW) to groundwater height (GW); SW = GW and another representing drawdown conditions, with GW > SW. The low flow stage is only modeled with SW = GW. Therefore, the number of BSTEM simulations for the sensitivity analysis totaled 324: two bank soil compositions, two vegetation assemblages, two flow stages, two relative GW and SW heights, three friction angles, three saturated hydraulic conductivities, and three cohesion values.

The second component of the BSTEM modeling is to determine whether discharge thresholds can be identified and used to predict erosion rates prior to and following Stage 1 and Stage 2 implementation. The 2008 and 1971 annual hydrographs (October 1 – September 30) are broken into flow-duration steps. Bank geometry, soil layer depth and composition, extent of roots, and length of reach data are obtained from bank morphology field surveys. Bank configuration (cross section with undercut profile) and slope are input from total station survey data.

The 2008 annual hydrograph, April 1 through Aug 1, is run in 8-hour steps and the model results (volume, length or area of erosion) are compared with bank erosion pin data for that year. If the predicted erosion data are not within +/- 40% of the actual data, then critical shear stress, cohesion, saturated unit weight and friction angle are adjusted from values within the envelope curve of Simon's data until replicable results are produced. Groundwater stage is also represented in the model using published hydraulic conductivities for the soils on site. Limitations to the applicability of BSTEM to Hog Park Creek do exist. I believe that the modeling is a good representation of the processes in the study area, but limitations need to be considered in the context of the precision of the results and the applicability to management. Known model limitations are outlined below.

Hydraulic conductivity values were obtained from literature (EPA 1996) in place of site-specific values. Specifics with the falling limb of the hydrograph are not represented in the bank erosion modeling exercise. There is the ability in the model to apply a user-defined pore water pressure for each of the five soil layers. I did not have any pore pressure information to use. The results would be better fine-tuned with ground water elevation and/or actual pore water pressure information, as this undoubtedly is significant in the bank erosion process, particularly when analyzing dam-related flow regimes because determining a maximum fall and rise rate are usually part of the flow prescription process.

- Although soil types do vary within the site, they are fairly consistent at any given site with one or two soil layers present throughout the site. About 1 or 2 major soil units are present in reaches 1, 2 and 3. The channel in site 4 is currently adjacent to a floodplain terrace composed of gravel and sand layers, similar to those in the main stem sites, with an additional clay horizon. Differences in bank height most likely result from these unique

soil layers and no analyses were undertaken using BSTEM to distinguish between inherent site characteristics and the different flow regimes.

- BSTEM does not consider shear stresses in relation to the location of the cross section within a unit. The location within a site corresponds to whether it is located in a slow velocity area, such as the inside of a meander bend, or if it lies on the outside of that meander bend, and hence experiences greater velocities, dispersed flow paths, and steeper or more varied hydraulic gradients.

- The erodibility of banks may change from season to season. Snow covers the bank in the early spring and banks are thoroughly frozen when the early spring releases occur. As high flows progress, the water overtopping the bank and spilling onto the floodplain melts the accumulated snowpack and saturates the banks. It is unknown how long the snowpack persists in the spring after the high flows recede and the impacts this excess saturation have on the erodibility of the banks.

- There is no site-specific information for the contribution to cohesion resulting from bank vegetation and how this may shift seasonally.

4   RESULTS

4.1   HYPOTHESIS 1: HYDROLOGIC ANALYSES

A focus of this research is discerning the changes in the hydrologic regime of Hog Park Creek

by flow regulation and augmentation. Daily mean discharge records in Hog Park Creek date

back to 1970, but no gauge records exist in the Hog Park basin prior to the construction of the

dam in 1965. In the absence of gauge records pre-dating flow regulation, multiple analyses are

used to identify and quantify changes in hydrologic characteristics of the regulated condition

and those of a representative unregulated flow condition. Section 4.1.1 begins with a

comparison of peak flow characteristics from field-collected data and regionally-based

empirical equations representing unregulated conditions. Section 4.1.2 supplements this

analysis with a discussion of the selection of gauge data from analogous streams in the region to

be used as a characterization for the unregulated hydrologic regime in Hog Park Creek. The

Indicators of Hydrologic Alteration analysis (Section 4.1.3) continues with the comparison of

representative pre-dam hydrologic data (1956 – 1963) with those of regulated Stage 1 (1965-

1985) and regulated Stage 2 (1986- 2008) data.

4.1.1   FREQUENCY ANALYSES

Two methods are employed to quantify discharges for given flood recurrence intervals. The

results from the calculations are compared as relative indicators of flood magnitude variation as

a consequence of flow augmentation and regulation. Regression equations derived from

empirical relations (Miller 2003) are used to predict discharges for given recurrence intervals to

represent an unregulated setting. The Log Pearson-Type III method is used to calculate daily mean peak discharges for given recurrence intervals based on the available data record and represents the regulated flow eras (1985-2008). Methods used in calculations and a more broad discussion of the appropriate application and limitations to these methods are more thoroughly discussed in the Methods section (3.2.1). Variation in the results of flood frequency calculations using predicted values (regional regression equation method) and observed hydrologic data (Log-Pearson III method) describe the magnitude of impacts related to flow augmentation and/or dam operation (Figure 4.1 and Figure 4.2). The record of mean daily annual peak flows is used to estimate the frequency curve of the population and is an approximation to the true frequency curve of the underlying population of the annual flood peaks (Table 4.1). The use of mean daily values as compared with the instantaneous peak values does result in errors in the estimate. The use of daily mean discharges will under-predict the instantaneous peak flow discharge and, due to the limited extent of gauge data, inherently contains high error. The use of daily mean discharge values underestimates the peak discharge value and results should be used to determine direction and magnitude and not relied upon for detailed analyses. However, the snowmelt-dominated hydrology allows the calculations to be particularly reliable because of the peak flow regularity, predictability, and rarity of extreme events (Miller, 2003). Note that the recurrence interval calculations are based on the Hog Park Flume location downstream of the dam, with a drainage basin of 32 km^2, not the entire Hog Park Creek watershed of 76 km^2.

Empirical equations are not precise and the goal of this analysis is to 1) provide trend data and not specific quantitative results and 2) support the analyses following this section. To gauge the accuracy of this approximation, confidence intervals have been constructed. Lastly, the 23-year

event represents the extent of annual time series available for the most recent era of regulation; flow predictions beyond a recurrence interval of 23 years are more speculative.
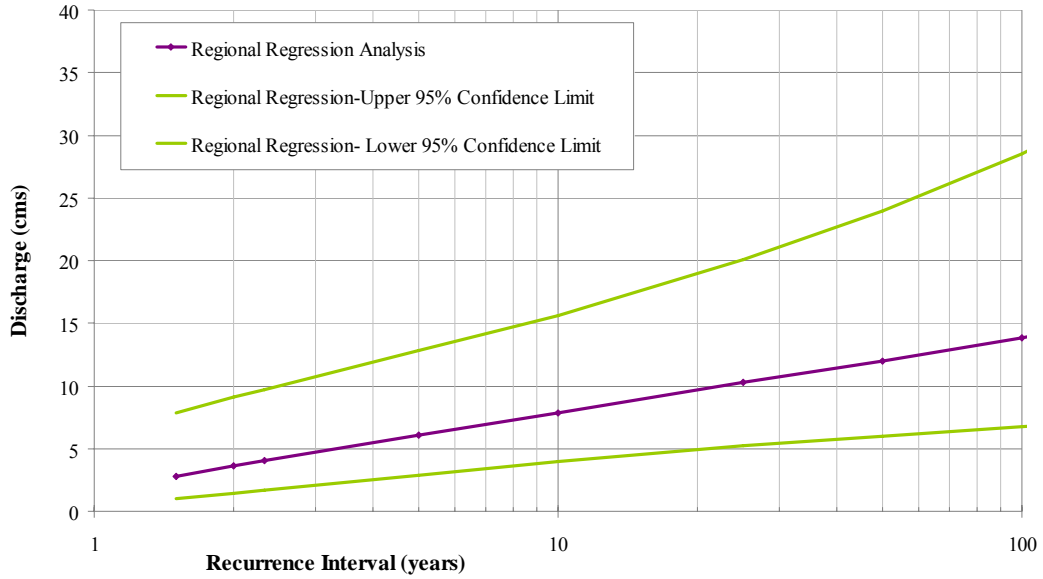
Figure 4.1: Regional regression-derived estimated discharges for various flood magnitudes representing an unregulated condition in Hog Park Creek.
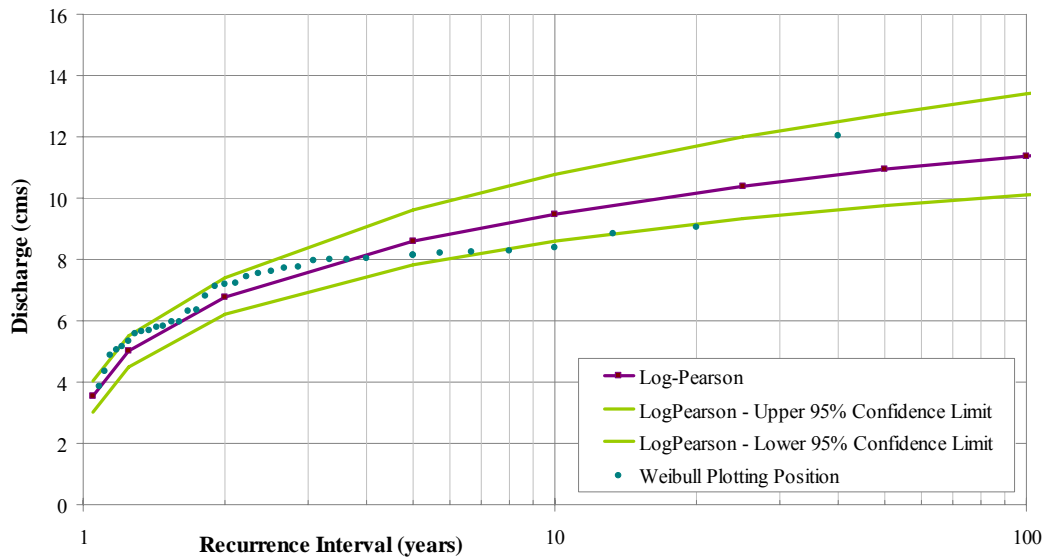
Figure 4.2: Calculated discharges for recurrence interval storm events using the Log Pearson Type III method (USGS Bulletin 17B), indicating the discharge associated with flows of given frequencies.

Table 4.1: Log-Pearson frequency analysis derived from City of Cheyenne BOPU (flume) data for water years 1986–2008 (the low outliers of 1986 and 2002 are omitted) compared with regional regression predictions (Miller 2003) representative of unregulated conditions.

Recurrence Interval (years)	Peak Discharge (m^3/s) – current[1] 1986-2009 (95% Confidence Interval)	Peak Discharge (m^3/s) – predicted historical[2] (95% Confidence Interval)	Ratio Q_{reg}/Q_{unreg}
50	11 (10,15)	12 (6,24)	0.9
25	10 (9,13)	10 (5,20)	1.0
10	10 (8,11)	8 (4,16)	1.25
5	9 (7,10)	6 (3,13)	1.5
2	6.7 (6,7)	3.6 (1,9)	1.9

The greatest observed variation occurs with high frequency, low magnitude flows where a historical 5-year event now occurs on an annual or biennial basis. For example, the discharge with a recurrence interval of 2 years increases from a predicted historical discharge of 3.6 m3/s to a measured discharge of 6.7 m3/s under current regulation. The discharge for a historical 10-year event (8 m3/s) now occurs approximately every five years. The discrepancies between discharges of floods of higher magnitudes are reduced and do not show as significant a shift in characteristics as compared with the shift in higher frequency flows. For example, the discharge of a 25-year event in unregulated conditions is 10.4 m3/s and during the last 23 years of regulation is 10.3 m3/s. These higher magnitude discharges have larger inherent error with the estimates because of the short time span of records. Mean daily discharges are used for the Log-Pearson analysis and the regional regression equations were derived from instantaneous peak discharges, so it is presumed that if instantaneous peak discharges were used for the Log-Pearson analysis as well, the difference between the discharges corresponding to high frequency

events would be greater. However, the scale of change observed in these analyses is larger than the scale of error in the results.

A comparison of recurrence interval discharges is plotted in Figure 4.3 and results are presented in Table 4.1. The discharge for recurrence intervals of 2, 5, 10, 25 and 50 years for the pre-dam time period is placed on the x- axis and the post-dam time period on the y axis. The 45 degree centerline describes agreement between the discharges of a given recurrence interval. If the discharge for a given recurrence interval remains the same for both the current and unregulated results, then the point would lie on the line. The points above the centerline indicate that discharges are occurring more frequently under regulation than compared with unregulated conditions. Points located below the line indicate discharges that are occurring less frequently than would be predicted for unregulated conditions.
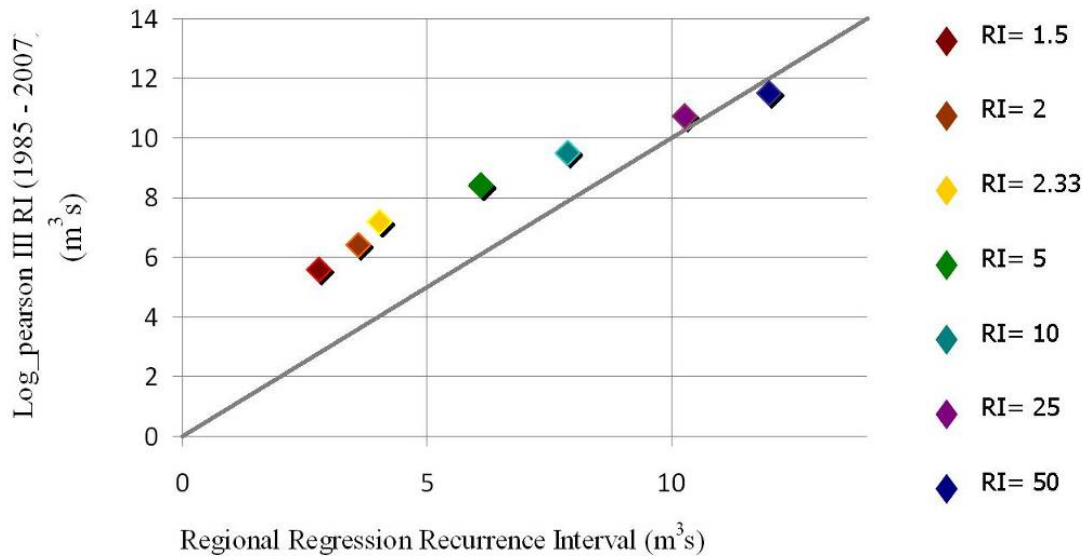
Figure 4.3: Regulated and unregulated magnitude of flows of a given recurrence interval calculated for current (y-axis) and unregulated (x-axis) conditions. Points below the mid-line display the relative decreases in discharge of a given frequency, and the converse for points above the line under current dam operations.

The chart describes the aforementioned results that discharges for frequently recurring high flows, such as those shown to do the most work in the channel, occur much more frequently and discharges of high magnitude floods have been minimally affected or are slightly reduced. The smaller magnitude predictions are more reliable than the long term estimates and indicate the greatest change in relative frequency between the two flow scenarios analyzed. These results are further supported by additional analyses in this section through the use of proxy gauge data and hydrologic modeling. The effects of this shift on sediment transport rates and bank erosion related to changes in the hydrologic regime are discussed.

4.1.2 PRE- AND POST-REGULATION HYDROLOGIC ANALYSES

Few gauges exist adjacent to Hog Park Creek that collected data prior to 1970, particularly meeting the stringent criteria of similar hydrologic unit, drainage size, and elevation. Table 4.2 provides characteristics of gauges identified as potential proxies for the Hog Park Creek unregulated and pre-dam dataset due, initially, to their spatial proximity to the Hog Park basin and having a dataset extending prior to 1970.

Periods of record for gauges are displayed in Figure 4.4 and the comparison of the gauge records are provided in Figure 4.5 Figure 4.8. The Encampment gauges are closest to Hog Park Creek and no dams exist upstream of the Encampment River Gauge. However, this gauge was deemed inadequate for several reasons. The larger drainage area of the Encampment River watershed allows for attenuation of flows (Table 4.8) and hence does not provide adequate replication of timing and duration of high flows. Also, the gauge was located downstream of the confluence with Hog Park Creek until the dam was constructed in 1965, and then placed upstream of the confluence with Hog Park Creek, resulting in discontinuous gauge records. The North Fork Little Snake River gauge is also excluded from analysis. The river system has

several water intakes in the headwaters of the basin which may affect the peak discharges and

low flow conditions. For example, note the stepped pattern for the North Fork Little Snake

River in Figure 4.6. Due to the seemingly significant impact that these tributary flow diversions

may have, this data record is also deemed inadequate. Battle Creek gauge has similar elevation

and basin size and has no significant diversions upstream of the gauge. In comparison of time

series data (Figure 4.8), Battle Creek gauge data appear to closely relate to Hog Park Creek in

both timing and duration of high and low flows.

Table 4.2: Characteristics of gauges regionally similar to Hog Park Creek

Gauge Name/ USGS Gauge Number	Elevation (m)	Area (km^2)	Period of Record
Hog Park Creek (CBOPU flume below dam)	2,550	32	01/01/1970 – present
Encampment River below Hog Park Creek 6623900	2,680	270	10/01/1956 - 09/30/1964
Encampment River above Hog Park Creek 6623800	2,520	187	1965 - present
North Fork Little Snake River 9251800	2,520	25	10/01/1956 - 09/30/1965
Battle Creek 9253400	2,550	34	04/01/1956 - 09/30/1963; 04/01/1985 - 09/30/1988

Time series discharge data are plotted for Battle Creek and the North Fork Little Snake River in

Figure 4.5. Further, in Miller's (2003) analysis using multiple regressions to classify hydrologic

regions in Wyoming, Battle Creek and Hog Park Creek are both placed into Region 1 and are

expected to have similar hydrologic characteristics. Regional regression predictions are plotted

for each gauge in Figure 4.9. For the following analyses, the Battle Creek gauge data pre-dating

1965 are used as a proxy to represent pre-dam unregulated flow data for Hog Park Creek.

	Pre- Regulation			Stage 1				Stage 2			
	1955	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005
Hog Park Creek											
Encampment R. below HP											
Encampment R. above HP											
Battle Creek											
North Fork Little Snake											

Figure 4.4: Period of record for gauges considered for representation of an unregulated dataset.
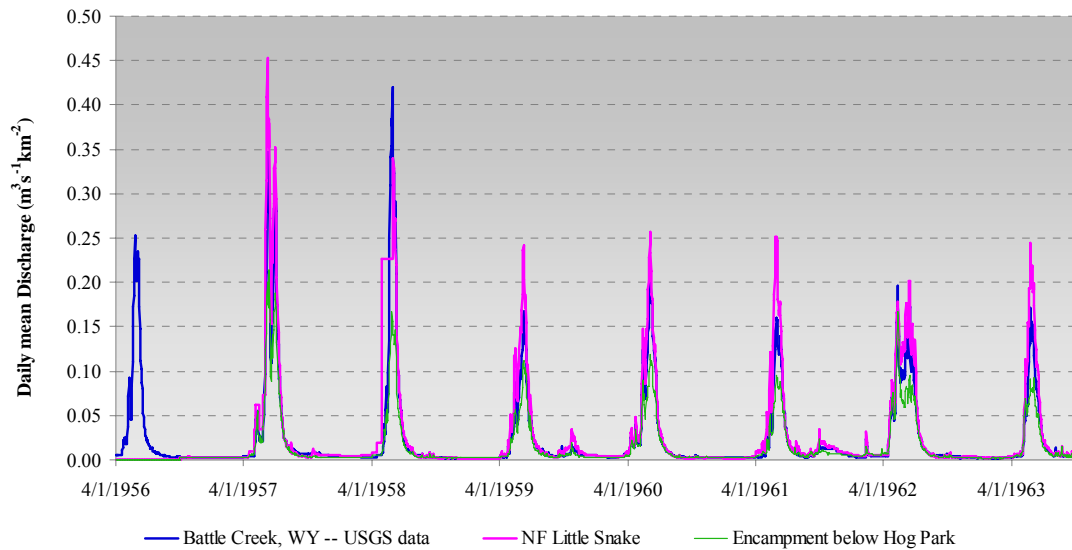
Figure 4.5: Annual hydrographs for the period of overlapping records of Battle Creek, the Encampment River and North Fork Little Snake River, the basins most comparable to Hog Park Creek when considering geographic proximity and elevation.
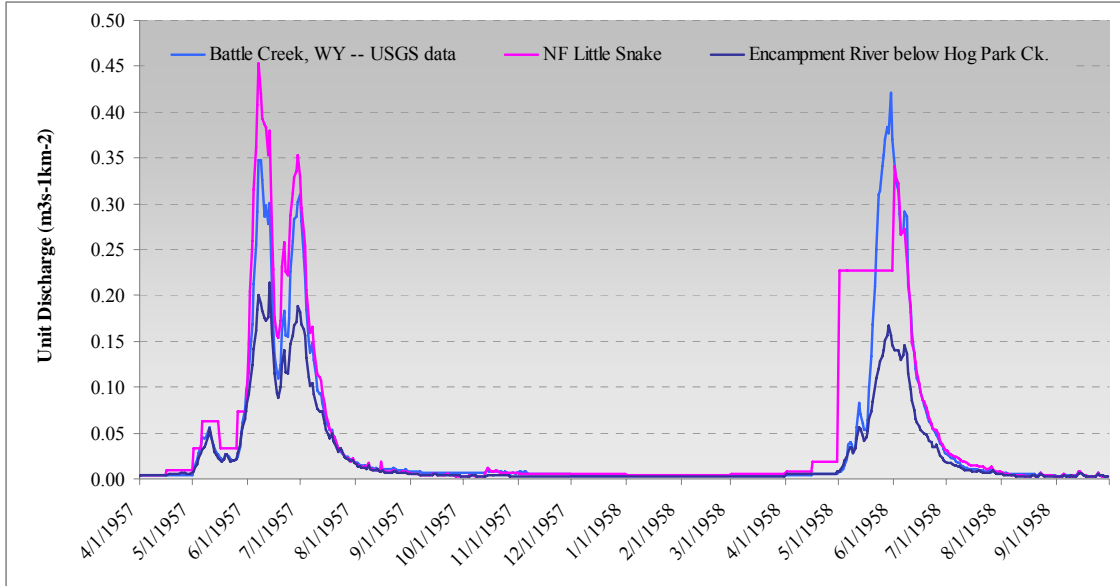
Figure 4.6: Comparison of gauges, 1957-1958.
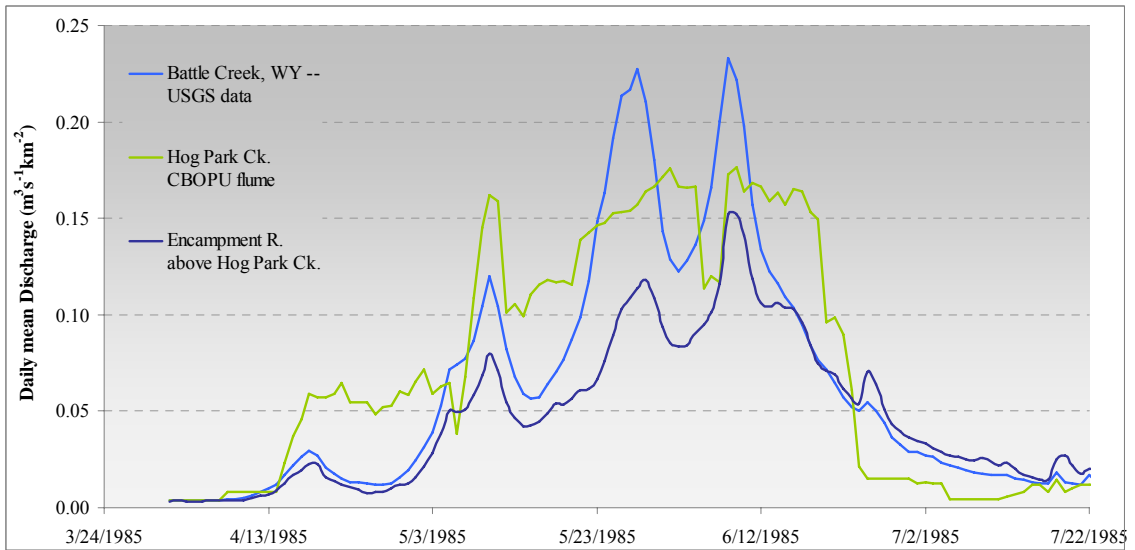
Figure 4.7: Annual hydrographs of Battle Creek and the Encampment River compared with Hog Park Creek following the completion of Stage 2 construction.

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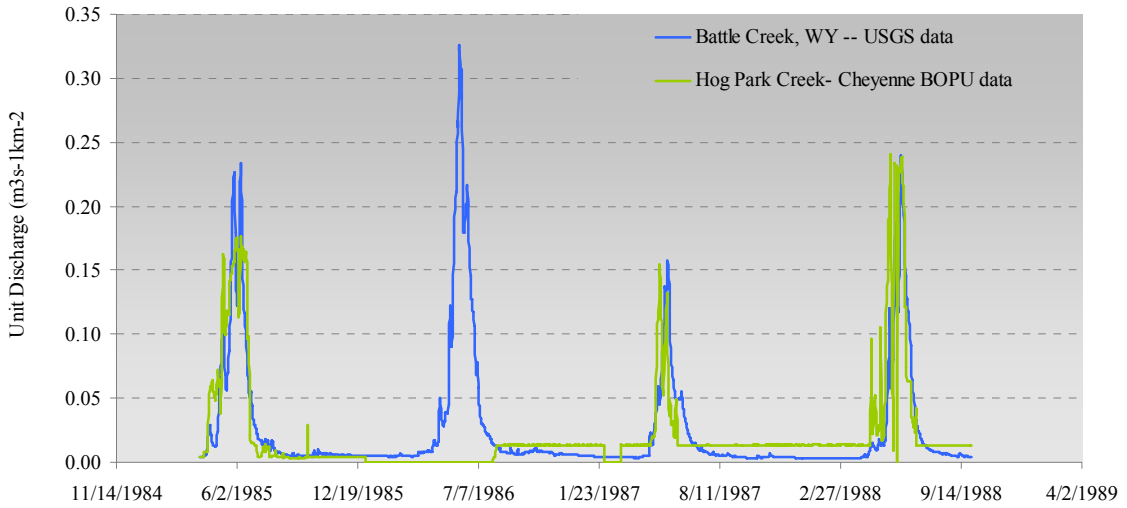
Figure 4.8: Time series comparison of Battle and Hog Park Creeks, 1985-1988. No data for Hog Park Creek are available for WY 1986.
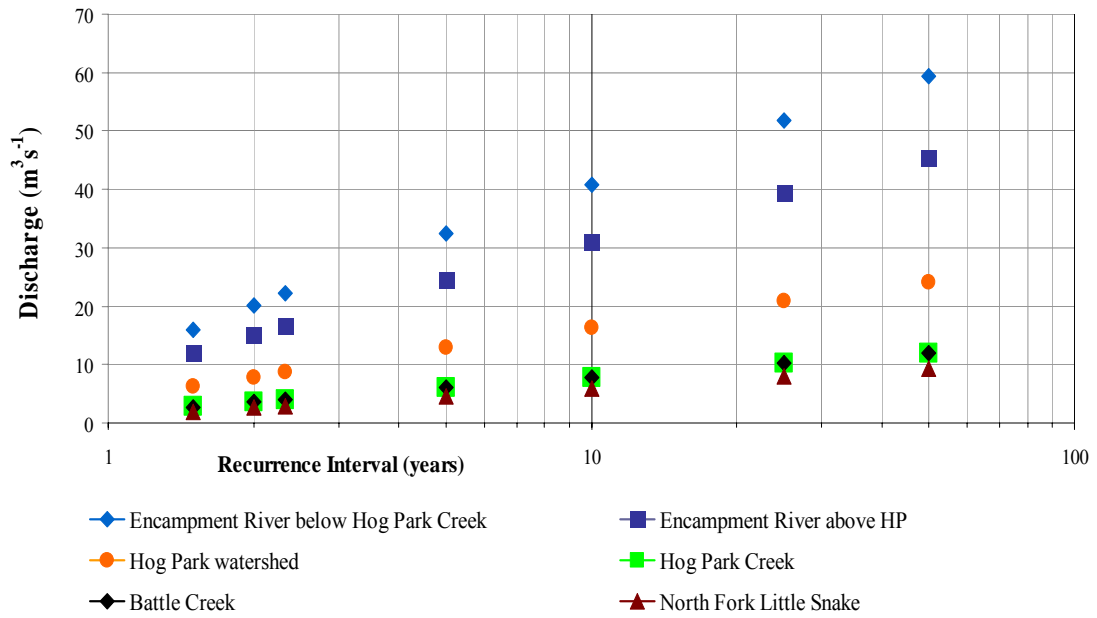
Figure 4.9: Recurrence interval calculations for various gauges. Notice the similarity of data from the Hog Park flume, North Fork Little Snake River and Battle Creek gauges.

Figure 4.8 shows that Battle Creek is a good proxy if this time period mimics actual flow

conditions. Extreme annual events and annual discharge variability are shown to be most

affected by regulation in snowmelt-dominated river systems (Graf, 2006). In his study, Graf

found that a suitable descriptor of the ability of a dam to impact the flow regime is a ratio of annual water discharge to storage capacity of the reservoir. He found that large dams in western states have a discharge-storage ratio ranging between 1.4 and 4.6. If the ratio is one or greater, then the dam stores more than the annual yield. The ratio between the storage capacity and the annual water yield of Hog Park Creek increases an order of magnitude from 0.14 to 1.17 between the Stage 1 and Stage 2 flow eras due to the augmentation of discharge from the North Fork Little Snake Basin. The ratio in Hog Park Creek is contrastingly low to larger rivers, although the shift from Stage 1 to Stage 2 represents a significant change in the hydrology of the basin. The historical time series for Hog Park Creek is provided in Figure 4.10 and doesnot include the Battle Creek dataset.
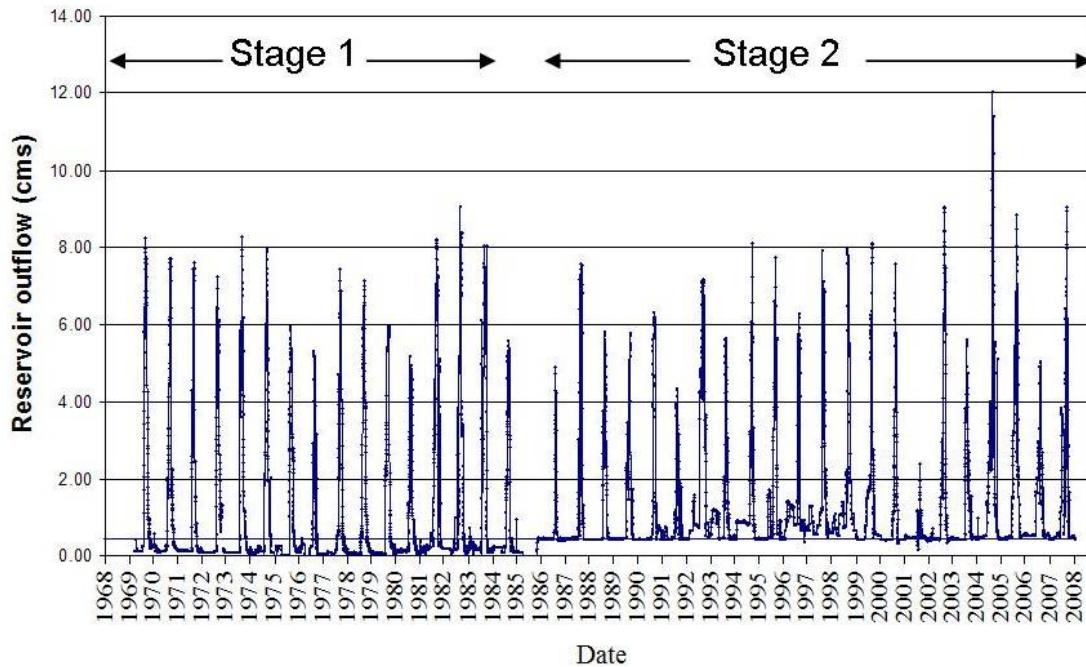
Figure 4.10: Hydrologic time series of the CBOPU data set. The x-axis is time, while the y-axis displays discharge values.

For IHA analyses, Battle Creek data represent pre-regulation (1956-1963) and the period of record for CBOPU flume data (1970 – present) is used for Stage 1 and 2. For comparison of these records, the discharge data have been normalized by expressing the daily mean discharge (m3/s) as a ratio to the watershed area (km2), which reduces the data to a similar base for comparison. The normalized data are then multiplied by the drainage basin area of Hog Park Creek (32 km2) to represent the correct magnitude of discharge. Combining records for Battle Creek (1956 – 1963) and CBOPU flume data (1970 – present) provides a nearly continuous record spanning 1956- present, with data gaps listed in Table 4.3. Note that the data gaps for 1990, 1996 and 1997 occur during peak flow periods.

Table 4.3: List of data gaps for period of record in IHA analysis, 1956 - 2008

Data Gaps 1956 – 2008
10/1/1963 – 9/30/1964
1/1/1965 – 1/1/1970
1/1/1980 – 11/30/1980
8/19/1982 – 12/31/1982
1/1/1985 – 7/31/1986
5/1/1990 – 5/13/1990
7/1/1996 – 7/31/1996
6/1/1997 – 6/30/1997
7/1/2008 – 7/7/2008

The flow eras in this analysis include eight years prior to dam installation (Battle Creek data 1956–1963), 23 years of Stage 1 data (regulated flow prior to dam enlargement, 1970-1983) and 22 years following enlargement of Hog Park dam (1986 – present) (Figure 4.11). Multiple hydrologic parameters of these three flow eras are contrasted using the Indicators of Hydrologic Alteration (IHA) software to assess the differences between the current operational regime and the unregulated (non-augmented) regime. Section 3.2.2 describes the model in detail. The

results of the computations are thus data sets of annual series of attributes for the respective

periods of record. The focus of this process is to provide a comparison of hydrologic attributes

of the natural and altered flow conditions.

In general, it can be observed that flow heterogeneity has been reduced. Figure 4.11 plots the

maximum daily mean annual discharge for the period of record against a ratio of the maximum

annual to daily mean annual discharge. Beginning with the dam enlargement in 1985, a

significant shift can be observed such that the variability in the annual hydrograph is dampened

as a result of higher than normal base flows and reduced peak flows, as described in the

recurrence interval analyses. Table 4.4 provides reservoir and annual discharge statistics

between the three time periods. The ratio of the reservoir storage capacity relative to the annual

discharge increases from 7.3 to 46.1. This metric relates to the ability of a dam to influence the

geomorphic properties of a river or stream system (Graf 2006). The increase in storage

capacity, combined with the flow augmentation, has the potential for considerable influence on

Hog Park Creek.
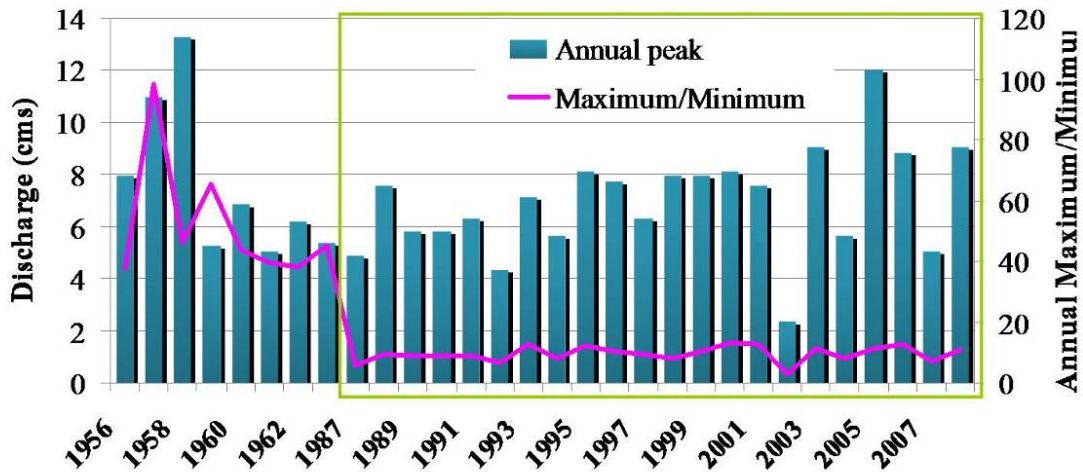
Figure 4.11: Mean daily annual maximum discharge plotted with the ratio of
maximum discharge to minimum discharge for the combined data set. The
highlighted section represents the time period following Stage 2 implementation.

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The Indicator of Hydrologic Alteration (IHA) software provides a multitude of analyses for describing observed changes in the flow regime between flow eras. This study analyzes those characteristics which most pertain to the geomorphic and ecological processes of the Hog Park Creek system. The model and the limitations of its use in this context are described in Section 3.2.2 and output parameters are summarized in Table 4.5. IHA can be a first approximation of relative risk to the extent that biologically relevant hydrologic alteration and statistically significant changes in IHA statistics between flow eras indicate that hydrology has been altered. In terms of potential biological importance, the size of detectable changes in IHA statistics over time might be more important than whether the changes are statistically significant (Richter et al., 1996). Because the pre-dam data set is comprised by data from the Battle Creek gauge, trends of magnitude and direction of change should be considered more, rather than the precise numbers. Median values for each parameter are provided, as well as the magnitude of change of each parameter for pre-dam data (1956-1963) compared with Stage 2 (1987–2008) and Stage 1 (1970-1983) versus Stage 2 flow eras. Data are insufficient in 1986 and are not included in the analysis. Tables comprising the full output from the Indicators of Hydrologic Alteration computations are provided in Table 4.5 and Table 4.6

Table 4.4: Annual discharge characteristics for the three flow eras.

	Pre-dam	Stage 1 (1970-1983)	Stage 2 (1987-2008)
Total Annual Discharge (m³/year): **Median**		**503,608**	**605, 094**
Maximum	_	747,243	1,024,623
Minimum		233,790	292,814
Maximum/ Median		1.5	1.7
Reservoir Storage Capacity: Annual Yield	_	**7.3** (3.7 Million m³ of storage)	**46.1** (27.9 Million m³ of storage)

The Stage 2 flow regime is significantly different in many parameters from Stage 1, but the

most significant differences result when comparing Stage 2 with the Pre-dam flow regime.

Differences in dam operation are most pronounced in low flow metrics (monthly medians July-

March; 1,3,7-day medians), high and low flow duration, and the average fall rate.

The significance count can be interpreted similarly to a p-value used in statistical tests.

Significance count values range from 0 to 1. A value close to 0 indicates that the difference

between the pre- and post-impact periods is highly significant. For this study, significance

count values ≤ 0.10 were considered significant.

Pre-Dam vs. Stage 1

Results from the Indicators of Hydrologic Alteration (IHA) indicate that only a few hydrologic

parameters have significantly changed when the Pre-dam flow data are compared to Stage 1

flow data (Table 4.5). The largest changes in Group 1, median monthly discharge, occur in

June and July, both months significantly increasing in median discharge. In Group 2, the largest

change occurs in the annual maximum 7-, 30- and 90-day discharges, with each increasing

during the Stage 1 regulated operational regime. The base flow index, a measure of the annual

minimum flow divided by the annual median flow, decreases by 40%. Although the Julian day

of maximum flow shifts earlier from May 31 to June 6, it is not statistically significant. The fall

rate significantly increased by 66% under Stage 1 operations. River stage also dropped more

quickly throughout the year as compared to unregulated conditions. Flow duration curves for

the different flow periods are portrayed in Figure 4.12 and relevant flow duration data for

different exceedance probabilities are summarized in Table 4.6. The highest annual flows, for

example those with an exceedance probability of 1 percent, are reduced in Stage 1 as compared

to flows prior to regulation, by approximately 11 percent. However, flows below the peak

annual discharge but of significant magnitude, on the right side of the graph, are typically

higher in the Stage 1 time period. Specifically, an increasing trend is observed in this region of

the flow duration curve, as those discharges that are exceeded 10, 15 and 25 percent

progressively increase in comparison, with percent changes of 41, 65 and 75 percent,

respectively.
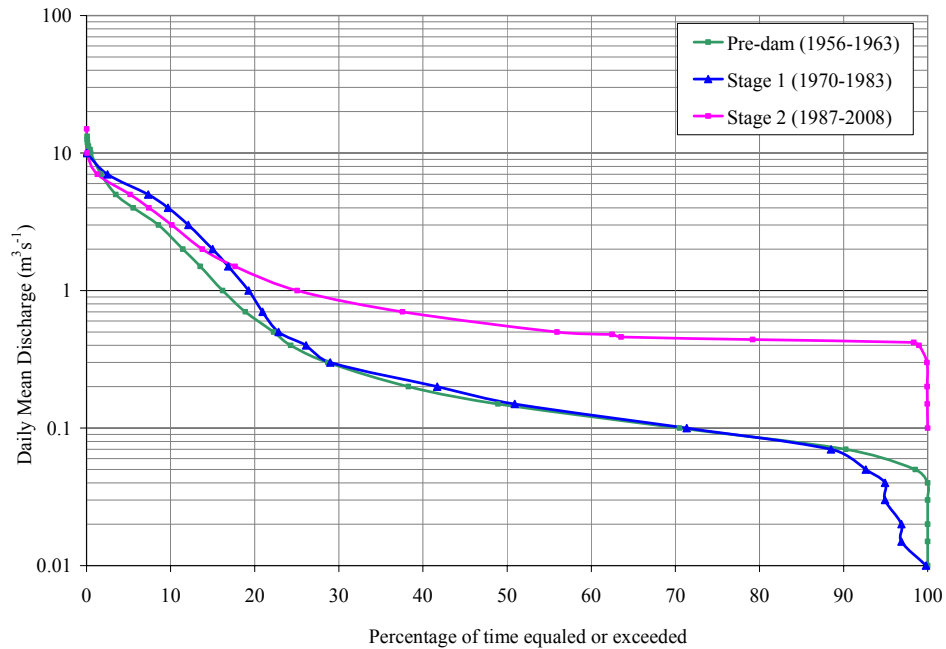
Figure 4.12: Duration curve for Pre-dam (1956-1963), Stage 1 (1970-1983), and Stage 2
(1986-2008) flow eras.

Pre-Dam versus Stage 2

Comparison of the flow regime between the pre-dam time period and following the expansion

of the dam shows a shift to a bimodal distribution of the peak flow. This early spring, low-

magnitude flood generally occurs in mid-to late-April as dam operators lower the reservoir

elevation to accommodate anticipated snowmelt runoff and trans-basin diversions. As

expected, of the three time periods analyzed, the most significant changes are observed in this comparison.

Group 1- Monthly flows

Median monthly discharge is increased during Stage 2 operations every month except for the month of June. The significance count is 0.00 for the differences in median flow of each month besides June (0.55) and May (0.005). Low flow discharges between August and April increased by 182 and 433 percent, from approximately 0.1 m3/s to 0.5 m3/s. The median discharge in May increases from 2.1 to 3.85 m3/s, an increase of approximately 83 percent. Median flows in June decreased by 31%, not a statistically significant change, but the median monthly discharges are greater in May during Stage 2 operations, as compared to June in the other flow eras. This most likely relates to flow releases earlier in the spring during Stage 2 operations. Though not tested as being significant in these analyses, the advance timing of high flow releases may have a significant ecological impact that is not measured in this analysis.

Group 2- Magnitude and duration of extreme annual discharges

Annual minimum 7-day median flows increased 511% and maximum 7-day medians flows slightly decreased by 9%. Low flow extremes are described by the base flow index, which is the average across all years of the annual minimum flow to median flow. The change in the base flow index is significantly different when pre-dam flows are compared to Stage 2 reservoir flow operations. Annual maximum flow durations also increase between pre - dam and Stage 1 operations. Annual maximum 1-day flows, the annual peak, increases 10%, and the annual maximum 7-day, a more sustained peak flow, increases 8.5%.

Group 3- Timing of extreme water conditions

The Julian date of the maximum average daily flow occurs approximately 15 days earlier. Although this shift is not statistically significant, it may be ecologically significant and have implications to aquatic biota. Mandatory low flow discharges are maintained throughout the winter months, hence, the low flow timing is an insignificant metric during Stage 2 operations because it represents just a slight deviation from that mandated minimum flow.

Group 4- Flow Duration and magnitude

Low flow conditions have changed significantly when compared to natural conditions. As shown in Figure 4.12, the discharges of frequently exceeded flows have increased. For example, the discharge that historically was exceeded 50% of the time (pre-dam), 0.16 m3/s, has the likelihood of being exceeded less than 1% of the time under the current operations. Stage 2 discharges with a probability of being exceeded of 50-95% dramatically increase, ranging from a change of 230 – 640%. The changes in high flows are less drastic, although high flows are constrained so that flows do not exceed the hydraulic capacity of a culvert downstream of the dam. The discharge with a probability of being exceeded only 1%, decreases 16% under Stage 2 operations compared with pre-dam discharges. Those flows that are most likely formational for channel morphology by influencing sediment transport and deposition processes, those being exceeded only 5-15 % of the time period, have increased between 20 and 50%, respectively.

Group 5- Rate and frequency of changes in discharge

Flashiness indices (H1A5) had varied significance. The fall rate is significant in all tests. An increase in the fall rate indicates that flows drop more quickly, whereas an increase in the rise

rate indicates that flows rise more quickly than historically. The rise rate did not vary

significantly (0.990) between the two flow eras. The number of reversals is of marginal

significance, 0.64.

Stage 1 versus Stage 2

The mean annual total discharge increases from approximately 500,000 m3 to over 600,000 m3

between the Stage 1 and Stage 2 time periods (Figure 4.13). The differences in hydrology are

less significant than the previous analysis of the pre-dam and Stage 2 time period, but notable

changes have occurred.

Group 1- Monthly flows

The median monthly discharge is significantly different during each month except for June.

The median monthly flows during the low flow time period have increased between 206 and

353% (Table 4.5). The increase in median monthly flows in March and April reflects the

change in reservoir operations from Stage 1 to Stage 2. The Stage 2 hydrograph generally has

two distinct peak discharges; an early spring, low magnitude flow release and a late spring, high

magnitude flow release. In Stage 2, the typical high flow months of June and July have a 61%

and 43% decrease in median monthly flows, respectively. For the transitional month of May,

historically the beginning of spring snowmelt runoff, Stage 2 median flows have increased 43%,

a likely result of flows being released from the reservoir earlier in the late spring .

Group 2- Magnitude and duration of extreme annual discharges

Annual 1-, 3-, 7-, 30- and 90-day minima are significantly increased. The magnitude of change

ranges from 335 – 900%, and represents an order of magnitude more change than the high flow

parameters. The high flow magnitudes have been reduced, but do not show as significant a

change as the low flow parameters. The peak one-day maximum discharge has decreased by

nearly 5%. However, this peak discharge increased in Stage 1 as compared to historical peak

discharges. Comparing Stage 2 high flows to those prior to the dam indicates an increase in

high flows of approximately 10%. Between Stage 1 and Stage 2, the high flow durations of the

3-, 7-, 30- and 90-day maximum flows have dropped between 7 and 17%.

Group 3- Timing of extreme water conditions

The Julian date of the high flows has shifted approximately two weeks earlier than both pre-

dam and Stage 1 time periods. The change in Julian date of minimum flow is also not

significantly changed.
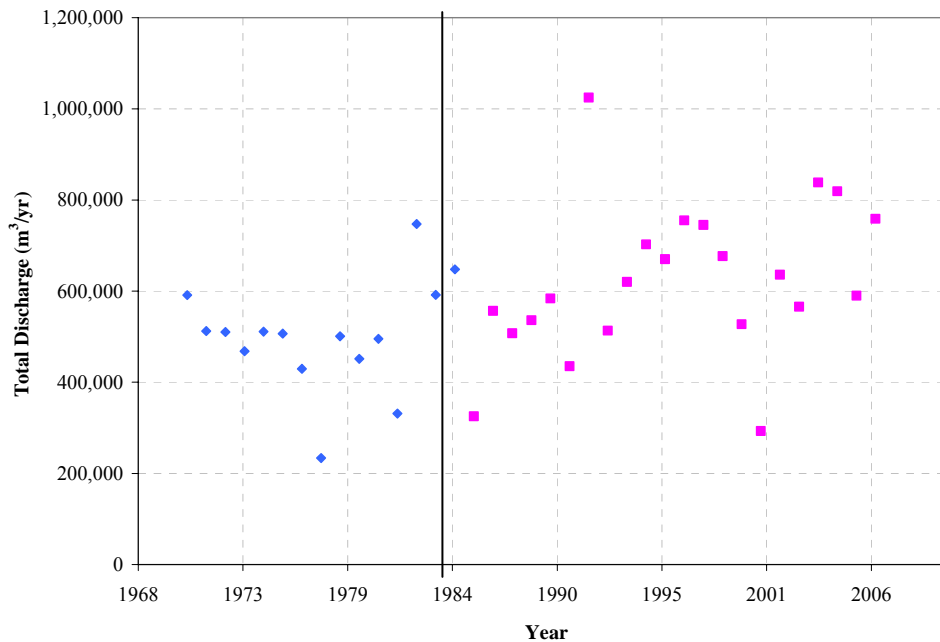
Figure 4.13: Total annual discharge from the reservoir in Hog Park Creek, Stage 1 (blue) and Stage 2 (pink). The two time periods are separated by the solid black line.

Group 4- Flow Duration

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Following the enlargement of Hog Park Dam, low flow discharges have significantly increased from approximately 0.1 m3s-1 to 0.4 m3s-1. These flows are maintained throughout the late fall and winter months. The increased storage capacity of the reservoir allows for more availability of water in the drier summer months. Although flows from Hog Park Creek are not directly used for municipal sources, they replace water in the Platte River system that is used by the municipality. The low flow is mandated by the USFS to provide adequate instream flows to support the recreational fishery. This increase is tested as a significant change, but may not significantly affect the geomorphic regime.

The median 1- and 3- day discharge is higher than both Stage 1 and pre-dam time periods. This increase in flows is most likely related to the early spring release and the bi-modal nature of high flows in the current operational regime. There is a large increase in the duration of high flows in these early months. The extended duration of these high flows most likely has a more significant geomorphic impact than the increase in base flow. Conversely, peak flow magnitudes have slightly decreased, as has the peak flow duration (Figure 4.14).
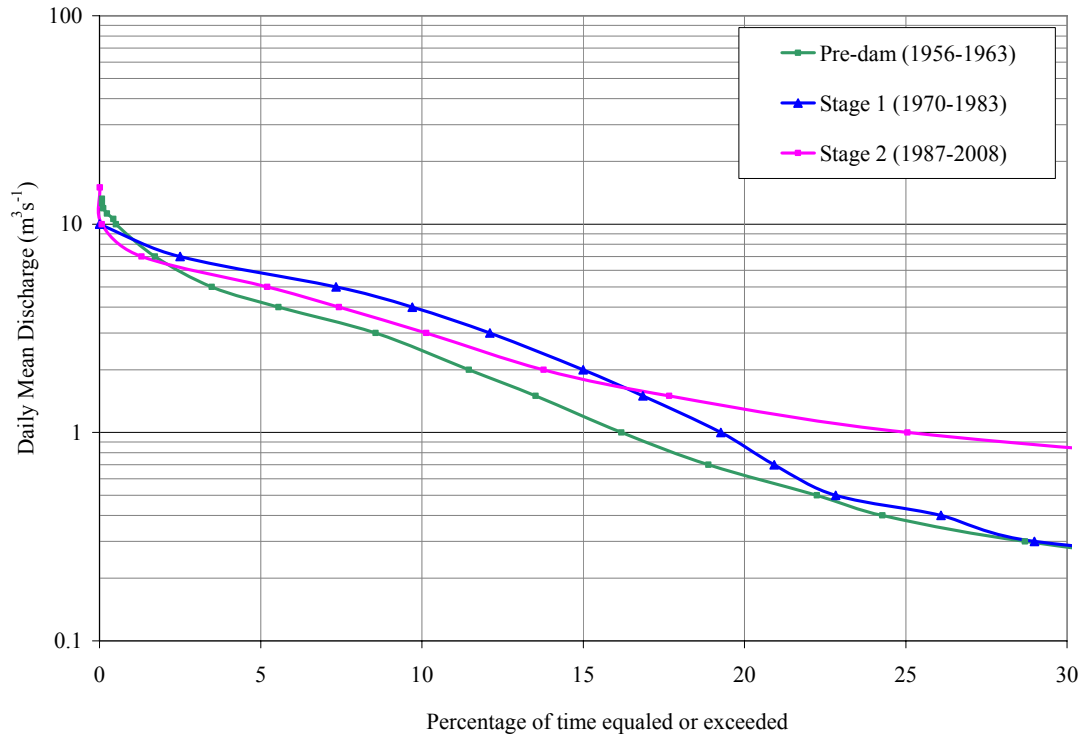
Figure 4.14: Flow duration curve for three flow eras, depicted for higher flows of less exceedance probability (0-30%).

Group 5- Rate and frequency of changes in discharge

The rate of the drop in the falling limb of the hydrograph has changed significantly under the different regulation scenarios. This increase in the subsidence of the water column leaves saturated banks unsupported because the groundwater drops less quickly than the rate of dropping surface water. The impacts on bank erosion of this situation are discussed in more detail in Section 4.3.

Table 4.5: Direction and magnitude of change when comparing discharge data of the three operational regimes.

Hydrologic Attributes	Pre-dam 1956-1963	Stage 1 1970-1983	Stage 2 1987-2008	Pre-dam vs. Stage 1		Pre-dam vs. Stage 2		Stage 1 vs. Stage 2	
				Percent change	Significance count	Percent change	Significance count	Percent change	Significance count
Group 1: Magnitude of monthly water conditions									
	Median (m³/s)	Median (m³/s)	Median (m³/s)						
January	0.09	0.11	0.44	22	0.29	389	0.00	287	0.0
February	0.09	0.13	0.48	44	0.19	433	0.00	276	0.0
March	0.1	0.14	0.5	40	0.19	400	0.00	302	0.001
April	0.15	0.14	0.80	-7	0.75	433	0.00	454	0.0
May	2.1	2.7	3.85	29	0.29	83	0.005	43.1	0.04
June	3.2	5.6	2.2	75	0.03	-31	0.55	-60.5	0.02
July	0.37	1.0	0.59	170	0.02	59	0.00	-42.7	0.07
August	0.17	0.16	0.48	-6	0.76	182	0.00	206	0.0
September	0.13	0.11	0.46	-15	0.32	254	0.00	301	0.0
October	0.16	0.1	0.45	-38	0.27	181	0.00	353	0.0
November	0.12	0.11	0.48	-8	0.65	300	0.00	335	0.0
December	0.11	0.11	0.48	0	0.96	336	0.00	320	0.0

Hydrologic Attributes	Pre-dam 1956-1963	Stage 1 1970-1983	Stage 2 1987-2008	Pre-dam vs. Stage 1		Pre-dam vs. Stage 2		Stage 1 vs. Stage 2	
				Percent change	Significance count	Percent change	Significance count	Percent change	Significance count
Group 2: Magnitude and duration of annual extreme water conditions									
	(m³/s)	(m³/s)	(m³/s)						
Annual minimum 1-day	0.07	0.04	0.43	-39	0.31	511	0.00	895	0.00
Annual minimum 3-day	0.07	0.04	0.43	-39	0.39	511	0.00	895	0.00
Annual minimum 7-day	0.07	0.05	0.43	-26	0.47	511	0.00	721	0.00
Annual minimum 30-day	0.08	0.09	0.43	7.9	0.89	435	0.00	396	0.00
Annual minimum 90-day	0.1	0.1	0.44	1.5	0.90	342	0.00	335	0.00
Annual maximum 1-day	6.5	7.5	7.2	15.6	0.22	10.2	0.46	-4.7	0.65
Annual maximum 3-day	6.2	7.5	7.0	21.1	0.18	13.6	0.5	-6.3	0.51
Annual maximum 7-day	5.7	7.3	6.2	27.5	0..05	8.5	0.38	-14.9	0.13
Annual maximum 30-day	4.3	6.1	5.3	42	0.03	23.9	0.04	-12.7	0.20
Annual maximum 90-day	2.4	3.5	2.9	44.8	0.03	19.6	0.08	-17.4	0.11
Base Flow Index	0.10	0.06	0.39	-0.04	0.13	290	0.00	532	0.00
Group 3: Timing of annual extreme flows									
Julian day 1-day minimum	264	240	275	-9.3	0.42	4.2	0.56	14.8	0.18
Julian day 1-day maximum	151	158	145	4.3	0.51	-4.0	0.49	-8.0	0.32
Group 5: Rate and frequency of water condition changes									
	(m³/s/day)	(m³/s/day)	(m³/s/day)						
Rise rate	0.07	0.07	0.06	2.14	0.98	-18.6	0.49	-20.3	0.8
Fall rate	-0.03	-0.05	-0.06	66.7	0.05	113	0.00	28	0.25
Number of reversals	45	46.5	48	3.33	0.83	6.7	0.64	3.2	0.85

Table 4.6: Flow duration and magnitude information for each flow era, calculated in the IHA analysis

Group 4: Exceedance probabilities

Exceedance Probability (%)	Pre-dam period: 1956-1963 (8 years)	Stage 1 period: 1970-1983 (14 years)	Stage 2 period: 1986-2008 (23 years)	Pre-dam compared to Stage 1	Stage 1 compared to Stage 2	Pre-dam compared to Stage 2
	Flow Value (m^3/s)			Percent change		
1	8.53	7.59	7.21	-11	-5	-16
5	4.15	5.85	5.02	41	-14	21
10	2.34	3.85	2.97	65	-23	27
15	1.14	2.00	1.76	75	-12	54
25	0.37	0.50	0.99	34	98	166
50	0.16	0.14	0.52	-10	266	230
75	0.10	0.10	0.44	4	342	360
80	0.09	0.09	0.43	-2	398	386
85	0.08	0.09	0.43	7	398	435
90	0.07	0.06	0.43	-21	651	494
95	0.06	0.03	0.41	-48	1328	639
99	0.05	0.01	0.14	-71	921	198

4.1.3   RESULTS OF TESTING HYPOTHESIS 1

($H_{o(1)}$): Dam operations have not significantly altered flow regime characteristics compared to an unregulated time period.

Although the hydrology had not dramatically shifted between the pre – dam time period and

Stage 1, results do not support Ho(1) for current dam operations. Regional regression analyses

indicate a dramatic increase in the frequency of peak flows on the annual and biannual

recurrence interval under the contemporary regime. Flows that have the probability to be

exceeded 90% of the time under current operations had the probability of exceedance of only

30% historically. Low flow discharges have increased greatly under the current operational

regime when compared to historical, pre-dam conditions. The discharge associated with flows

recurring every 1 to 5 years has also significantly increased. Extreme high flows have increased

slightly, and the timing of flow releases has shifted to earlier in the spring. These results are

supported by both the frequency duration curve analyses and IHA analyses.

Graf (2006) presents the metric ratio of the storage capacity of the reservoir to the annual mean

discharge, which he identifies as a good indicator of the potential footprint of a dam on the

environment downstream. If the reservoir to annual yield ratio is greater than one, Graf showed

that dams have the ability to greatly influence the hydrologic regime in the channel. If the ratio

is less than one, then that potential is much less. The storage capacity of Hog Park Reservoir

increased from 3.7 million m3 to 27.9 million m3 between Stages 1 and 2, with a ratio increase

from an average of 7.3 prior to the expansion of the dam to 46.1 following the Stage 2

enlargement. Graf found that large rivers in the West averaged a ratio of about 20, while rivers

with large dams in the Pacific Northwest averaged a ratio of the storage capacity to total annual

discharge of 5.

Results from the IHA analysis support the alternative hypothesis that dam operations have significantly altered the flow regime characteristics when comparing the pre-dam time period to the time period following the enlargement (Stage 2, 1985). The winter and spring monthly flow metrics were determined to be significantly different, in the range of a 300% increase in base flows, increasing from 0.1 m3s-1 to 0.4 m3s-1. This significant increase in low flows may not be as influential in the sediment transport processes as the early-spring high flow release.

The low and high pulse duration changes have proven to be highly significant, as well as the fall rate. Metrics that did not test as being of high significance but may be of an added ecological importance include the timing of maximum discharge, which resulted in a decrease in magnitude of 8%, with peak flow occurring an average of 13 days earlier than historically. The annual discharge is nearly doubled because of augmentation from the Little Snake River drainage. There is an early release in the spring to allow for additional storage of spring runoff in the reservoir, causing an earlier and bimodal high flow peak. Even though the average total annual discharge has increased by 20% in Hog Park Creek, the annual 1-day maximum discharge has increased by only 10%, which is compensated by the 300% increase in base flows. The maximum to minimum annual discharge ratio for each year of record was observed to have decreased greatly. In the time series prior to dam construction in 1963, the ratio of maximum to minimum discharge averaged 52. Following 1986, the ratio averages eight, which relates to a decrease in the maximum to minimum ratio of more than 80%. All of these metrics indicate a significant decrease in the inter-annual variability in the flow regime.

The rate at which stage drops has also increased during the most recent operational period. The increased rate of drawdown may decrease bank stability. Saturated banks with excessive pore water pressures are prone to failure, especially in situations when the river stage drops more quickly than the groundwater stage (Simon et. al., 2000; Nanson and Hickin, 1986; Thorne,

1982). There is no groundwater stage data available for this site, but the hydrologic analyses

show that river stage drops more quickly than historical conditions, and this may contribute to

increased bank erosion rates since 1965.

It is important to note that the existing low flows are mandated with the intention of improving

the quantity of habitat for brook and brown trout (Hubert et al., 1997), while high flow releases

are suppressed due to the size of a culvert below the dam. During the winter, these higher than

normal base flows are believed to prevent snow bridges, leaving the channel exposed. This

allows for much greater freeze-thaw potential, which prepares banks for exacerbated erosion

during the spring (Wolman, 1959; Lawler, 1993; Couper and Maddock, 2001. The study site

was inaccessible during high flows in spring, most likely the time period of maximum erosion,

due to lingering deep snow. Inferences regarding timing and response to different stages are

developed through erosion modeling and are discussed in more detail in this section and Section

4.3.3 of the Results.

Hydrologic variables related to the duration of floods are particularly important in this study.

Because of the consistency and predictability of Hog Park Creek as a snowmelt-dominated

system, the annual snowmelt floods are important in maintaining sediment transport dynamics

and riparian vegetation recruitment (Merritt and Wohl, 2002; Stella et al., 2006). These

variables used in this analysis are determined by their correlation with the sediment transport

regime and ecological processes, as the three items are inextricably intertwined in the river

system and prove important for management considerations. Since the physical structure of

aquatic habitats is a result of the interaction between streamflow magnitude and frequency and

the physical landscape (Leopold et al.1964), a complete analysis of the diversity of flow

variables is included in this analysis. Similarly, the snowmelt hydrology maintains a high level

of predicitability in timing and the related indices correlate with the ecological function of benthic macroinvertebrates, and critical life stage survival of aquatic species.

4.1.4   ECOLOGICAL CONTEXT

Dams may alter the downstream flux of water and sediment that can, in turn, modify biogeochemical cycles as well as the structure and dynamics of aquatic and riparian habitats. A biological analysis was not included in this study, but observations relevant to aquatic biology were made during field data collection and deserve mention in this paper. During Wolman pebble counts in September 2008, an abundance of egg masses and caddis fly larvae were observed in South Fork Hog Park Creek, and very few were observed in main stem Hog Park Creek. The lack of macroinvertebrates is important because they are the foundation of the food web and impacts to them could affect the larger species that prey upon them, such as the sport fish that provide valuable economic and aesthetic benefits.

Macroinvertebrates are sensitive to different chemical and physical conditions and many aspects of the physical stream environment affect the composition and abundance of stream macroinvertebrates. These factors include substrate, current velocity, water temperature, dissolved oxygen concentration, and water chemistry. Macroinvertebrates may be specific to certain conditions, such as water temperature and substrate size, and variation in flow can cause reductions in macro invertebrate abundance and diversity (Lamberti et al., 1991). For example, significant drivers of impacts to macroinvertebrates in Hog Park Creek may be greater current velocities and channel depths during certain times of the year than optimal for some species. Increased shear stresses may hamper species establishment by increasing bed movement and faunal displacement. Preferential erosion of finer sediments combined with the reduced sediment supply results in bed coarsening and a change or reduction in habitat quality and

quantity for benthic organisms. Excess shear stress may also cause bed scour and channel incision, isolating the channel from the floodplain and disrupting hyporheic flow paths between them (Petts, 1984; Collier et al., 1996; Wondzell and Swanson, 1999). The most drastic hydrologic shift due to regulation in this study was the more than 500% increase in summer low flows. This shift occurs during the season of greatest metabolic activity for macroinvertebrates. Water storage and non-seasonal releases can severely alter downstream food webs and aquatic productivity (Wootton et al., 1996). Changes in the water quality, for example changes in water temperature downstream of a dam, can cause changes in the macroinvertebrate community. Thermal regime alterations can modify the species type and density, hence affecting the entire food web.

The timing and predictability of flows may be important for perennial snowmelt-dominated streams given the importance of such conditions during critical life history stages of riverine fauna (Richter, 2001). For example, Fausch et al. (2001) found that rainbow trout (Oncorhyncus mykiss) invasion success was best explained by the match between timing of fry emergence and the timing of months with low flood probability.

The temperature regime imposes fundamental constraints on animal physiology. Depending on the species present in the watershed, the timing of daylight, temperature or discharge may all be cues for life history stage succession. The Global Water pressure transducers installed for this study in sites 2 and 3 simultaneously collect a stage measurement along with a water temperature (Figure 4.15 shows the period of April–June 2008). As depicted in the chart, the earlier release of peak flows melt snow still present on the banks, as can be seen where the water temperature in the creek is observed to significantly drop. This reduction in stream temperature may affect seasonal cues for invertebrates. No known studies to date have examined the impact of this reduced temperature due to regulated flow releases earlier in the

season on macroinvertebrates and the food web. Similarly, Hog Park Creek no longer has snow

cover overtopping it during winter months due to the increased base flows. This consequently

affects the sunlight hours for organisms which often depend on daylight hours as cues to

different life cycle stages.
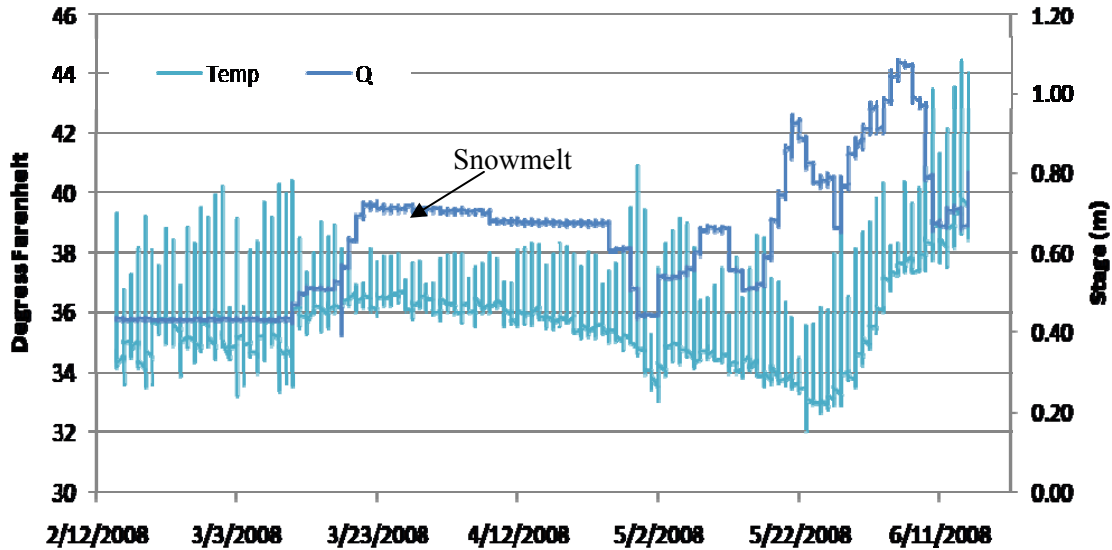
Figure 4.15: Pressure transducer data from site 2 Hog Park Creek, 2008. Note the abrupt decrease in water temperature as the river stage exceeds 0.7 meters due to melting of snow accumulated on the bank of the channel.

4.1.5   SEDIMENT TRANSPORT CONTEXT

Hydrologic changes also impact the sediment transport regime. Stream bed substrate

contributes to roughness in the channel, refugia for organisms, and morphologic stream features

for habitat diversity. It is not only the hydrograph which is of concern, but also its effect on the

sediment transport regime and the sediment budget. With the lack of sediment passage at the

dam, it is presumed that a majority of the sediment input comes from fine sediment eroded from

the banks in the upper reaches, but this is likely to be rapidly carried out of the system in

suspension. Coarse sediment is not being supplied to the system in adequate amounts to

replenish gravel bars, as observed in the field and in cross sectional analyses. Regional regressions identified the magnitude of a 2-year event to currently be 6.7 m3/s (increased from historical 3.6 m3/s). Previous research indicates that flows with recurrence intervals of approximately every two years are identified as the flow that, over the time span of the channel, does the most work mobilizing sediment and defining the channel morphology (Williams 1978, Wolman 1984). The historical 2-year event is exceeded annually during the current operational regime. The current two-year recurrence interval discharge surpasses that of the historic 5-year (6.1 m3/s) recurrence interval discharge, indicating a significant increase in the duration of time the channel experiences these formative discharges. The reduction in peak flows over time will result in less vegetation and physical habitat structure heterogeneity, a reduction in sediment input, and potentially reduce the groundwater resupply of the floodplain. In turn, this changes the availability of suitable habitat for various life stages of aquatic organisms.

4.2   HYPOTHESES 2-4: PLANFORM ANALYSIS RESULTS

In the following section, spatial and temporal changes in planform channel morphology (width, lateral migration, complexity) are measured at multiple sites from a sequence of historical aerial photographs over a 28-yr period prior to operation of Hog Park Dam in 1965, and over a 29-yr period after dam operations began. The temporal changes in planform attributes are quantitatively assessed in reference to land-use patterns, decadal precipitation trends, and pre- and post-dam time frames using multiple regression. Changes associated with the dam are examined in relation to distance downstream of the dam and base-level controls, using regression analyses, and statistically compared to a nearby undammed reference stream with similar climatic, geomorphic, and land use features (gauge details presented in Section 4.1).

Analysis of Variance (ANOVA) is a general linear model used in subsequent analyses to compare means of continuous variables across classes. A covariance analysis model (ANCOVA) combines both ANOVA and regression for continuous variables, or covariates, and specifically is used in this analysis to compare pre- and post-flow regulation time eras (Section 3.2). ANCOVA tests whether certain factors have an effect on the outcome variable after removing the variance for which quantitative predictors (covariates) account. This analysis assumes that the continuous independent variable (i.e., width, lateral migration, complexity) is significantly related to the dependent variable (level of grazing, flow era, precipitation trends, and reach-specific characteristics) and that the significance does not change between categories (or groups). The category of 'reach-specific characteristics' does not pertain to specific and identified variables, but is a proxy for inherent reach-scale characteristic. This includes parameters such as location within the watershed, morphologic attributes and distance downstream of the dam. The null hypothesis of the ANCOVA analysis is that the response variable is not significantly different between groups.

4.2.1 WIDTH

Width measurements were collected using the planform statistic tools developed by the National Center for Earth-surface Dynamics (NCED). The user digitizes right and left bank lines from ortho-rectified aerial photographs in GIS and then the tool uses an algorithm to find evenly spaced points that are representative of the center point between the bank lines. It then connects these points into a new interpolated center line. Widths, radii of curvature and arc angle measurements are collected at a user-specified distance; in this study, every three to five meters. Each reach within each time series had a minimum of 250 data points. The total channel width measurements include islands, but exclude mid-channel bars and side channels, due to the

criteria set for digitizing bank lines. Because of clarity issues in scanned and ortho-rectified aerial photos in GIS, the wetted edge of the channel was digitized in each photo instead of the vegetated bank. All photo series were taken in September/October (low flow), except 2001, which was taken in mid-June at high water.

In this section a linear multiple regression approach is used to determine correlations between width and the variables of historical land use, precipitation trends and reach-specific characteristics. A best subset regression is used to determine which predictor (independent) variables should be included in a multiple regression model, by computing all of the possibilities contained in the dataset and outputting the best models. Model suitability is based on two descriptors, Mallow's Cp and the Adjusted R2. The Cp provides a criterion for designating subsets used to select a reduced model from several regressors. The coefficient of determination, or R2, is the proportion of variability in a data set that is accounted for by the statistical model. It provides a measure of how well future outcomes are likely to be predicted by the model. The adjusted R2 improves upon R2 by adjusting for the number of variables in the model.

A basic ANOVA statistical test is used to determine whether mean widths are significantly different between the pre-dam and post-dam (Stage 2) time periods. Construction of the dam began in 1962, hence the 1966 width data are grouped into the post-dam class. The hypothesis that changes in planform variables are detectable between the two time periods was rejected, with reach 3 being the least significant with a p-value equal to 0.04.

One goal of this analysis is to compile historical anthropogenic data (magnitudes of grazing and flow regulation) and decadal precipitation trends by reach (independent variables) in order to explain changes in the dependent variable. This procedure is difficult in the river setting.

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The assumptions necessary to appropriately test multiple correlations may not be met because 1) the assumption of independence is violated and 2) the trends are not linear through time or by variable. The assumption of normality is satisfied by taking a subset of the entire population, which created an acceptably normal distribution. This procedure, known as pseudo-sampling, also aids in satisfying the assumption of independence. A robust model is used, Proc Mixed in SAS, which can accommodate data sets that do not satisfy the assumption of homoscedascity of variance. The independent variables are categorical and include grazing (three levels - none, low, moderate), decadal precipitation trends (two levels - wet, dry), year of the aerial photo series (six levels - 1936, 1955, 1966, 1973, 1983, 1991, 2001) and flow era (three levels - no regulation, moderately regulated, heavily regulated).

Grazing levels were derived from a Medicine Bow report by Wendy Haas (1979) as partial fulfillment for her Master of Science. The report discusses the Medicine Bow National Forest in general, with specifics dates and grazing level information specific to Hog Park Creek. Grazing level information is presented in Table 4.7. Decadal precipitation trends were derived from data from the National Climatic Data Center, which identifies trends of below and above average precipitation levels (Figure 4.16). Bank stabilization efforts in the 1980's likely have effects on channel width, but are not included in these analyses due to limited information on them and their variability in complexity and scale. The matrix in Figure 4.17 represents the data used in the multiple regression. The analyses included interaction terms.
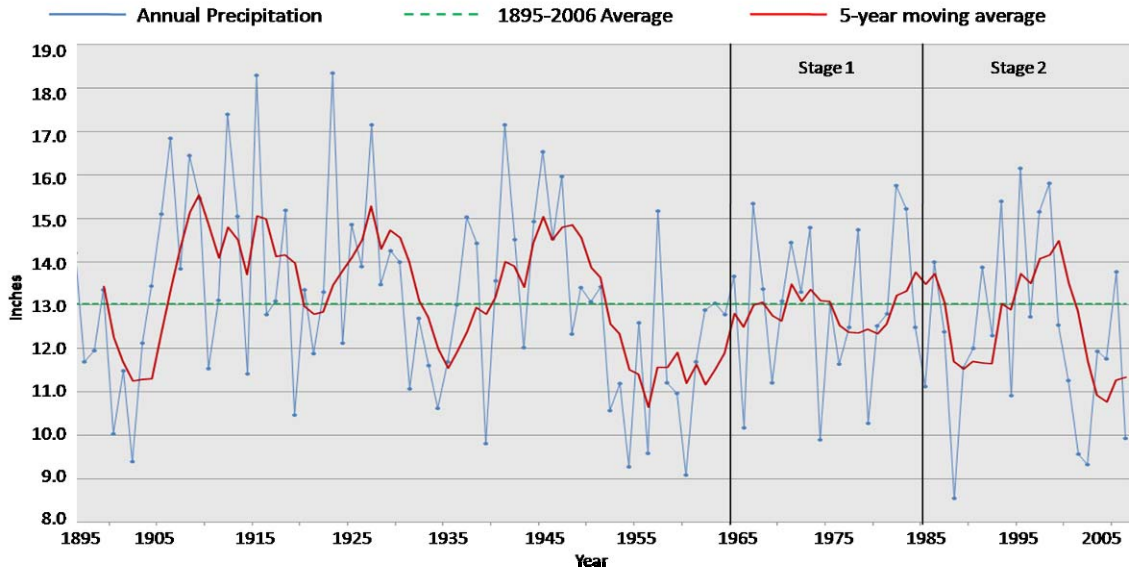
Figure 4.16: Wyoming historical precipitation trend information provided at NCDC website.

Table 4.7: Timeline of the changes in the relative magnitude of grazing in the Hog Park Creek study areas (information derived from Hass, 1979).

Year	Description of changes and characteristics of grazing management
Pre - 1960's	Heavy impact sheep and cattle grazing
1962	Sheep grazing discontinued; Cattle grazing continues at high levels.
1978	Grazing levels reduced to relatively moderate impact in all reaches.
1989	Grazing magnitude reduced to very little impact in reach 1 because of installation of exclusion fencing. Grazing impact magnitude remains low to moderate in reaches 2, 3 and 4.

Figure 4.17: The relative influence of land use, climate and flow regulation through time in Hog Park (reaches 1, 2 and 3) and South Fork Hog Park Creeks.

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The multiple regression summarized here is best used as an indicator of trajectory and relationships, but the p-values should be viewed with caution. For the regression analysis, an alpha < 0.05 is considered to be significant. Such a strong level of significance is used due to the potential violation of the requirement for points sampled independently. Subsampling was used to satisfy the requirement, but ad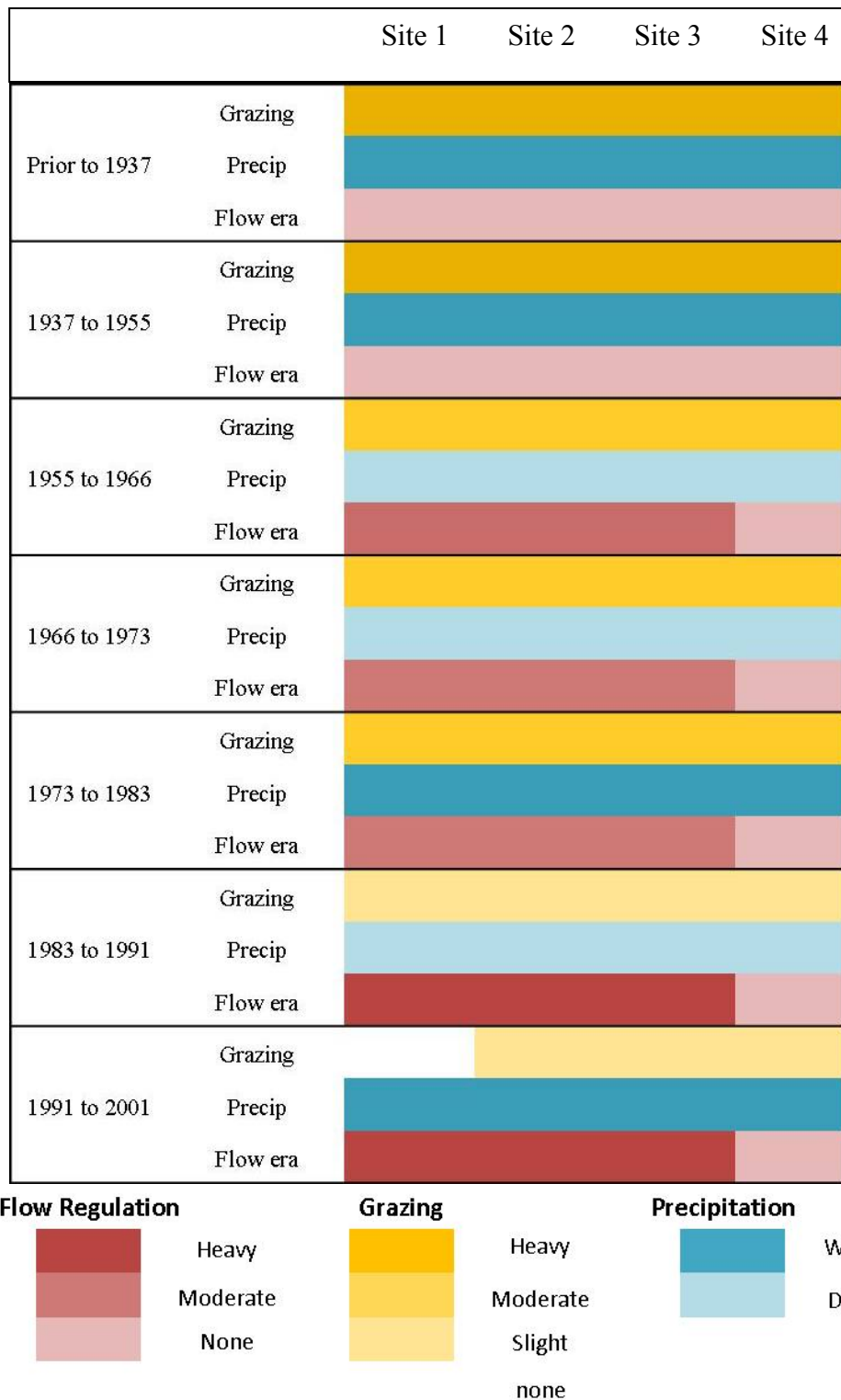ditional caution is taken for evaluating the p-value in this case. Table 4.8 lists the single parameters and interactions terms that tested as significant explanatory variables for changes in average reach-scale width through time.

Table 4.8: Best model subset using multiple regression

Parameter	Estimate	Pr > |t|
Reach 1 * year 1955	4.0	0.0001
Reach 3	2.6	0.0005
Regulated flow era	2.2	0.04
Year 1991	-1.3	0.08
Reach 1 * year 1937	3.5	0.0009
Reach 2 * year 1955	2.2	0.04

The single effects model indicates that flow regulation (1965- 1985) and reach (3) are highly significant (both p < 0.001), while grazing and year (a proxy for precipitation) are not (p = 0.13 and 0.05, respectively). The moderately regulated flow era represents the time period 1965 – 1985, while the heavily regulated flow era spans 1985 – 2008, as determined in hydrologic analyses. The heavily regulated flow era tested nearly significant, with an alpha = 0.13. The Stage 1 operational regime nearly tested as significant when interacting with reach 1, with an alpha = 0.09. This suggests that dam operations, regardless of location in the watershed, precipitation trends and grazing levels, significantly explain an increase in average width.

Location within the watershed also plays a role in variations in width throughout the basin.

Reach 3 is a highly significant single effect, meaning that because of its location in the

watershed and reach-scale characteristics, reach 3 channel widths are greater than the other

reaches.

The interaction terms of reach 1 and 1937, and reach 1 with 1957, explain an exceptionally

large amount of variation in channel widths. The earliest aerial photographs and the reaches

most proximal to the dam are highly correlated with variation in width, presumably related to

differences in channel complexity. Reach 3 is also shown to be significantly different, which

indicates that neither land use nor flow regulation improves the correlation with reach 3.

The year 1991, and the airphoto series subsequent to dam expansion in 1985, also test

significant in the single effects model. The years are placed in the model as a categorical proxy

for precipitation values. Precipitation data from the National Climatic Data Center (NCDC) and

the Wyoming Climate Center for the Webber Springs SNO-TEL gauge data are discussed here

in conjunction with 3-year moving averaged discharge data to explain the correlation between

precipitation trends and annual stream discharge characteristics. It is my assumption that years

with relatively high levels of snow accumulation may not directly relate to channel widths

because, due to flow regulation and augmentation, snow pack accumulation does not correlate

with peak flow discharges in Hog Park Creek. For example, the highest annual maximum

discharge occurred in 2005, but corresponds with a relatively average snow accumulation of

108 cm for the year. The second highest 3-year average discharge occurred between 2000 and

2002, with a relatively low average annual snowpack of 80 cm. However, the annual maximum

precipitation accumulated in the year 1982 (135 cm) and corresponds with a relatively high flow

year. The maximum annual 3-year average flow occurred in 1997-1999 and has a

correspondingly high precipitation average of 120 cm (50 in). Over the period of record for the

Webber Springs gauge, 1979-2008, the years with the highest precipitation include 1982 (141 cm), 1997 (134 cm), 1995 (128 cm), 1984 (123 cm), 2006 (121 cm) and 2008 (117 cm). However, the decade preceding the 1991 photos was drier than average. Prolonged drought, or prolonged wet periods, over time, will affect channel widths through channel widening or narrowing, vegetation species shifts, and potential level of grazing impacts if forage elsewhere is sparser. Historically, widespread droughts in Wyoming, as determined from stream flow records, were most notable during three periods: 1929 to 1942, 1948 to 1962, and 1976 to 1982. The driest years in the Webber Springs record include 2002 (70 cm), 1987 (70 cm) and 2001 (76 cm). The year of 1936 is notably the driest year of the 21st century as recorded by state records.

The significance of the 1991 widths is assumed to correlate more strongly to dam operations than precipitation levels, since 1983-1991 was a relatively dry period, but the drought technically ended in 1982. Notably, grazing effects did not test significant in the single effects model nor in any interaction terms, indicating that grazing levels may not significantly explain variation in channel widths.

Width measurements with distance downstream from Hog Park Dam are displayed in Figure 4.18 for the years 1955, 1983, and 1991. Important to note is the nonlinear trends through time in each reach, including reach 4. Linear trends can be expected in reaches not experiencing major perturbations as they adjust to downstream changes in climatic, geologic and topographic controls. The peak in 1955 in the lower extent of reach 1 results from ponded water behind a beaver dam. Widths are highest directly downstream of the dam in 1983 during the enlargement construction process. Widths are greater in reach 1 in 1991 and 2001 as compared with earlier years and these most recent aerial photo series in reach 1 depict a scenario of continued widening.

Prior to dam installation, reach 2 follows similar trends as reach 1, but the magnitude of change is muted, or dampened, in comparison with reach 1. Variability in widths is markedly decreased in reach 2 between 1955 and 1983. The channel narrows in reach 2 during initial dam construction, and then increases following expansion of the dam in 1983, although the magnitude of change in reach 2 is not as large as in reach 1. Widths continue a generally increasing trend in reach 2, surpassing those of reach 1, through the latest aerial photograph series in 2001. The later widening in reach 2 may be a delayed response to flow regulation. The reduction in width in reach 1 between 1991 and 2001 coincides with a reduction in side channels, gravel bars, sinuosity and overall complexity in the channel (including beaver dams). Active channel area may not actually be reduced, but more confined to a homogenous, single-thread channel.
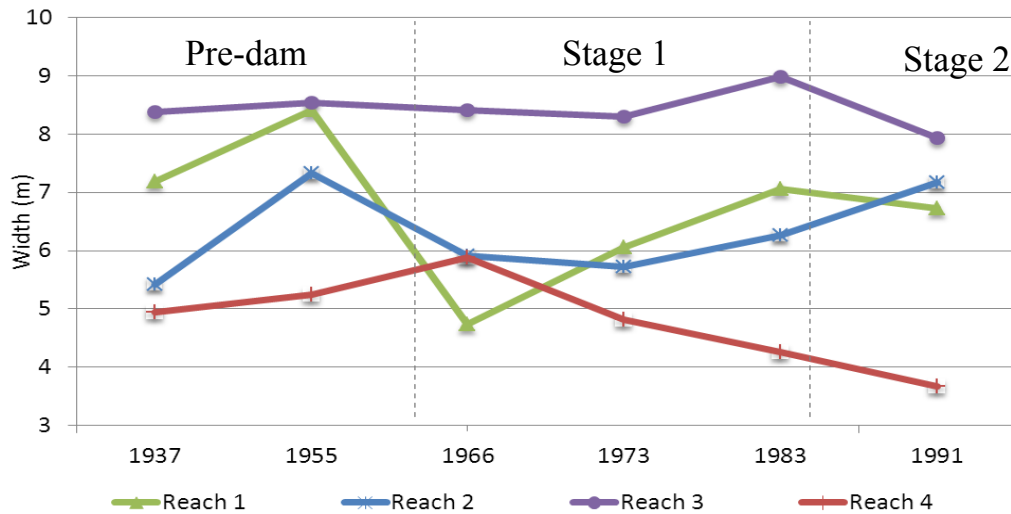

Figure 4.18: Average reach-scale width measurements as measured in GIS from aerial photographs

Reach 3 is in the main channel of Hog Park Creek and the majority of its flow is regulated by Hog Park Dam, but it is below the interception of the unregulated flow of South Fork Hog Park

Creek, and the trends in width are variable. Responses to flow regulation in reach 3 may be muted compared with the upstream reaches. The reach experiences channel widening, but the changes through time are less dramatic than compared to reaches 1 and 2. However, width decreases in reach 3 between 1983 and 1991. The reduced channel width in reach 3 is not interpreted to be a reduction in bank erosion, but a consequence of a loss of morphologic complexity and sinuosity. Reach 4 is the reference channel in that it is unaffected by flow regulation, but widths vary in a nonlinear fashion through time as well. Multiple factors may be influencing planform change in reach 4, most notably impacts associated with road crossings, the removal of beaver, and land use in the upper watershed (most notably logging and grazing). Trends in changes in width may be observed through time and one would expect this change to be of varying magnitude, but similar direction across all reaches if precipitation is the only changing variable. Flow regulation may be a significant factor in changes in reaches 1 and 2, but confounding this is the presence of grazing. Increases in mean widths are observed to occur in reaches 2 and 3 in the 1980's, while reach 1 displays a decreasing trend. Specific explanations for the observed trends in planform change are not addressed in this study. However, reasonable interpretations may be made with respect to numerous factors, as discussed in the introductory section of this thesis. This distance downstream of the dam will have a spatial effect on planform changes, as well temporal differences, in the extent and timing of responses to perturbations. Proximity to local base level controls may also affect the channel adjustment process. Reach 1 has a base level control immediately downstream where the channel becomes underlain by bedrock and gradient increases. Reach 3 also has a bedrock control immediately downstream of the reach. However, reach 2 does not have a significant control in the downstream direction. The lack of a base control feature allows perturbations to travel throughout reaches and potentially cause delayed, compounded, and/or complex

responses. Instream structures were placed throughout reaches 1, 2 and 3 in the 1980's to reduce erosion in the reach. The boulders placed have caused additional bank scour and have also affected the bank erosion rates, but on a more site-specific scale. The timing of bank erosion responses to the dam, as a function of spatial proximity to the dam, is illustrated in Figure 4.19.

A key difference between width changes prior to the dam and following flow regulation is the nature of the widening. More complexity is observed in the earlier channels in the form of side channels and gravel bars, often created by beaver activity, whereas increasing width post-1965 is not due to additional channel complexity, but to less variability and increasingly homogenous channel widths. Occasional multiple channel segments have evolved into single-thread channels with reduced sinuosity. Measures of channel complexity are discussed in more detail in Section 4.2.3.

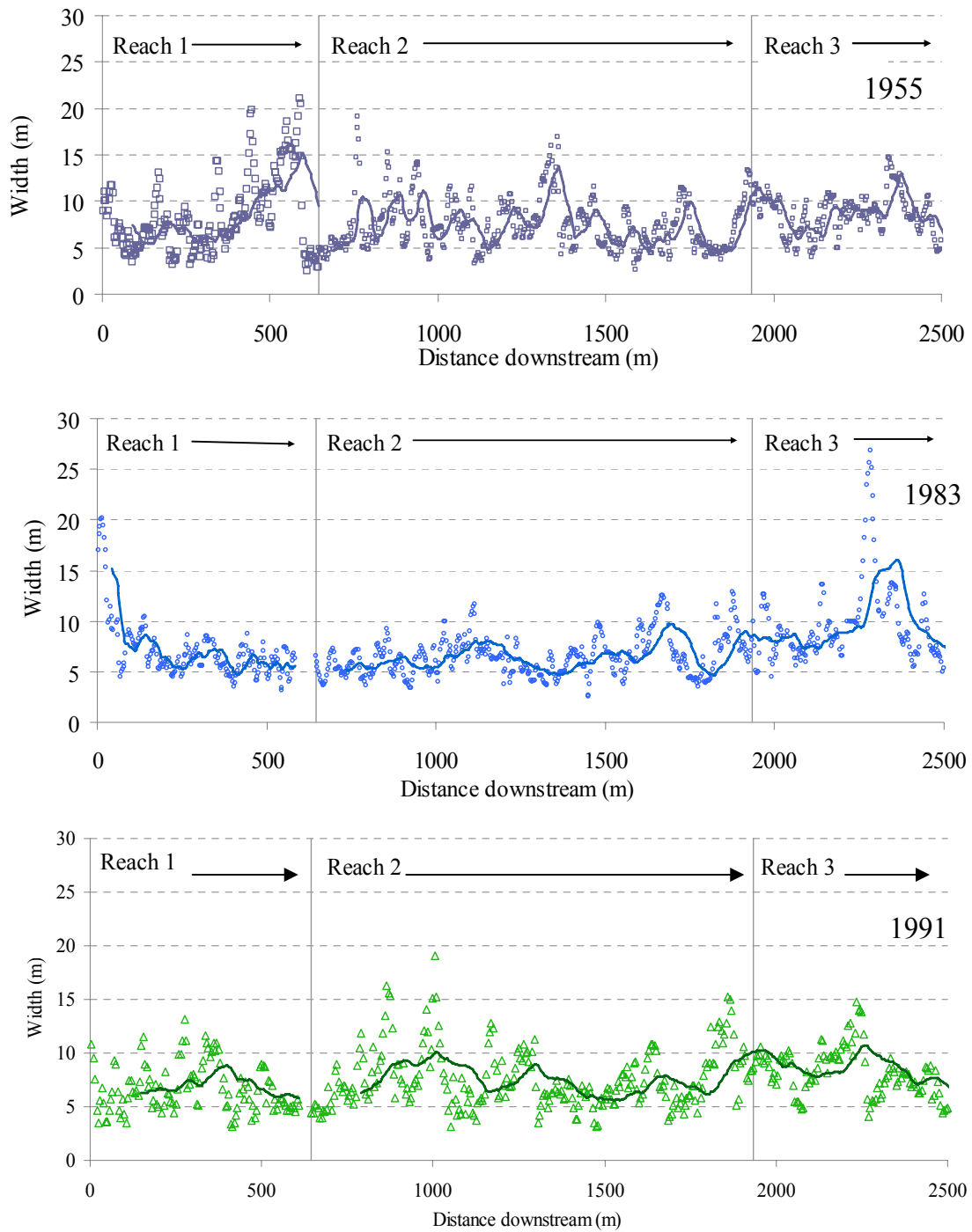Figure 4.19: Average amounts of erosion with distance downstream of Hog Park Dam derived from aerial photographs. The 1955 data represent pre-dam channel widths, 1983 follows the construction of the dam in 1965, but is prior to the completion of the enlargement in 1985 (although construction began in 1982), and 1991 represents 6 years after completion of enlargement and subsequent increase in flow augmentation.

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4.2.2   LATERAL MIGRATION

Applying the NCED Stream Restoration Toolbox Planform Statistics tool, right and left banks

are digitized from the 1937, 1955, 1966, 1973, 1977 (limited extent), 1983, and 1991 air photos

and used to generate river centerlines. Comparing the location of the centerlines of subsequent

years has allowed for the calculation of an average meander migration rate over that time

period. The graphs in Figure 4.20 and Figure 4.22 display normalized migration rates (total

migration length as a ratio to reach length) through the time series of the aerial photographs.

Lateral migration rates across all reaches follow variable trends through the 1980's and then

experience a drop in rate from 1991 to 2001. Reach 4, the reference reach, follows a generally

increasing trend from the 1930's through the 1970's, and drops slightly in the 1980's (perhaps

an effect of the severe 1982 drought). Reach 1, directly downstream of the dam, experiences a

large increase in migration rate during the expansion of the dam in 1983 (Stage 2), and then

lateral migration rates drop significantly following the completion of dam expansion, a trend

opposite to the other three reaches. The dam was constructed in 1965, following which both

reaches 1 and 2 increase in lateral migration rate. Reach 3 (downstream of the confluence with

South Fork Hog Park Creek) and reach 4 (reference reach) display a decreasing migration rate.

Reach 3 experiences a sharp rise in lateral migration rate following Stage 2.

Total Stage 1 lateral migration has decreased in reaches 1 and 2 when compared with post-

regulation (Stage 2) lateral migration. However, in reaches 3 and 4, the total lateral migration

within the reach has increased following flow regulation. On an individual reach basis, the pre-

dam lateral migration rate is less than the post-dam rate across reaches 1, 2 and 3. The

magnitudes of change for reaches 1 and 2 are -0.65 and -1.0, respectively, while reaches 3 and 4

are -0.41 and -0.52, respectively. Reach 3 would be expected to have a higher lateral migration

rate due to the increase in channel size, and reach 4 as the smallest would be expected to have

the lowest rate, containing the lowest relative discharge at any given time amongst the three reaches. However, both reaches 1 and 2 are higher than 3 and 4, and the smallest, albeit unregulated reach 4, has a greater magnitude of change in lateral migration rate than reaches 2 and 3. A standard t-test suggests that the difference between lateral migration rates pre- and post-dam for reaches 1, 2 and 3 is significant at alpha = 0.10 (p = 0.06), but not for alpha = 0.05.
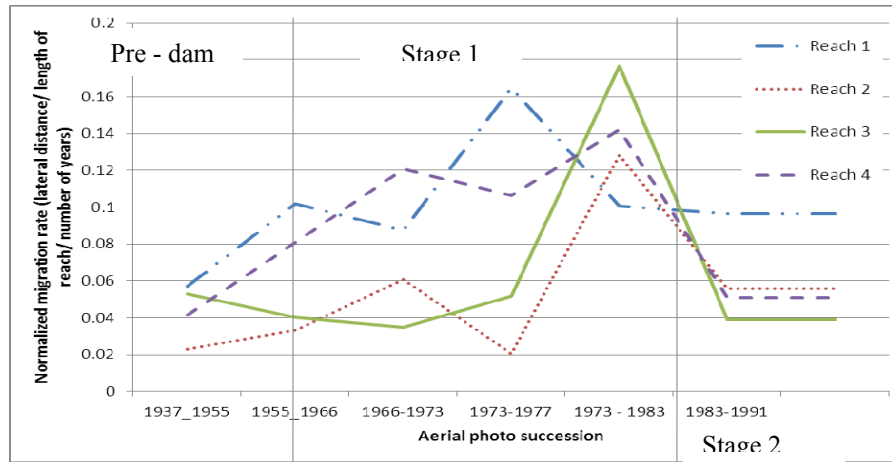
Figure 4.20: Normalized lateral migration rate by reach between successive aerial photograph years. Absolute migration distances are summed in each reach, normalized by reach length and divided by the span of time between photographs to determine an annual rate.

The coefficient of variation (standard deviation/mean) is plotted for reaches 1, 2 and 3 in Figure 4.23. The coefficient of variation in the data is greater immediately following regulation. These variations may be due to rapid adjustments (straightening and homogenization) following the lack of variability in the flow regime and pervasiveness of base flows. The coefficient of variation for several years following the regulated flow regime shows less channel change, associated with a less dynamic hydrograph. Several meander wavelengths have been reduced in the last two decades of aerial photographs.
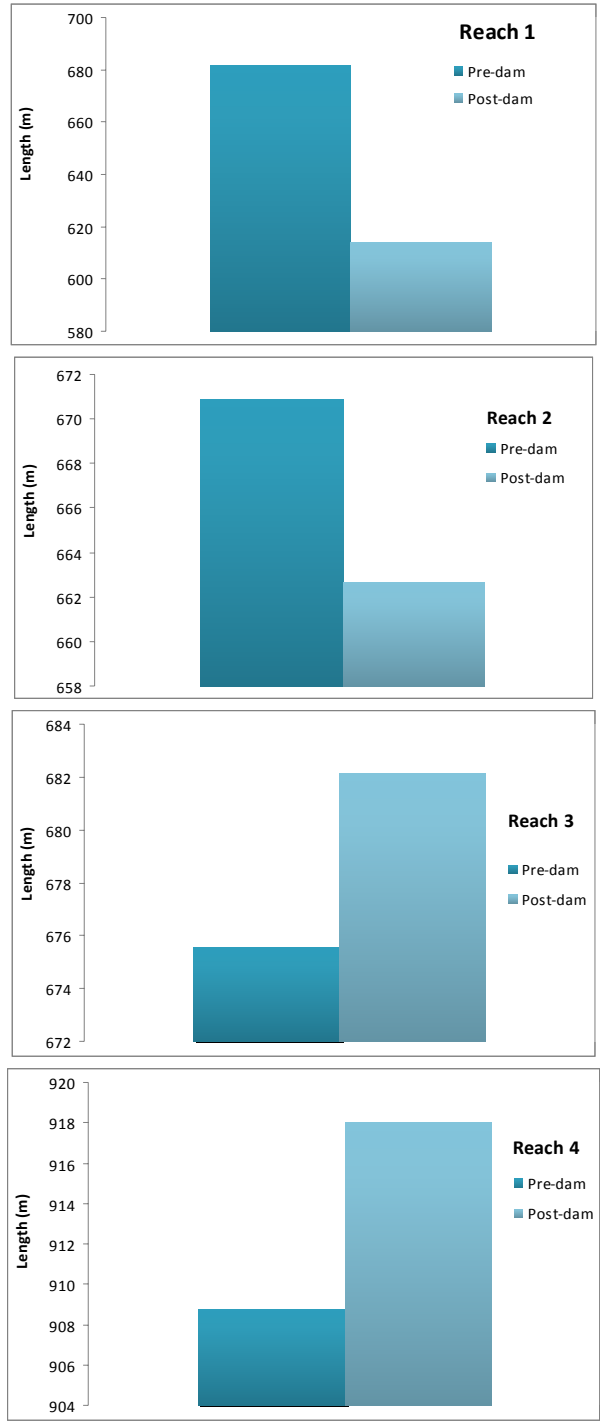
Figure 4.21: Total lateral migration distances averaged for each reach, comparing pre- and post-dam time frames. The values represent summed absolute values of migration distance length measured every 3-5 m longitudinally between each series of aerial photographs. The pre-dam data set is comprised of the changes from 1937 to 1955 and 1955 to 1966. The post-dam category includes datasets from 1966 to 1973, 1973 to 1983, 1983 to 1991 and 1991 to 2001.

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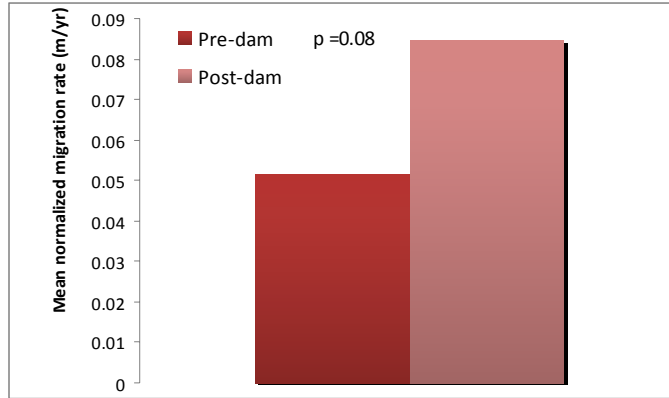
Figure 4.22: Migration rate for reaches 1, 2 and 3. The migration is calculated from the summed lateral migration distance for the reach divided by the number of years between each photo series. The rates are significant at alpha = 0.10, but not alpha = 0.05.
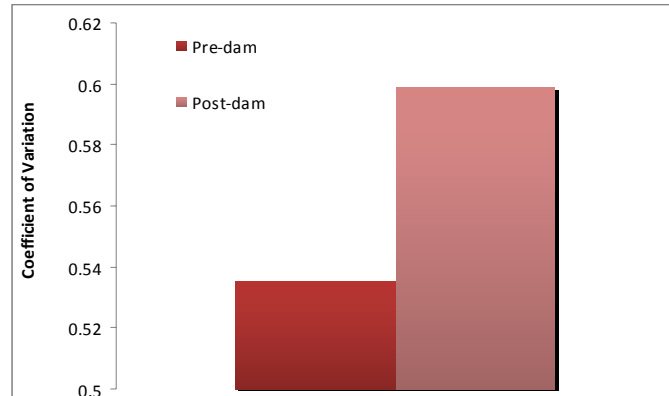
Figure 4.23: Variation in lateral migration rates comparing the period prior to Stage 1 implementation and following Stage 1 implementation.

4.2.3   COMPLEXITY

Complexity is measured using the variance of sample width in each reach. A significant change in complexity occurs in the upper reaches when testing whether the means are equal between pre- and post-dam timeframes (Table 4.9). Complexity scored relatively similarly, by reach, in 1937 and 1955. Following the implementation of Stage 1, the two uppermost reaches decrease in complexity. Values stay low through the 1983 airphoto series and begin to increase in 1991.

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Reach 2 has higher complexity values than reach 3 for the period of record, barring the photo series from years 1966 and 1973, in which they are similar. Reach 4 varies through time, with complexity slightly reduced in 1973 and beginning to rise in 2001. Complexity values in reaches 1 and 2 follow similar trends as changes in width from 1936 – 1973, but after Stage 2 the width begins to increase and complexity values decline.

Channel complexity is not well-captured in the analysis performed. Lack of airphoto quality motivated the use of the complexity metric, but it lacks the definition to correctly identify changes in channel complexity. However, visual observations of aerial photos suggest that channel complexity does decrease in Hog Park Creek following the construction of Hog Park dam and the related reduction in flow variability. Side channels have been reduced, as well as the abundance and distribution.

In general, stream morphology has homogenized, tending toward a lack of variability in width, depth and most likely velocity (Table 4.9). Gravel bar area has been reduced (based on visible analysis) as well as meander wavelength. The channel has widened and straigthened to convey the increased discharge. The greatest changes in channel complexity occur during the flow release operations of Stage 2. Lateral migration rates also display a sharp decrease for reaches 2, 3 and 4 after 1985. Lateral migration rates increase abruptly from 1966 to 1973 and remain fairly steady from 1973 to present. These results suggest that in reach 1, following the initial construction of the dam, the channel significantly adjusted its morphology to compensate for the regulated flow and sediment regimes. The reach transformed to a straightened, wider, more homogenous form. The same apparent trend occurred in both reaches 3 and 4 following Stage 2 implementation, with a reduction in lateral migration rates and an increase in channel width. Lateral migration rates are also reduced in reach 4 between 1986 and 1991, but the

change in width does not significantly increase. Channel width consistently decreases in reach

4 from 1966 through 1991.

Table 4.9: Summary of t-test results for planform characteristics testing whether the period 1936 – 1955 mean values vary significantly in comparison to the time period 1966 – 1991. No distinction is made between Stage 1 and Stage 2 time periods.

Parameter	Reach	p-value
Width	1	<0.001
	2	0.001
	3	0.07
	4	0.0001
	combined (reaches 1, 2 and 3)	<0.001
Lateral Migration	1	0.29
	2	<0.001
	3	0.04
	4	0.008
	combined (reaches 1, 2 and 3)	0.06
Complexity (width variance)	1	0.02
	2	0.30
	3	0.52
	4	0.35
	combined (reaches 1, 2 and 3)	0.21

4.2.4   RESULTS OF TESTING HYPOTHESES 2-4

The null hypotheses examine whether the specific channel form parameter has not changed as a

result of flow regulation. Each associated alternate hypothesis proposes that this parameter has

changed.

$(H_{o(2)})$: No detectable temporal changes in channel mean width have occurred since installation or changes to the dam.

$(H_{o(3)})$: No detectable temporal changes in lateral migration rates have occurred since installation or changes to the dam.

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(H$_{o(4)}$): No detectable temporal changes in complexity have occurred since installation or changes to the dam.

Hypothesis 2 is rejected in support of the alternate hypothesis that channel mean width has

changed since installation of the dam. Alternate hypothesis 3 is partially supported and

alternate hypothesis 4, involving channel complexity, is partially supported as well.

Aerial photographic and statistical analyses determined that a large majority of changes in

central tendency of the river system can be attributed to flow regulation. Width changes appear

to be influenced by flow regulation in reach 1. Changes in width in reach 2 followed similar

trends as did reach 1, but the responses are delayed and not as dramatic. The response to flow

regulation is dampened in reach 3 due to the supplemental flow of South Fork Hog Park Creek

(reach 4). Additionally, reaches 3 and 4 are both experiencing increases in width, which may

reflect additional erosion related to grazing, structures placed in the stream, proximity to the

dam and /or local base level controls. Lateral migration rates have changed but not in the same

direction and magnitude as width changes. An abrupt change is seen, however, in a dramatic

decrease in lateral migration distance following Stage 1 implementation. Mean lateral

migration rates have decreased in the upstream reaches, 1 and 2, while in reaches 3 and 4 the

mean lateral migration distance has increased. Across all reaches, normalized migration rates

compared between pre- and post-Stage 1 installation result in a p-value = 0.08. These rates

provide a description of the short-term sinuosity increase along the channel. To the extent that

sinuosity increase requires lateral migration, the rates provide a somewhat independent estimate

for the channel segments within the system undergoing lateral movement.

Proximity to the dam is observed as an influential factor on the extent and timing of planform

change. Local base level controls (for example, locations where the channel is underlain by

bedrock) appear to have a large role in controlling lateral migration rates as well as changes in

width. Both of the controls can have moderating effects, and may help in explaining why the observed changes in planform parameters vary by reach and through time. Confounding influences such as continued grazing and the placement of instream large wood and boulders may also have influenced the channel planform morphology through time. These analyses suggest, however, that the greatest influence on the channel planform through time is the hydrologic regime.

4.3   HYPOTHESES 5-7: BANK EROSION ANALYSIS

Section 4.3.2 relates field-measured bank erosion rates to cross-section-specific physical characteristics to determine predictors of reach-scale variability in erosion rates. Next, erosion pin data, with 98 erosion pins and 3 years of data, are used for the secondary analyses and will be presented in Section 4.3.2. The Bank Stability and Toe Erosion Model (BSTEM) is employed in Section 4.3.3 to determine sensitivities and influence of variability in site-specific parameters. This section concludes with an analysis using BSTEM to quantify differences in erosion of the contemporary flow regime and a flow regime derived from the pre-dam dataset.

4.3.1   CROSS SECTION ANALYSES

Two methods are used to quantify the rates of erosion and aggradation in the study sites. The goal is to identify trends in aggradation versus degradation and quantify the amounts of both between cross sections and sites. Secondarily, physical site-specific parameters are tested to determine drivers and controls on localized erosion rates. The initial analysis quantifies volumes of erosion within the active channel using WinXSPro. Repeat cross section measurements, with a total of 48 cross sections and 3-5 years of data for each, are available for the first analysis. Most cross sections were surveyed in 2007 – 2009. Only cross sections 1.0, 2.0 and 3.0 at each site were surveyed in the years 2004 and 2005. In the data summaries

below, these cross sections have an additional two years of data incorporated into the total erosion amounts.

The complex bank geometry, particularly bank undercutting (length of undercutting), prevalent throughout the sites is not captured in the cross sectional surveys due to limitations with the survey equipment. The undercutting was captured using erosion pins (2006 - 2009) and bank profile measurements (2008, 2009). The difference in area of each cross section was measured between years and overall trends were identified between sites. The area measurements were calculated within the bounds of the annually active channel, determined by the transition from vertical bank to horizontal floodplain. The top of the bank location was identified during cross section surveys and is used as the edge of the channel area measurement in this analysis. The location of the bank top, and thus the total area of the cross section, changes concurrently with adjustments in the bank (i.e., mass wasting), however slightly from year to year. Plots of cross section geometry for each cross section and each year are provided in Appendix D.

Cross sectional area changes between successive years for each site are presented in Table 4.10. Negative values indicate a decrease in cross sectional area, or aggradation, and positive values indicate an increase in cross sectional area, or degradation. The cumulative change in all sites combined across all years indicates that the area as a whole is experiencing a net increase in channel area. This means that the sediment input and the hydrology are not balanced. The causes are most likely two-fold; 1) flows have been released in such a way that erosive flows are much more pervasive, largely due to the flow augmentation, and cause more erosion compared to historical conditions; and 2) adequate sediment is not being re-supplied to the reaches downstream of the dam because sediment through-flow is blocked by the dam structure. The upper watershed is assumed to be a sediment depositional zone, more so than a sediment transport zone, and the most likely cause of net degradation is hypothesized to be due to the

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dam operations and flow augmentation. The annual hydrographs for the years of the study,

2005-2008, are provided in Figure 4.24.

Table 4.10: Change in cross-sectional area in each site across all years. Results obtained by summing changes in area in each cross section (48 total) for each year of data collection (2005-2009). In 2004 – 2005 only 3 cross sections per site were surveyed.

Total cumulative change in cross - sectional area for each site (m^2)					
Water Year (Oct. 1 – Sept. 30)	Site 1	Site 2	Site 3	Site 4	Cumulative change by year (m^2)
2004-2005	0.0	0.7	0.7	0.2	1.6
2005-2006	0.7	0.4	0.5	0.0	1.6
2006-2007	-1.7	-0.2	0.1	-0.5	-2.3
2007-2008	2.6	5.8	2.7	0.7	11.8
2008-2009	2.2	-0.2	3.0	2.5	7.5
Cumulative change by site	**3.8**	**6.5**	**7.0**	**2.9**	**20.2**

Comparing the regulated sites to the unregulated, there is a substantial difference between the

results of the change in cross sectional area. Sites 1, 2 and 3 increased in area between 3.8 and

7.0 m2 total, while Site 4 increased 2.9 m2. Site 2 cumulatively experienced net erosion

between all years except the 2006-2007 transition (Water Year 2007). The planform analysis of

the most recent air photos supports this observation of increasing width in all reaches between
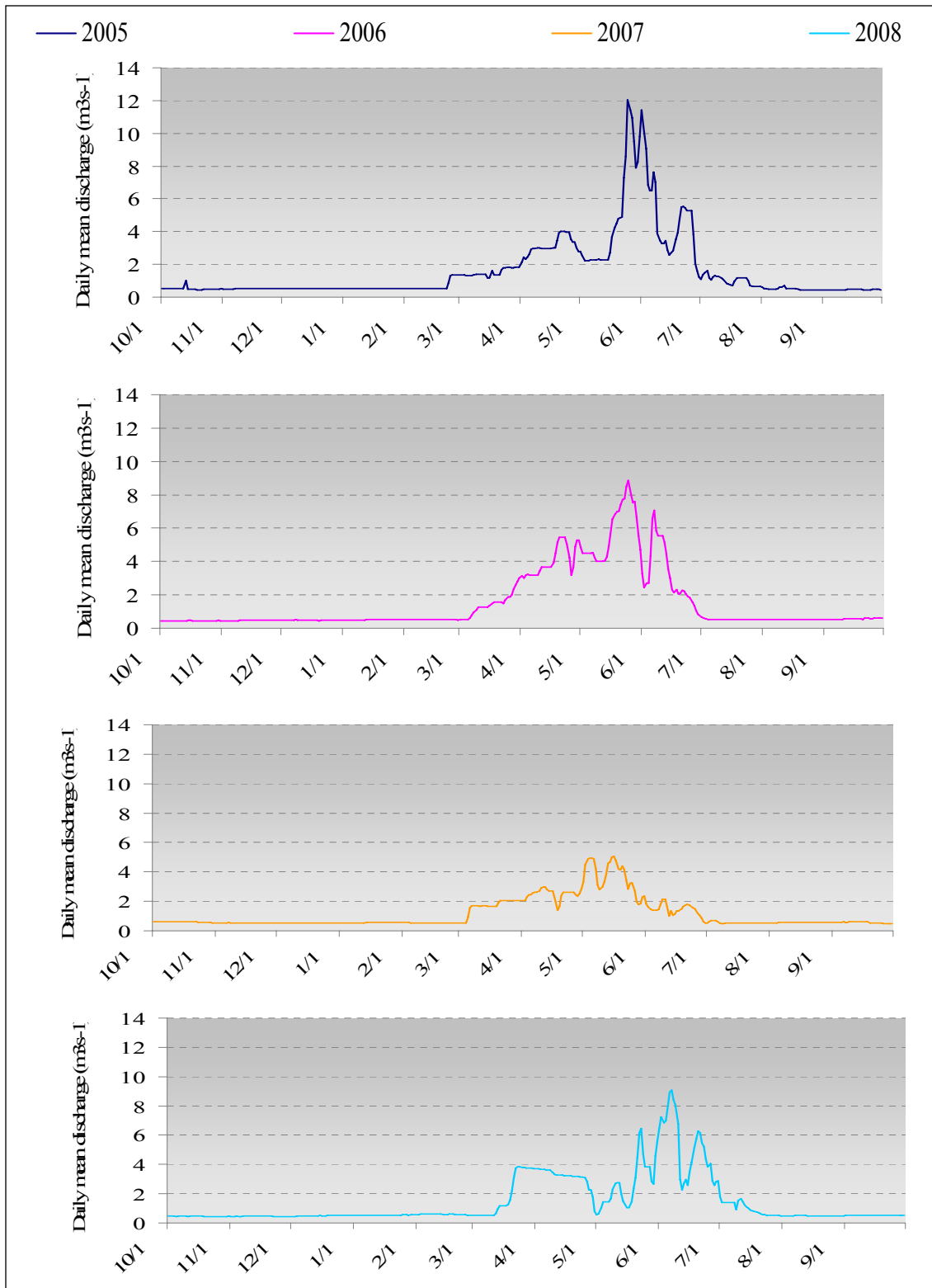
1986 -1991 and 2001.

Figure 4.24: Discharge for water years 2005 – 2008

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At all sites, channel widening has been occurring over the time period 2004-2009. Within most sites, the largest increase in active channel area generally occurs in channel bends when compared to straight channel segments where there are greater hydraulic forces acting in the bank. However, in Site 3, several cross sections in straight channel segments have larger increases in channel area than cross sections located at channel bends. Net change did not relate to drainage area, however, as Sites 2 and 3, physically separated by the confluence of South Fork Hog Park Creek, are relatively similar in net erosion amounts. These cross section analyses and field observations indicate that the lower bank, particularly transitions between soil layers, is a major component of materials being eroded, with the finer loam soils eroding preferentially. The predominant form of erosion of the banks occurs as scour and undercutting of the toe, leading to mass wasting. In the following discussion, hydraulic scour of the bank and toe is captured largely by the erosion pin data, while mass failure of the bank is captured by the changes in cross sectional area. The two analyses provide complementary information in locations with bank undercutting and complex bank morphology. Trends of erosion in each site are discussed below.

Site 1

Located approximately 400 m downstream of the outlet of Hog Park dam, Site 1 is the most upstream site surveyed (Figure 4.25). Planform analyses indicate that the channel morphology of site 1 underwent significant widening following the installation and enlargement of the dam, and in recent years has maintained a relatively stable average reach width. Historically, beaver presence created a drastically different channel than is present today, with additional ponding, backwater areas and side channels. The contemporary channel has gained a greater homogeneity without the influence of beaver dams on the hydrology.

Figure 4.26 presents the length of lateral erosion as measured during repeated erosion pin surveys. Figure 4.27 and Figure 4.28 present cross sectional area changes at repeat cross sections. Figure 4.27 displays the positive and/or negative changes in area each year at each cross section. Figure 4.28 is the cumulative amount of erosion at each cross section over time. The x-axis labels are cross section numbers with the 'L' and 'R' designating the left bank and right bank. Generally, the erosion pin measurements apply only to a specific location, and do not account for aggradation or erosion amounts in the other locations in the cross section. Cross section surveys, as measured here, do not account for undercutting of the banks, as is captured with the erosion pins, but account for net aggradation or erosion within the cross sectional area. These two measurement techniques most often agree with the magnitude of erosion measured each year, but do differ in some cases as discussed throughout this section. Most disagreement arises when scour occurs locally on the bank and at the erosion pin, but deposition, often in the form of a failed slump block, is deposited in the main channel of the cross section, often resulting in net aggradation.

Site 1 experienced the least amount of hydraulic erosion and mass wasting of the three main-stem sites surveyed, but did show greater erosion rates than Site 4, South Fork Hog Park Creek. The greatest amount of erosion in site 1 occurred in the outside of the meander bends where greater shear stresses are exerted against bank materials during higher flows (Table 4.11). The most erosion occurred at the upstream-most cross section, 0.9, which is at the outside of a tight bend. The thalweg, or main flow, of the channel is forced against the bank in this location, and with excessive turbulence continues to degrade the bank. This site experienced mass wasting of the banks in the vicinity of cross sections 2.2, 2.3 and 2.4 in 2008 and 2009. Note that cross sections 0.9, 2.0 and 2.2 all rank among the highest cumulative erosion locations. When comparing among cross sections, it is important to note that cross sections 1.0, 2.0 and 3.0 had

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additional cross section surveys completed in 2004 and 2005, which gives them two additional

data points computed in the total amount of erosion as compared to the other cross sections.
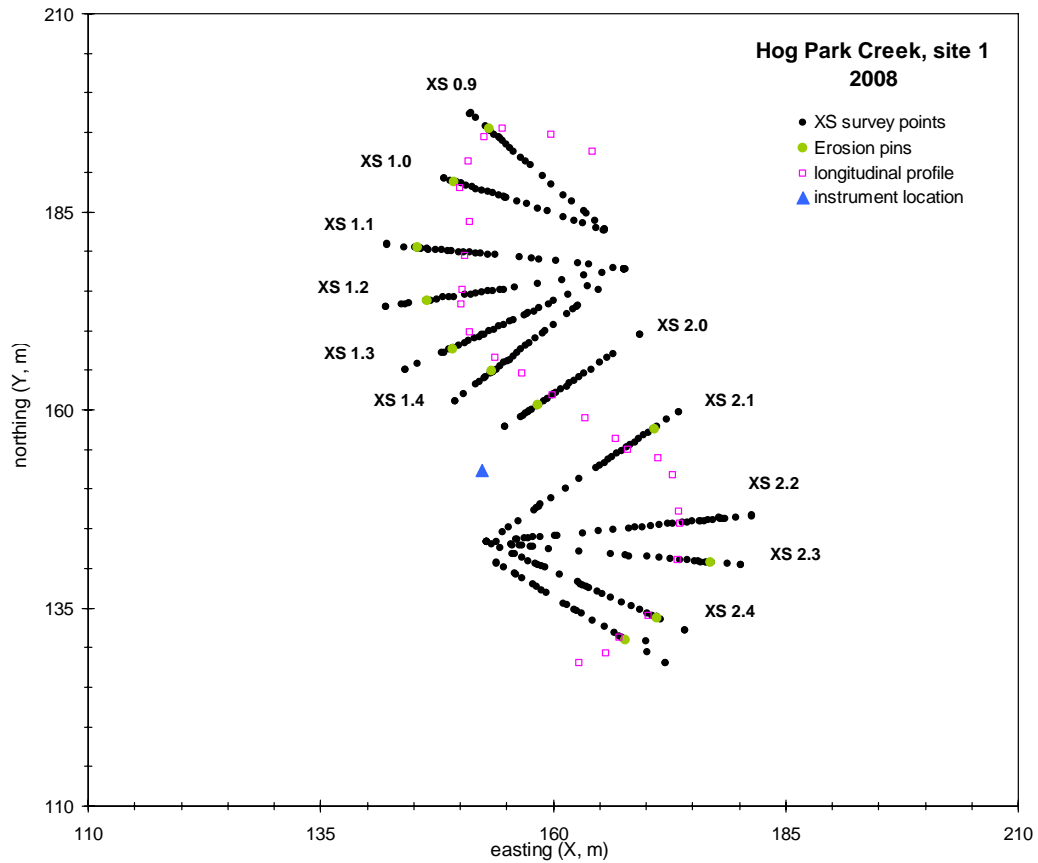

Figure 4.25: Planform schematic generated from survey data, Site 1 2008.

Through time, net erosion has occurred in the mid-length of the reach (cross sections 1.3, 1.4,

2.0, 2.1), associated with both the outside of a meander bend, and increased hydraulic scour

from the highest velocity flow adjacent to the bank at higher discharges. At the outside of

channel bends, high shear stress increases as does flow resistance. Cross section 2.2 has

experienced hydraulic scour, but bank failure has not occurred in recent years, partly due to the

extensive sedges growing on the stream bank and the added bank strength provided by their

roots. Further downstream at the bottom of the reach, cross sections 2.4 and 3.0 have

experienced a slight amount of aggradation.

Table 4.11: Summary of erosion results for each cross section, Site 1, across all years.

| Cross Section	WY 2005	WY 2006	WY 2007	WY 2008	WY 2009	Cumulative change	Location in channel planform
XS 0.9	-	-	0.2	0.7	0.6	1.5	Bend, upstream of apex
XS 1.0	0.3	0.4	-0.1	0.0	0.3	0.9	Bend, apex
XS 1.1	-	-	-0.2	0.1	-0.2	-0.3	Straight
XS 1.2	-	-	-0.1	-0.3	0.4	0.0	Bend, upstream of apex
XS 1.3	-	-	-0.4	0.6	0.3	0.5	Bend, apex
XS 1.4	-	-	-0.1	0.4	0.3	0.6	Bend, downstream of apex
XS 2.0	0	0.3	0.0	0.1	0.3	0.7	Straight
XS 2.1	-	-	-0.1	0.0	0.5	0.4	Straight
XS 2.2	-	-	-0.4	0.4	0.0	0.0	Bend, upstream of apex
XS 2.3	-	-	-0.2	0.3	0.1	0.2	Bend, apex
XS 2.4	-	-	-0.2	0.2	-0.3	-0.3	Bend, downstream of apex
XS 3.0	-0.3	0.0	-0.1	0.1	-0.1	-0.4	Straight
Cumulative Change	0.0	0.7	-1.7	2.6	2.2	3.8	
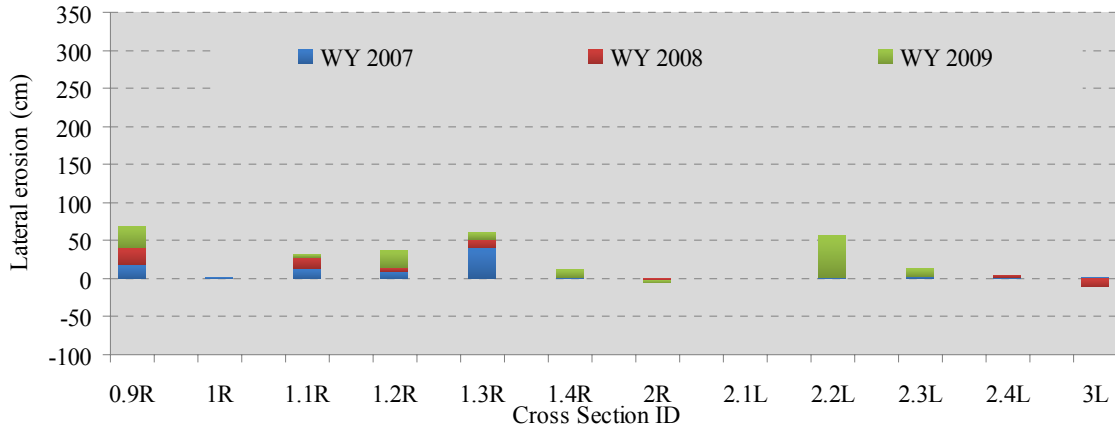
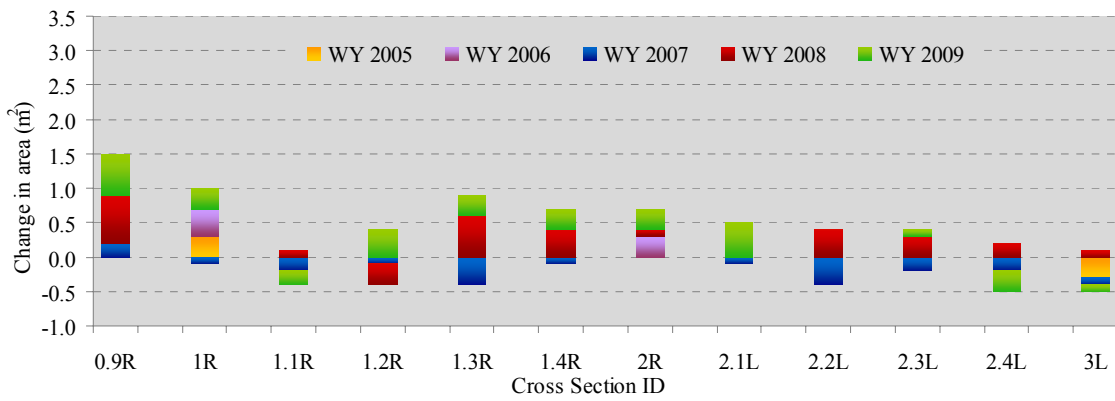Figure 4.26: Results of erosion pin surveys in site 1, 2006-2009.

Figure 4.27: Cumulative erosion in site 1 2004 - 2009, as measured by repeated cross section surveys.
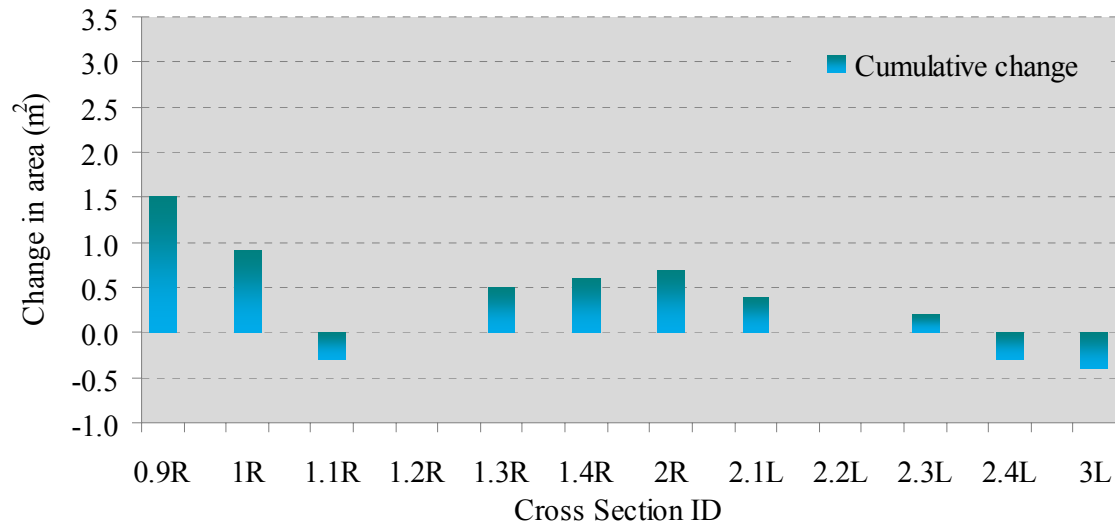

Figure 4.28: Total annual change in cross sectional area in each cross section, Site 1.

Site 2

The stream flows out of the higher gradient canyon into the unconfined meadow in which site 2 is located (Figure 4.29). No additional water sources contribute to Hog Park Creek between site 1 and 2. Site 2 is upstream of the confluence with South Fork Hog Park Creek. Along the extent of site 2, a sandy, gravelly soil layer is overlain by a finer, sandy silt soil layer. This uppermost soil layer benefits from the added cohesion provided by the roots of the riparian vegetation. The gravelly soil layers exhibit the most pervasive erosion related to hydraulic scour with the transition between the two soil layers evidently most susceptible to scour. Erosion pins along the site indicate that hydraulic scour occurs through most of the site. More scour occurs at Site 2 than at site 1and site 4, but less than site 3.

As in the other reaches, the most erosion throughout the years of study occurred along the stretch of bank that lies on the outside of the meander bends. In this section of channel the banks are more susceptible to high shear forces because the fastest velocity water in the channel is hydraulically forced along the bank, and thus the greatest amount of shear force is positioned along the bank in higher flows. Cross sections 1.0 and 2.2 experienced the most cumulative erosion at the site (Table 4.12).

In 2008, the bank in cross section 1.0 had become undercut extensively and ultimately failed, even though still attached by a dense root system. A tension crack at the top of the bank was noted during field observations. The material evacuated from cross section 1.0 may contribute to the lower erosion amounts in cross section 1.1. Cross section 1.3 also failed in recent years and in 2008 the erosion pin was found completely detached from the bank. At cross section 1.3, the bank was undercut extensively, which will ultimately lead to its failure. However, due to the tenacity of the root system of the mesic grasses, the failed block remained attached to the bank, protecting it from additional scour. The top of the bank is now positioned perpendicular to

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the channel and provides substantial protection from hydraulic forces (see Figure 4.30).

Extensive failure of bank material is also occurring along cross section 1.4, where a tension

crack persists where mass wasting has not yet occurred. All results are provided in Figure 4.31
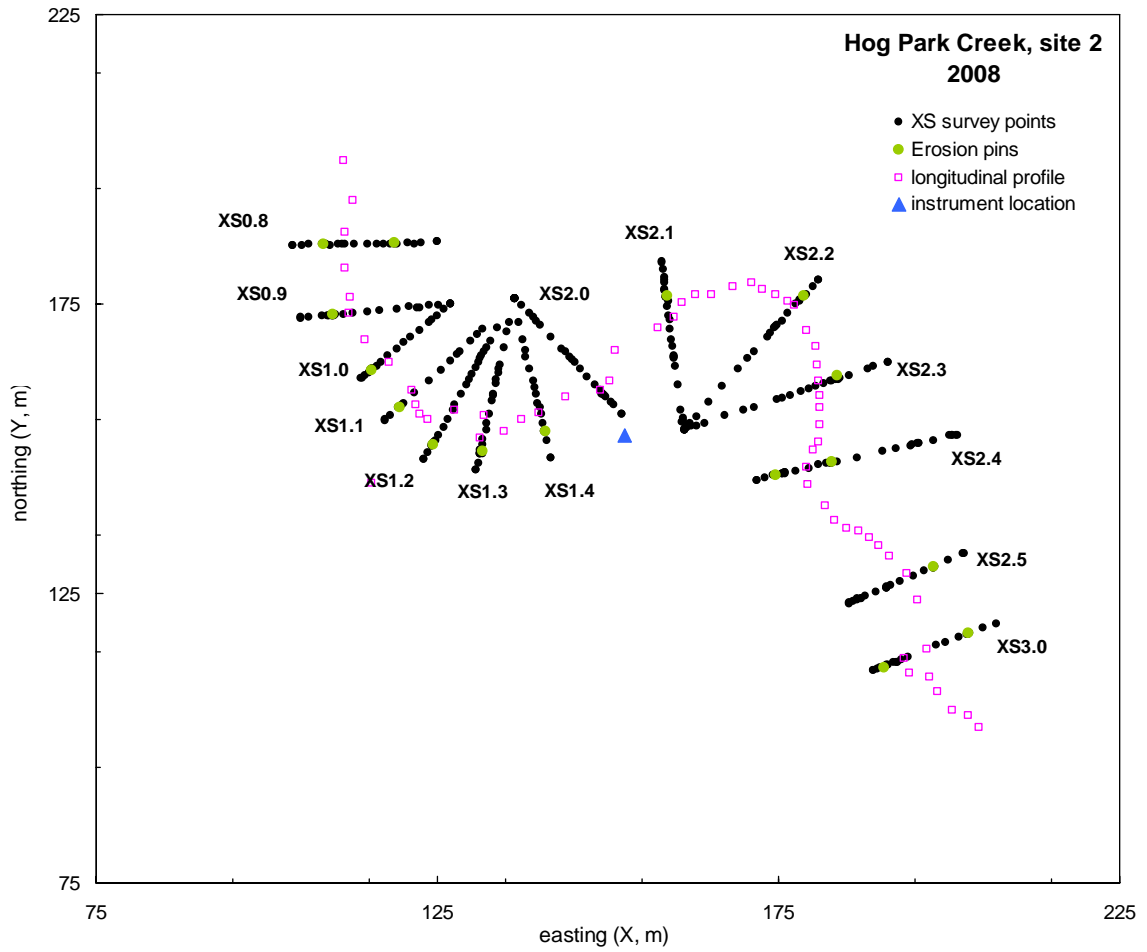
and Figure 4.33

Figure 4.29: Planform schematic of Site 2, generated from survey data, 2008.

Figure 4.30: Photo of partially failed bank in site 2.

Table 4.12: Cumulative erosion for each cross section in Site 2, across all years.

| Cross Section	WY 2005	WY 2006	WY 2007	WY 2008	WY 2009	Cumulative change	Location in channel planform
XS 0.8	-	-	-0.4	0.1	-0.2	-0.5	Straight
XS 0.9	-	-	0.1	0.0	-0.6	-0.5	Straight
XS 1.0	0.4	0.5	0.1	0.9	-0.2	1.7	Straight
XS 1.1	-	-	0.0	0.1	-0.1	0.0	Bend, upstream of apex
XS 1.2	-	-	0.2	0.5	0.2	0.9	Bend, upstream of apex
XS 1.3	-	-	0.2	-0.5	0.2	-0.1	Bend, apex
XS 1.4	-	-	-0.1	0.4	0.2	0.5	Bend, downstream of apex
XS 2.0	0.1	0	0.1	0.0	0.4	0.6	Straight
XS 2.1	-	-	-0.3	0.1	-0.2	-0.4	Bend, upstream of apex
XS 2.2	-	-	0.1	1.4	0.2	1.7	Bend, apex
XS 2.3	-	-	0.1	0.6	0.1	0.8	Bend, downstream of apex
XS 2.4	-	-	0.0	0.3	0.2	0.5	Straight
XS 2.5	-	-	-0.1	0.7	-0.2	0.4	Straight
XS 3.0	0.2	-0.1	-0.2	0.2	0.2	0.3	Straight
Cumulative Change	0.7	0.4	-0.2	**5.7**	-0.1	6.5	

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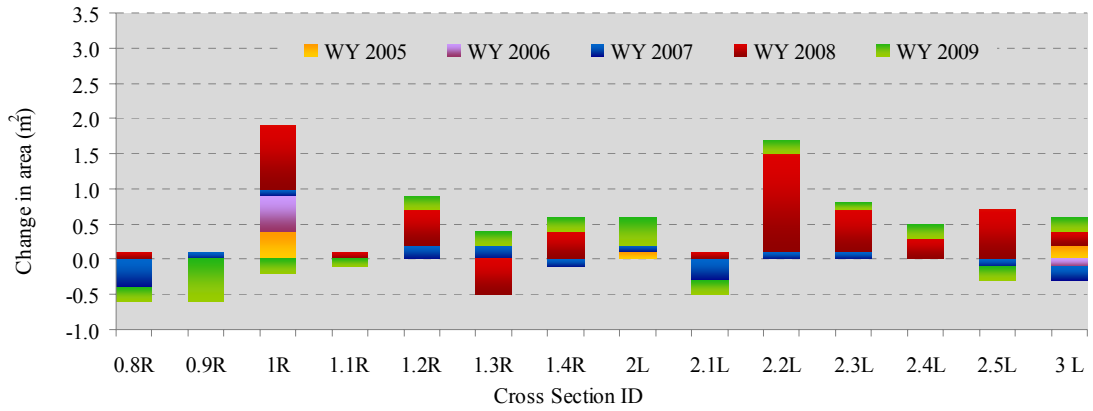
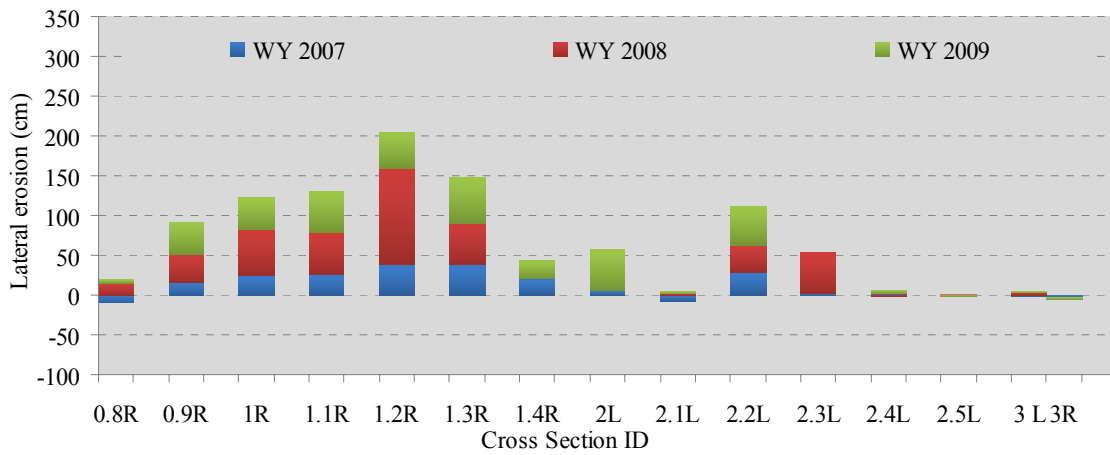Figure 4.31: Total annual change in cross sectional area in each cross section, Site 2.

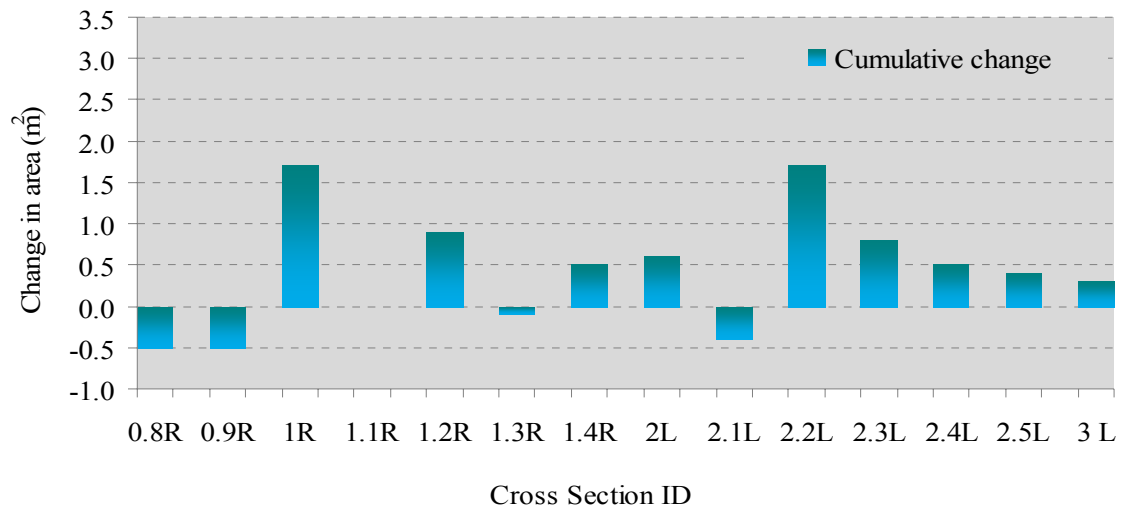Figure 4.32: Results of erosion pin surveys in site 2, 2006-2009.

Figure 4.33: Cumulative erosion in site 2, 2004 - 2009, as measured by cross section surveys.

Site 3

Site 3 is downstream of the confluence with South Fork Hog Park Creek. It is the longest site and has the largest channel capacity of the sites (Figure 4.34 through Figure 4.36). Previous beaver activity has encouraged side channels and main channel widening. There is minor beaver activity currently in the upper portion of site 3, but no dams or lodges exist today. Ephemerally wetted side channels and perennially wetted backwater areas may be attributable to past activity, however. Site 3 experienced net erosion across all years, with Water Year (WY) 2009 producing the largest change and WY 2007 the least.

Across site 3, the most hydraulic scour, as recorded by erosion pins, occurs at cross sections located in straight channel segments (Table 4.13). Cross sectional change in area indicates that cross section 1.5 has experienced the most erosion.

Soil layers in site 3 are similar to those of site 2, with a gravel and sand layer overlain by a finer, silty soil layer. In the mid- to- lower extent of the site, a third, and more gravelly layer is exposed. This layer consists of a higher proportion of gravel in a sand matrix. In the straight sections of the site, upper bank grasses grow thick, and their massive root structure provides added cohesion to the bank. In the upper extent of the site, upper bank vegetation is sparser and in some areas, specifically cross sections 1.5 and 1.6, cattle trampling has left the bank top denuded of mesic vegetation (Figure 4.36). Here the bank vegetation is sparsely composed of more xeric species, for example sage brush, instead of the woody shrubs and mesic grasses that are established elsewhere at the site.
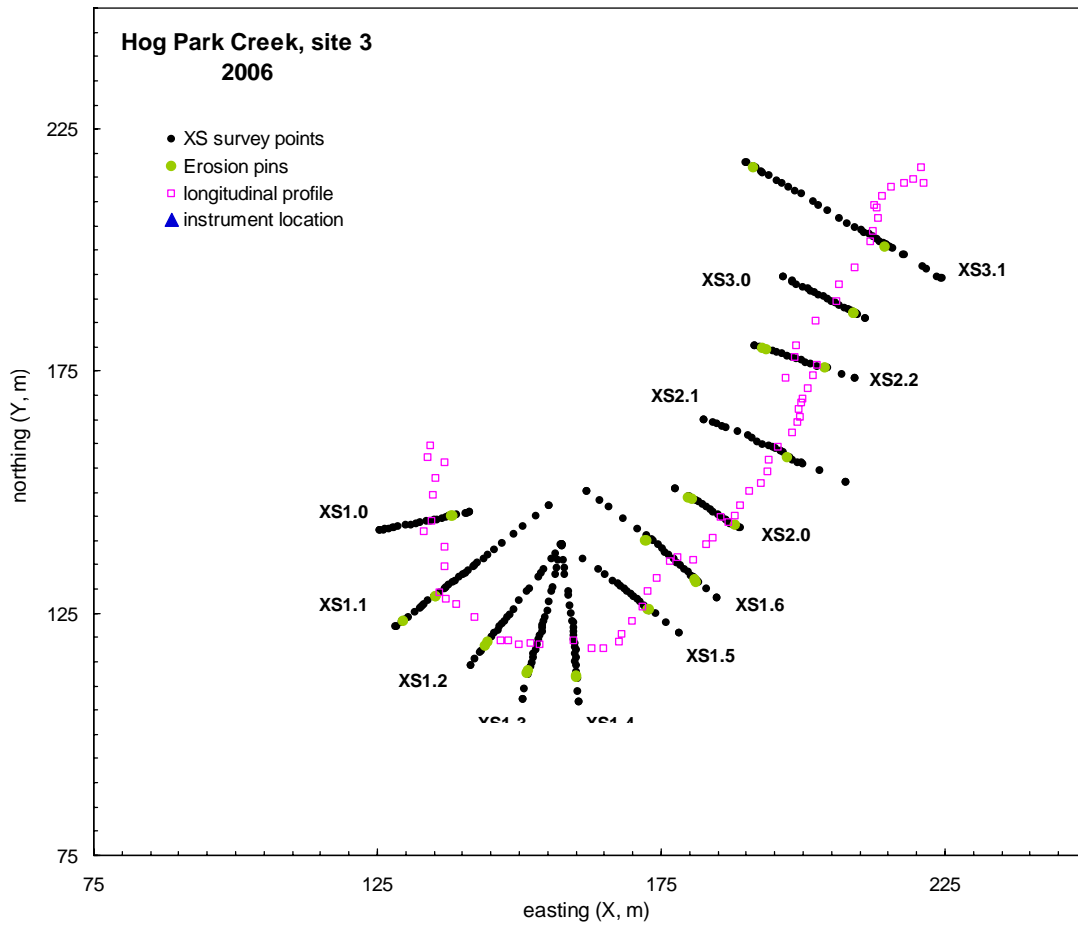
Figure 4.34: Planform schematic generated from survey data, Site 3, 2006.

Figure 4.35: Example of bank undercutting and mesic grasses providing cohesion to the soil, site 3 cross section 2.1.

Figure 4.36: Evidence of bank erosion and alluvial sediment deposition, site 3 cross section 1.6.

A tension crack that persisted at cross section 1.3 eventually failed in 2008 (Figure 4.37 Figure

4.39). Evidence of cattle trampling was documented in field notes and the bank was described

as crumbling, with gravel deposition occurring at the toe, from the source at the top of the bank.

Cross section 1.5 experienced mass wasting in both 2008 and 2009 (Table 4.13). The channel

area in cross section 1.6 has aggraded, most likely a result of eroded materials from cross

section 1.5, which lies just upstream. Site 3 experienced a bank slough in cross section 2.0

between 2007 and 2008 that contributes a significant amount of the erosion observed in the site

throughout all years. The lower pin in cross section 2.1 was noted in field observation (2008) as

having not captured the total extent of erosion that occurred.

Table 4.13: Summary of erosion results for each cross section, site 3, across all years.

| Cross Section	WY 2005	WY 2006	WY 2007	WY 2008	WY 2009	Cumulative change	Location in channel planform
XS 1.0	0.9	0.3	0.0	0.0	0.3	1.5	Straight
XS 1.1	-	-	-0.1	0.5	0.3	0.7	Straight
XS 1.2	-	-	0.1	0.2	0.2	0.5	Bend, upstream of apex
XS 1.3	-	-	0.0	0.5	-0.2	0.3	Bend, upstream of apex
XS 1.4	-	-	-0.1	-0.3	0.3	-0.1	Bend, downstream of apex
XS 1.5	-	-	0.2	1.7	1.5	3.4	Straight
XS 1.6	-	-	-0.2	-0.2	-0.4	-0.8	Straight
XS 2.0	-	-	-0.1	-0.3	0.1	-0.3	Straight
XS 2.1	-	-	0.4	0.1	0.3	0.8	Straight
XS 2.2	-	-	-0.3	0.4	0.3	0.4	Straight
XS 3.0	-0.2	0.2	-0.2	0.3	0.6	0.7	Straight
XS 3.1	-	-	0.4	-0.2	-0.3	-0.1	Straight
Cumulative Change	0.7	0.5	0.1	2.7	**3.0**	7.0	
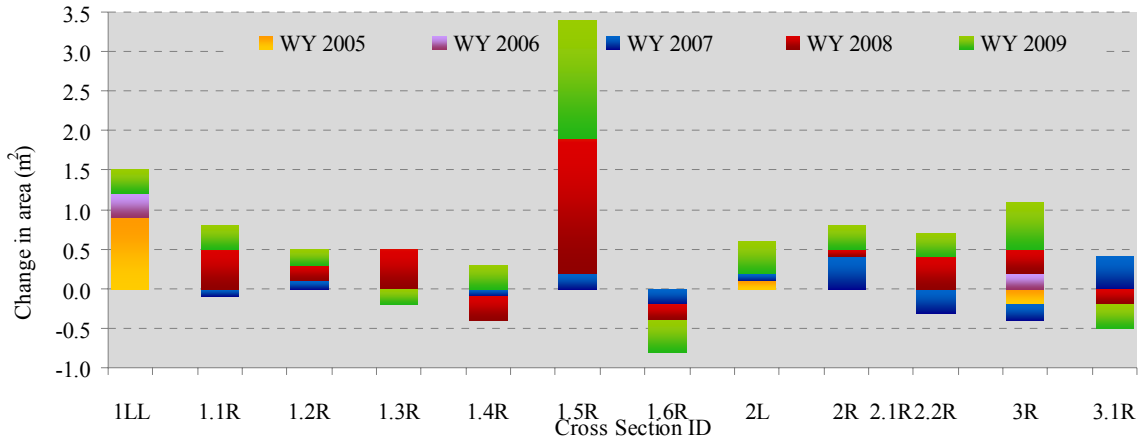
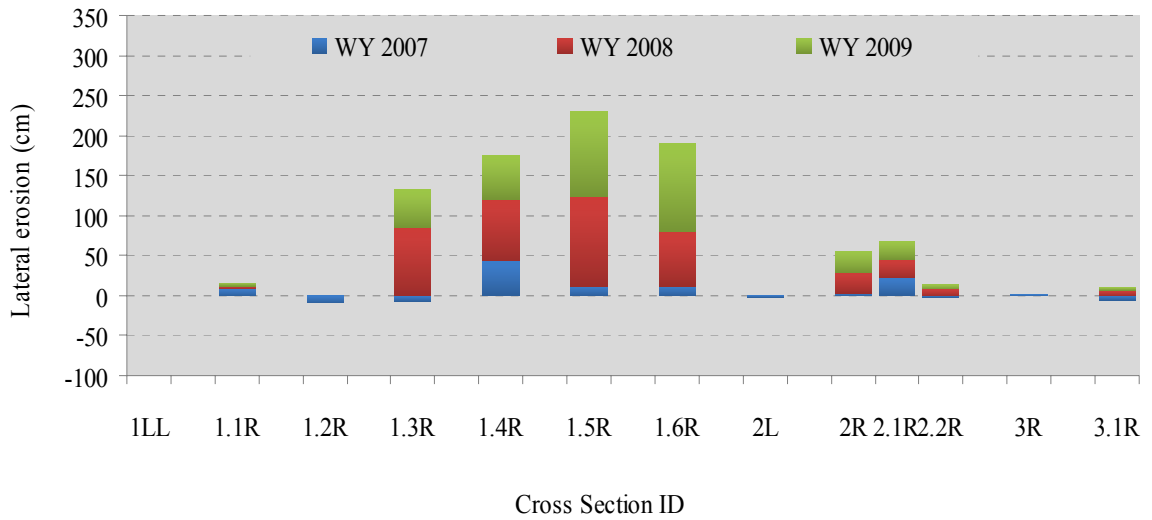Figure 4.37: Total annual change in cross sectional area in each cross section, site 3.

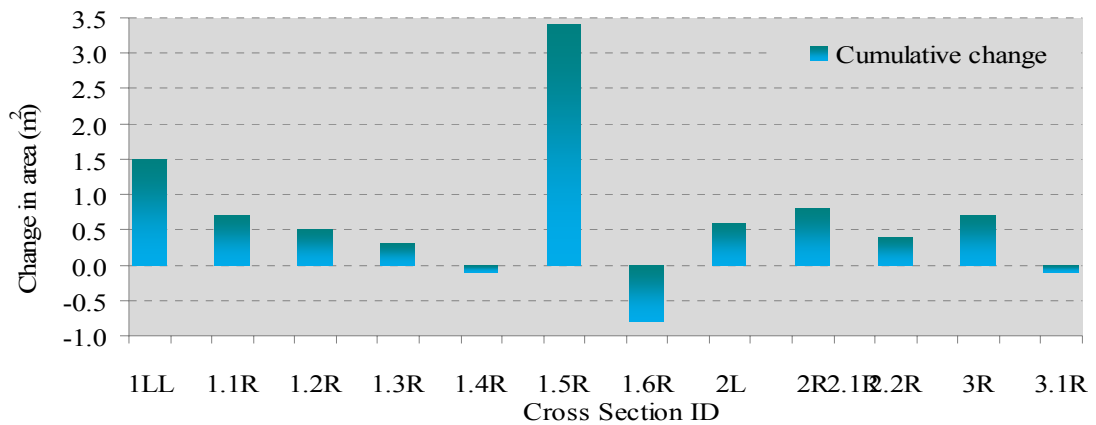Figure 4.38: Results of erosion pin surveys in site 3, 2006- 2009.

Figure 4.39: Cumulative erosion in site 3, 2004 - 2009, as measured by cross section surveys.

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Site 4

Lacking any significant water diversions, dams, or augmented flows, South Fork Hog Park Creek provides a useful reference condition to assess the magnitude and direction of channel changes occurring in the main stem of Hog Park Creek downstream of the reservoir. South Fork Hog Park Creek has similar underlying geology, elevation and climate, vegetation characteristics, and land uses, with the exception that it is not affected by a reservoir, as the main stem channel of Hog Park Creek. South Fork Hog Park Creek contributes flow to main stem Hog Park Creek between sites 2 and 3 (Figure 4.40). Site 4 is located approximately 200 m upstream of the confluence.
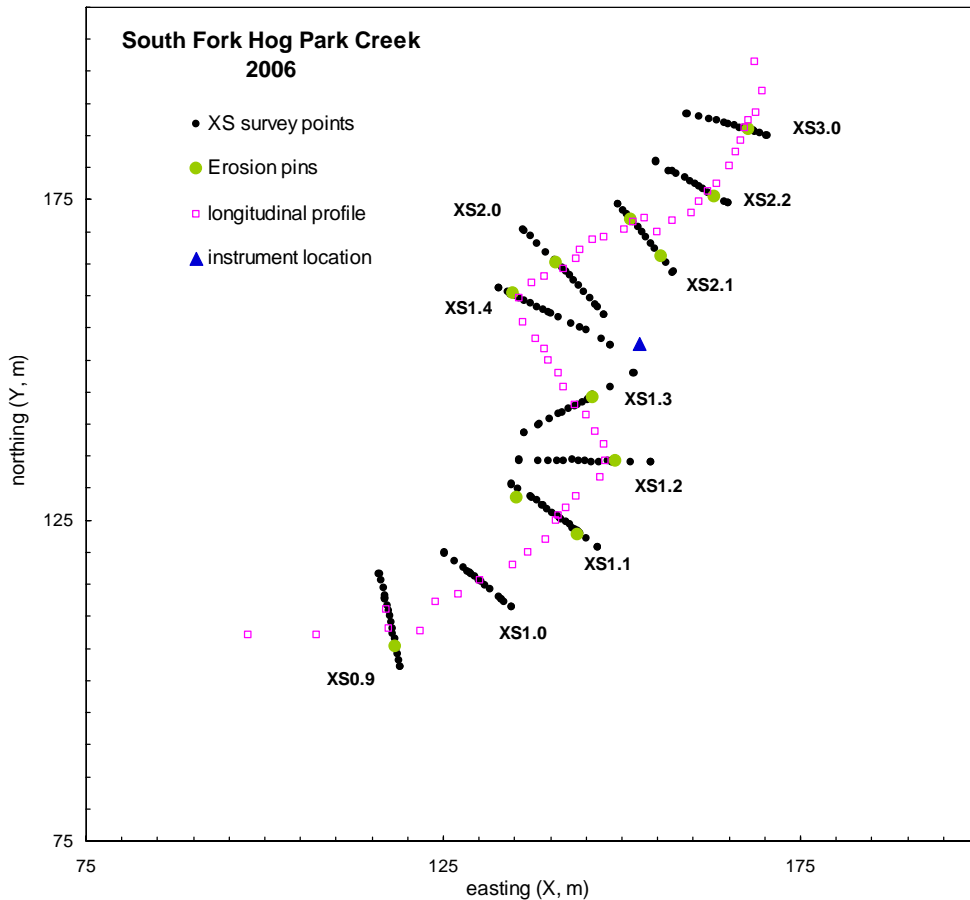

Figure 4.40: Planform schematic generated from survey data, site 4, 2006.

Erosion in the form of both hydraulic scour and mass wasting occurs along the outside of the meander bend in site 4 (Table 4.14). Cross sections 1.1, 1.2, and 1.3, 1.4 are located along an exposed high bank terrace. This location also shows sign of cattle trampling and degradation of the upper bank vegetation. Significant bank erosion also occurred at cross sections 0.9, 1.4, 2.0, and 2.1 in 2009 (Figure 4.41 through Figure 4.43). Site 4 has the lowest amount of erosion over time when compared to sites 1, 2, and 3. The terrain throughout site 4 is somewhat anomalous to the other three sites. A portion of the channel in the site runs along a high terrace and additional soil layers are exposed in this section, including a cohesive clay lens in the highest banks (Figure 4.44 and 4.45).

Table 4.14: Summary of erosion results for each cross section, site 4, across all years.

Cross Section	WY 2005	WY 2006	WY 2007	WY 2008	WY 2009	Cumulative change	Location in channel planform
XS 0.9	-	-	-0.3	0.1	0.4	0.2	Straight
XS 1.0	-0.1	0.2	-0.1	0.2	-0.1	0.1	Straight
XS 1.1	-	-	-0.1	0.1	0.0	0.0	Bend, upstream of apex
XS 1.2	-	-	0.0	-0.1	0.8	0.7	Bend, at apex
XS 1.3	-	-	0.0	-0.2	0.6	0.4	Bend, downstream of apex
XS 1.4	-	-	-0.1	-0.1	0.4	0.2	Bend, downstream of apex
XS 2.0	0.0	0.1	0.0	0.2	0.3	0.6	Straight
XS 2.1	-	-	0.1	0.1	0.2	0.4	Straight
XS 2.2	-	-	-0.1	0.1	-0.1	-0.1	Bend, at apex
XS 3.0	0.3	-0.3	0.1	0.3	0.0	0.4	Straight
Cumulative change	0.2	0.0	-0.5	0.7	1.9	2.3	

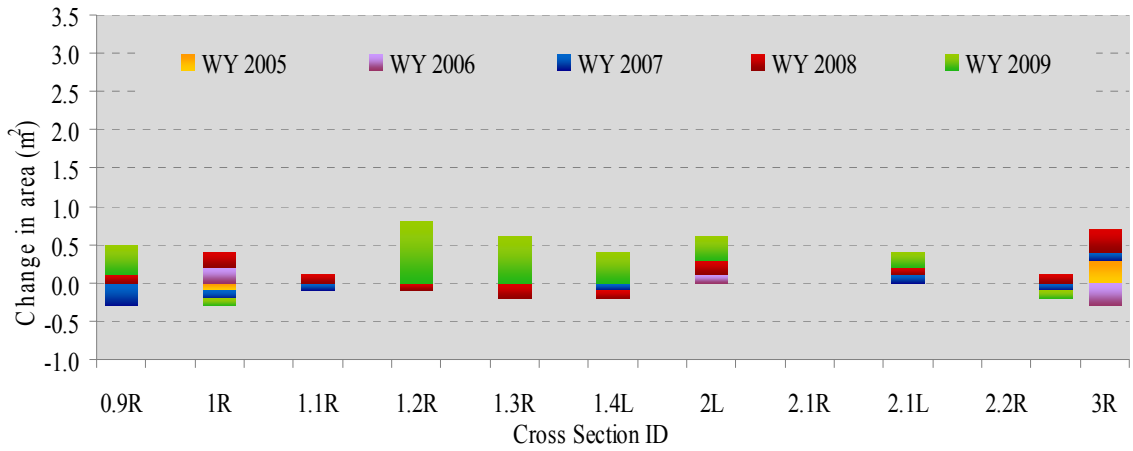Figure 4.41: Total annual change in cross sectional area in each cross section, site 4.
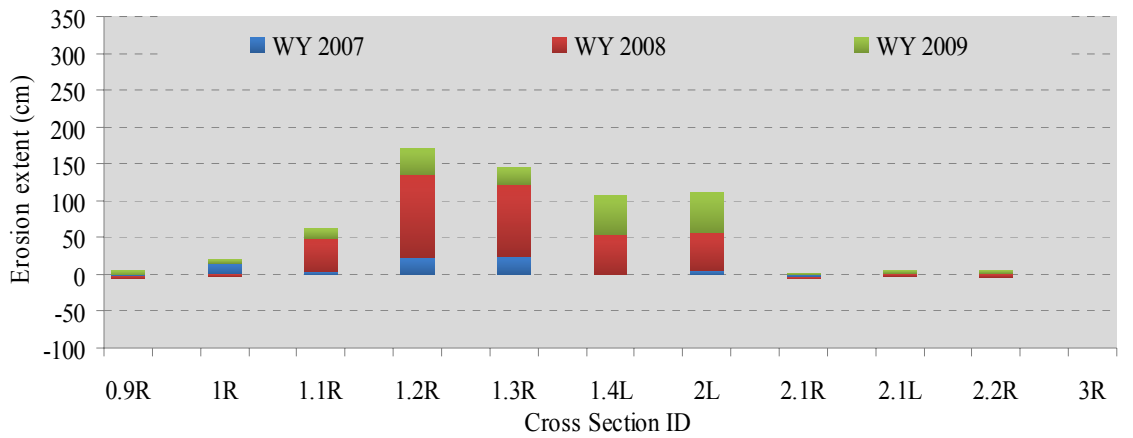

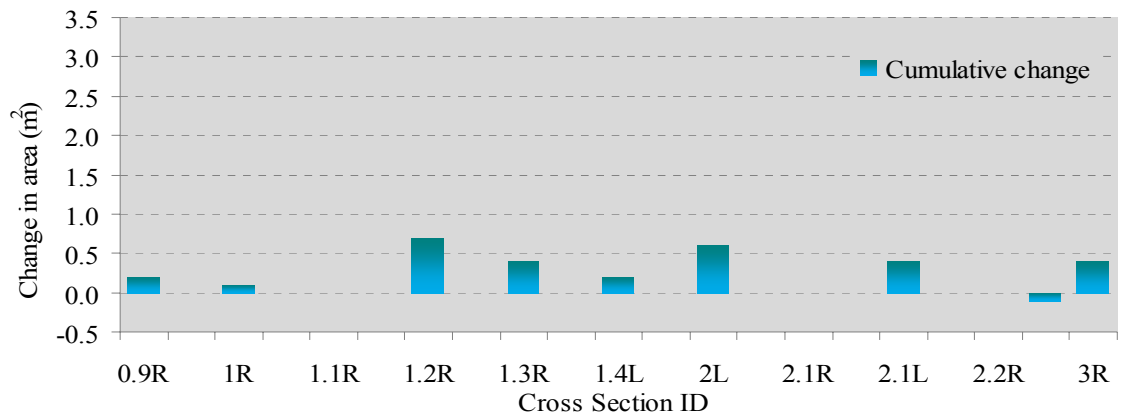Figure 4.42: Results of erosion pin surveys in site 3, 2006- 2009.

Figure 4.43: Cumulative erosion in site 4, 2004 - 2009, as measured by cross section topographic surveys.

Figure 4.44: A photograph of vertical banks. Note the clay lens mid-bank, which is unique to site 4.

Figure 4.45: Photograph of site 4, looking downstream.

4.3.2   FIELD SURVEY AND HYDRAULIC DATA ANALYSIS

To determine the amount of correlation between bank erosion and independent variables collected during field surveys, a correlation model is applied to measured physical characteristics within each site. The methods of data collection are thoroughly described in Sections 3.1.2, 3.1.3, and 3.1.4. Lateral erosion of the bank, as measured using erosion pins during 2006-2008, is applied in a correlation model with several site- and reach-specific characteristics. Erosion pins were placed in vertical banks in many cross sections, as portrayed in Figure 4.46, and resurveyed in 2007, 2008 and 2009. The erosion pin data are provided in Appendix C.

Figure 4.46: Erosion pin locations in a vertical bank, Site 4, 2009. The erosion pin locations are denoted with orange markers.

The resulting correlation coefficient (R^2) is 1 or -1 for perfect correlation and 0 for no correlation. The significance of each correlation is tested using an F-statistic and a corresponding p-value indicating the confidence level. A Bonferroni adjustment for multiple

comparisons is used for testing 20 variables at $\alpha = 0.10$ ($\alpha = 0.10/20 = 0.005$), which results in significance. All statistical analyses are performed using the SAS software package (SAS Institute, 2001).

Initially, all data were combined to identify any significant outstanding trends across all sites. Correlations were found, but none exceeded an R^2 value of 0.5 (Table 4.15). This suggests that site-scale characteristics may play a role in bank erosion rates. Similarly, this was not an exhaustive deduction of possible parameters with relationships to bank erosion rates in these study sites, and many other variables may not be accounted for in these tests.

Table 4.15: Covariate analysis results of bank physical parameters

Parameter	R^2
Near bank velocity (2008)	.02
Bank Height.	0.19
Root depth/ Bank height ratio	0.15
Bank composition	.06
Bank angle	.06
Width: Depth ratio	.02
Thalweg depth	.06
Relative height of maximum velocity	.05

To strengthen the aforementioned correlations, data are separated by site and again by location within a site. Location within a site was split between the inside of a meander bend, the outside of a meander bend, or in a relatively straight section of channel. Correlations are improved by comparing lateral bank erosion by site and within the site, although in most cases the

contribution to an improved R^2 value was minor. The most significant correlations found are with bank height and root depth/ bank height ratio. Two of these parameters includes a component of bank height, however, which may be an indication of colinearity.

The ratio of root depth to bank height acts as a proxy for size of contributing area and the relative decrease in the significance of riparian root depth with a downstream progression. Results indicate that bank height increases with accumulated drainage area for the main stem sites, but site 4 encompasses the smallest drainage area and displays the highest bank heights and depths of erosion. This anomaly is most likely due to the location of the channel against a high terrace and the existence of a cohesive clay-rich layer. Where the site is not influenced by the positioning against the high terrace, the bank heights are no longer anomalous.

The data suggest no significant correlation with bank composition (specified by a single layer, or more than one bank layer). In all sites, the top-most layer is a loamy soil, which is likely to occur even if there is only one soil layer present. The secondary layer in most sites is a sand and gravel composite layer. In Site 4, a third, cohesive clay layer exists that is not apparent in the other three sites. The bank composition varies little between sites, so correlations tend not to be significant. There is a slight correlation with thalweg depth that relates to the depth of water in the cross section at the time of survey and location in the site. The lack of correlation may be due to the location of the thalweg in proximity to the bank, and whether the habitat is a run, riffle, or pool, which ultimately reflects slope and stream power at the site.

The data suggest a slight correlation with near-bank velocity and relative height of maximum velocity. There is a slight positive trend between these two variables, which indicates that in areas of lower depth, there is little erosion occurring; where the thalweg is directly adjacent to the bank, more erosion is expected. No relation is observed with bank angle. I attribute this to the difficulty of assigning a single bank angle to a cross section, especially with the prevalence

of undercut banks and multiple soil layers. Each soil layer within the cross section transect was assigned a bank angle, ranging from 0 to 360 degrees, to account for undercut banks. Initially, erosion rates were plotted against the independent variables as one group and the trends observed have relatively low correlation values (R^2). The variability between sites may be attributable to untested parameters such as hydrology (peak flow, groundwater), land use, reach slope and stream power, for example. Correlation improves slightly when comparisons are separated by site, but little significant improvement in correlation occurs when erosion rates are identified by location in the meander (not outside vs. outside. This significance in differentiation by site is that site-scale variables may account for a large proportion of variability in erosion that is not captured by any of the tested parameters, especially vegetation type and individual cross section soil properties.

4.3.3 BANK STABILITY AND EROSION MODELING

Streambank degradation is a concern for the USFS, the managers of the land downstream of Hog Park Dam, since the area is a popular recreation area well known for its fishing and hunting. Managing excessive streambank erosion is important for preserving the integrity of the freshwater ecosystem and minimizing impacts to the subalpine meadow. Initial analysis in this study focuses on hydrologic changes, comparing the various characteristics from three different operational time periods. Also, aerial photographs and statistical analyses were used to determine morphologic trends of adjustment over time. This third step, assessing the mechanisms and timing related to observed erosion rates, allows for the correlation of erosion rates to hydrologic and planform features.

SENSITIVITY ANALYSES

A sensitivity analysis was conducted in BSTEM to learn which model parameters, as modeled at this site, relate most to the occurrence of erosion. These results were then used to adjust model input parameters until model results reflected measured annual erosion rates. This was a necessary step, as time and funds limited the ability to collect site-specific geotechnical data. A robust data set was provided by the National Sedimentation Laboratory. In particular, a site that has similar elevation, climatic and geologic characteristics as Hog Park Creek, has an extensive set of field-collected geotechnical data. The sensitivity analysis used envelope curves from these data sets combined with soil, discharge and channel morphologic data from Hog Park Creek. A relative stability analysis tested the model's sensitivity to the various input parameters. Modeling suggests that cohesion, surface water stage, and groundwater elevation are highly significant (Table 4.16). Friction angle, the number of soil layers, and vegetation were less significant, but do explain some variability. These results were then used to guide parameterization of the model for the erosion threshold analysis in Section 4.3.4.

Table 4.16: Notable results of the BSTEM model sensitivity analysis; notice the significance of cohesion, vegetation type and surface water depth.

Parameter	Estimate	Standard Error	p-value
Friction angle 25%	-0.47	0.17	0.01
Friction angle 50%	-0.237	0.17	0.033
Cohesion 25%	-2.05	0.17	<0.001
Cohesion 50%	-1.25	0.17	<0.001
Saturated unit weight 25%	0.23	0.17	0.05
Saturated unit weight 50%	0.13	0.17	0.04
Surface water discharge bankfull	-0.23	0.14	<0.001
Groundwater in relation to surface water depth (pore water pressure)	0.48	0.18	0.002
Dry vegetation vs. mesic vegetation (root cohesion)	0.60	0.14	0.011
Composite soil vs. loam soil	-0.11	0.06	0.04

Soil properties have not been directly affected by the presence of the dam, but indirect effects may include anthropogenic impacts (i.e., logging), bank stabilization, and vegetation, which may be altered by the presence of the dam and by cattle grazing. Vegetation plays a role in bank stability through root reinforcement and hydrologic influences. Both field and numerical modeling research have demonstrated that the addition of root cohesion to streambanks improves stability under a range of hydrologic conditions (Abernethy and Rutherfurd, 2000; Wynn et al. 2004; Simon et al., 2006; Pollen, 2007).

An ANOVA test was run on the set of parameters tested, the independent (or response) variable being the Factor of Safety (FS) and the categorical dependent variables being the 25th, 50th, 75th percentile values of cohesion, saturated unit weight, and friction angle. Other parameters include vegetation type, soil type and stage, with a total of 280 model runs. The results of the sensitivity analysis provided additional guidance in the parameterization of the erosion threshold modeling in Section 4.3.4.

COMPARISON OF EROSION RATES ASSOCIATED WITH ANNUAL HYDROLOGY

As a contribution to the investigation of morphologic changes in Hog Park Creek, the objective of BSTEM is to determine whether dam operations may be exacerbating or ameliorating bank erosion. The BSTEM modeling will attempt to determine the differences in the timing of erosion and the quantity of bank erosion under two different regulation scenarios. The BSTEM modeling in this study is not an exhaustive analysis of the driving and resisting forces involved in bank erosion. Several studies have provided robust analyses of the geotechnical forces contributing to bank erosion and stability.

Two annual hydrograph time series, 1971 and 2008, will be used to make these comparisons (Figure 4.47). These two years were chosen because 1) a robust data set of bank composition, soil types and cross section erosion is available for water year 2008 (defined as October 1st,

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2007 – September 30th, 2008), and is ideal for model calibration, 2) they occur within different

stages of dam regulation (Stage 1 and Stage 2, respectively), and 3) they had similar amounts of

snow accumulation in the winter. According to historical precipitation records, both years may

be considered a year of average precipitation. However, the volumes of water discharged and

the characteristics of the hydrograph throughout the two time periods vary due to dam

operations. Both flow eras are augmented with additional discharge from a trans-basin water

diversion from North Fork Little Snake River, but considerably more flow is augmented

following the enlargement of Hog Park Dam, as compared to the time period following the

construction of the initial dam. Mandates for low flows also very significantly between the two

flow eras. Between Stage 1 and Stage 2, flows that may be influential in sediment transport and

formational for channel morphology are significantly different.

Key points to be considered for this erosion modeling experiment are the flow regime

components of frequency and duration, particularly because of the relationship between the

amount of time certain stages of flow are experienced in the channel and how this directly

relates to the amount of erosion and sediment transport that can occur. Some hydrologic

characteristics to note for the contemporary flow regime are that the stage is statistically higher

at base flow, higher earlier in the spring and with an increased fall rate as compared to Stage 1

operations. Contemporary dam operations include an early spring release, as can be seen in

Figure 4.47. These early releases occur while snow remains on the banks and floodplain, and

are earlier than historical high flows. The differences in the flow eras are discussed in detail in
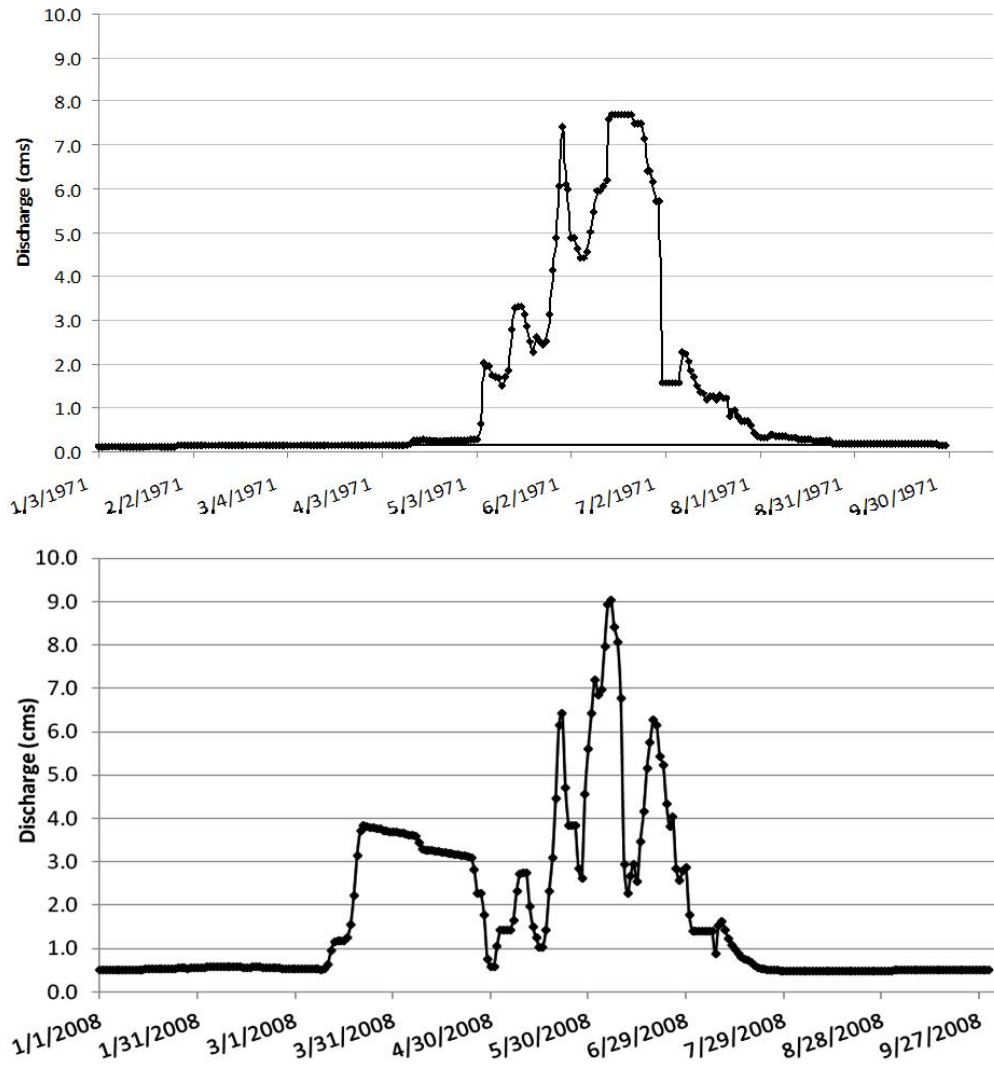
section 4.1.

Figure 4.47: Annual hydrographs of the two water years (WY) used for comparative erosion analysis.

Geotechnical data collected in similar subalpine meadow systems are used in place of site-specific information due to the inability to collect these data within the Hog Park Creek area. As discussed in the previous section, the results of the sensitivity analyses, as well as field-collected erosion information, guided BSTEM parameterization. The sensitivity analyses determined the parameters that, when modeled for this specific site, have the most influence on bank erosion and stability. When calibrating BSTEM to match field-collected erosion data,

those parameters that are most appropriate for the site were adjusted until annual erosion

simulated in the modeling was a realistic replication of the location and the amounts of

measured erosion occurring in the study area on an annual basis. A reasonable calibration was

gained when erosion amounts were within +/- 30 % of observed erosion rates. This goal for

calibration is based on the lack of geotechnical information. Since the analyses are essentially a

comparative analysis, and not deemed appropriate for erosion prediction, the comparability of

30 % between the modeled and observed data was deemed appropriate for a trend analysis.

Because of the lack of site-specific geotechnical information, this modeling exercise should not

be considered robust. However, modeling the two time periods, without accounting for some of

these geotechnical unknowns, still provides some indication of the thresholds of water stage that

will initiate bank erosion once they are exceeded. The modeling exercise also predicts timing of

erosion, and determines the hydrologic characteristics of dam operations that may be related to

bank erosion rates.

BSTEM was run using annual hydrograph data collected by CBOPU. The water years that are

used in the analysis have a similar May snow accumulation (depth), and hence should have

similar runoff characteristics if watershed conditions were undisturbed. However, different

levels of flow augmentation and release and the resultant amounts of erosion are analyzed using

this comparative technique.

Mean daily discharge records were adjusted by creating a rating curve for comparing Site 2

pressure transducer (stage) data to the CBOPU discharge records, generating a stage-discharge

rating curve for each site (Figure 4.51). This generated site-specific stage information for both

the 1971 and 2008 hydrographs. The flume data extend to 1970, and thus allowed an accurate

portrayal of an annual hydrograph from the Stage 1 and 2 time periods, but the pre-dam time

period was not modeled because pre-dam records are not available.

The bank geometry and bank material parameters are based on a single cross section, cross section 1.4, from site 2 based on field data collected in 2008. This particular cross section was chosen because it had a complete data set; experienced mass failure in 2008; and is a good representation of erosion throughout the study area. The same geometric attributes were used for the 1971 modeling runs since no cross section data are available for the Stage 1 time period. The banks are nearly vertical with an angle of approximately 85 degrees. Note that no adjustments of channel or cross section morphology were made between the different years modeled. Soil composition surveys in 2008 parameterized the bank layer depth and general soil characteristics for the model (relative density of roots, soil type, etc.). The same soil and vegetation conditions are used for each scenario, the only difference between the years modeled being the hydrograph. The changes in bank erosion rate and timing that may be due to an altered hydrology can be distinguished by using similar input parameters.

Soil layers were delineated by relative root densities and soil type. Bank soil characteristics from bulk sample sieving and the associated hydraulic conductivities for these soil types were used in defining the soil layers. The uppermost layer was defined by dense roots from the portion of bank just below it with similar soil characteristics but less dense roots. The third layer contained similar soil, but no roots. The fourth layer marked the transition to the second soil layer, a gravel and sand composite, with the two layers differing by the relative amount of gravel between them, with the bottom-most layer comprised of more gravel (Figure 4.48). The model accounts for two different forms of erosion. First, the toe erosion (fluvial scour) module is run for the first step and erosion is computed in terms of average applied boundary shear stress, maximum lateral retreat; eroded area of the bank, bank toe and bed; and lastly the total eroded area. The second module within the model is a bank failure (mass wasting) module. The bank failure module considers shear stress, root strength, pore water pressure and

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water table elevation. Results are expressed in terms of a Factor of Safety rating (Fs), failure width and failure volume.
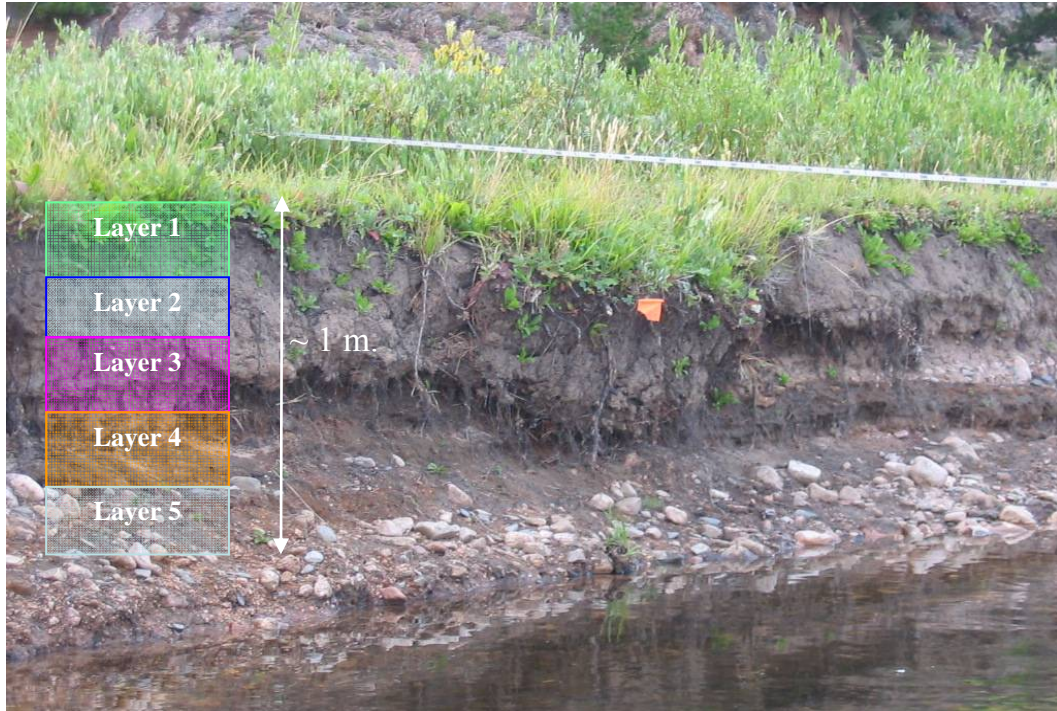

Figure 4.48: Example of soil layers in Hog Park Creek as described in bank geometry parameterization.

The initial parameters of the model were set-up starting from low flow in the winter, progressing through peak flows, the falling limb, and until low flow levels were reached in the late summer when hydraulic forces were no longer causing toe erosion, as modeled. The model is run in stage-duration steps throughout the annual hydrograph. A new step was delineated for each 24-hour period and the toe erosion and mass wasting module are run for every fifth stage-duration step. The model was run in 8-hour increments to account for groundwater stage drops (according to hydraulic conductivities). Relative groundwater position is an important variable and care was taken to calculate the groundwater drop with consideration for the fall rate of the

surface water stage. No adjustments were made for the groundwater infiltration rate at the intersection of soil layers, where interference to hydraulics can reduce infiltration and actually cause failures (Simon 2007). Tension cracks are not incorporated into the modeling, but they were observed in many banks in the study area. Tension cracks will positively contribute to bank mass failure potential.

The 1971 hydrograph experienced winter low flows through May, when discharge began to ramp up. Two peaks occurred; the peak discharge of 7.4 m3/s occurred on May 30, followed by a second peak of 7.71 m3/s on June 16. The second peak lasted 11 days and was followed by a relatively sharp decline in stage, of 0.38 m, over 6 days. Low summer flows of approximately 0.3 m3/s were reached by the end of July.

Figure 4.49 and Figure 4.50 display modeling results for 1971 and 2008, respectively. River stage (m) is represented by the solid black line as measured on the primary y-axis. Colored boxes represent the five bank layers, as shown in **Error! Reference source not found.**, and the indicated stage coincides with those bank layers. The purple line represents lateral erosion (cm) that is produced using the toe erosion module, as measured on the secondary y-axis. The blue points signify the Factor of Safety (FS). A bank failure, as modeled using the mass wasting module, occurs when the FS is computed as less than 1. Banks are considered stable when the FS is computed to be greater than 1. Due to tension cracks in the bank and other environmental variables, a value of FS between 1.3 and 1.01 is considered 'conditionally stable'. The zone of conditional stability is indicated by the horizontal grey line. When blue x's drop within or below the grey area, bank failure, or mass wasting, has the potential to occur.

As shown in Figure 4.49, low flows in the spring of 1971 initiated some erosion, but the Factor of Safety remained well above the zone of 1 to 1.3. As flows increase from a base flow of 0.3 m3s-1 to a discharge of 4.3 m3s-1 (a stage of 0.3 and 0.8 m, respectively), significant erosion

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occurs in the form of fluvial erosion in the mid bank level. Through the rising limb of the

hydrograph, the location of the mid- to lower height of the bank experiences fluvial erosion and

results in undercutting. Preferential erosion scoured the bank in the location of the transition

between the gravelly and loamy soil layers. Due to the additional support of the water in the

channel, mass failure did not occur in situations of the highest stage.

As modeled by BSTEM, conditions susceptible for bank mass failure occurred following an

abrupt drop in surface water, resulting in a perched groundwater table. This sharp drop in

channel stage allowed the saturated bank to go unsupported by water in the channel, and with

the preparatory undercutting of the toe from the spring high flows, driving forces (pore water

pressure) exceeded resisting forces of the bank materials. Although it is during the drawdown

stage where mass failure has the most likely potential to occur, it appears that the most

significant component of the hydrologic regime contributing to increased erosion rates is the

small flood pulses which induce hydraulic scour in the rising limb. The amount of time that

these scouring flows work on the streambank greatly increases the potential for mass failure

later in the season.

The 2008 hydrograph has an early release, at approximately 3.5 m3s-1 (.75 m. stage) for over

30 days. The flow then drops at the end of April, with a rising limb dominated by repeated

rising and falling river stages. Three peaks occur throughout the summer, the first occurring

May 22, a discharge of 6.4 m3s-1 (Stage=0.91m), the second and highest discharge occurs June

7 (stage 1.01 m) and the third occurs June 20 (stage of 0.89 m). The water stage then drops 0.3

meters over the time span of 3 days. Summer low flows are reached in early July. In situations

where the stage dropped quickly in 2008, groundwater levels were calculated using published

hydraulic conductivity rates (EPA 1996). The lack of on-site groundwater elevation data

introduces considerable uncertainty in the modeling results. As noted in the 1971 modeling,

BSTEM computed erosion to be most likely when groundwater elevation was higher than surface water, following extensive undercutting.
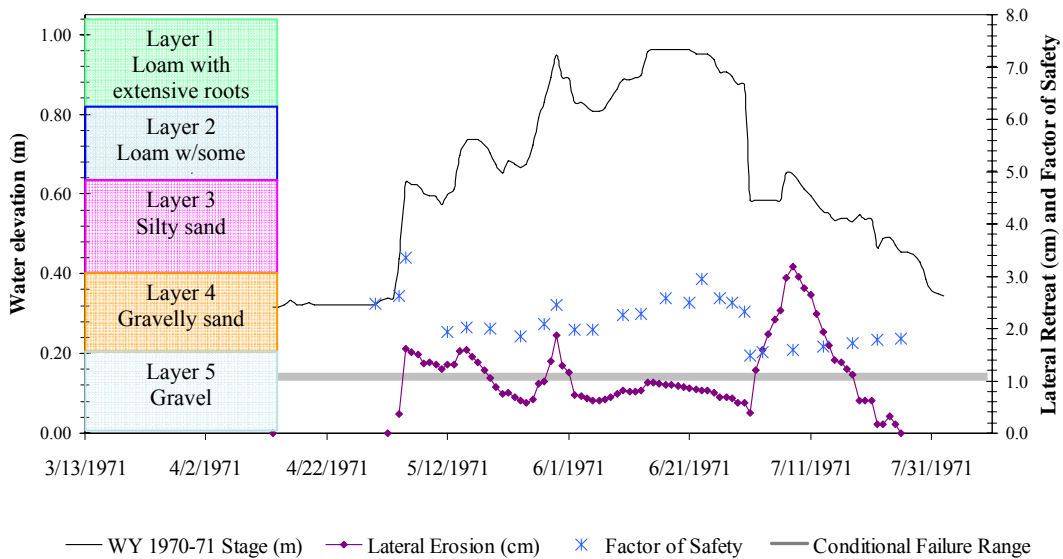

Figure 4.49: Results of BSTEM modeling for the water year 1971.

As modeled, early spring high flow releases extensively scoured the bank toe in 2008 (Figure 4.50). Mass failure had the potential to occur near the end of the month-long release. A potentially significant factor not accounted for in the modeling is the additional strength due to the frozen nature of the banks in the winter. Point measurements of bank strength collected in February 2008 indicated that banks were solidly frozen through all soil columns. The nature of thawing in relation to stage and duration of flow is unknown and unaccounted for in this modeling exercise.
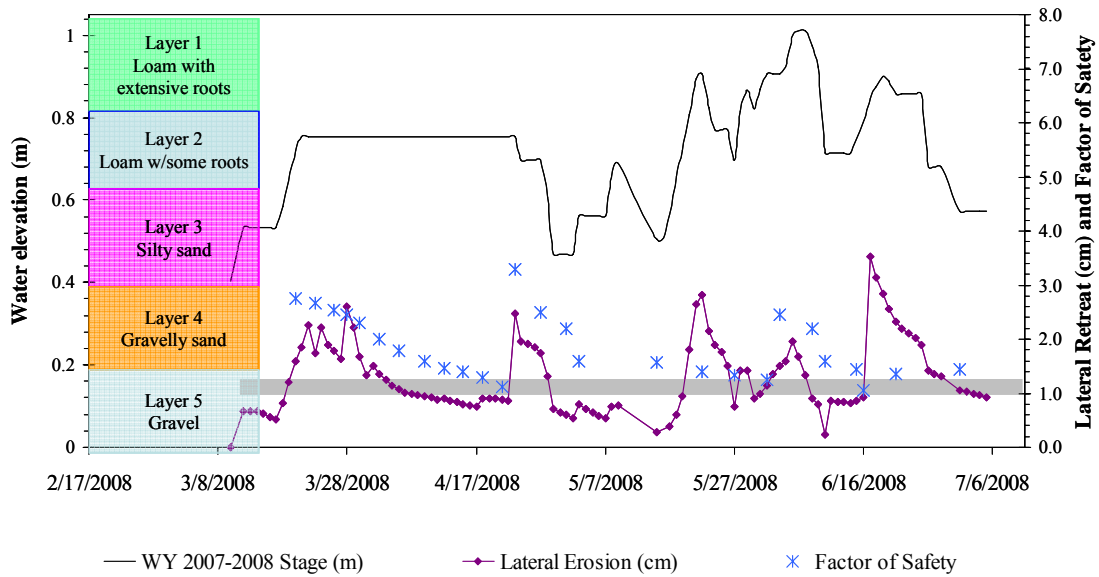
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Figure 4.50: Results of BSTEM modeling for the water year 2008.

As stage fluctuated throughout the rising limb of the hydrograph, toe erosion continued without

significant drops in FS. The peak stage of 1.01 m again did not initiate bank mass failure. The

Factor of Safety dropped when the peak flow receded at a faster rate than the hydraulic

conductivity of the soil. The condition of the excessively undercut bank and the perched water

table initiated erosion, with the FS dropping below 1.0. Conditions were susceptible to failure

throughout the extent of the falling limb, until low flows were reached and the groundwater

elevation was equivalent to the surface water elevation.

Total lateral retreat in 2008 exceeded that of 1971 by nearly three times (Table 4.17). Lateral

retreat is attributed to fluvial scour and is an indirect contributor to mass wasting. As modeled,

the most significant contribution to mass failure of banks is the excessive undercutting at the

intersection of different soil layers. This is seen extensively across the study area. In cross

section 1.4 in reach 2, the soil layers most vulnerable to fluvial scour are those at the

intersection of the two different soil types. These layers occur within the bank at the heights

between 0.38 m and 0.78 m (0.62 and 0.22 m below the top of the bank).

Table 4.17: Comparison of results of BSTEM modeling for WY 1971 and 2008.

	1971	2008
Total eroded area (m^2)	0.16	0.45
Total lateral retreat (cm)	56.4	74.3

The stage at which the most fluvial scour occurs coincides with discharges between 0.4 and 4.0

m3s-1 (Figure 4.51). The soil layer above this is composed of much higher root densities and

benefits from the additional cohesion provided by the roots. In both Stage 1 and Stage 2

operations, these discharges occur more frequently and for longer durations than prior to flow

regulation and augmentation. Of noticeable influence is the early spring release of 2008, lasting

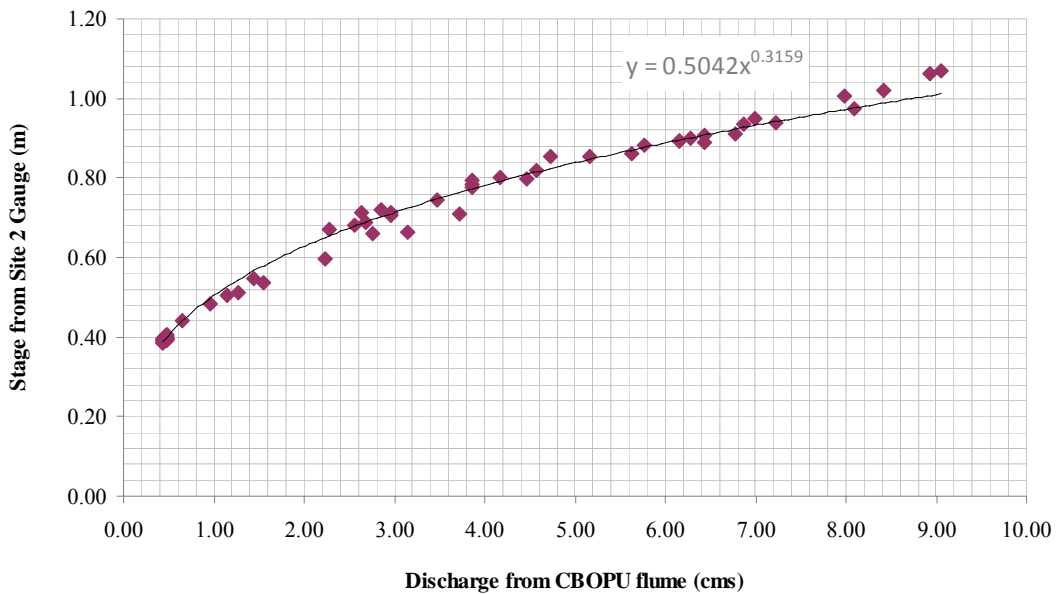approximately 30 days and contributing to a significant portion of lateral erosion.

Figure 4.51: Discharge stage rating curve WY 2008.

The change in operation of the dam between the time periods directly relates to scour of the banks, attributed to an increase in erosion rates following dam regulation. Erosion rates are increased in Stage 2, not only due to the additional amount of scour, but also to the exacerbation of cantilever failure. Even though not modeled here, it can be deduced that both Stage 1 and Stage 2 operational time periods likely produced more bank erosion than the pre-dam time period, as observed in the planform analyses. This result is based on the amount of time that flows during which finer soil layers are prone to erosion are experienced on an annual basis, particularly in relation to the early spring water transfers. High flows have increased in duration during both stage 1 and stage 2 time periods because of the early season water transfer.
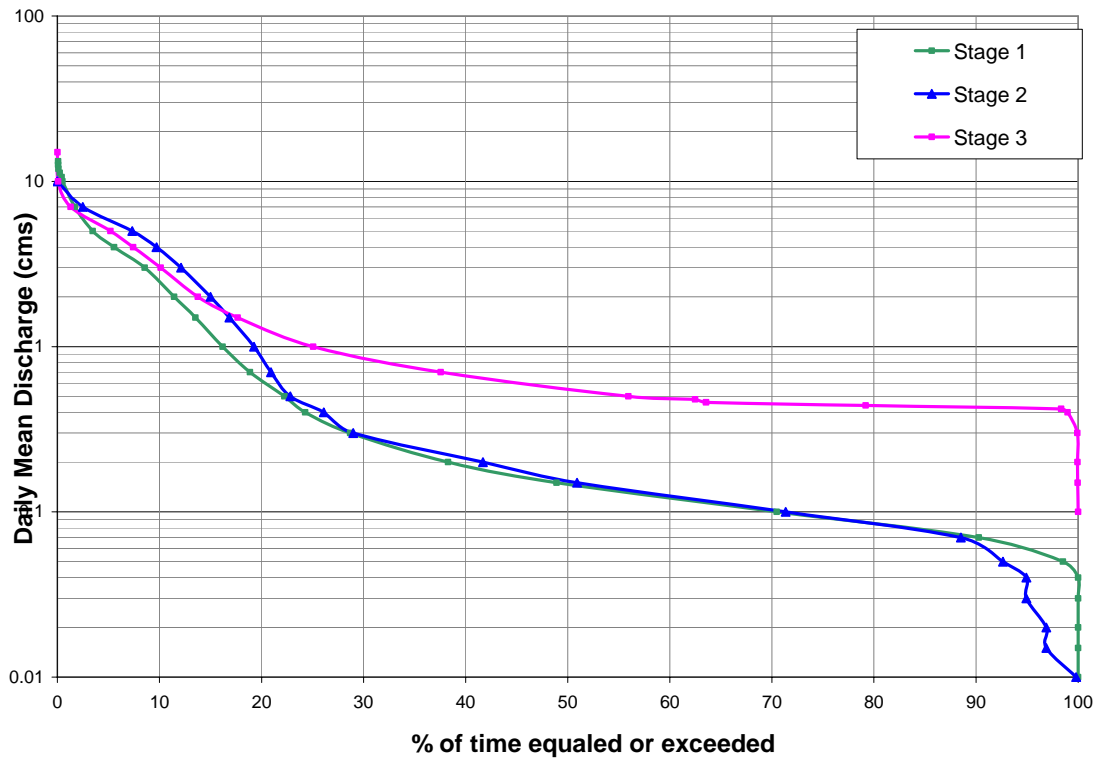

Figure 4.52: Flow duration curve for the three flow eras.

The bank was stabilized during the highest annual discharges because of the additional cohesion provided by the riparian roots. The annual high discharges are reduced in the Stage 2

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operational period, and this is not seen to be a factor in higher erosion rates. Therefore, the

highest flows did not cause erosion, but the extended duration of high flows did.

Similarly, sub-aerial preparation by freeze-thaw may also be a cause of increased erosion.

Several studies have demonstrated that freeze-thaw can contribute to the lack of resistance of

stream bank soils to fluvial erosion (Wolman, 1959; Lawler, 1993; Couper and Maddock,

2001). Freeze-thaw processes are likely enhanced under current exposed conditions relative to

historical conditions when the channel was covered by snow throughout the winter, due to the

mandated higher base flows and the earlier release of the reservoir.

Due to the lack of site-specific geotechnical information, limitations are inherent to this

modeling procedure. The foremost limitations of the modeling are the lack of site-specific data

and the reliance on data collected from a similar area. The results are intended to provide

relative trends and potential thresholds, but should not be interpreted as providing precise

enumeration of bank erosion.

4.3.4   RESULTS OF TESTING HYPOTHESES 5 - 7

Each of the following null hypotheses proposes that a specific parameter does not significantly

affect bank erosion rates. Each associated alternate hypothesis proposes that this parameter is a

significant control.

($H_{o(5)}$): Bank erosion rates, as simulated by the Bank Stability and Toe Erosion Model
        (BSTEM), are not significantly elevated under the current hydrologic regime.

($H_{o(6)}$): Bank erosion rates are not correlated to inter-reach characteristics.

($H_{o(7)}$): Bank erosion rates are not correlated to intra-reach characteristics.

Hypothesis 5 tests whether erosion rates have maintained relative consistency through time and

are not affected by operations of the dam or flow augmentation in general. Planform analyses

relating to changes in channel width through time are one basis used to reject this hypothesis. Changes in channel width were significantly correlated with operational regimes, and these correlations suggest an increase in width following Stage 2 implementation. If extrapolated to a decadal trend, as in the planform analysis, erosion is not occurring as quickly as the time period following the 1985 construction of the enlargement of the dam.

Bank erosion modeling supports this conclusion. Two operational regimes were compared to discern specific discharge characteristics that lead to an increase in susceptibility of the stream bank to failure. In a comparison of the Stage 1 and Stage 2 time periods, there is a noticeable difference in the timing and amounts of erosion occurring between the two time periods. Hypothesis 6 is rejected, since analyses of repeated cross section surveys and erosion pin measurements indicate that erosion rates vary between different hydrologic regimes, but also across reaches. As observed in aerial photographs, the most notable changes in channel form occur in reach one, directly downstream of the dam, and following the enlargement of the dam. Significant changes in channel area are observed in site 2 as well, but with a delayed response in the 1990's. Site three produces the most erosion, but appears to be less affected by dam operations over time, considering the relative magnitude of change in channel width between time periods. These results suggest that reach-scale characteristics such as morphology, confinement, gradient, radius of curvature, etc., play a role in determining erosion rates in the Hog Park Creek basin.

Erosion pin analyses suggest that there are inter-reach characteristics that exert a large-scale control, or influence, on bank erosion rates as well. The correlations with reach-scale characteristics indicate were weak and suggest that site-specific controls must influence erosion processes. Bank morphology data, near-bank velocity distribution data, and erosion values derived by erosion pins were used to test Hypothesis 7. This hypothesis is also rejected, and

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analyses determine that intra-reach characteristics do influence erosion rates. Site-specific values such as the ratio of root depth to bank height and velocity adjacent to the bank will predict trends in lateral erosion amounts and these correlations are improved when stratifying by location in the channel in relation to meander bends.

As erosion modeling indicates, hydraulic scour of the toe occurs in the early spring releases, preparing the bank for failure either during that extended release, or when the water stage in the channel drops quickly, leaving the banks supersaturated and prone to failure. The peak flows of the season do not cause excessive failure, as the water in the channel lends support to the banks. If the stage drops quickly following the peak flow, failure is likely to occur again if those banks remain severely undercut, supersaturated and with low bank strength. Cross section surveys support this observation that early spring releases may contribute the most significantly to direct erosion or preparation of the banks for mass failure. Detailed cross section surveys suggest that the channel is widening, and these rates vary by site and by location within the site. However, it appears that these rates of channel widening have decreased in the last decade, when compared with rates of channel widening since 1985. Although hydraulics drive local dynamics in bank erosion, the operational regime has a larger influence.

5   SYNTHESIS AND DISCUSSION

A unique opportunity for a case study in a small catchment with temporal and spatially

constrained variables exists within Hog Park Creek watershed. Land use has varied through

time in the watershed, but a striking discordant impact has occurred with the construction of

Hog Park Reservoir. The existence of the channel-spanning dam in the upper reaches of the

river system provides for a direct and identifiable disruption in the function of the two main

drivers of geomorphic process; water and sediment. Channel form is an expression of the

sediment and hydrologic regime on decadal timescales. Disruption of water and sediment

processes can lead to degradation of other physical and biological components of a river

ecosystem.

Dams influence the magnitude, frequency, timing and duration of flows, as well as the ability of

the river to transport sediment and the amount of sediment available for transport (Williams,

1984; Petts, 1979). Hence, the operation of the dam influences downstream channel responses.

If the transport capacity exceeds the available sediment supply or if the transport capacity is less

than the available sediment supply, a reach may shift from a dynamic equilibrium to

degradation or aggradation zones, respectively (Figure 5.1). Many analyses of the geomorphic

and hydrologic impacts of dams have focused on large dams in the lower extent of river

systems. With a large mass of watershed upstream and contributing stream networks, it is not

always feasible to separate impacts relating to the dam from other potential drivers (i.e., mass

wasting, agriculture, urbanization) that have compounding and interacting effects. The Hog

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Park Creek watershed is slightly different because the dam was constructed in the upper watershed, so contributing impacts are relatively minor compared to larger river systems. Rivers are influenced by factors including climate, geology, and topography that act over long timescales of hundreds to thousands of years (Grant et al., 2003; Church, 2002). Over shorter timescales of tens to hundreds of years, the dominant factors controlling a river can include lithology, geologic structure, beaver activity and human land use (Wohl, 2000). On the reach-scale, sediment supply, flow regime, valley characteristics (especially gradient), riparian vegetation and streambank cohesion are major controlling factors of channel geometry (Thorne, 1996). Land use will alter one or more of these variables, either directly or indirectly, and as land use shifts through time, compounding changes occur in the river system.
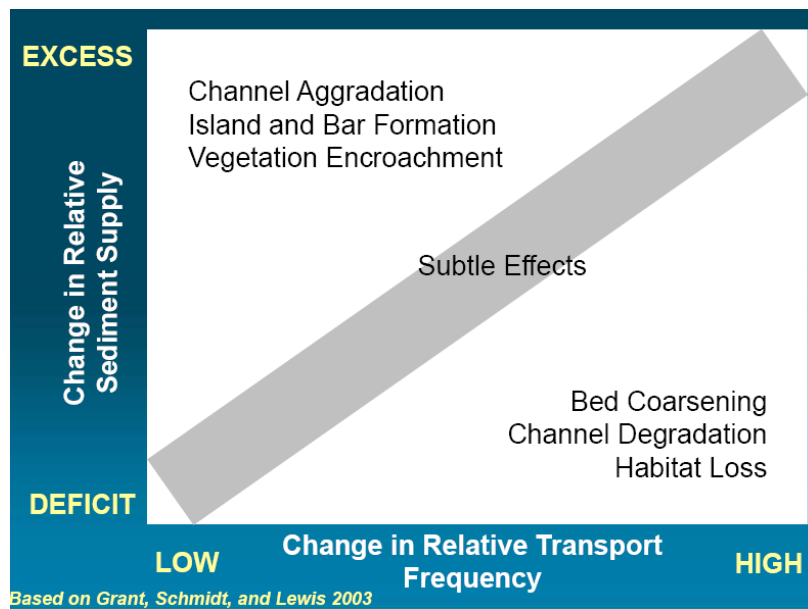

Figure 5.1: Relative magnitudes of change in the sediment regime and hydrologic regime and the level of corresponding change predicted in the downstream channel (figure adapted from Stillwater Sciences, unpublished) and Grant et al. (2003).

Simultaneous land uses elicit concomitant responses. For example, as a dam alters the flow and sediment regime of a channel, a direct impact includes reduced sediment supply to a reach and

reduced overbank flooding. An indirect impact of the alteration of the flow regime may include a reduction in groundwater recharge, leading to a shift in riparian vegetation species and bank cohesion. Likewise, bank erosion or channel scour may occur as an indirect response to the lack of sediment flux into the downstream reach. The magnitude of the alteration determines the magnitude of channel responses, as does the geomorphic nature of the system and its ability to accommodate change. Thresholds exist which, once surpassed, elicit heightened responses to even minor perturbations. Furthermore, a single response can initiate a secondary, consequent response, which further initiates reach-scale morphological adjustments. The spatial and temporal fluctuations of the disturbances in the watershed since human presence need to be appreciated in order to understand the drivers of the current channel morphology.

It is important to consider the landscape context of a dam before drawing conclusions about its downstream effects. At the site of Hog Park Dam, the contributing drainage area is 32 km2 (12.2 mi2). The surface area which now comprises the reservoir is a large, low gradient valley which originally functioned as a low energy, transport-limited zone (Figure 5.1). Contributing streams to the upper watershed are short, small in size (< 14 km2) and underlain by a resistant geology. Historically, this upper watershed most likely contributed relatively little to the downstream sediment budget because ample discharge rarely persisted to transport the sediment that was available. Dams are efficient at trapping sediment, and many studies relate to the impact that the disruption in sediment continuity can have on morphologic and ecologic channel conditions. The impact of Hog Park Dam may not be as extensive since the upper watershed is atypical relative to many other dammed watersheds, serving as a sediment deposition zone. The glacially scoured upper valley trapped sediment, lacking the discharge to transport it farther through the system. Most likely, the impact on the sediment budget following Stage 1 implementation is similar to the impact today, following Stage 2 (Figure 5.2). If the sediment

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regime, or budget, is only minimally impacted by the dam (as is assumed), then the geomorphic responses that are observed in the channel downstream of the dam are in response to hydrologic alterations and land use changes.

In this study, a sediment transport analysis and/or sediment budget is not feasible, based on the considerations that 1) there is sparse information available relative to that needed to model the transport, 2) modeling with high spatial/temporal resolution requires vast amounts of data, and 3) a robust approach is needed to provide an accurate analysis.

Isolating hydrologic effects from those of sediment transport provides an interesting opportunity to analyze the impact that flow augmentation and changes in the hydrologic regime may have on geomorphic processes. Sediment transport is disrupted in the system due to the existence of the dam and there are changes in the river as a result, but, due to the lack of historical sediment data throughout the system, this report relates shifts in geomorphic processes (bank erosion, planform change) to changes of hydrologic components. I assume that the lack of sediment continuity is not a dominant driver of geomorphic change in this particular setting.

Figure 5.2: Time series depiction of changes in storage capacity with (a) the only image of the reservoir area with no impoundment in 1983 when the Stage 2 enlargement was in construction and flows bypassed the dam, (b) the same 1983 airphoto with the 1977 reservoir surface water extent superimposed, (c) an airphoto taken in 2001 with the full extent of Stage 2 storage capacity.

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Below Hog Park Dam, the channel meanders 4.1 km before it reaches the confluence with

South Fork Hog Park Creek. South Fork Hog Park Creek is an unregulated system with no

diversions upstream and has experienced much of the same land use activities as Hog Park

Creek. South Fork Hog Park Creek is used as a reference channel. In all, two reaches lie above

the confluence and one below, comprising regulated, non-regulated and partially regulated

reaches in the study. Reach 3 is the partially regulated reach. That receives additional flow and

sediment from South Fork Hog Park Creek. These contributions are not anticipated to greatly

alter the overall water and sediment budgets in the main stem, but do create a slightly different

regime than the two reaches upstream.

Reaches 1 and 2 are separated by a granitic bedrock canyon 0.25 km in length. The

confinement ratio is high throughout the canyon. The channel bed and banks are resistant to

erosion due to the crystalline bedrock and therefore inhibit extensive channel change under

normal flow conditions. Downstream of reach 3, Hog Park Creek flows through another

bedrock canyon, a portion of the Encampment wilderness, until it reaches the confluence with

the Encampment River. Excess energy as a result of sediment-free discharge and the nearly

doubled annual discharge in Hog Park Creek could be dissipated through either incision in the

channel bed or erosion of the stream banks. The frequency of bedrock outcropping has limited

the extent of channel incision in the channel bed. Incision may be occurring, but slopes

generally change over much longer timescales than planform changes, thus, the incision process

may be less detectible than the changes in width and complexity. Evidence of incision is

observed in the mainstem of Hog Park Creek. Minor vertical scarps along the outer margins of

point bars suggest some minor channel incision is occurring due to a lack of resupplying

sediment. Knickpoints are minimally observed throughout the river and propagation would be

limited to those stretches between bedrock control points, which create local base level controls.

Although no historical data exist that could support the assumption of limited incision, it can be indirectly inferred from the lack of incision occurring in tributaries to Hog Park Creek. However, it is apparent that some incision has occurred as floodplain species are shifting due to the increasingly xeric conditions. Lodgepole pine saplings are observed encroaching on the floodplain, which indicates a declining water table depth. Instead of major incision, preferential erosion of finer bank soils through widening and lateral migration appears to be the main form of channel adjustment and energy dissipation.

Initial construction on Hog Park Dam began in 1963. The channel had already been impacted by decades of land use, including logging and sheep and cattle grazing. Pre-dating these was the removal of beaver in the area, with direct hydrologic impacts. The heavy logging era ended in the 1920's. The heaviest grazing ended in 1950 and the system had a short recovery period for the next decade, although the heavy cattle grazing did not end until 1962. Additional grazing restrictions were put into place in 1978 and by 1989 cattle were no longer provided entry in reach 1, although moderate grazing allotments have remained in place in reaches 2, 3 and 4 up to the present. Additional storage capacity for Hog Park Reservoir was required as additional easements for water rights from the North Fork Little Snake River were obtained for trans-basin diversions into Hog Park Creek. Construction for the enlargement of the dam began in 1982, with the current augmentation of 27.9 million m3 being realized in 1985.

5.1 HYPOTHESIS 1- HYDROLOGIC ANALYSIS

Results from the hydrologic analyses support the alternative hypothesis that dam operations have significantly altered the flow regime characteristics when comparing the pre-dam time period to the time period following the enlargement (Stage 2, 1985). The annual discharge is nearly doubled due to flow augmentation from the Little Snake River drainage. There is an

early release in the spring to allow for additional storage of spring runoff in the reservoir, causing an earlier and bimodal high flow peak. High flows have slightly decreased under current operations; for example, the annual 1-day maximum discharge has decreased by 9%. This is compensated for by the 300% increase in base flows. The maximum to minimum annual discharge ratio for each year of record was observed to have decreased greatly (Figure 5.3). All of these metrics indicate a significant decrease in the inter-annual variability in the flow regime.

It is important to note that the existing low flows are mandated with the intention of improving the quantity of habitat for brook and brown trout (Hubert et al., 1997), while high flow releases are suppressed due to the size of a culvert below the dam. During the winter, these higher than normal base flows are believed to prevent snow bridges, leaving the channel exposed. This allows for much greater freeze-thaw potential, which prepares banks for exacerbated erosion during the spring. Metrics that did not test as being of high significance but may be of an added ecological importance include the timing of maximum discharge, which resulted in a 3% shift in magnitude, with peak flow occurring an average of 11 days earlier than historically.

Hydrologic variables related to the duration of floods are particularly important in this study. Small flood durations, specifically those of the 2- to 5-year recurrence interval, have gretly increased, whereas high magnitude, low frequency floods are greatly reduced. The change in frequency and duration of discharges of 2- to 5-year recurrence are perceived to play a large role in bank erosion in Hog Park Creek during contemporary times. Because of the consistency and predictability of Hog Park Creek as a snowmelt-dominated hydrology, the annual snowmelt floods are important in maintaining sediment transport dynamics and riparian vegetation recruitment (Merritt and Wohl, 2002; Stella et al., 2006).

The variables used in this analysis are determined by their correlation with the sediment transport regime and ecological processes, as the three items are inextricably intertwined in the river system and prove important for management considerations. Since the physical structure of aquatic habitats is a result of the interaction between streamflow magnitude and frequency and the physical landscape (Leopold et al., 1964), a complete analysis of the diversity of flow variables is included in this analysis. Similarly, the snowmelt hydrology maintains a high level of predicitability in timing and the related indices correlate with the ecological function of benthic macroinvertebrates and critical life stage survival of aquatic species.

As the basic building block of the food web, a shift in aquatic organisms can directly impact larger species populations as well. Fish may be impacted by the shift or reduction in macroinvertebrate food supplies, as well as by reduced hydrologic heterogeneity, which can result in reduced channel complexity (Figure 5.3). For example, a study by Risley et al. (2010) indicated that a loss of channel complexity in the McKenzie River basin, which is associated with reduced floods and widespread channel stabilization, is the primary factor related to the observed population declines for all nine species studied. The dams also have caused direct ecological effects by blocking access to habitat, changing the amount and timing of available critical habitat, and changing water temperature during important seasons for different life stages.
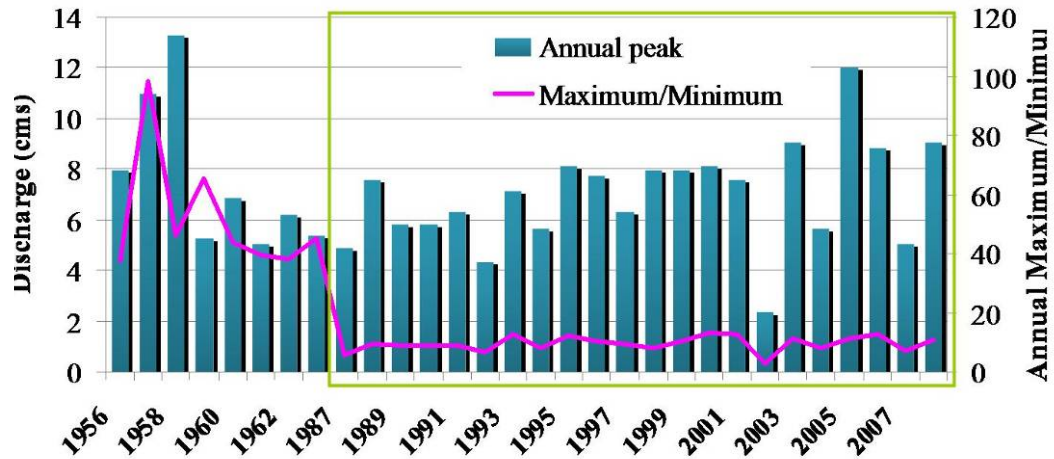
Figure 5.3: Discharge data summarizing the loss of flow heterogeneity throughout the three flow eras. The highlighted box displays the Stage 2 operations.

Hydrologic changes also impact the sediment transport regime. Stream bed substrate contributes to roughness in the channel, refugia for organisms, and morphologic stream features for habitat diversity. It is not only the hydrograph which is of concern, but also its effect on the sediment transport regime and the sediment budget. With lack of sediment passage at the dam, a majority of the sediment input comes from fine sediment from the banks in the upper reaches, but this is likely to be rapidly carried out of the system in suspension. Coarse sediment supply from the upper watershed is not arguably being interrupted in significant quantities. The lack of adequate amounts of coarse sediment to replenish gravel bars, as observed in cross sectional analyses and through field observation, is most likely a result of the increased duration and frequency of higher flows. Although incipient motion analyses were not done, it is hypothesized that flow releases in the early spring and the extended high flow durations characteristic of Stage 2 operations likely increase quantities of sediment transport annually, lending to the apparent diminution of coarse sediment in Hog Park Creek. The historical 2-year event is exceeded annually during the current operational regime. The current two-year recurrence interval discharge surpasses that of the historic 5-year (6.1 m3/s) recurrence interval

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discharge, indicating a significant increase in the duration of time the channel experiences these formative discharges.

With only larger sediment retained and with twice as much annual discharge, stream power is presumably greatly increased in the system and the changes in channel geometry, migration rate, and substrate composition are expressions of the dissipation of this excess energy. The channel capacity is greater now than it used to be. This morphologic adjustment suggests that excessive change has occurred due to the presence of the dam.

High flood flows create off-channel habitat, including side channels and backwaters, which are important for various species and life stages, and are often critical for juvenile and rearing fish. The reduction in peak flows over time will result in less vegetation and physical habitat structure heterogeneity; a reduction in sediment input; and potentially reduce the groundwater resupply of the floodplain. In turn, this changes the availability of suitable habitat for various life stages of aquatic organisms. Downstream effects of reduced peak flows on riparian vegetation can be a loss of species cover and diversity due to a lack of regeneration and recruitment, and habitat alteration due to bank erosion.

 Dams alter the fluvial geomorphic processes which modify the biogeochemical cycles as well as the structure and function of aquatic and riparian habitats. It is difficult to infer any life history impacts resulting from flow regulation in Hog Park Creek without a more in-depth analysis of the species composition in the creek and nearby systems. Additional work could determine the viability of current populations and favorable riverine processes and conditions to improve the aquatic organism diversity and abundance and the recreational fishery in Hog Park Creek.

5.2   HYPOTHESES 2 - 4 PLANFORM ANALYSIS

The null hypotheses examine whether the specific channel form parameter has not changed as a
result of flow regulation. Each associated alternate hypothesis proposes that this parameter has
changed.

($H_{o(2)}$): No temporal changes in channel mean width have occurred since installation or changes
to the dam.

 ($H_{o(3)}$): No temporal changes in lateral migration rates have occurred since installation or
changes to the dam.

($H_{o(4)}$): No temporal changes in complexity have occurred since installation or changes to the
dam.

Hypothesis 2 is at least partially rejected in support of the null hypotheses that channel planform

characteristics have changed since installation of the dam. However, the presence of multiple

potential drivers of water and sediment yield, combined with natural channel variability, can

make it very difficult to conclusively demonstrate that observed changes in channel dynamics

are greater than those in the reference system or are primarily attributable to flow regulation. As

explained in detail earlier in this thesis, Hog Park Creek has many sources of spatial variability.

The planform analysis began with aerial photographs spanning 1937 – 1991 ortho-rectified into

GIS, from which planimetric variables such as width, lateral migration and complexity were

derived. Covariance analyses and linear models were used to assess changes by pre- and post-

dam time period, and determine whether distinctions can be made between flow regulation and

the alternate drivers such as decadal precipitation trends, location in the watershed and relative

impact of cattle grazing. The null hypothesis that parameter characteristics were not different

following Stage 1 implementation was rejected, in support of the null hypothesis that some

changes could be attributable to the dam. Correlations were weak, however, and trends

appeared spatially, differentiating the reference and partially regulated reaches from the main

stem regulated reaches. Trends also varied temporally, indicating that changes could not be

attributable to flow regulation alone. This suggests that spatial variability in controls and perturbances accounts for these changes as well. For example, the observed significant response of width to flow regulation in reaches 1 and 2 is dampened in reach 3 due to the supplemental flow of South Fork Hog Park Creek (reach 4). However, reaches 3 and 4 are both experiencing increases in width, which may reflect additional erosion related to grazing. The planform changes in reach 4 do not follow linear trends through time, contributing to the complexity of interpretation of the results using reach 4 as a reference reach.

Lateral migration rates have changed but not in the same direction and magnitude as width changes. Width was compared with sample variance and lateral migration rates by reach. A channel experiencing dynamic equilibrium would, in theory, exhibit a direct relationship between width and complexity. These two increase in correlation up until the 1990's in reaches 1 and 2 and in 2001 for reach 3. Following this shift, width increased, with a decrease in complexity. The contemporary increase in width corresponds to a decrease in sinuosity, complexity and gravel accumulations throughout reaches 1, 2 and 3.

An abrupt change is seen, however, in a dramatic decrease in lateral migration distance following Stage 1 implementation in reach 1. Similarly, the lateral migration rates decrease abruptly in the time span between 1983 and 1991, with all reaches dropping to the lowest recorded rates of lateral migration in the timeframe of analysis. Coincidental with this timing is a decrease in complexity, particularly in reaches 1 and 2. These rates provide a description of the short-term sinuosity increase along the channel. This analysis has shown, however, that increasing lateral migration rates may not be directly attributed to sinuosity changes, but also to homogenization of the channel to a form of more uniform width and less channel complexity. Complexity, as measured by variance in width, did not result in statistical significance, which is most likely attributable to the metrics used for complexity. A visually dramatic loss of

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complexity occurs following 1955 (Figure 5.4 and Figure 5.5). Beaver ponds provide increased

habitat diversity and complexity to the aquatic ecosystem (Naiman et al., 1988; Olson and

Hubert, 1994). This diversity in habitats allows for diversity in bed material size distribution

and dissipation of flow energy, which are all important to aquatic species. The dams and ponds

trap silt and organic material, eventually filling and raising the level of the valley floor (Ives,

1942). The meadows created by filled beaver ponds provide increased habitat diversity in the

terrestrial ecosystem, as well.

Figure 5.4: Beaver dams and ponds in reach 2, Hog Park Creek, 1955.

Figure 5.5: Beaver presence in reach 2 in 2001

Beaver numbers were greatly repressed by the late 1860's and undoubtedly impacted hydrologic function of both the floodplain groundwater and stream flow. However, complexity in the channel remained relatively high in 1937 and 1955, until a dramatic decrease is observed in the 1966 aerial photographs. The reduction in variability of discharge, or increased channel

discharge and sediment deprivation, is causing a reduction in side channels and gravel bars, so
that the main channel is evolving into a narrower single-thread channel.

5.3   HYPOTHESES 5 - 7 BANK EROSION ANALYSIS

Each of the following null hypotheses proposes that a specific parameter does not significantly
affect bank erosion rates. Each associated alternate hypothesis proposes that this parameter is a
significant control.

($H_{o(5)}$): Bank erosion rates, as simulated by the Bank Stability and Toe Erosion Model
        (BSTEM), are not significantly elevated under the current hydrologic regime.

 ($H_{o(6)}$): Bank erosion rates are not correlated to inter-reach characteristics.

($H_{o(7)}$): Bank erosion rates are not correlated to intra-reach characteristics.

Results from the planform analysis show that significant changes have occurred to the
morphology of Hog Park Creek, and that these can be directly correlated to dam operations.
However, results show that rates of erosion are not similar across all reaches and that variability
in the amount and timing of erosion does exist at the reach and site scale. Cross section
analyses indicate that erosion rates may vary between and within reaches, but that all cross
sections within each reach have experienced an increase in area during the last 5 years.
Streambank degradation is a concern for the USFS, the managers of the land downstream of
Hog Park Dam, since the area is a popular recreation area for fishing and hunting. Management
of the watershed to minimize elevated streambank erosion from reservoir operations is
important for preserving the integrity of the freshwater ecosystem and minimizing impacts to
the high alpine meadow. Cross section analyses indicate that erosion is occurring across all
reaches in the study site. To identify the causes of reach-scale variability, rates of bank erosion,
derived from erosion pins, are correlated with site-specific bank morphology and hydraulic

attributes. These analyses indicate that there is some correlation between and within reaches, but that site-specific variation does occur. Both the root depth: bank height ratio and thalweg depth significantly correlated to erosion pin data; the coefficient of determination ranged between 0.19 and 0.28. The low correlation values suggest that untested parameters must account for a portion of the intra-reach variability.

Bank erosion modeling was conducted in BSTEM to identify the mechanisms most likely associated with the erosion rates and the variation between sites. Sensitivity analyses showed that bank instability, as modeled with data from Hog Park Creek, is most sensitive to soil cohesion values and the surface water level relative to the groundwater level. Hence, hydraulic attributes may account for some site-specific variation.

The bank erosion modeling, conducted at a single representative site, was used to assess erosion rates for the different operational periods. The hydrograph from 1971 was used to assess bank stability for Stage 1 operations and the 2008 hydrograph was used to represent erosion rates for Stage 2 operations. As modeled through a contemporary annual hydrograph, toe scour occurs during both the early spring reservoir flow release and on the rising limb of the late spring reservoir flow release. Mass wasting is most likely to occur during the falling limb of the flood hydrographs, particularly when the groundwater elevation in the adjacent floodplain is higher than the channel water-surface elevation. Bank failure did not occur during the peak discharge of the late spring reservoir release because of both the cohesion provided by roots to the upper bank layers and the additional support provided to the bank by the water in the channel. Instead, once banks were destabilized by hydraulic scour of the toe, those banks failed during the decline in water-surface elevation when supersaturated banks were left unsupported.

The banks in Hog Park Creek tend to be a fine soil overlying a unit of gravelly, coarser particles with a fine matrix. As river stage rises from winter base flows, hydraulic scour and

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undercutting of the toe occur. As the stage reaches the transition between composite and finer layers, the excess energy of the water focuses on the less resistant banks. The locations of greatest undercut coincide with those stages of low flow experienced during the early spring release and in some sites the low flow stage under contemporary operations. This low flow stage has increased approximately 300% since Stage 2 operations began.

The willows and grasses along the channel have adequate root strength to maintain cohesion during the high flow stages that reach the upper bank layers. Hence, the bank is being preferentially eroded in the soil column where roots are absent and soil transitions occur. Once stage rises to the extent of the roots, the additional cohesion provided by roots in the upper bank layers inhibits erosion. Annual high floods do not appear to initiate mass failure, but rapid drawdown scenarios that leave saturated banks unsupported, in combination with the extensive undercutting from lower flows, lead to mass wasting.

6   CONCLUSION

To assess channel response to altered flow and sediment discharge, multiple analyses across a range of spatial and temporal scales were conducted: a covariate hydrologic analysis relating pre- and post-dam time periods, an examination of the channel planform change, and a study of bank erosion dynamics. The three components of the study examine an extensive time span, with multiple drivers of variability, then relate the interactions back to fine-scale hydraulic and geotechnical interactions. The magnitude of changes to the hydrologic system was the first component. The planform response of the river channel over 43 years and its relationship to its floodplain, riparian vegetation and bounding valley walls was the next component. The final component was the qualitative comparison of sediment input into the river, its transport capacity and the covariate analysis of geotechnical predictors and the erosion response.

The magnitude and timing of sediment-transporting small and large floods in Hog Park Creek are different during Stage 2 management than they were during Stage 1. The differences are best summarized by project operations and by reach, but operations are the basis of the differences. The flood magnitude is now lower, but the interval between large floods is shorter, as is the duration. In reach 1, directly downstream of the dam, erosion was greatest immediately following installation of the dam, coupled with a loss of channel complexity, side channels and gravel bars. Through time, reach 1 has shifted to a single-thread channel with reduced sinuosity and reduced morphologic heterogeneity. In reach 2, the responses to the shift in hydrology are similar as in reach 1, but slightly dampened and delayed. In reach 3, the

planform effects from the altered hydrology are more muted due, presumably, to the input of South Fork Hog Park Creek.

The physiographic character of the Hog Park basin is a mitigating factor in the interruption of coarse sediment by Hog Park Dam. Based on aerial photography analysis, Hog Park Creek at the present-day reservoir location was a meandering pool-riffle channel. This type of channel is typically transport-limited (Montgomery and Buffington, 1997). The valley in which this reach of Hog Park Creek flowed is broad and unconfined, a form inherited from previous glacial erosion. This type of setting is typically a sediment sink, because only a relatively small volume of the coarse sediment transported from the steep headwaters can be transported through the low-gradient reach to the lower river during floods.

The sediment supply entering the study area from upstream most likely remained essentially unchanged between the periods of Stage 1 and Stage 2 operations. In 1964, Stage 1 operations included a sufficiently high dam at the present location to interrupt all coarse sediment supply from upstream, which has persisted to contemporary times. Otherwise, land use has remained generally similar. Between Stage 1 and Stage 2 operations, the most influential alteration in the fluvial system has been the alteration in the hydrograph.

Even though large flood pulses have been more punctuated during Stage 2 operations, sediment transport has increased due to the increased frequency of small and medium flood pulses. It appears that there remains excess capacity to transport all of the sediment supplied to reaches 1 and 2. Sediment input into the lower channel from hillslopes has remained likely unchanged, mainly due to the relatively low gradient unconstrained floodplain. Channel reaches of this type are considered to be supply-limited. As a consequence, Stage 2 sediment routing through reaches 1 and 2 is similar to Stage 1, and most sediment supplied to the reach is exported to reach 3, with minimal storage in the channel.

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Changes in sediment transport capacity in reach 3 are more complex. An expected outcome is that channel adjustments associated with excess sediment supply should be observed if the sediment supply from the upper reaches (bank scour) has increased, while the duration of large floods has been reduced. However, no expressions of the channel changes expected from such increase in sediment supply are observed in the planform study; neither avulsions, braiding, nor significant channel widening have occurred. Reach 3 is experiencing continued channel widening and bank erosion. The channel complexity has decreased since the onset of Stage 2, and this phenomenon appears to continue a trend that initiated at the onset of Stage 1 operations (1965).

Hog Park Creek is currently a supply-limited system, with most sediment delivered via bank erosion downstream of the dam. Prior to the inception of Stage 1 (1965), Hog Park Creek appeared to have received minimal delivery of coarse sediment from the upper watershed. Tributary streams in the upper watershed may have contributed significant amounts of coarse sediment to the channel, but this was largely a depositional zone. Currently, there appears to be a paucity of excess sediment in the study area. This is a consequence of the multiple effects of flow alterations: sediment-transporting flows have been increased on an annual basis, although large flood frequency has been reduced. The change in channel geometry has allowed for greater conveyance for transporting more flow. Thus, the hydraulic conveyance of the channel has increased even as the sediment supply is reduced.

Cross sections increased in area, but overall changed relatively little over the period of repeat surveys. As a cumulative site-scale measure of erosion, the change in cross section area in each site was summed (approximately 15 cross sections per site) and the cumulative net erosion ranged from 3 to 7 square meters between 2005 and 2009. The forces acting on the banks have changed via flow regulation, including seepage via water level fluctuations and increased shear

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forces, with the result of bank erosion and channel change. However, this response is mediated

as channel geometry changes. As width increases relative to depth, the shear stress on the banks

is decreased. The channel has perhaps adjusted to the current flow regime during the twenty

years since Stage 2 implementation. Determining whether the channel has reached dynamic

equilibrium is beyond the scope of this study, however.

Understanding process controls and landform responses is difficult, because: (a) erosion is

characteristically episodic, with the erosion process rate varying with the magnitude and

frequency of high flows and the associated stream power; (b) many geomorphologic systems

are affected by complex responses and lag times; and (c) multiple historical impacts have

occurred over time. Dam operation and land use patterns together influence spatial and

temporal changes in channel morphology and planform. Stream channel modifications that

occurred at segments downstream of the dam may have exacerbated disturbance effects rather

than contributing to the channel's natural adjustment to large-scale impacts. Adjustments to dam

operations should consider relationships between discharge, sediment load, channel geometry,

land use, and riparian vegetation. The historical analysis suggests that managers who seek to

minimize impacts to the physical and ecological components need to consider a stream system's

reactions to historical disturbances and current stream processes to enhance appropriate

geomorphic processes, ecological sustainability and habitat resilience.

6.1   FUTURE STUDIES

As realized throughout the analyses in this study, there is great potential for additional analyses

of this dataset. More work should be done comparing hydraulic variables with bank erosion.

An extensive velocity profile data set now exists from which many parameters may be derived

(see Appendix E). Also, longitudinal profile data analysis and geotechnical data analysis could complement this study.

To improve the current understanding of bank erosion processes, another idea for future studies are in-bank devices that can monitor bank erosion timing since the site is inaccessible for the important peak and receding limb periods. However, freeze-thaw impacts are not incorporated into the bank erosion modeling, nor is seepage undercutting, and this presents opportunities for future analysis.

Understanding the relationship between discharge and bedload transport rate through a reach and the ability of the existing channel to transport the bedload (sediment transport capacity) benefits many applications, including prediction of the effects of land use or flow regime change and in predicting future change. The present analysis is insufficient to predict whether the channel might continue to adjust to create increased capacity under the Stage 2 flow regime, or whether the channel has reached a new state of equilibrium. A sediment supply and transport analysis would determine the state of the other key component of the geomorphic regime: the sediment regime.

If it is a goal of management agencies to improve habitat for greenback cutthroat trout, then life stage flow requirements should be studied and operations modified to resemble a flow regime more suited to support the life history requirements at critical stages of development. Currently, management requirements are in place to maintain high base flows and minimize spring high flows for the success of brook and brown trout. Since the flows are operated today to support game fisheries of brown and brook trout, studies should be undertaken to determine whether the base flows are actually encouraging species success. If regulation is inhibiting the vitality of the benthic macroinvertebrate populations, then perhaps adjustments should be made. An ecological analysis, for both benthic macroinvertebrates and fish, would be an excellent

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opportunity to determine whether these flows are accomplishing their goal, and whether there may be other alternatives.

6.2   GENERAL MANAGEMENT RECOMMENDATIONS

This thesis provides a synthesis of the hydrologic and morphologic channel changes experienced in Hog Park Creek over the last 50 years. A secondary and potentially long term outcome of this study is to derive a sustainable management scenario for dam operations from the knowledge of the observed changes in the watershed. The understanding of the geomorphic and ecological responses to previous dam operations is pivotal in developing a flow management scenario that benefits both the dam managers and the dynamics of the watershed. The ultimate goal is an operational regime that provides both a sustainable and resilient river system that supports the recreational and resource land uses in the study area.

Several studies of floods and human impacts in fluvial systems have found direct relationships to dams and downstream changes in complexity (Graf, 2006; Sheldon and Toms, 2006). An ideal spawned by these and other studies is that restoration of a naturalistic flood regime would increase the complexity of these systems.

As Postel and Richter (2003) summarize from an extensive literature review, managing river flows to sustain ecosystem integrity may be attained through the following principles:

1. *A modified flow regime should mimic the natural one, so that the natural timing of different kinds of flows is preserved. The characteristics of the flow to be preserved should be assimilated from literature review of species in the area, and field analysis of benthic macroinvertebrates, the building blocks of the food web.*

2. *A river's perenniality and nonperenniality should be maintained.*

3. *The seasonal pattern of higher base flows in wet seasons should be retained. Floods should be present during the natural wet season.*

4. *It is better to retain certain floods at full magnitude and eliminate others entirely than to preserve all or most floods at diminished levels. The maintenance of range of flows*

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assists in maintaining the heterogeneity of physical habitat in the stream and maintaining pool, riffle and run habitats.

As shown in Hog Park Creek, base flows have been greatly increased and peak flows slightly dampened. To develop a hydrograph that better simulates 'natural' conditions, annual precipitation trends can be used to prescribe flow regimes for upcoming years. Climate change, cloud seeding and beetle impact should all be considered as potential alterations to controls in the watershed and, as more research arises, incorporated into flow management.

Variability of the flow regime drives sediment transport, productivity and disturbance regimes that fundamentally influence food web interactions, riparian vegetation form and other ecological attributes of the river ecosystem. A basic premise is that the biotic characteristics of the aquatic ecosystem will be restored by protecting or restoring specific components of the hydrologic regime.

In contemporary operations, the variability of the annual hydrology in Hog Park Creek has been decreased. I think that the mandated high base flows and dampened peak flows should be revisited to determine if they are helping or hindering the success of target fish species at various life stages. An easement issued to CBOPU in 1982 mandated a minimum flow requirement (0.42 m3/s) to provide aquatic habitat, and a maximum flow requirement (8.5 m3/s) to reduce adverse effects to the stream channel below the reservoir. As a result, base flows are significantly increased through the late summer and winter. Though tested as significant, the increase in discharge from 0.1 m3s-1 to 0.4 m3s-1 does not initiate a significant influence on the geomorphic processes of sediment transport or bank erosion. The releases due to water transfers in the early spring do have more influence on geomorphic processes because the flows are high and they are sustained for a much longer duration. The river stage at these flows coincides with the intersection of soil layers in the banks. The intersection of the soil layers are prone to scour and exhibit extensive undercutting at the sites in main stem Hog Park Creek.

The highest annual flows do not appear to cause excessive erosion and are an important component of the flow regime to maintain.

Restoring large flood flows can produce a healthy geomorphic response by increasing habitat complexity and heterogeneity. Bank erosion modeling indicates that these high flows do not cause excessive bank erosion; but literature cites the benefits that result from channel and floodplain interaction during high flows. Factors that hinder floodplain formation include processes that limit the connectivity between the active channel and floodplain, or minimize floodplain creation. For example, the reduction of peak flows not only minimizes overbank deposition, but also reduces the processes that create and recycle floodplains (such as bar formation and bank erosion). Anecdotal evidence suggests that average annual peak flows likely ranged between 5 and 5.6 m3s-1. Channel adjustment has occurred since these discharges were recorded (CBOPU 1988, unpublished). Management guidelines should mimic the natural hydrograph and adjust the high flow values according to the capacity of the current channel configuration.

Mimicking the natural conditions also means a better understanding of the flows entering the impoundment. Currently, gauging of the natural inputs can be improved upon to provide a better record of natural flows and the amount of water entering the reservoir. Annual hydrographs ideally should be developed through adaptive management scenarios, by developing a hydrograph based on the snow pack accumulation. Sediment supply and transport are beyond the scope of this study, but form another important component. In restoring the hydrological regime, the system is not functioning in equilibrium if the sediment transport regime is not also restored. The additional studies and resources above, if undertaken, will help to guide future management.

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APPENDIX

A
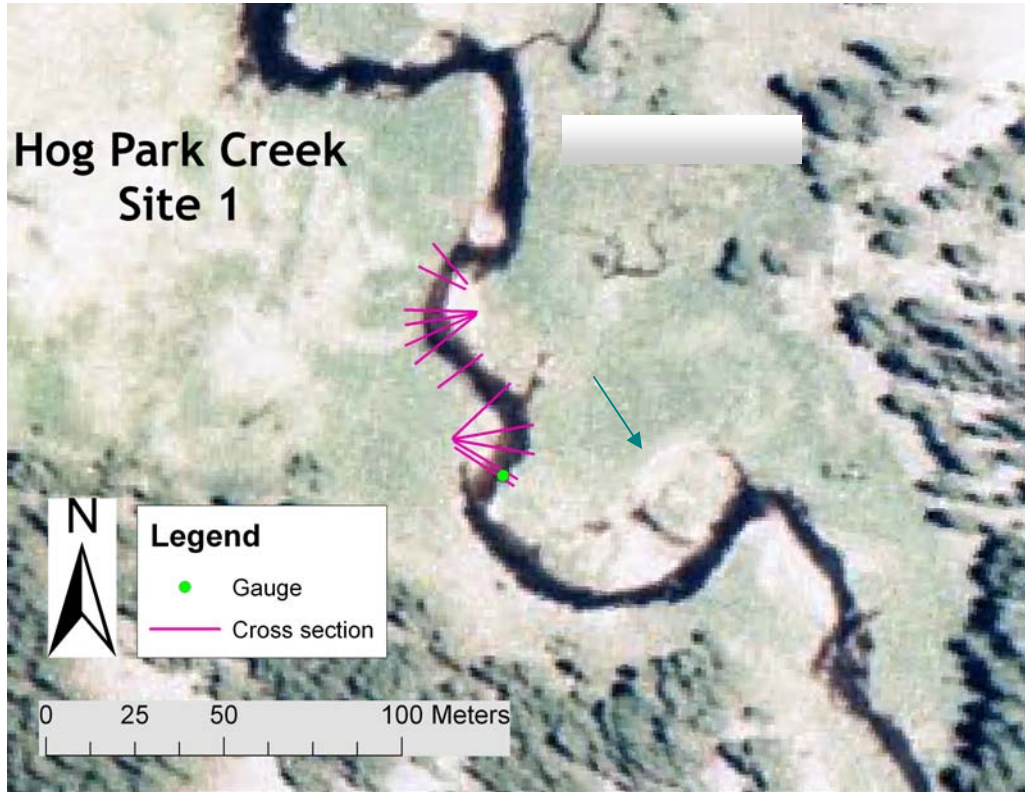
Site 1

Figure A.1:Aerial photograph (2001) showing cross section locations and crest gauge.
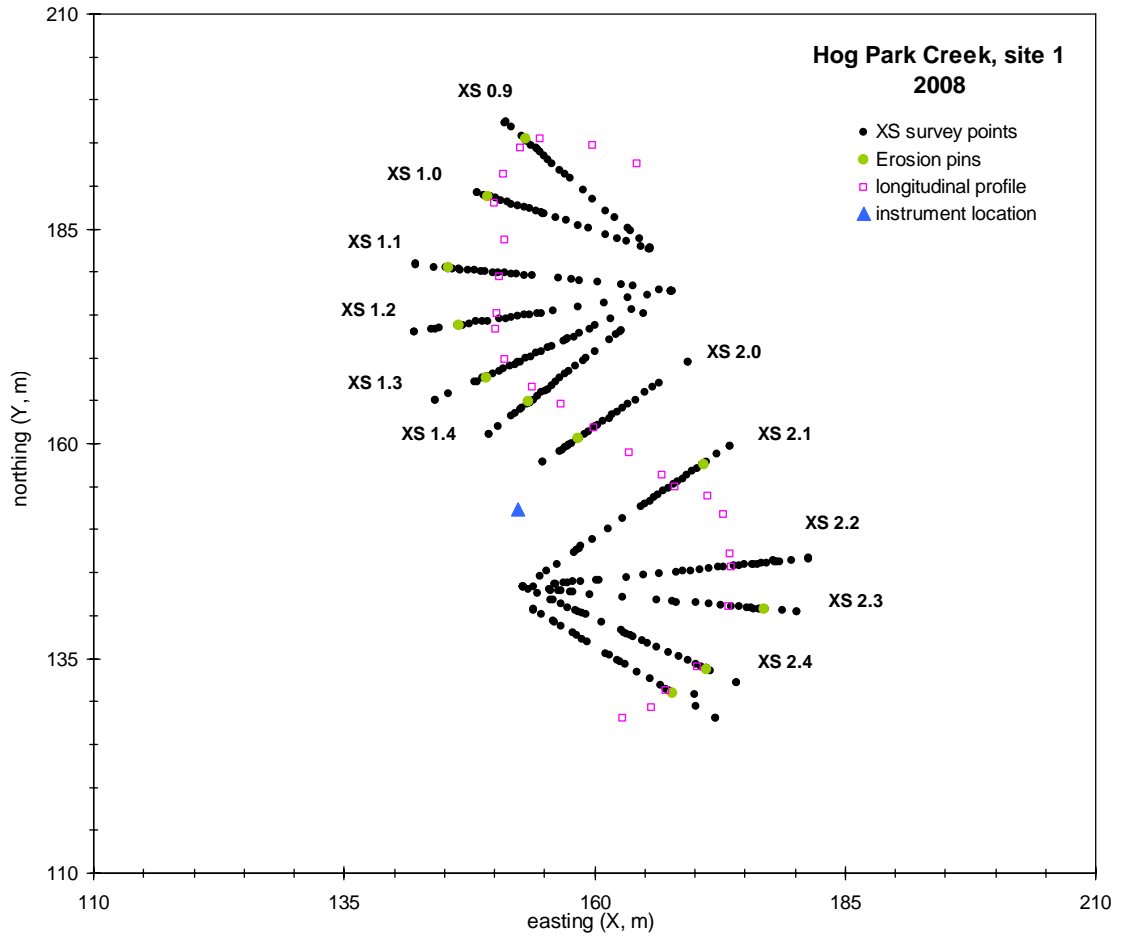
Figure A.2: Planform schematic generated from survey data, Site 1, 2008.

Figure A.3: Looking downstream at Site 1 from the top of the site, 2008.

Figure A.4: Downstream end of Site 1, 2008. Note the instream structures placed in the 1970's.
These are downstream of the study site.

Table A.1: Particle size distribution information for Site 1. Samples collected in riffles, 2008.Particle size distribution information for Site 1. Samples collected in riffles, 2008.

Site 1			Riffle surface Particle count			Type
Size (mm)			**Size Distribution**			**Type**
D16*	19		mean	39.0	silt/clay	0%
D35	32		dispersion	2.1	sand	0%
D50	40		skewness	-0.01	gravel	76%
D65	52				cobble	24%
D84	80				boulder	0%
D95	110					

			Riffle Surface Particle Count			
Size (mm)			**Size Distribution**			**Type**
D16	20	3.4	mean	44.7	silt/clay	0%
D35	39	12	dispersion	2.3	sand	0%
D50	53	17	skewness	-0.09	gravel	58%
D65	73	20			cobble	42%
D84	100	29			boulder	0%
D95	130	39				

* Particle-size data are reported in terms of D_i, where i represents some nominal percentile of the distribution and D represents the particle size, usually expressed in millimeters, at which i percent of the total sample is finer. For example, 84 percent of the total sample, by weight, would be finer than the D84 particle size.

Figure A.5: Looking upstream in Site 1. Note proximity to the dam, 2007. Photo by D. Cenderelli.

Site 1 Erosion Type
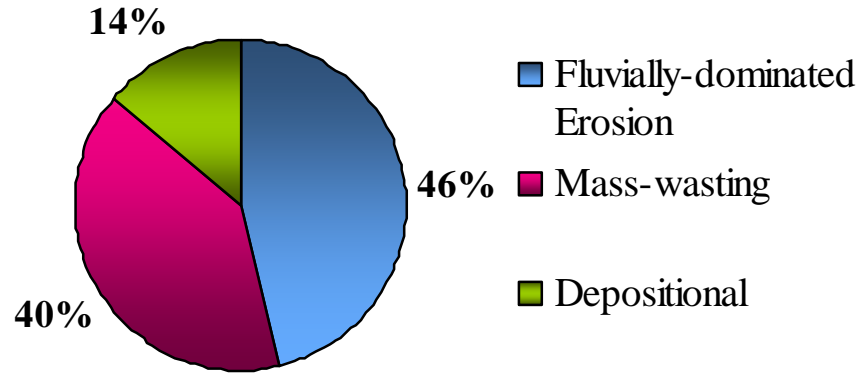

Fluvially-dominated Erosion

Mass-wasting

53% 47%
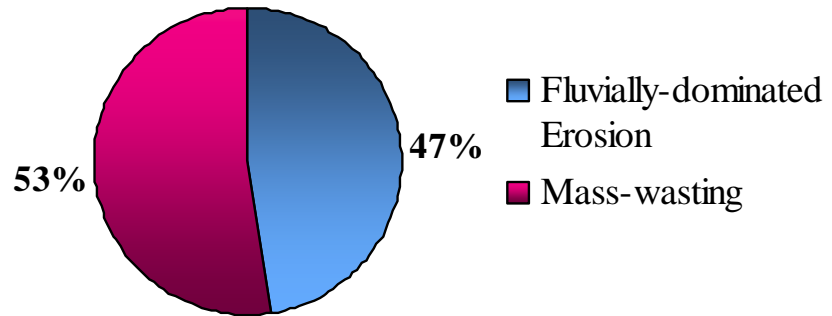
Figure A.6: The types of erosion occurring and the respective percentage of length of the right bank throughout Site 1 experiencing the type of erosion.

Figure A.7: typical bank erosion along right bank in Site 1, 2007. Photo by D. Cenderelli.
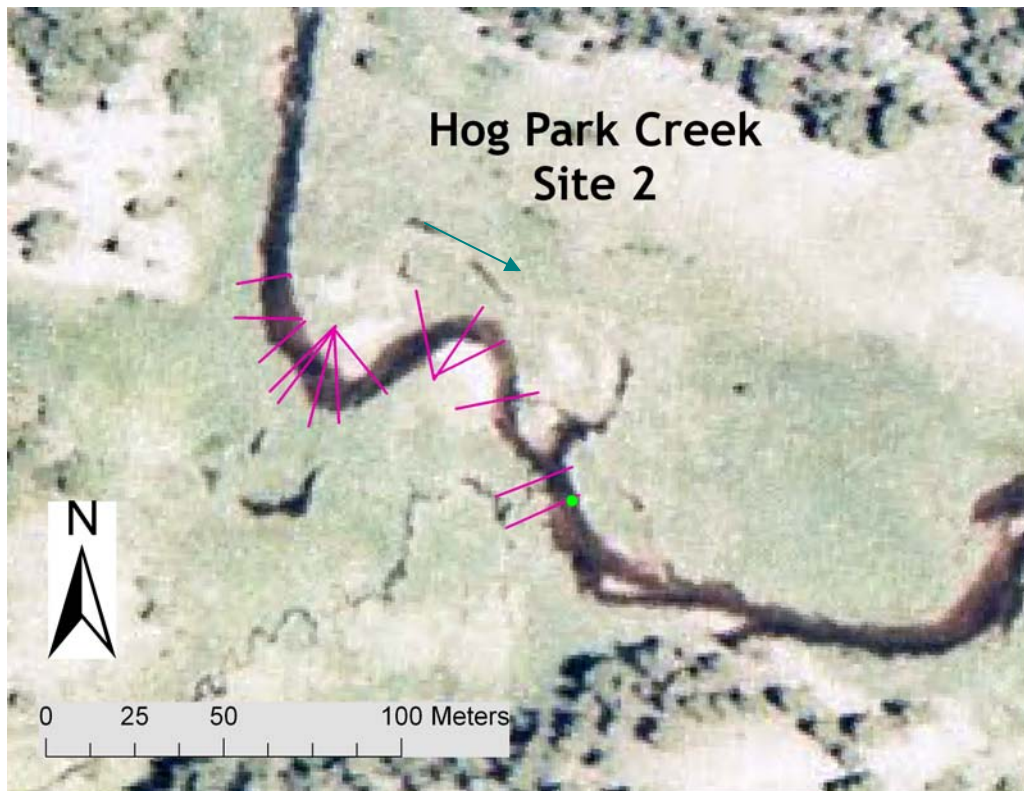
Figure A.8: Aerial photograph (2001) showing cross section locations and crest gauge.
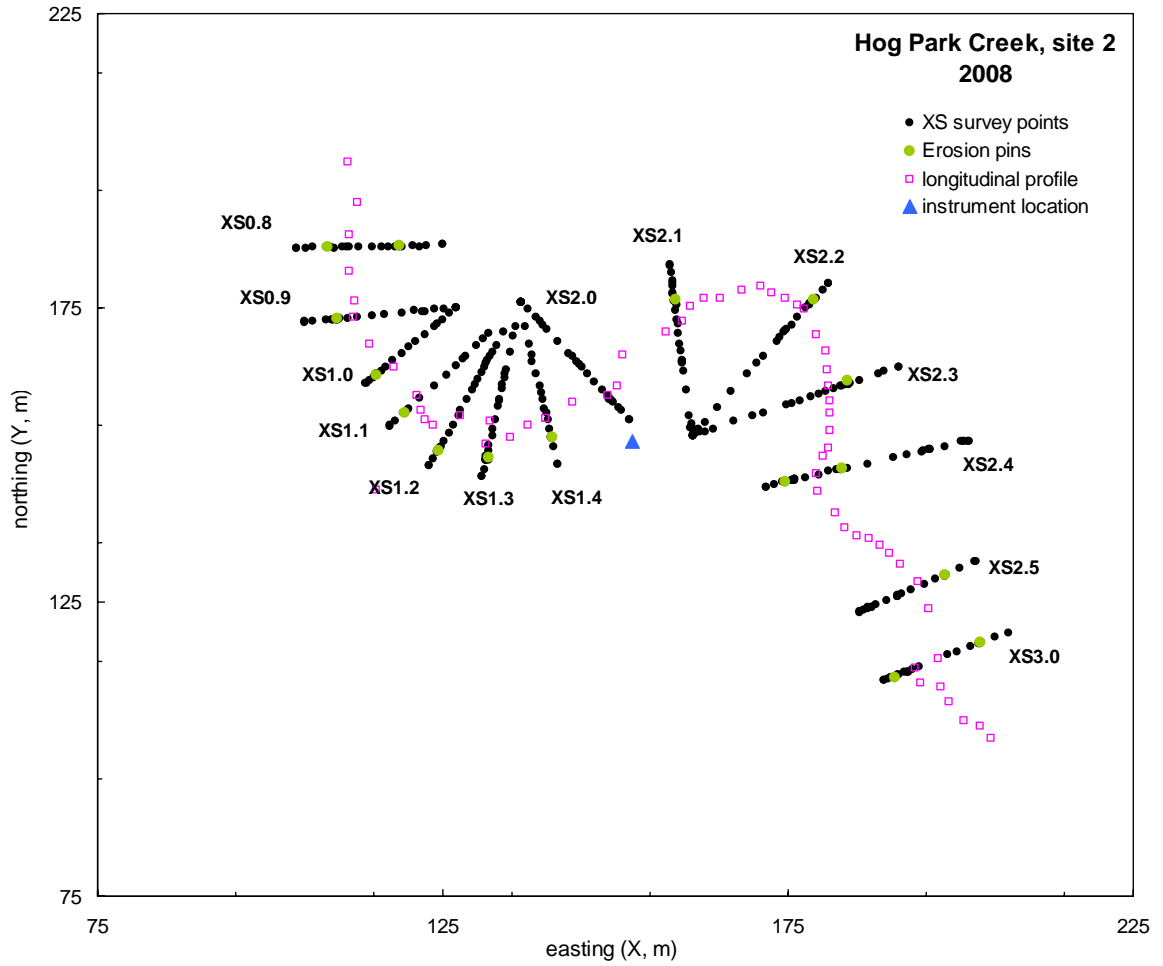
Figure A.9: Planform schematic of Site 2, generated from survey data, 2008.

Figure A.10: Site 2 looking downstream, 2007. Photo by D. Cenderelli.

Table A.2: Particle size distribution information for Site 2. Samples collected in riffles, 2008.

Site 2			Riffle-surface Particle Count			
Size (mm)			Size Distribution			Type
D16	19	3.4	mean	45.7	silt/clay	0%
D35	39	12	dispersion	2.4	sand	0%
D50	54	17	skewness	-0.08	gravel	56%
D65	74	20			cobble	44%
D84	110	29			boulder	0%
D95	140	39				
			Riffle-surface Particle Count			
Size (mm)			Size Distribution			Type
D16	6.3		mean	22.7	silt/clay	0%
D35	16		dispersion	3.9	sand	0%
D50	33		skewness	-0.15	gravel	76%
D65	48				cobble	24%
D84	82				boulder	0%
D95	120					

220

Figure A.11: Site 2, at the midpoint of the site, looking downstream, 2007. Photo by D. Cenderelli.

Site 2 Erosion Type

32%

68%

Fluvially-dominated Erosion

Mass-wasting
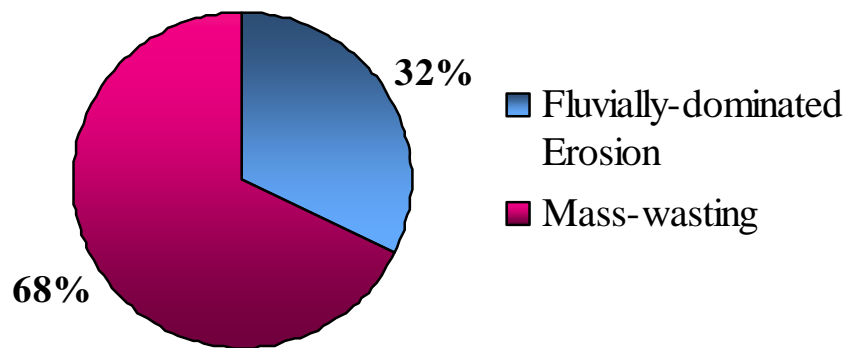
Figure A.12: The types of erosion occurring and the respective percentage of length of the right bank throughout Site 2 experiencing the type of erosion.

Figure A.13: Bank erosion in Site 2, 2008.

Figure A.14: Bank erosion along right bank in Site 2, 2009. Note the coarser gravel deposit at the toe, and preferential erosion occurring mid-bank.

Figure A.15: An example of slumping in Site 2, 2008. A tension crack exists in the bank top. The orange flag indicates an erosion pin location, indicating a cross section, also is located here.

Figure A.16: Bank slump and bank failure in Site 2, 2008.

Figure A.17: Aerial photograph (2001) of Site 3, with cross sections (pink) and pressure transducer (green circle) locations indicated.
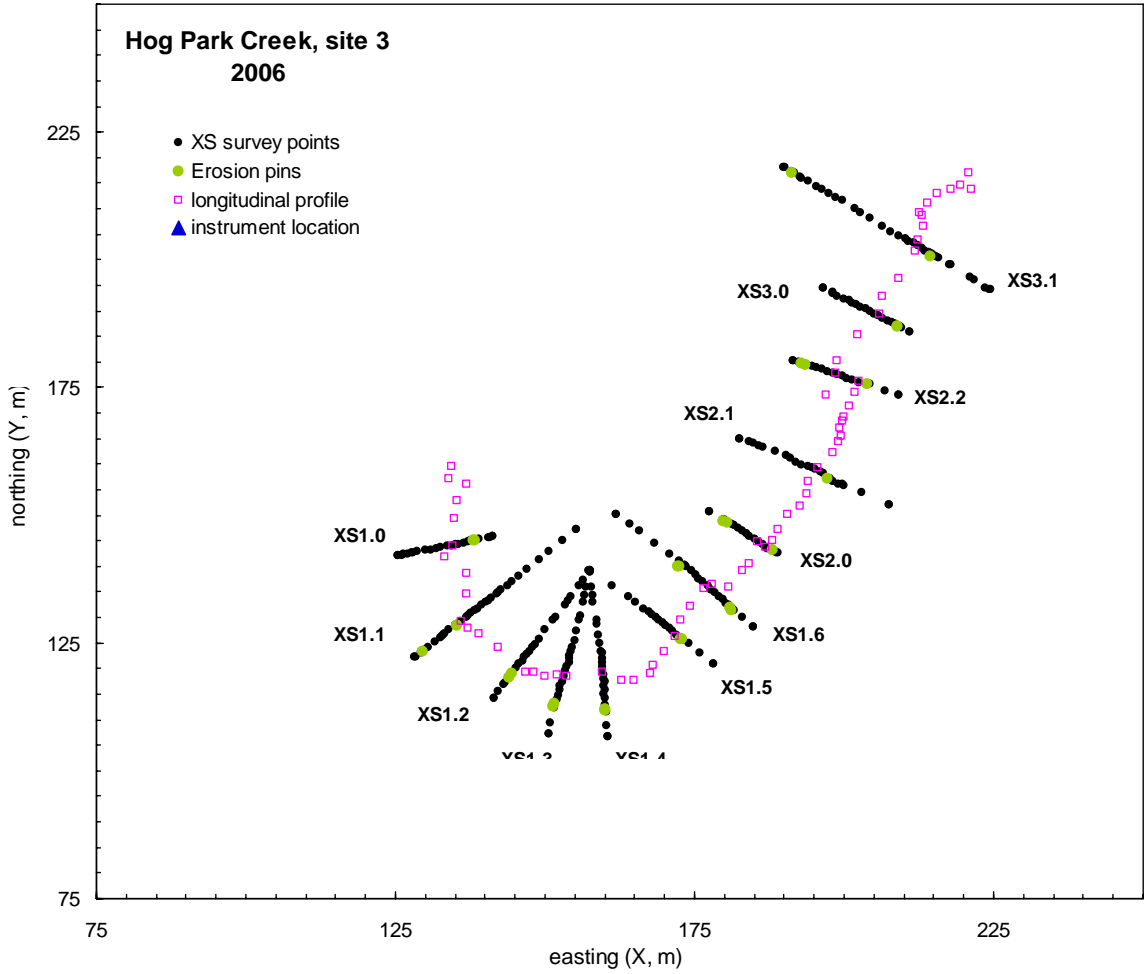
Figure A.18: Planform schematic generated from survey data, Site 3, 2006.
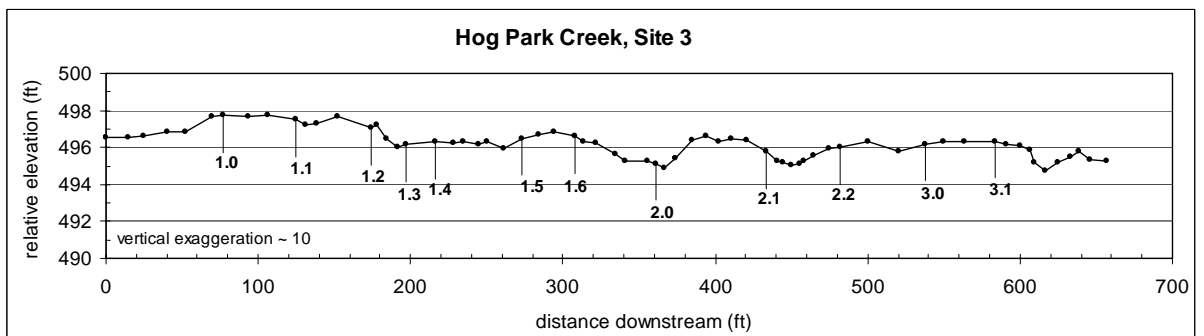
Figure A.19: Longitudinal profile of Site 3, 2006.

Figure A.20: Looking downstream in Site 3 from the top, 2007. Note the white PVC pipe housing the pressure transducer recording stage data. Photo by D. Cenderelli.

Figure A.21: Cross section locations in Site 3, 2007 (photo by D. Cenderelli).

Table A.3: Particle size distribution information for Site 3. Samples collected in riffles, 2008.

Site 3			Riffle-surface Particle Count			
Size (mm)			Size Distribution			Type
D16	6.4	3.4	mean	15.2	silt/clay	0%
D35	12	12	dispersion	2.5	sand	9%
D50	22	17	skewness	-0.19	gravel	91%
D65	27	20			cobble	0%
D84	36	29			boulder	0%
D95	43	39				
Site 3			Riffle Surface Pebble Count			
Size (mm)			Size Distribution			Type
D16	2.2		mean	9.1	silt/clay	0%
D35	8.3		dispersion	5.0	sand	15%
D50	17		skewness	-0.24	gravel	83%
D65	24				cobble	2%
D84	38				boulder	0%
D95	54					

Figure A.22: Bank erosion in Site 3, along outside of meander bend, 2007 (photo by D. Cenderelli).

Site 3 Erosion Type

- Fluvially-dominated Erosion
- Mass-wasting
- Depositional

14%

46%

40%

Figure A.23:   The types of erosion occurring and the respective percentage of length of the right bank throughout Site 3 experiencing the type of erosion.

Figure A.24: Bank profile in Site 3, 2009. Note the orange flag tied to an erosion pin.

Figure A.25: Bank profile in Site 3. 2009.

Figure A.26: Bank profile in Site 3, 2007 (photo by D. Cenderelli).

Figure A.27: Bank erosion in Site 3 at low summer base flow, 2008.

Figure A.28: Bank profile in Site 3. This section is used by cattle in the fall for access to the channel, 2008.

Figure A.29: Erosion pin measurement in Site 3, 2007 (photo by D. Cenderelli).
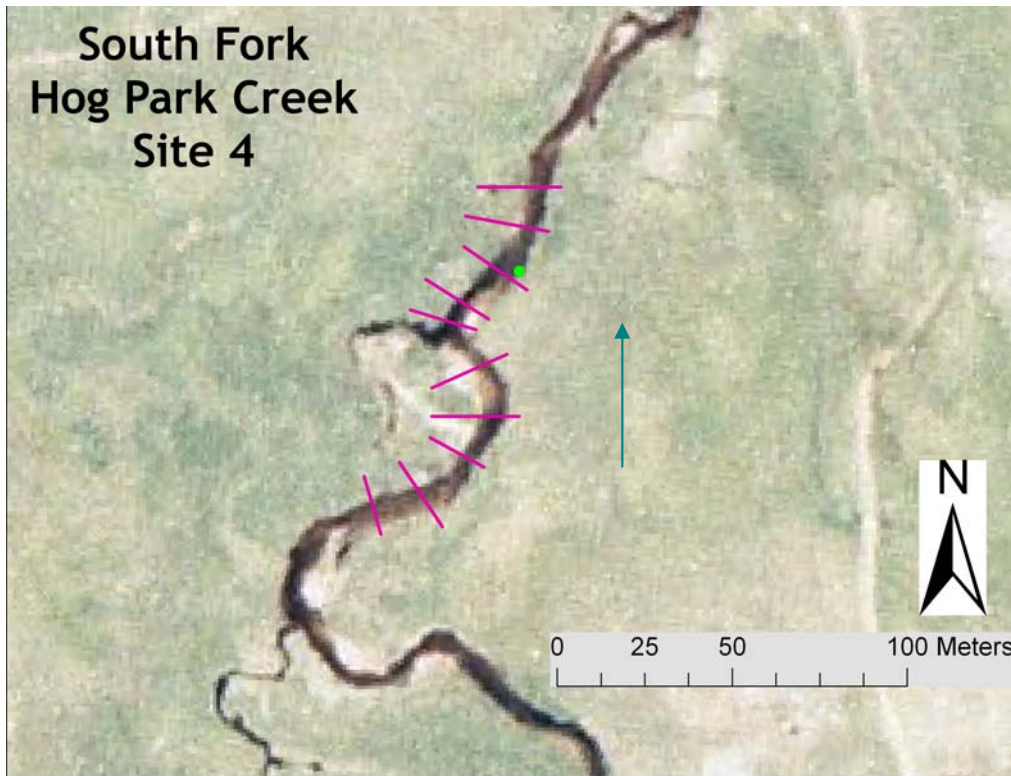
Figure A.30: Aerial photograph of Site 4 from 2001. Pink lines mark cross section locations and the green dot identifies the location of the crest gauge.
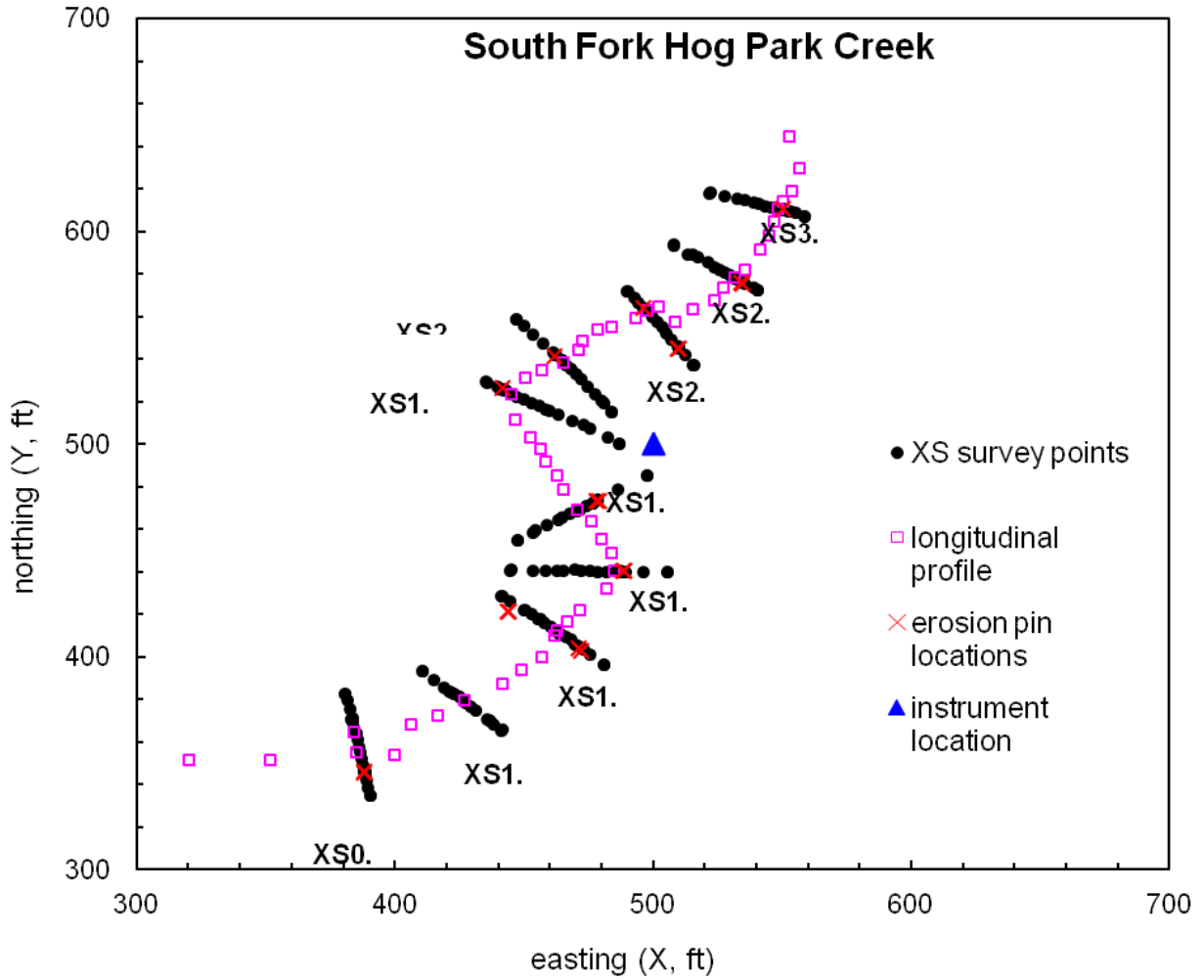
Figure A.31:   Plan view of Site 4 generated from 2006 survey data (D. Cenderelli).
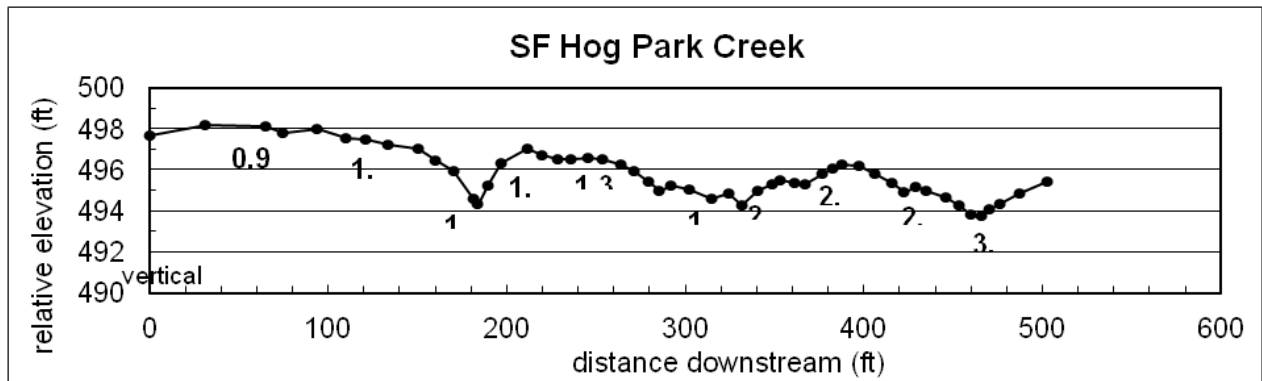
Figure A.32: Longitudinal profile of Site 4, numbers indicate cross section locations.

Figure A.33: Looking upstream in Site 4. Photo location approximately midway through the site. White PVC pipe house the crest gauge, 2009.

Figure A.34: Looking upstream from the bottom of Site 4, 2009.

Table A.4: Particle size distribution information for Site 4. Samples collected in riffles, 2008.

Site 4			Riffle Surface Pebble Count			
Size (mm)			Size Distribution			Type
D16	37		mean	52.7	silt/clay	0%
D35	44		dispersion	1.4	sand	0%
D50	51		skewness	0.03	gravel	75%
D65	58				cobble	25%
D84	75				boulder	0%
D95	90					
Site 4			Riffle Surface particle count			
Size (mm)			Size Distribution			Type
D16	16	3.4	mean	35.1	silt/clay	0%
D35	23	12	dispersion	2.2	sand	0%
D50	35	17	skewness	0.00	gravel	76%
D65	47	20			cobble	24%
D84	77	29			boulder	0%
D95	110	39				

Site 4 Erosion Type
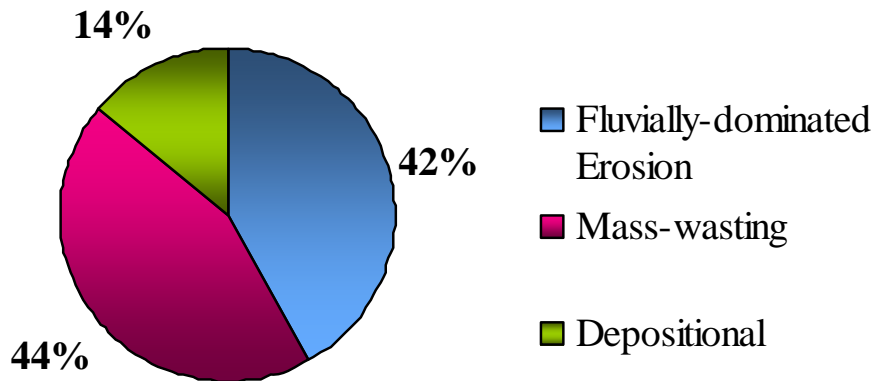
Figure A.35: The types of erosion occurring and the respective percentage of length of the right bank throughout Site 4 experiencing the type of erosion.

Figure A.36: Bank profile in Site 4, 2008.

Figure A.37: Erosion along outside of meander bend in Site 4, 2007 (photo by D. Cenderelli).

Figure A.38: Cattle observed in Site 4, 2008.

APPENDIX

B

APPENDIX B- CROSS SECTION DIAGRAMS

Site 1
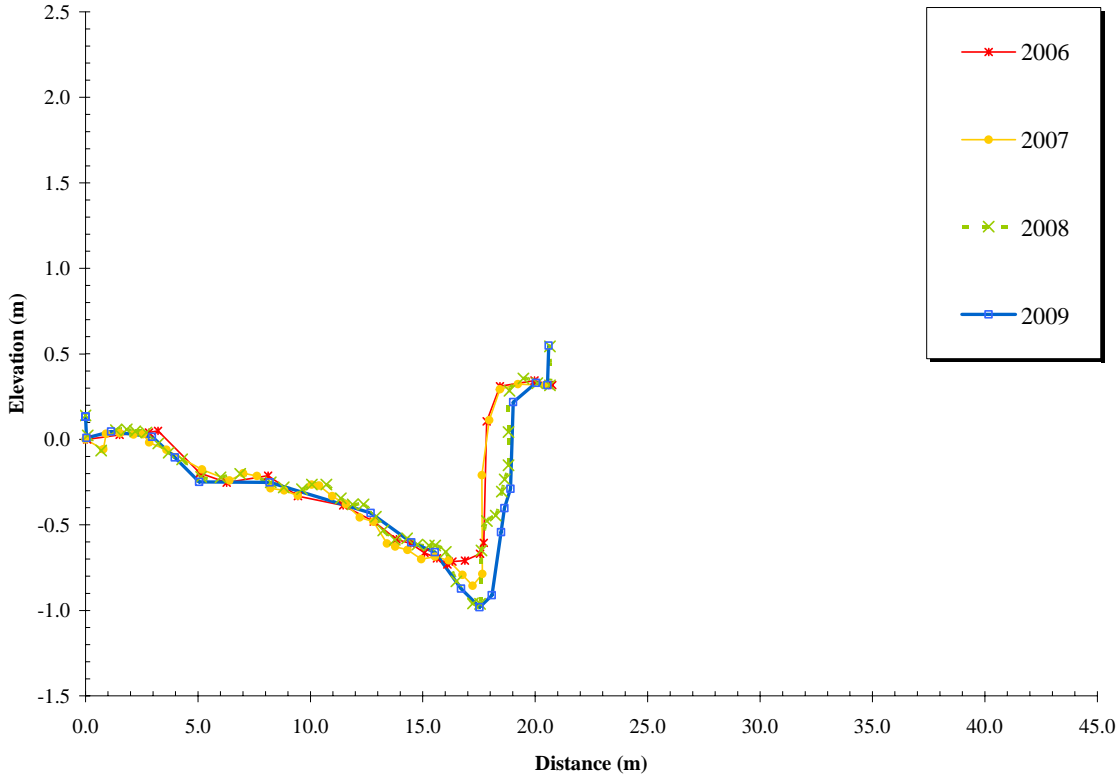
Figure A.39: Site 1, Cross Section 0.9
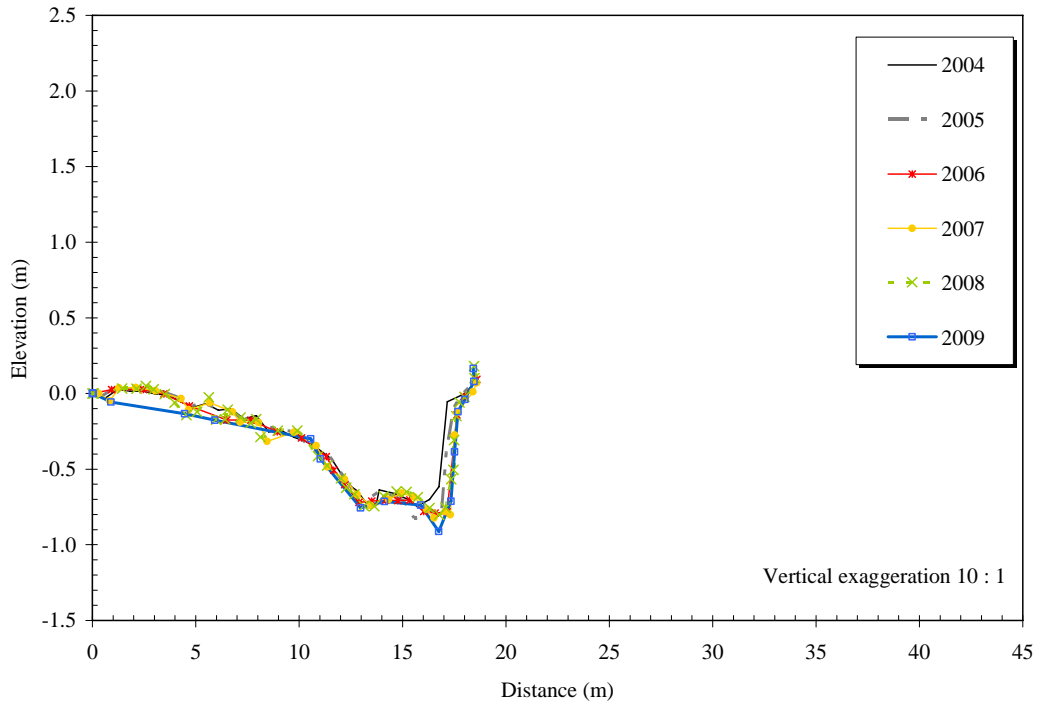
Figure A.40: Site 1 Cross section 1.0
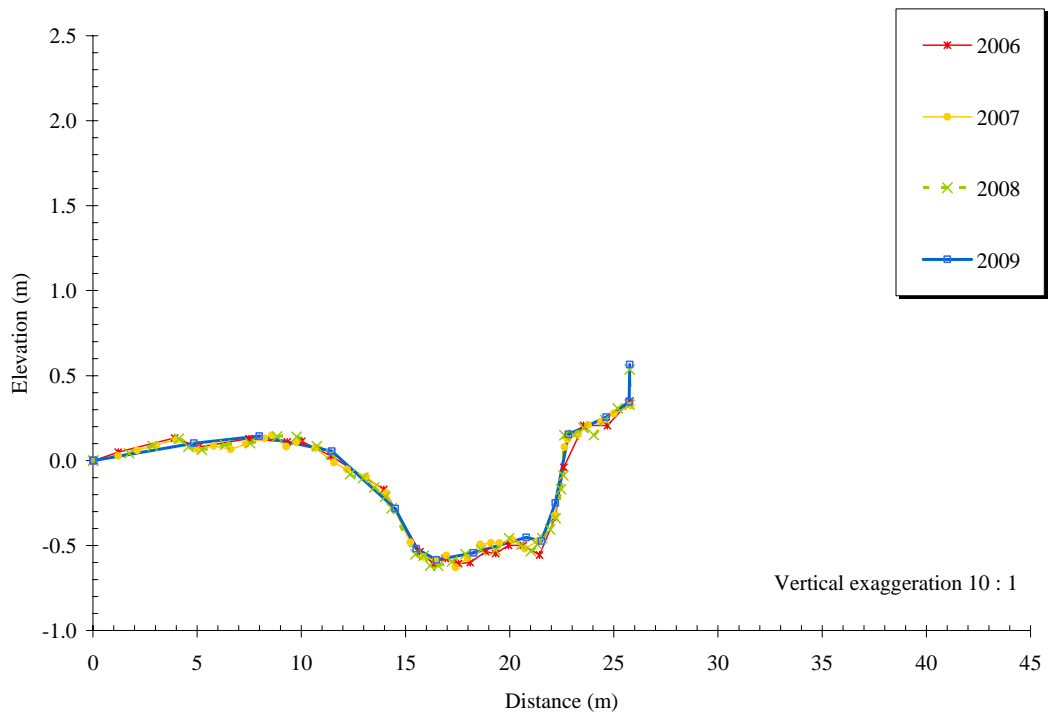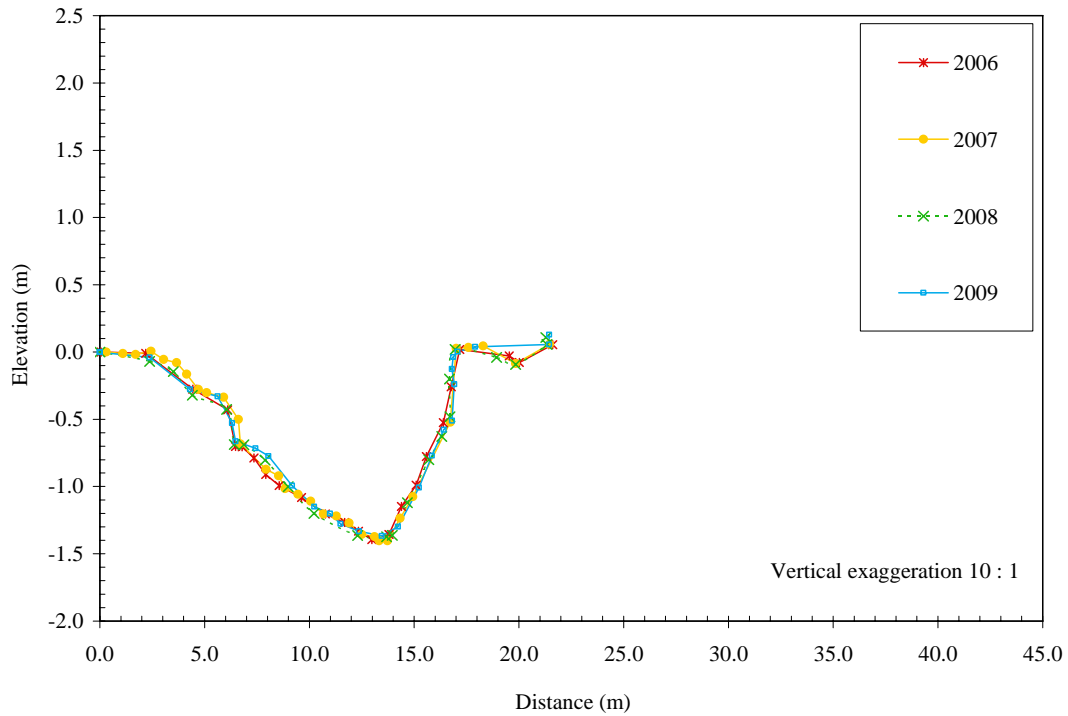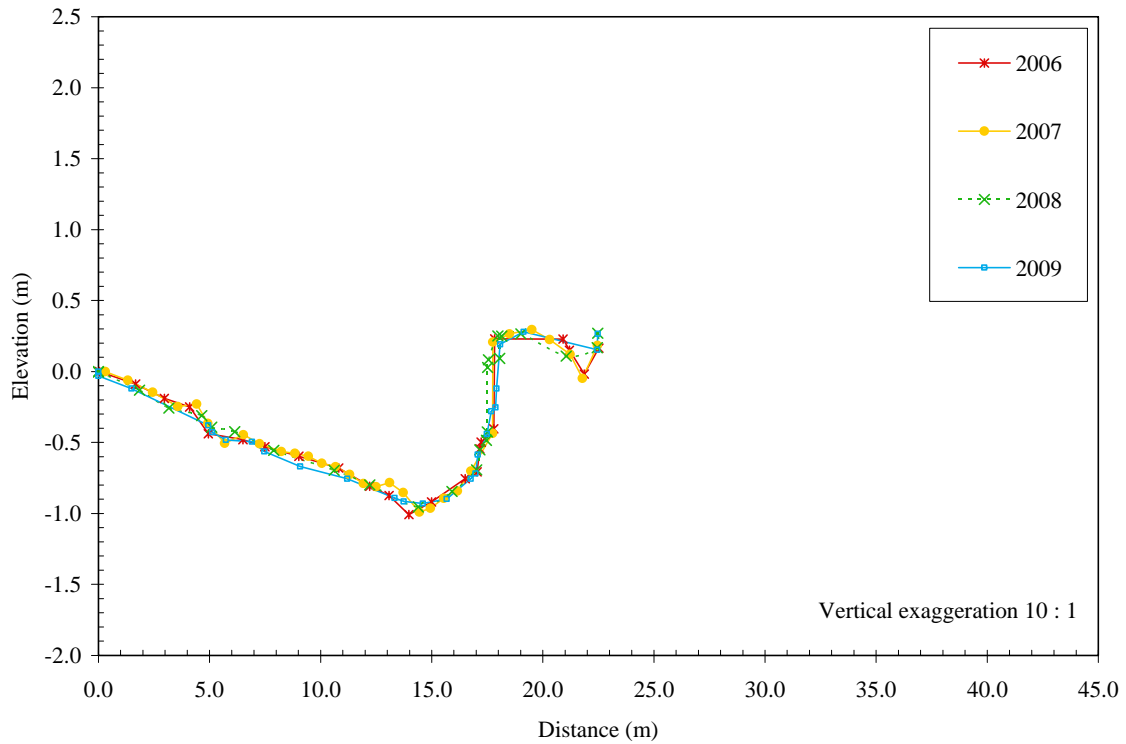

Figure A.41: Site 1 Cross section 1.1

240
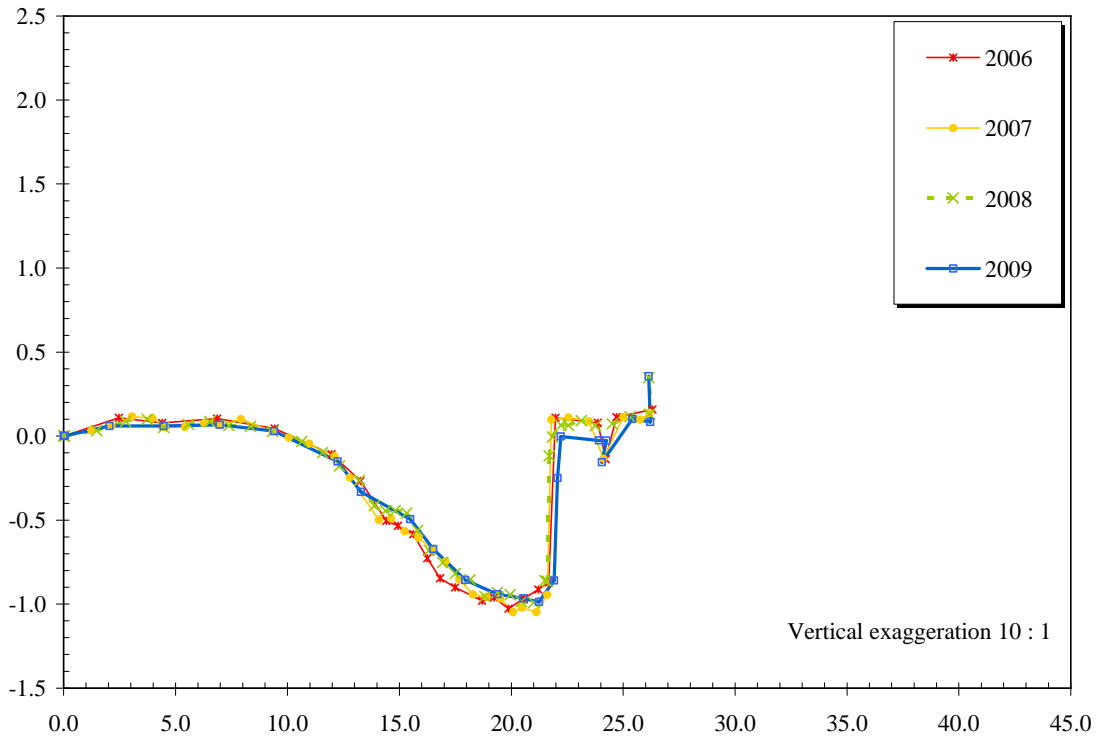
Figure A.42: Site 1, Cross Section 1.2
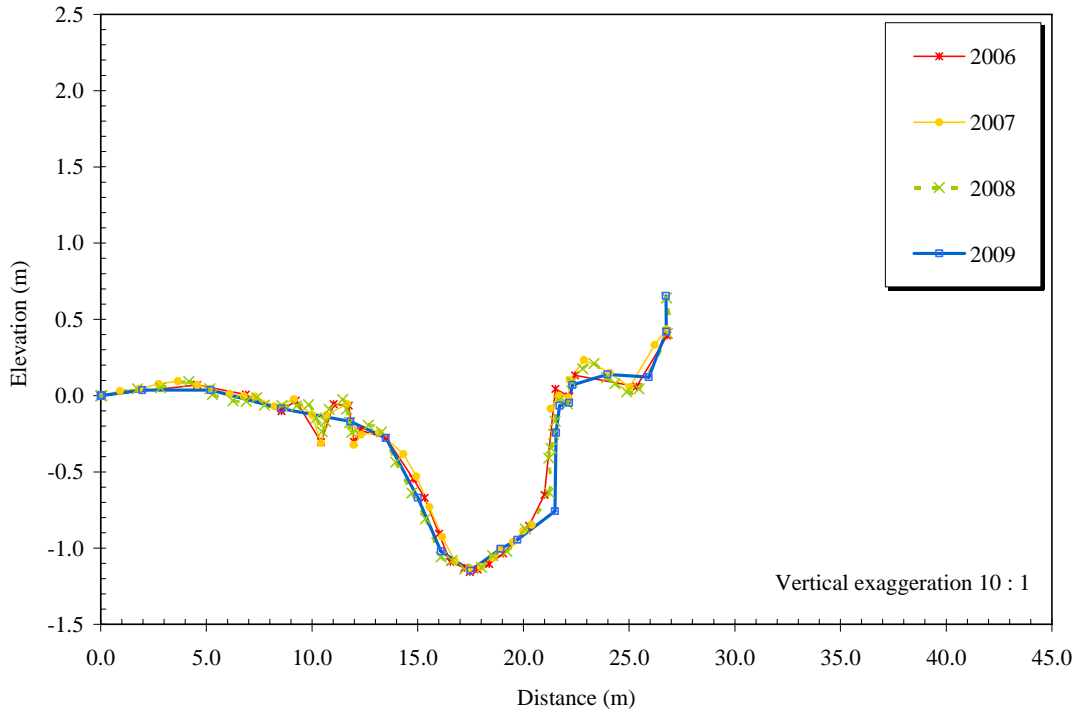
Figure A.43: Site 1, Cross Section 1.3
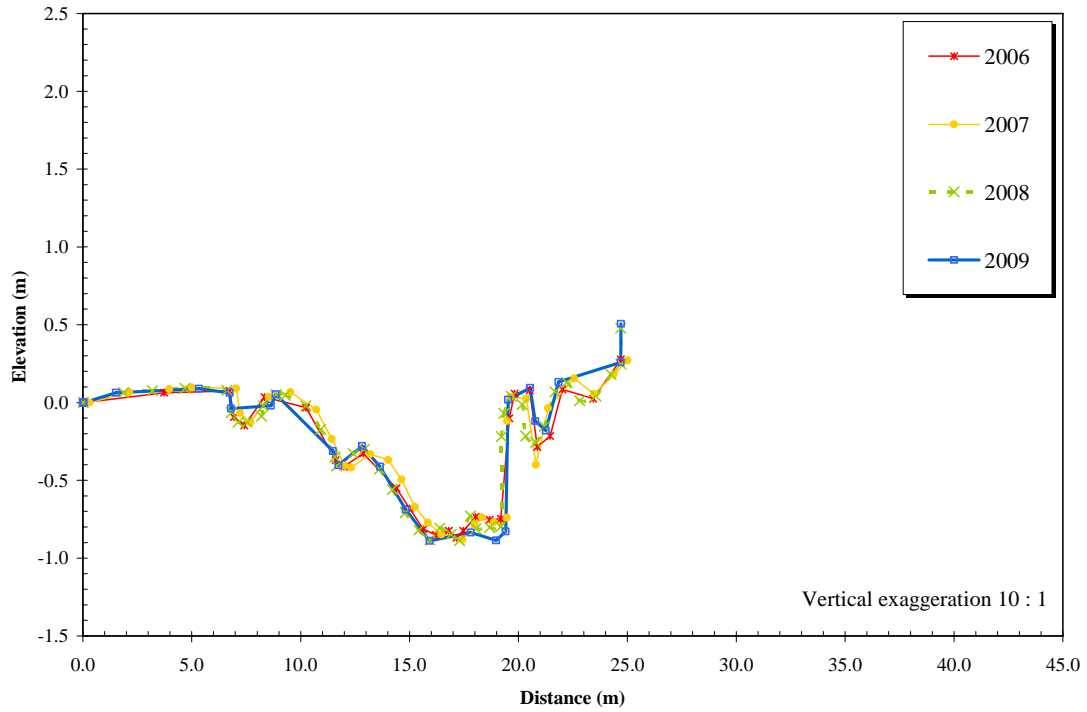
Figure A.44: Site 1, Cross Section 1.4
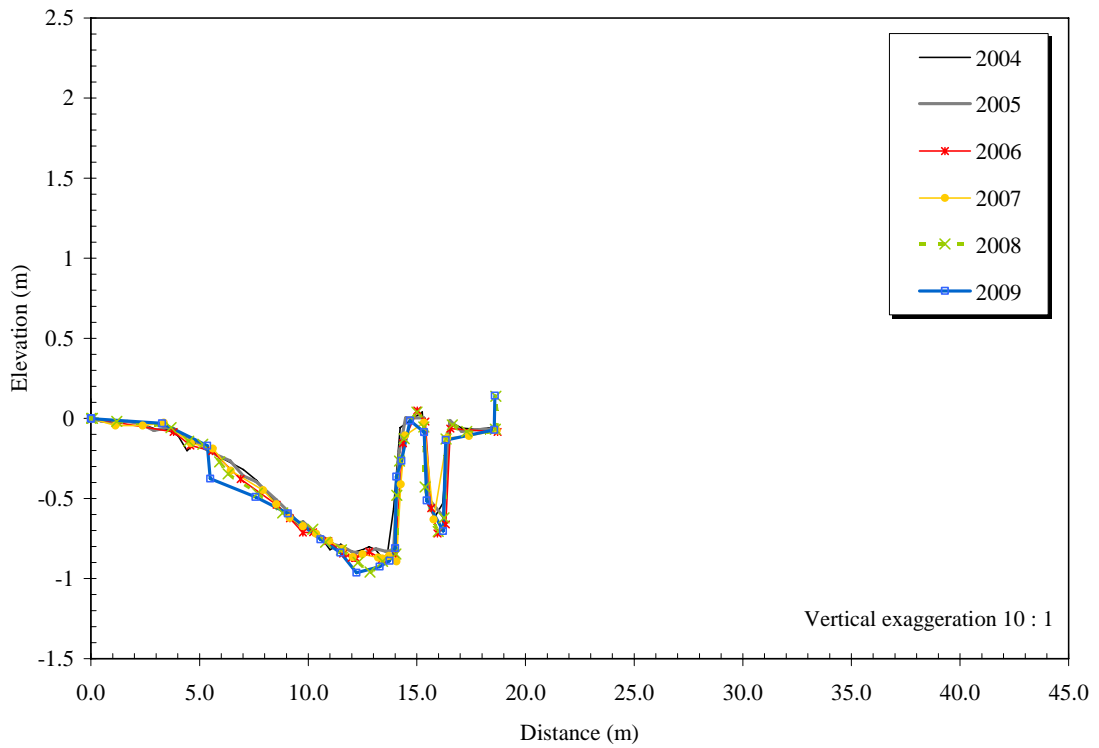
Figure A.45: Site 1, Cross Section 2.0

242
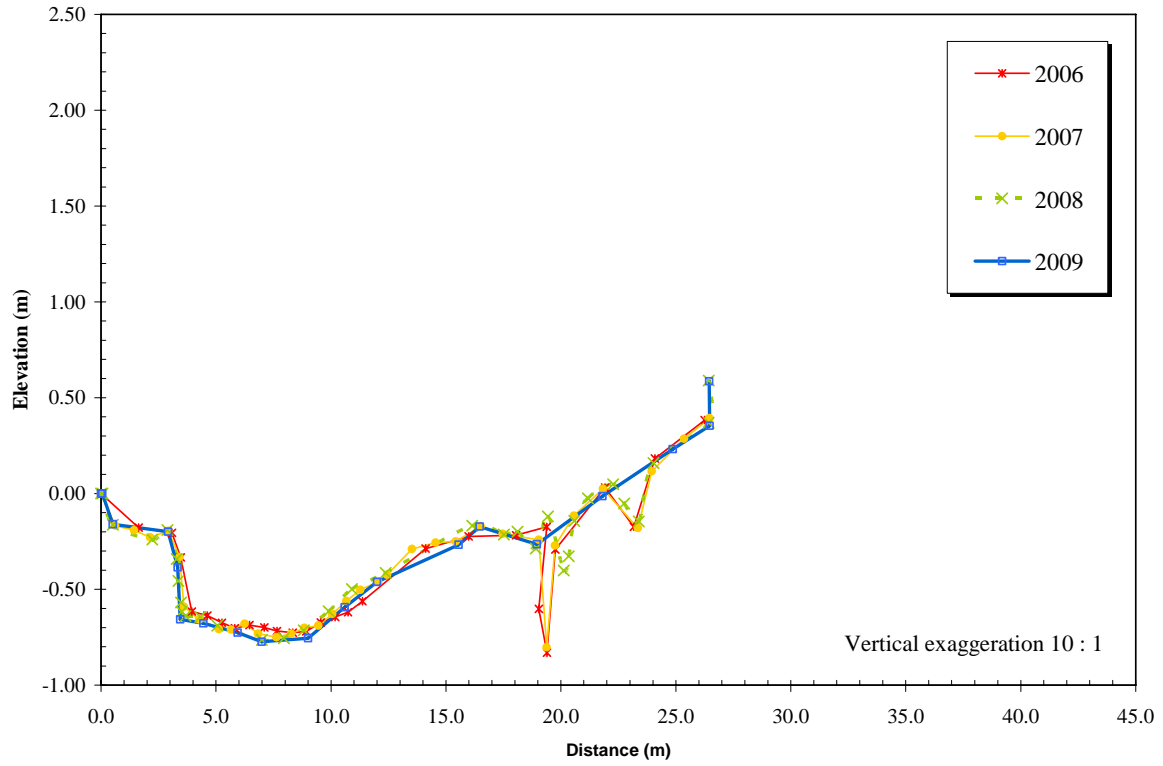
Figure A.46: Site 1, Cross Section 2.1
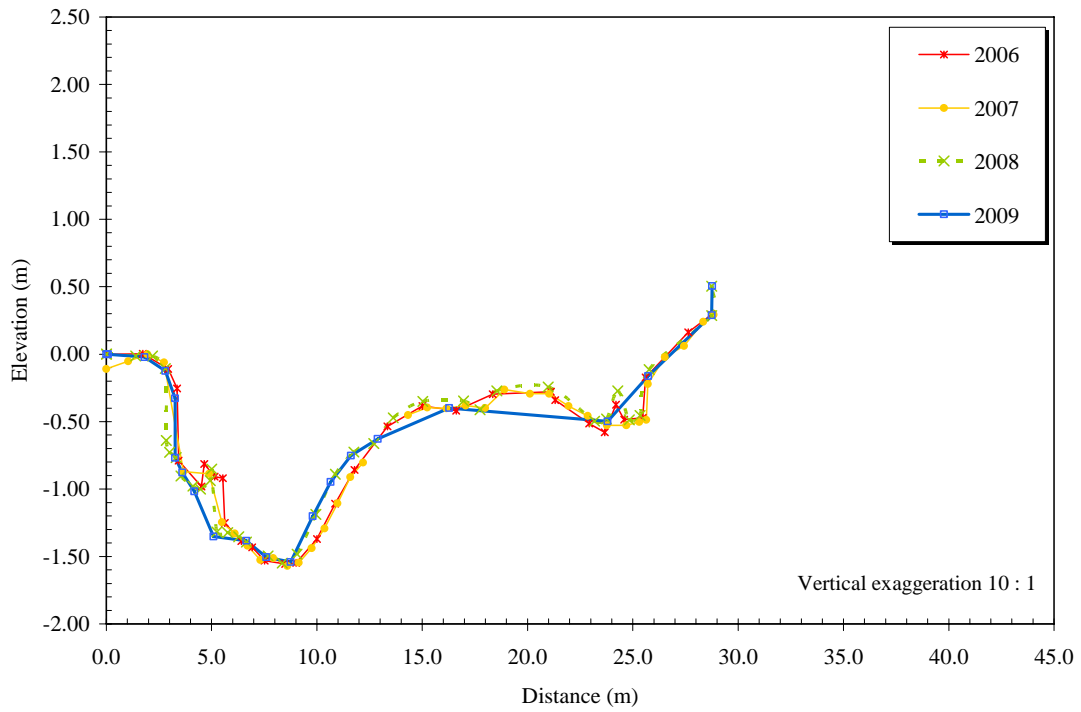
Figure A.47: Site 1, Cross Section 2.2

243
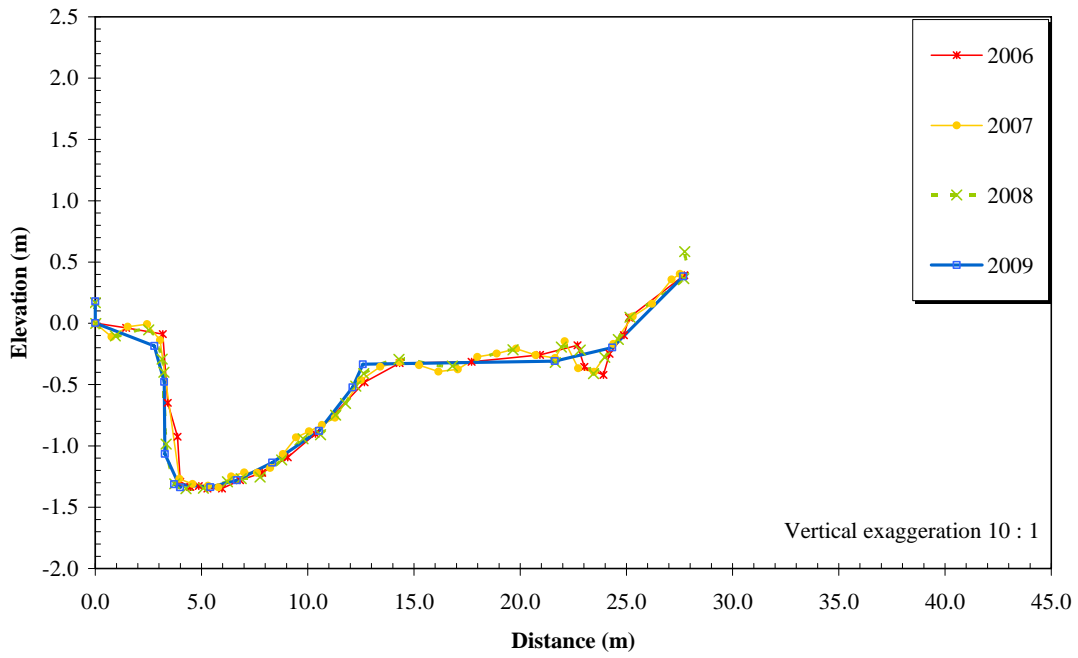
Figure A.48: Site 1, Cross Section 2.3
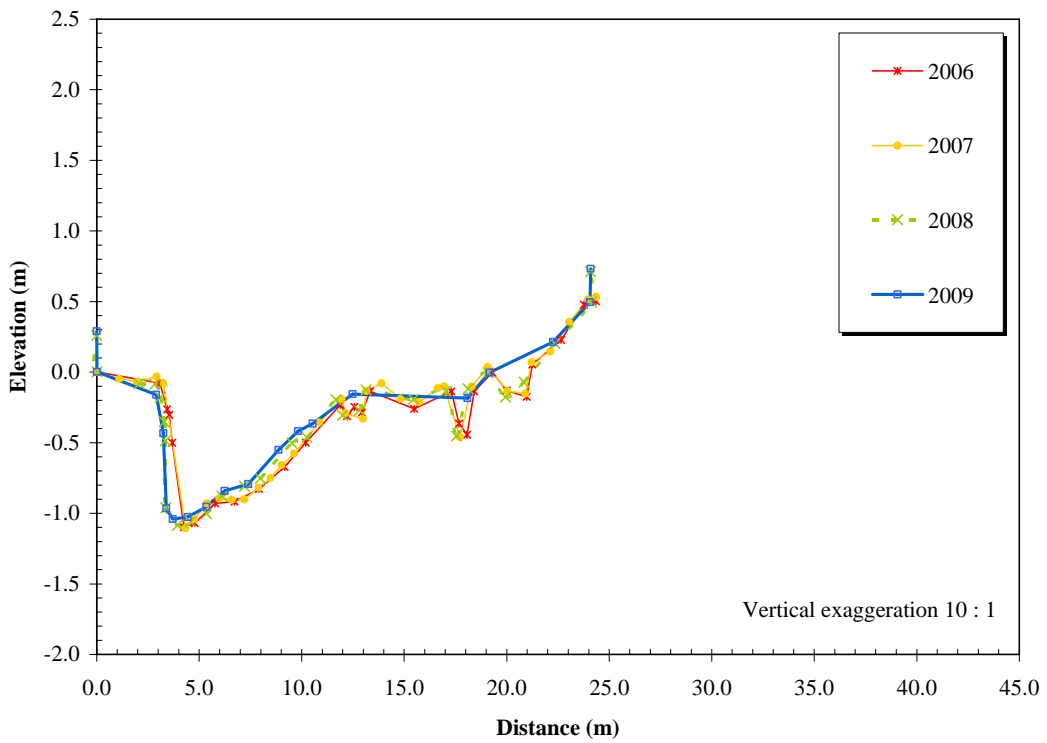
Figure A.49: Site 1, Cross section 2.4
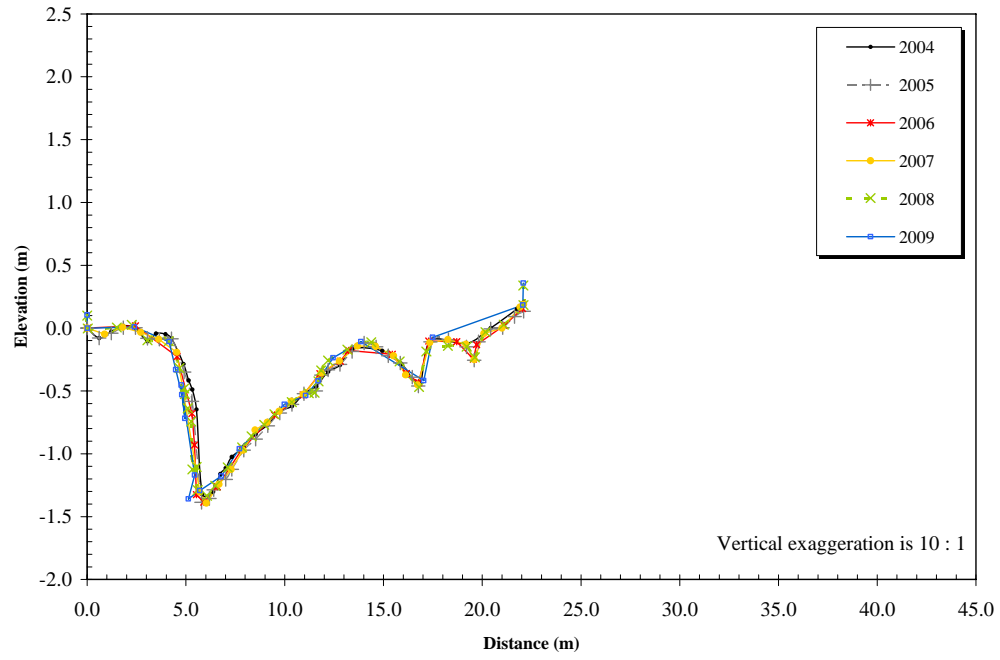
Figure A.50: Site 1, Cross section 3.0
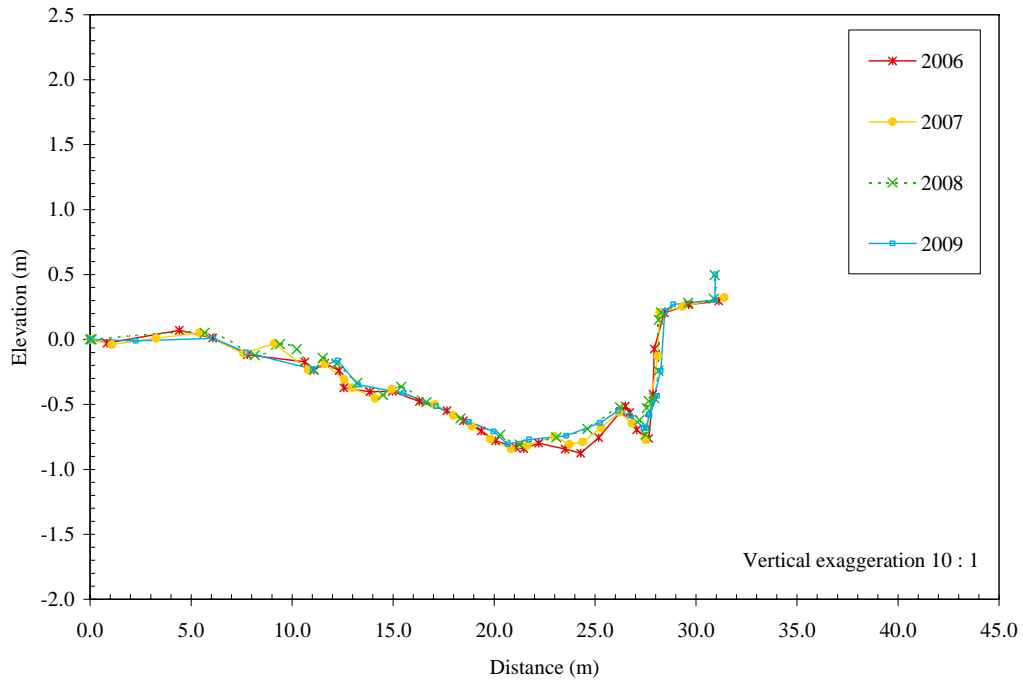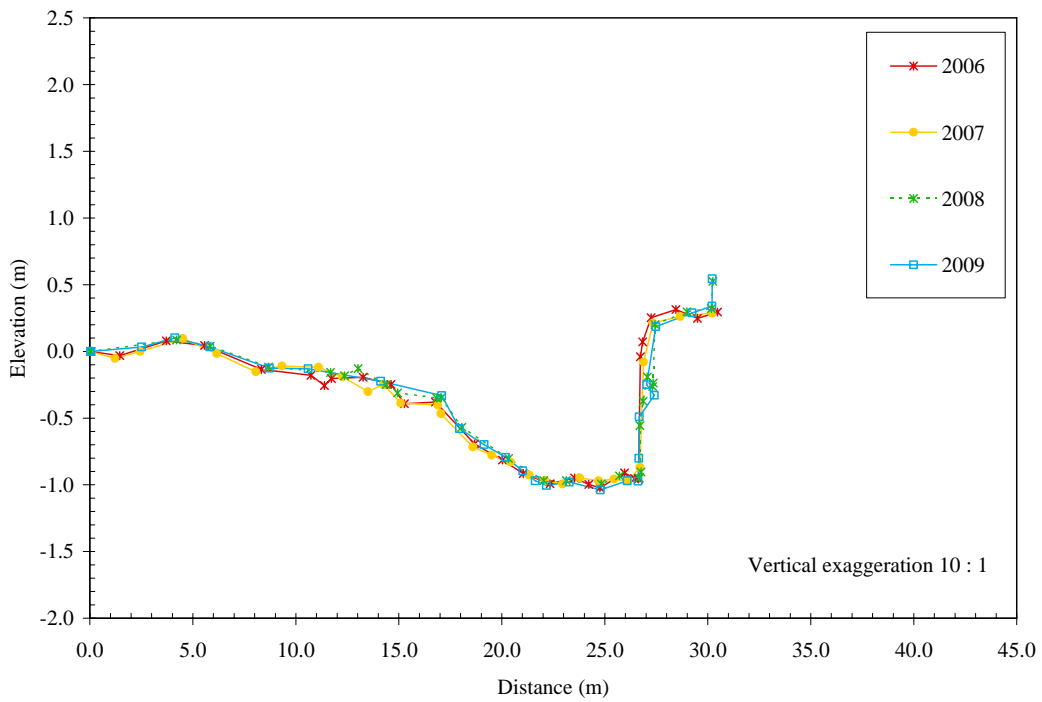
Cross Section Diagrams Site 2

Figure A.51: Site 2, Cross Section 0.8

Figure A.52: Site 2, Cross section 0.9
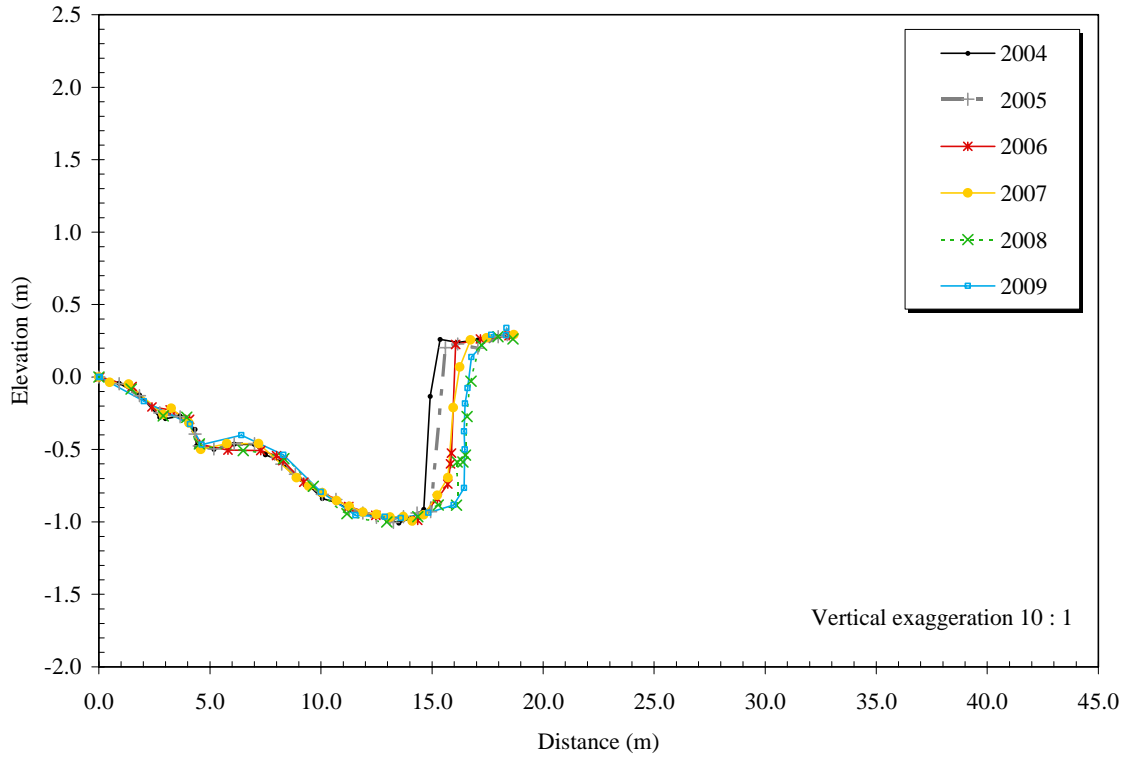
Figure A.53: Site 2, Cross section 1.0
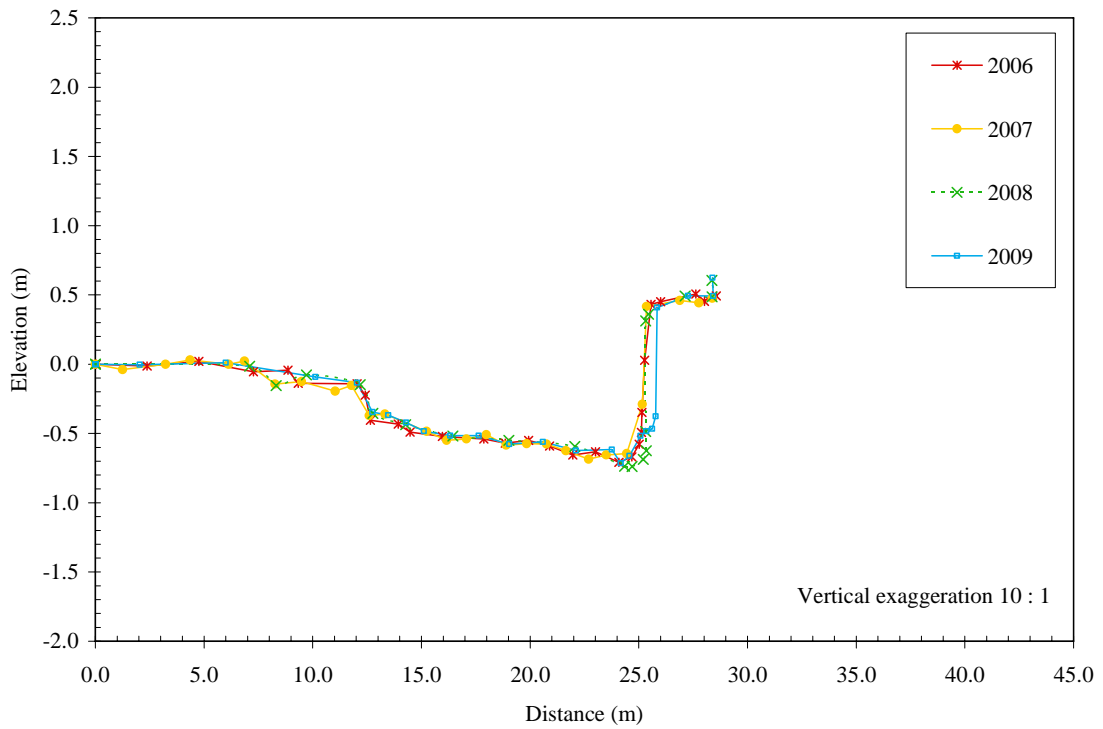
Figure A.54: Site 2, Cross section 1.1

Figure A.55: Site 2, Cross section 1.2

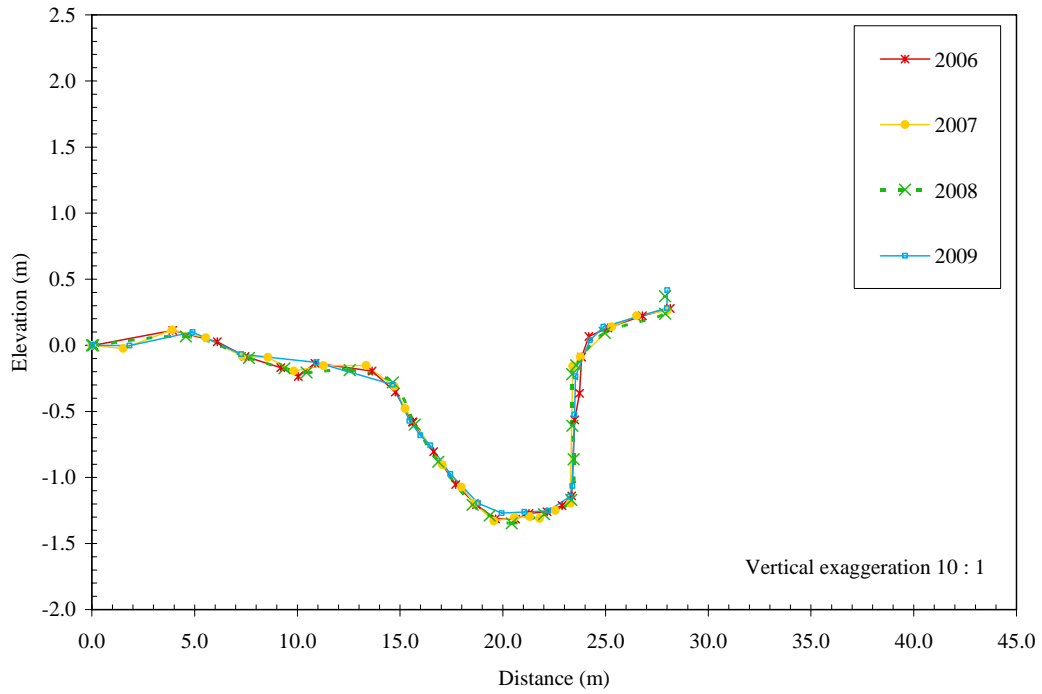**Figure A.56: Site 2, Cross section 1.3**

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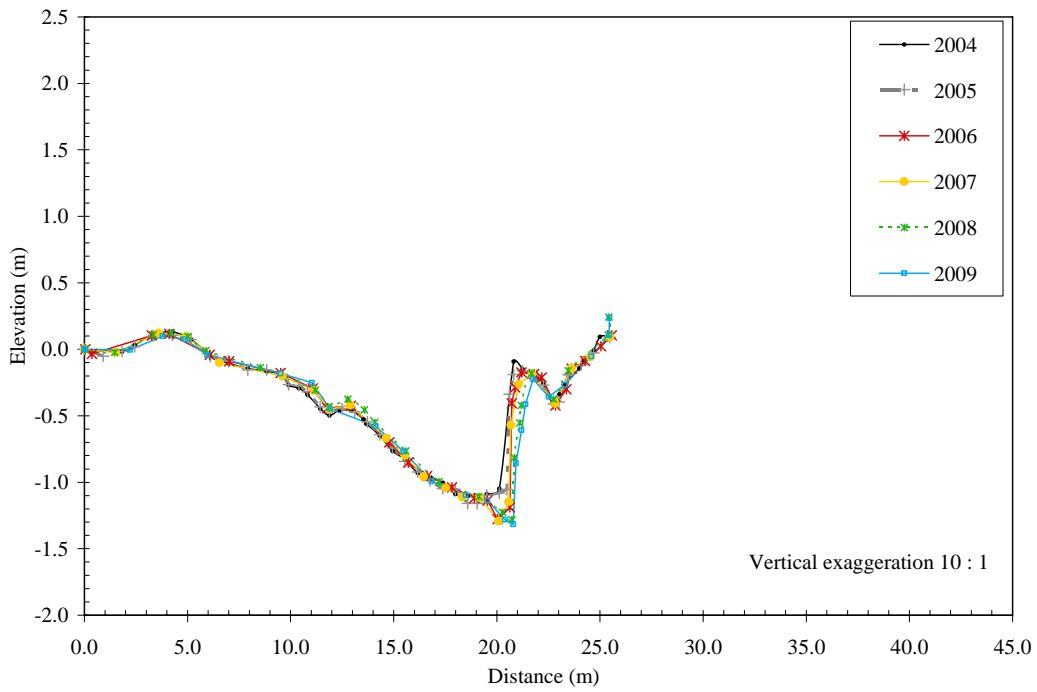**Figure A.57: Site 2, Cross section 1.4**
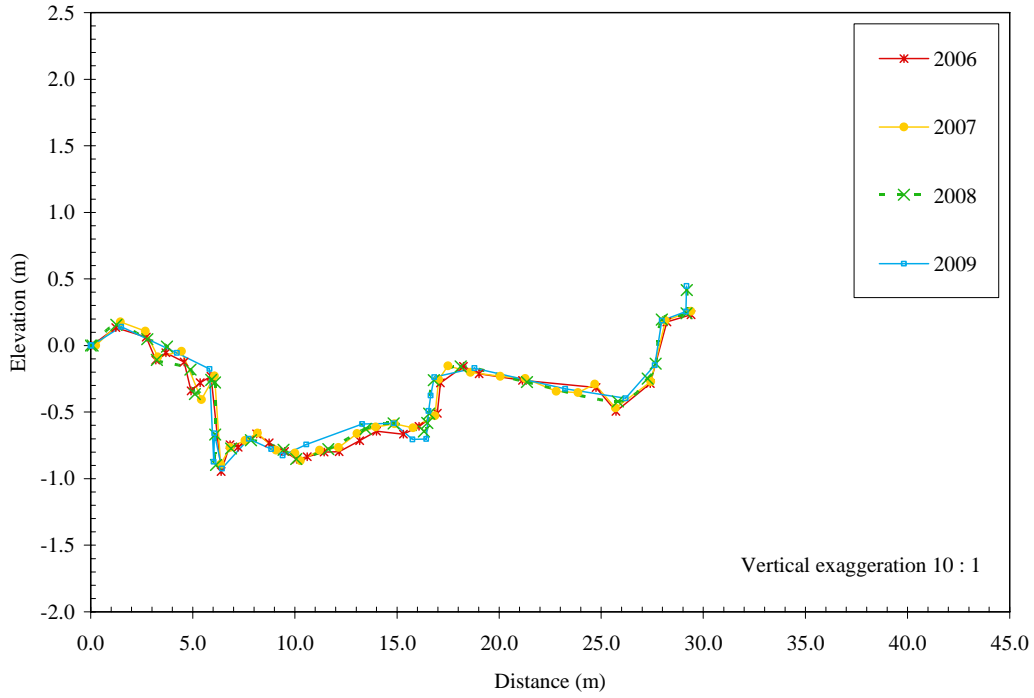

Figure A.58: Site 2, Cross section 2.0

Figure A.59: Site 2, Cross section 2.1
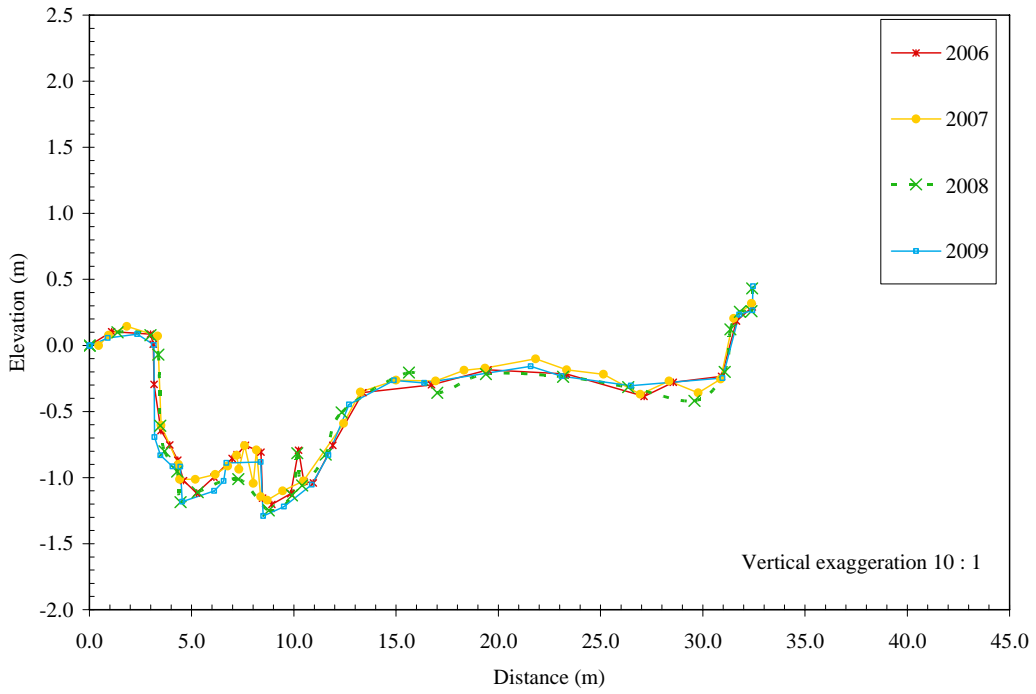

Figure A.60: Site 2, Cross section 2.2

Figure A.61: Site 2, Cross section 2.3

Figure A.62: Site 2, Cross section 2.4

Figure A.63: Site 2, Cross section 2.5
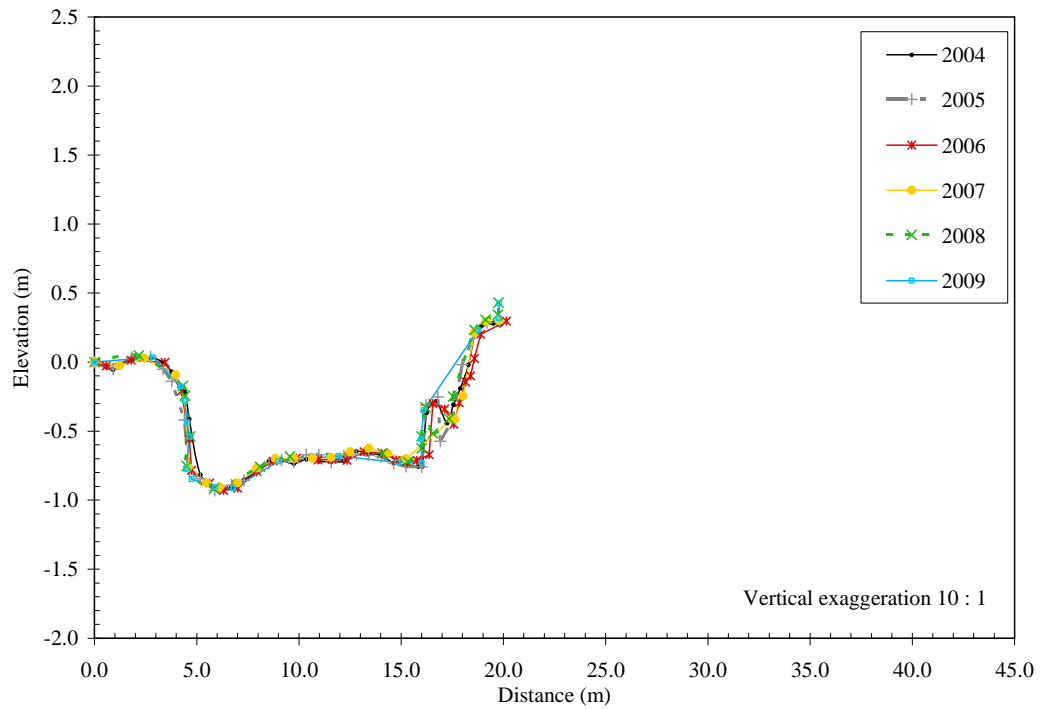
Figure A.64: Site 2, Cross section 3.0

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CROSS SECTION DIAGRAMS SITE 3
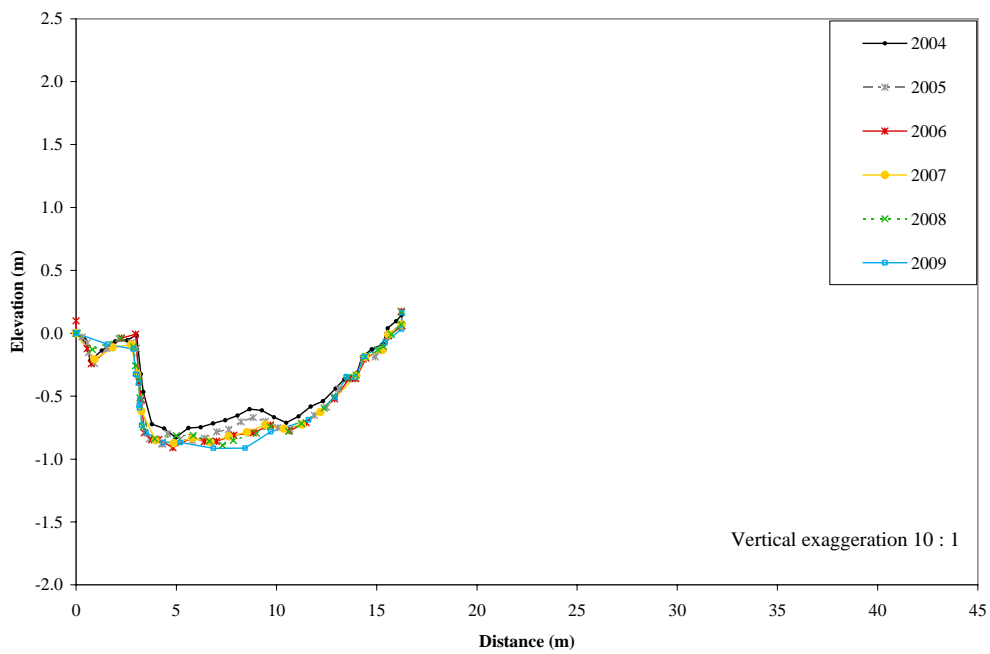
Figure A.65: Site 3, Cross section 1.0

Figure A.66: Site 3, Cross section 1.1
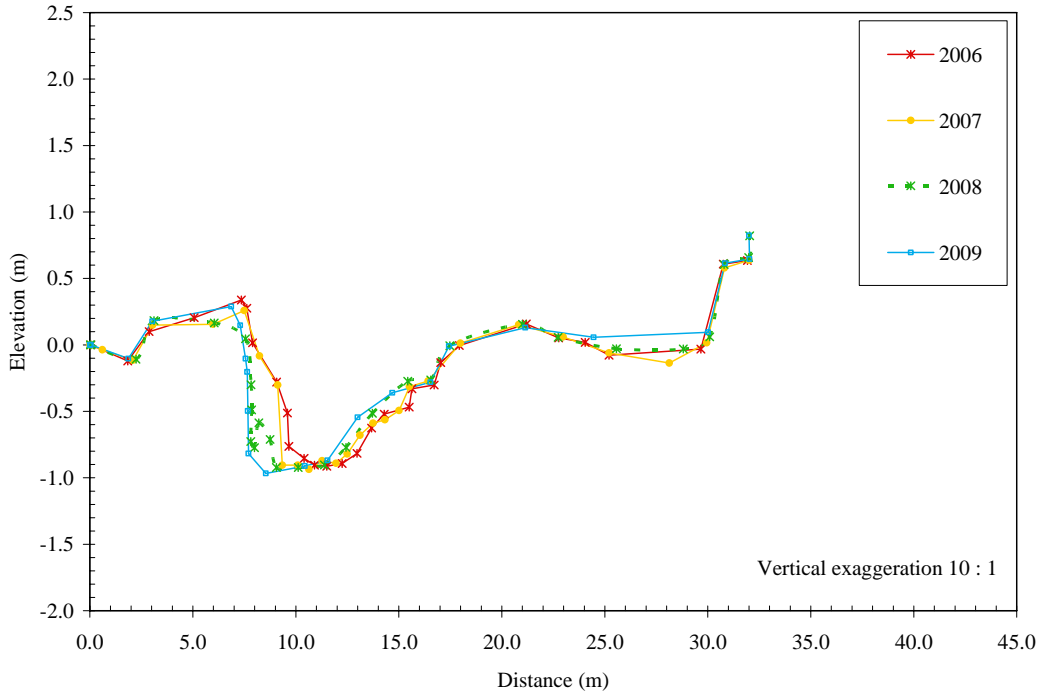

Figure A.67: Site 3, cross section 1.2

Figure A.68: Site 3, Cross section 1.3
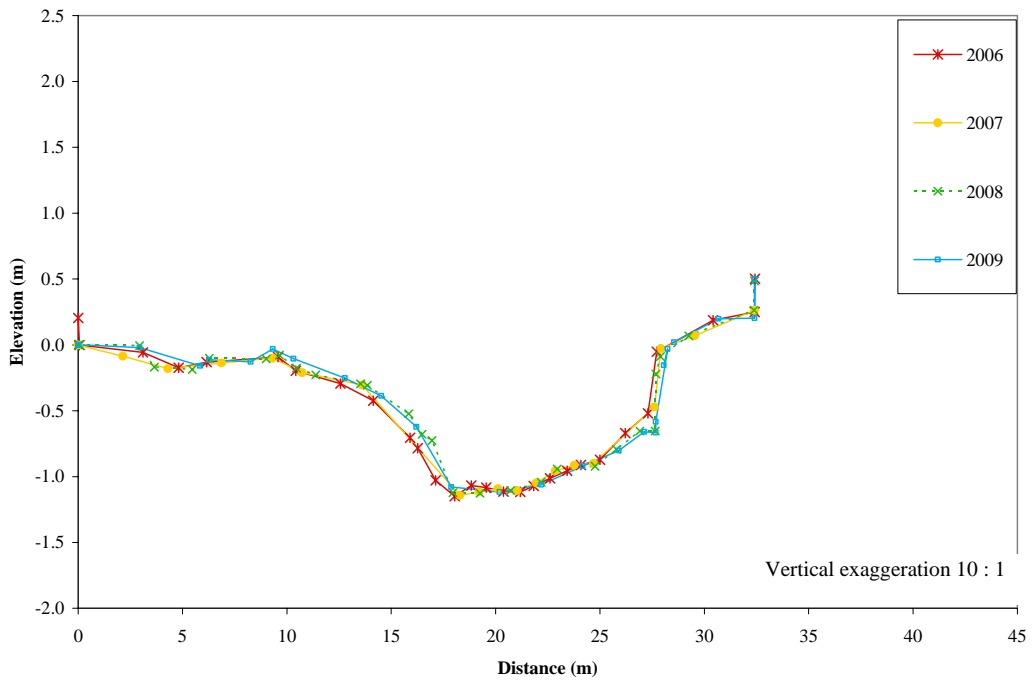
Figure A.69: Site 3, Cross section 1.4
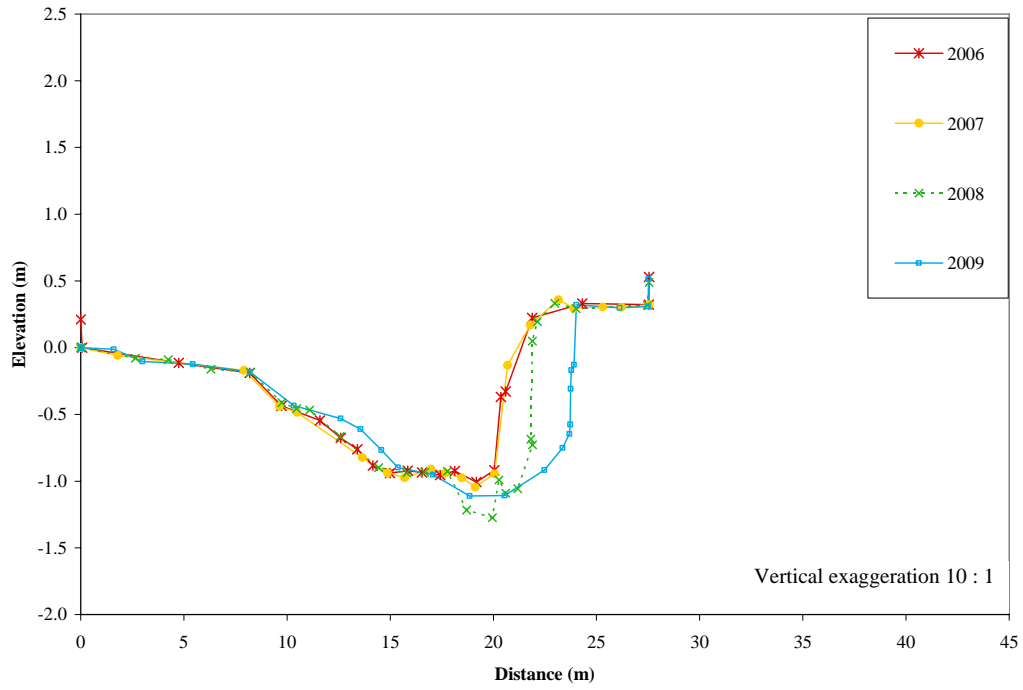
Figure A.70: Site 3, Cross section 1.5

Figure A.71: Site 3, Cross section 1.6

Figure A.72: Site 3, Cross section 2.0

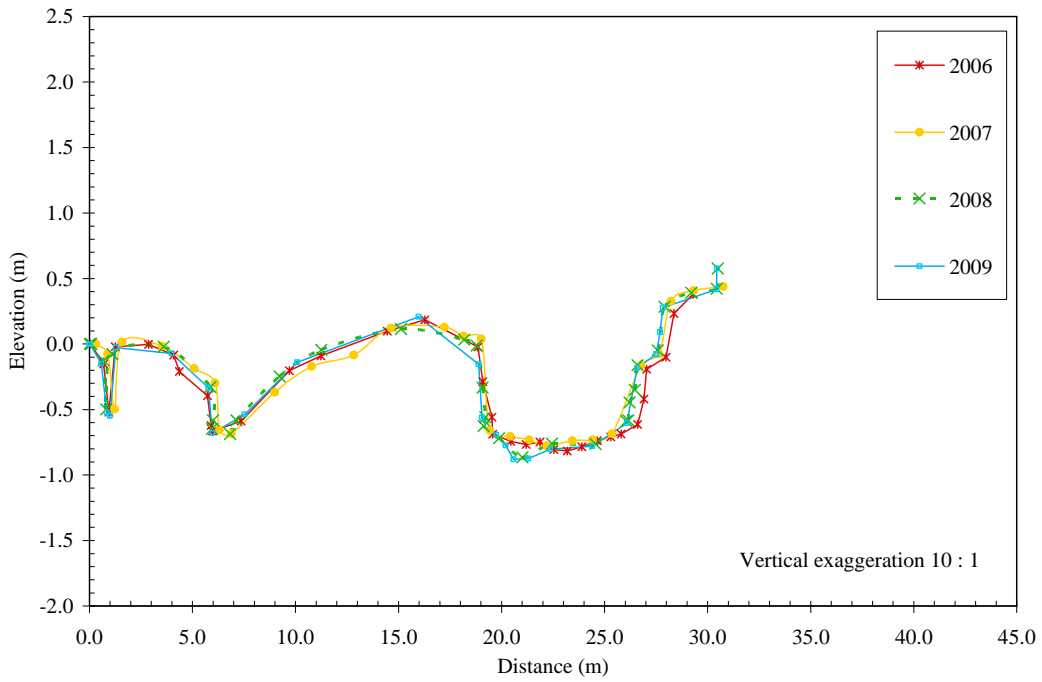**Figure A.73: Site 3, Cross section 2.1**

257
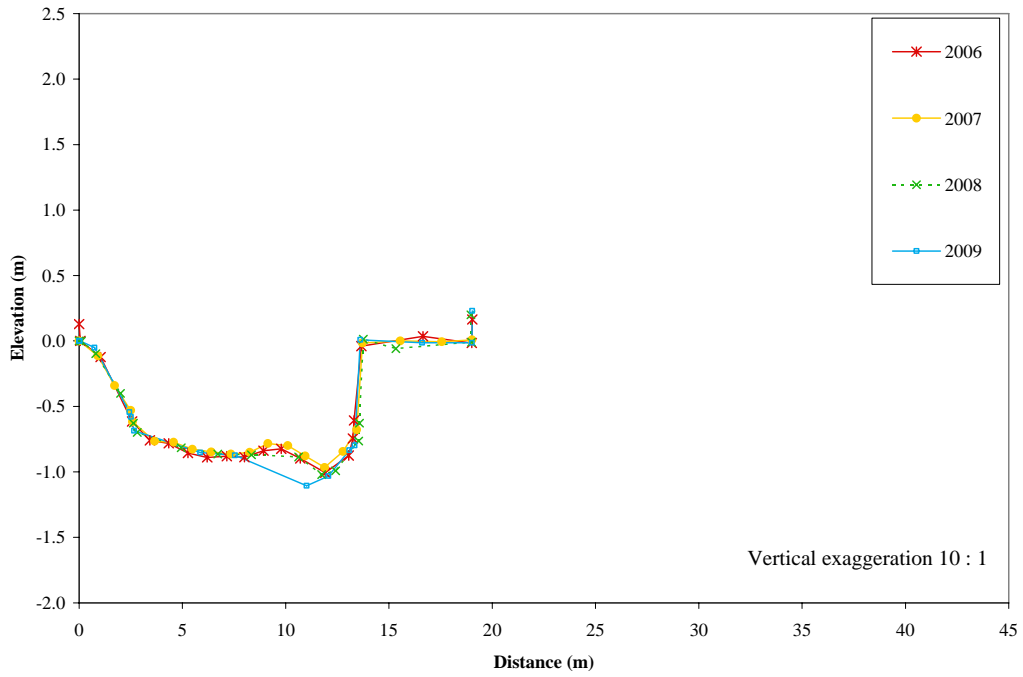
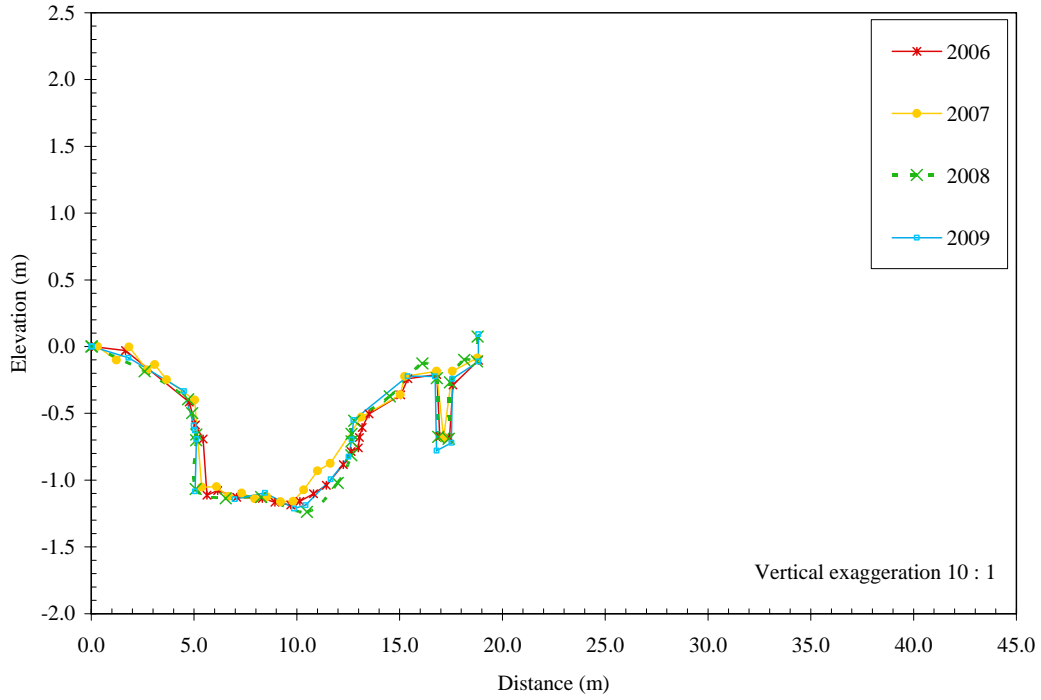**Figure A.74: Site 3, Cross section 2.2**
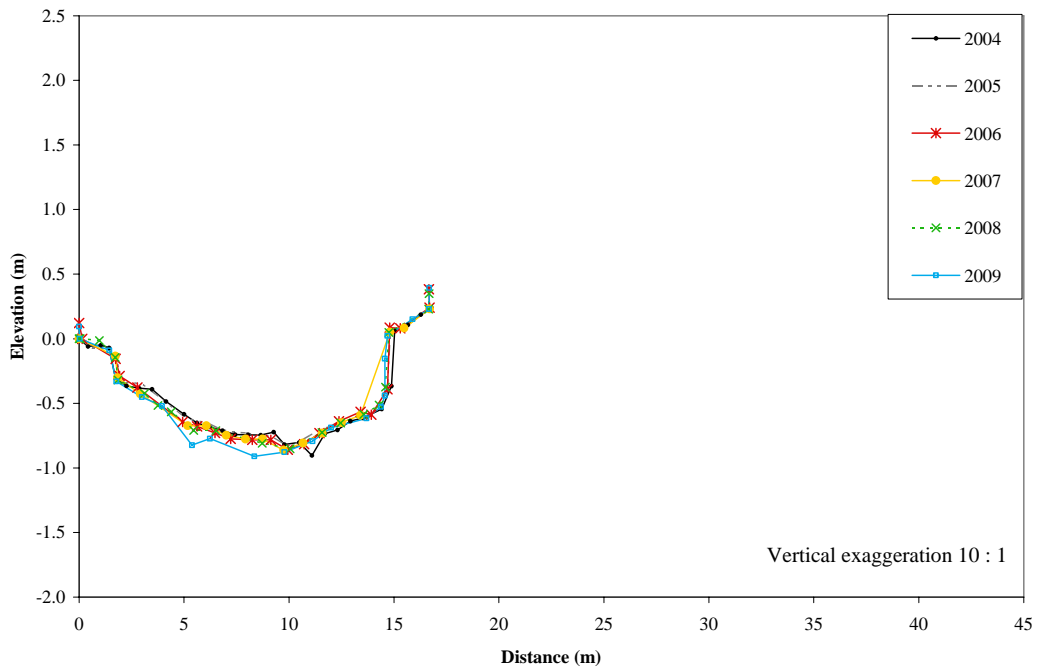
Figure A.75: Site 3, Cross section 3.0
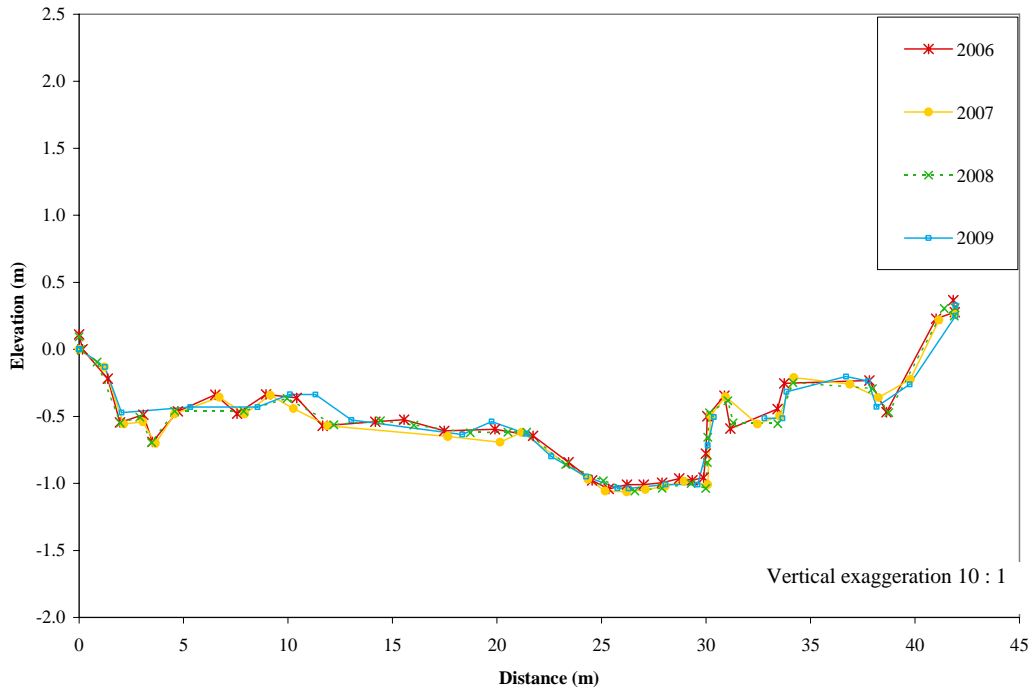
Figure A.76: Site 3, Cross section 3.1

CROSS SECTION DIAGRAMS SITE 4
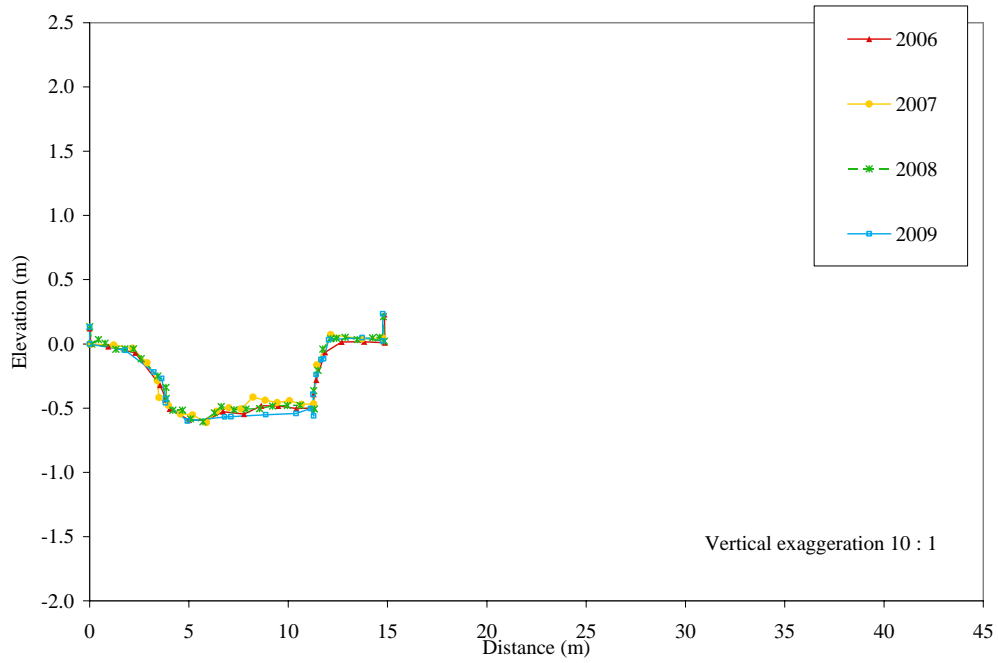
Figure A.77: Site 4, Cross section 0.9
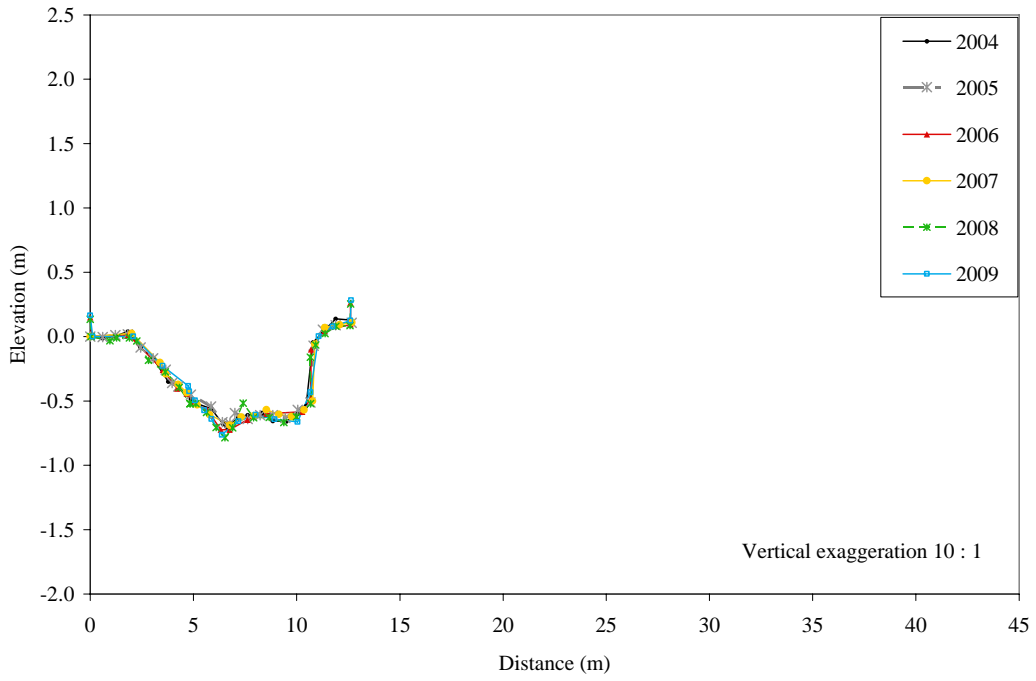
Figure A.78: Site 4, Cross section 1.0
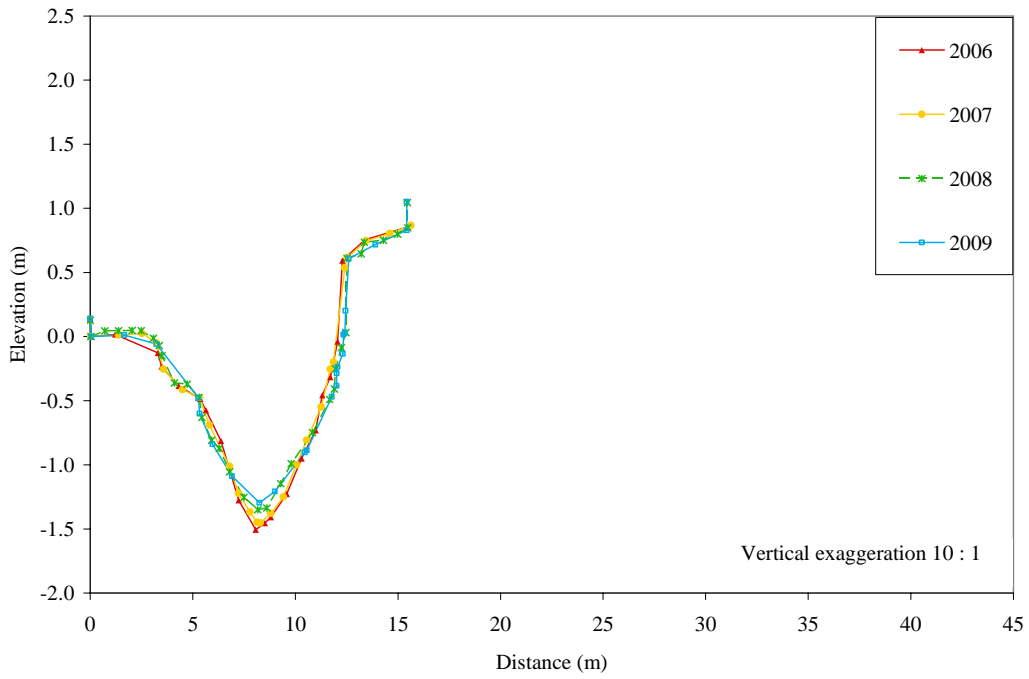
Figure A.79: Site 4, Cross section 1.1

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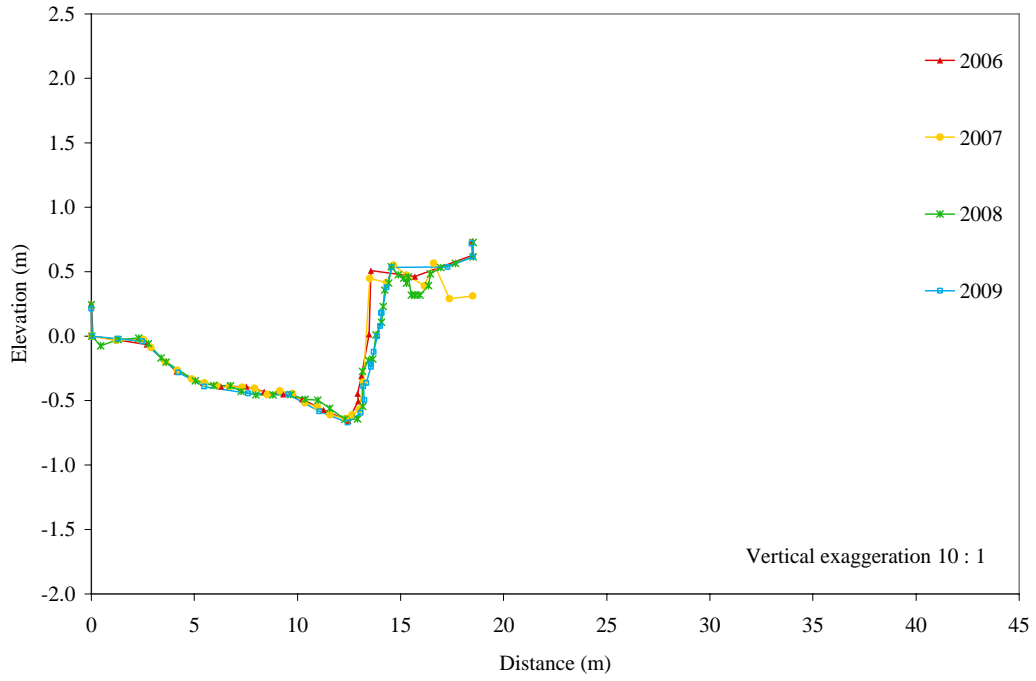
Figure A.80: Site 4, Cross section 1.2
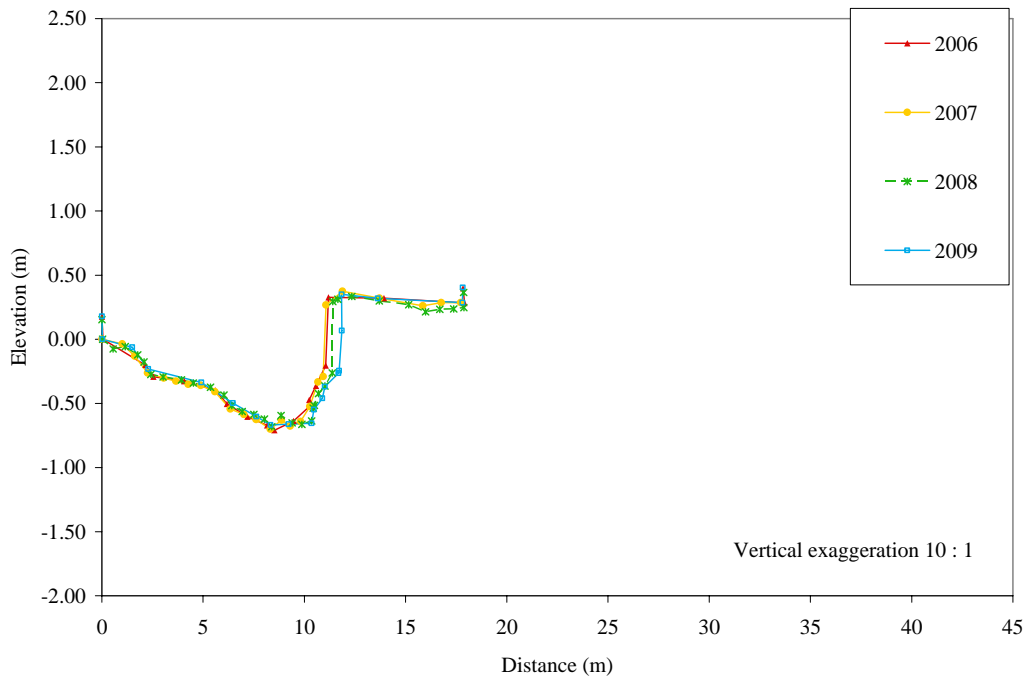
Figure A.81: Site 4, Cross section 1.3
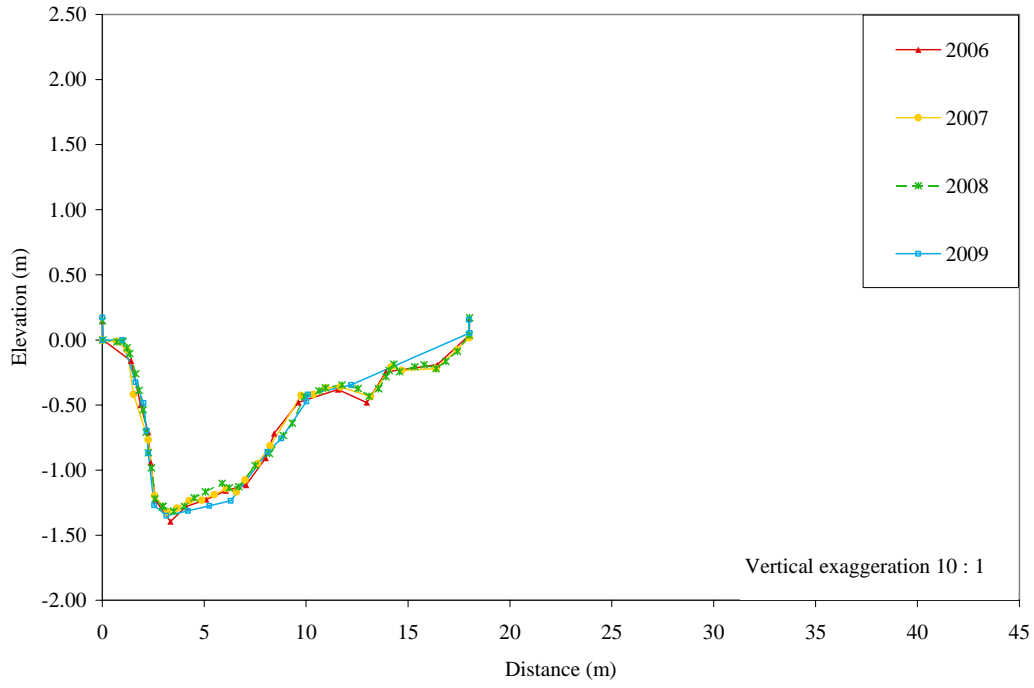
Figure A.82: Site 4, Cross section 1.4
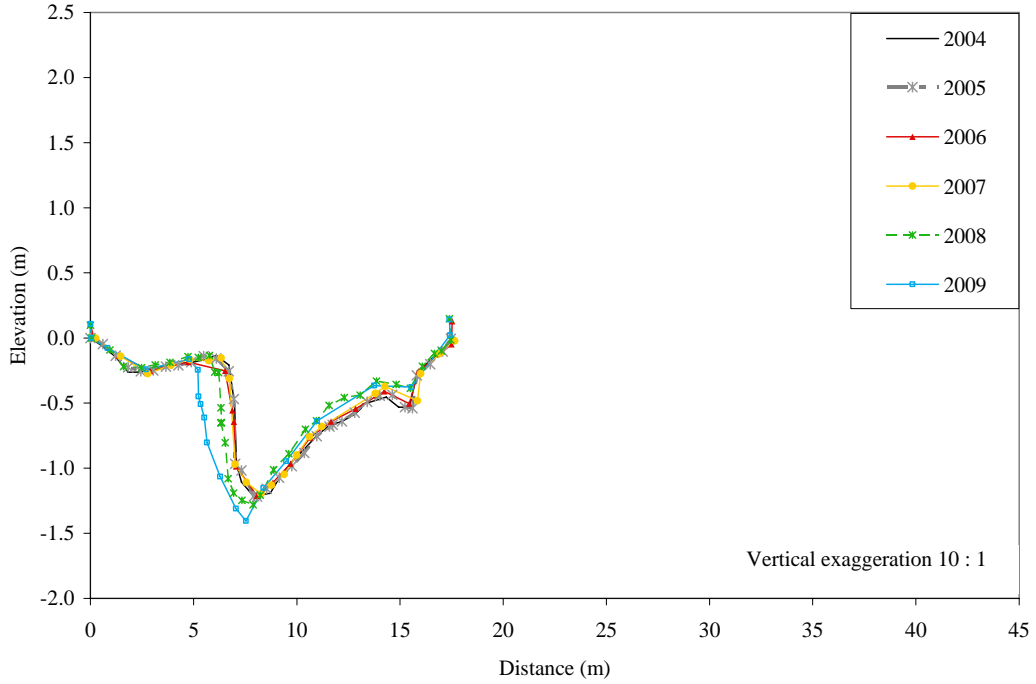
Figure A.83: Site 4, Cross section 2.0

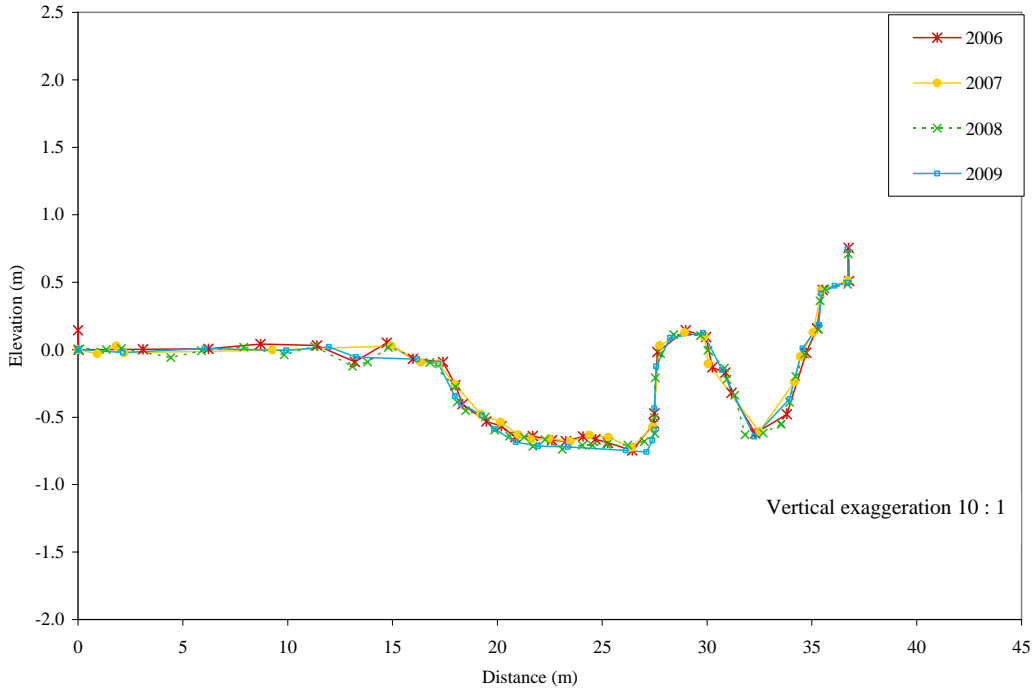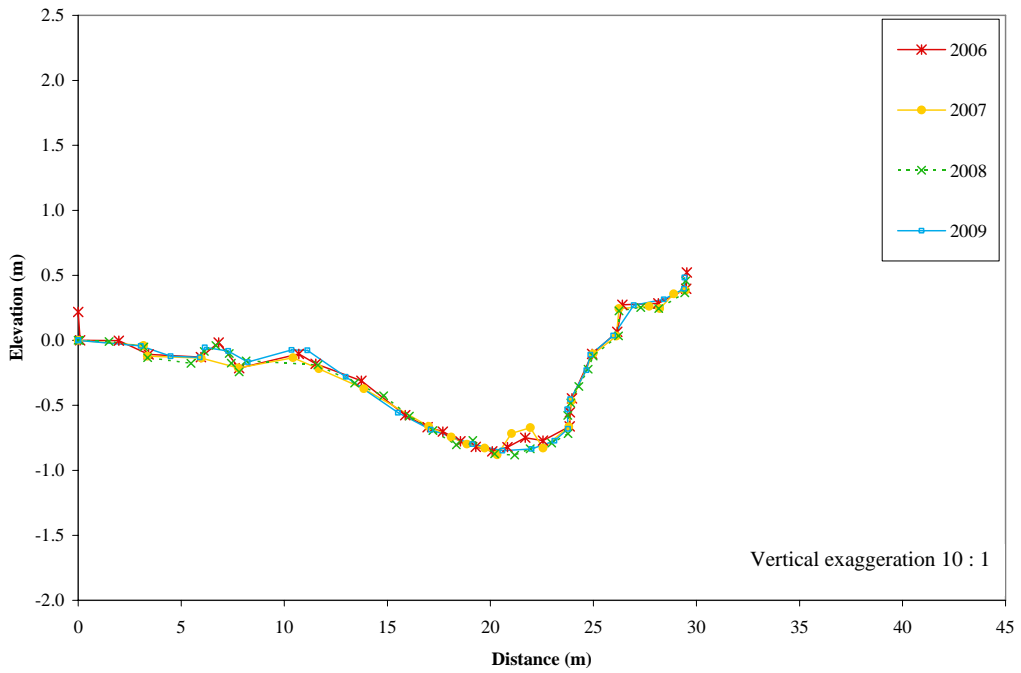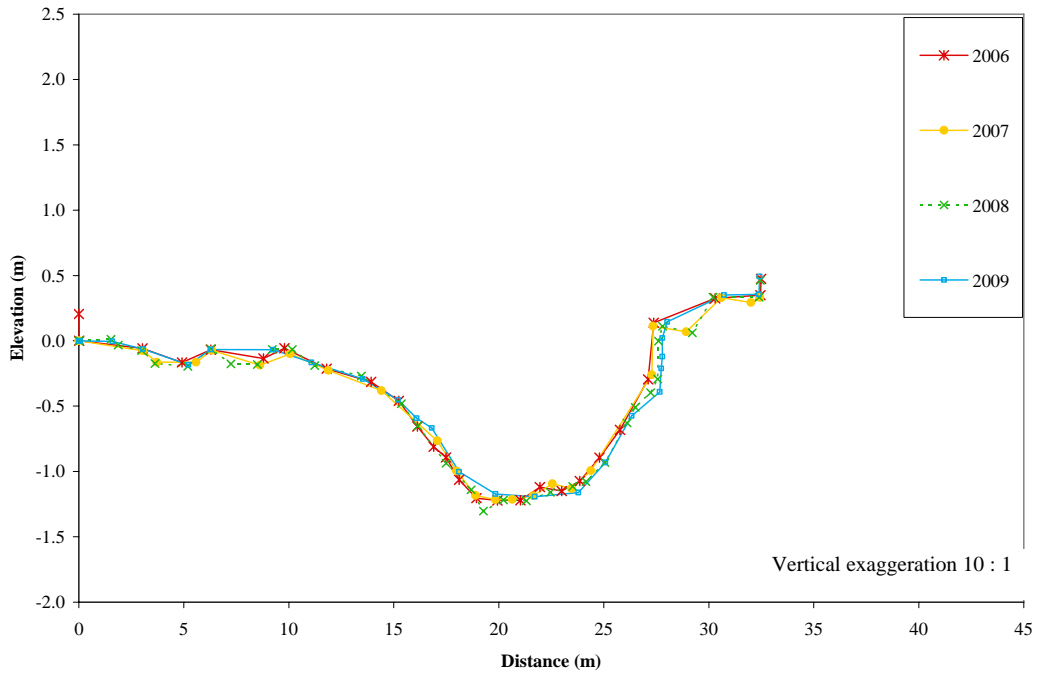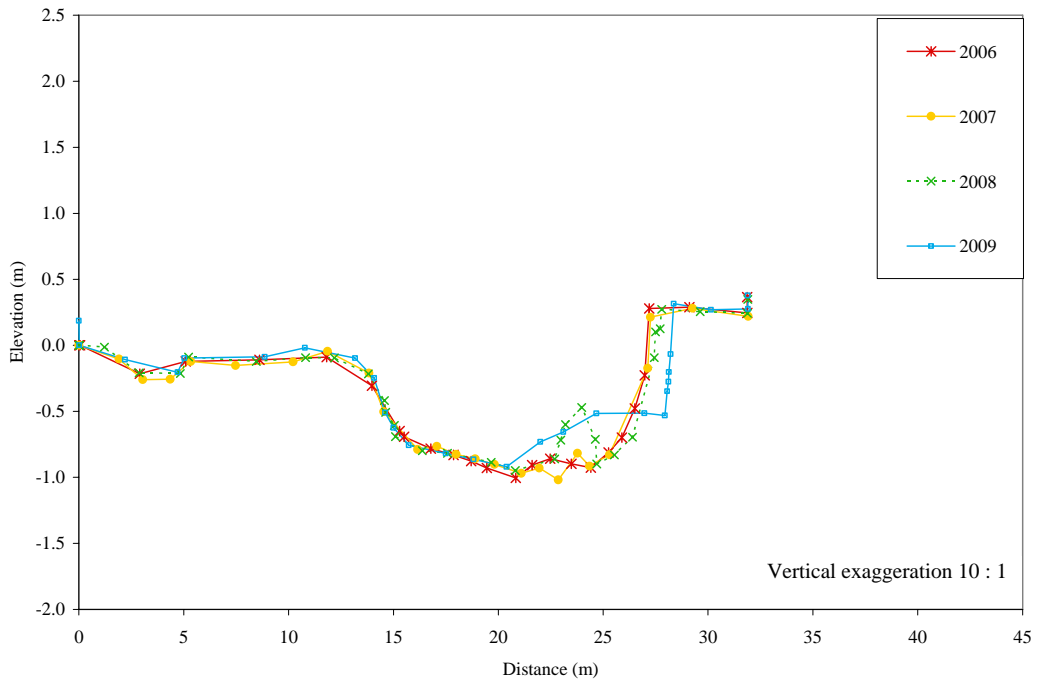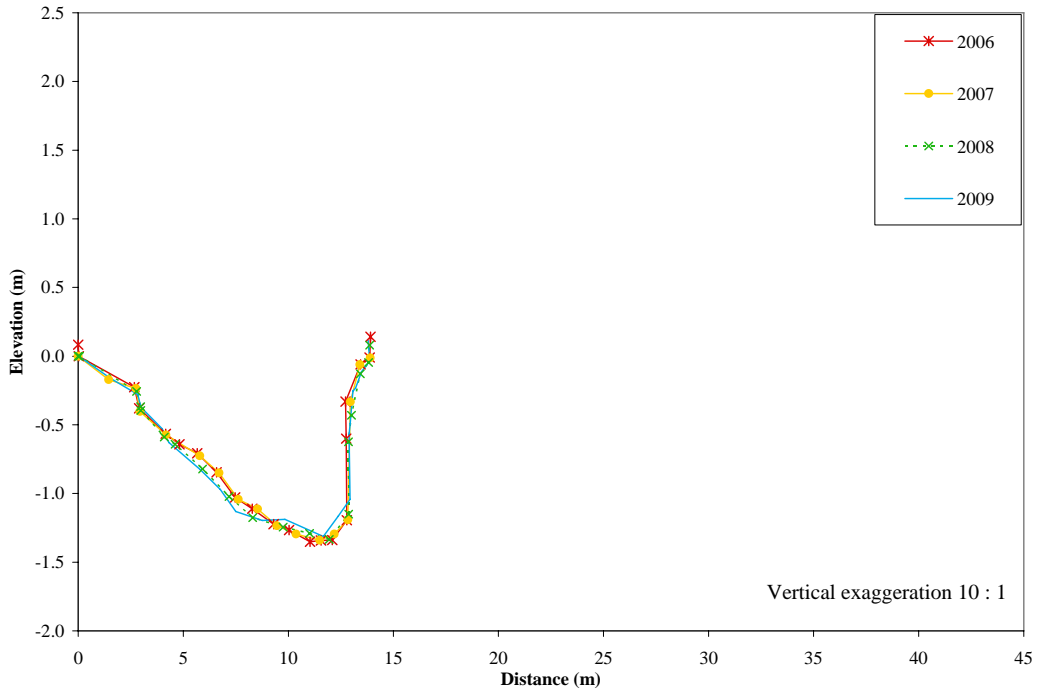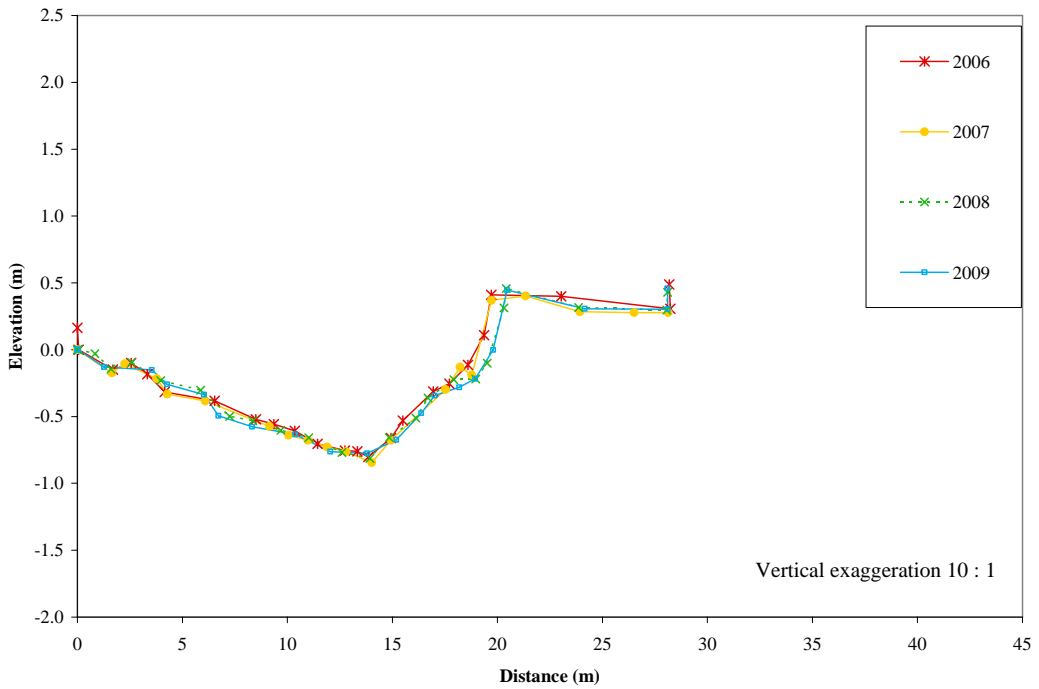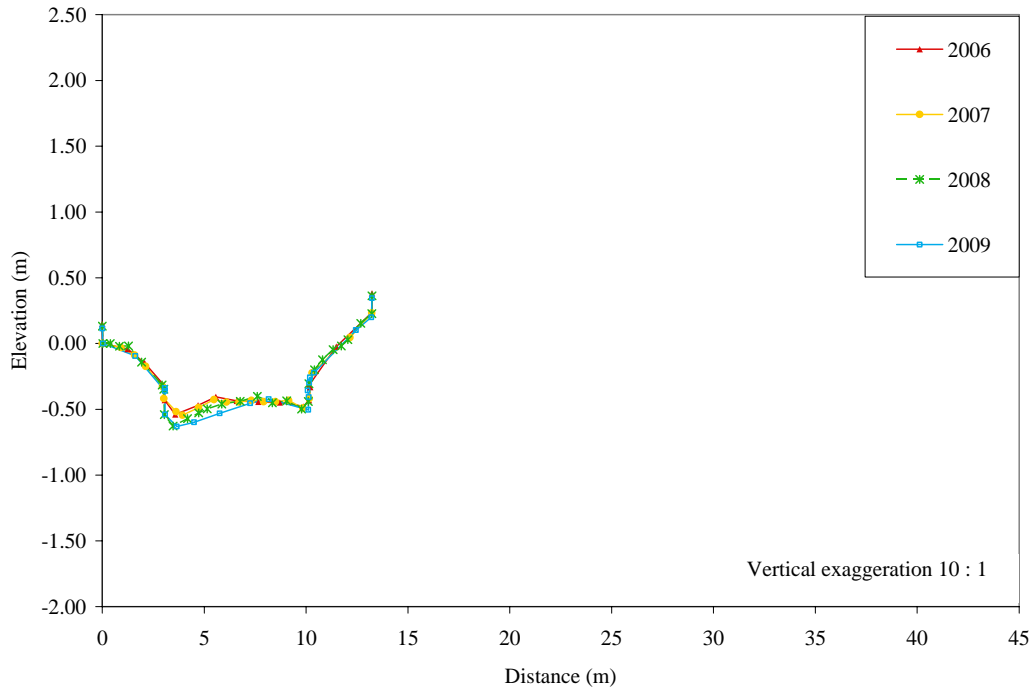**Figure A.84: Site 4, Cross section 2.1**
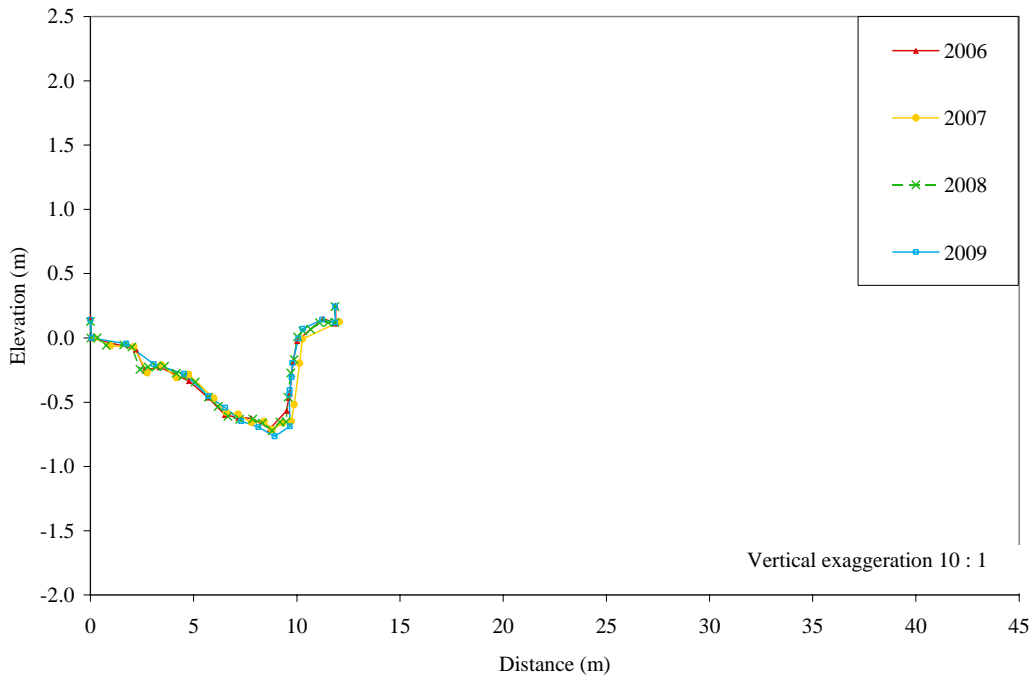
Figure A.85: Site 4, Cross section 2.2
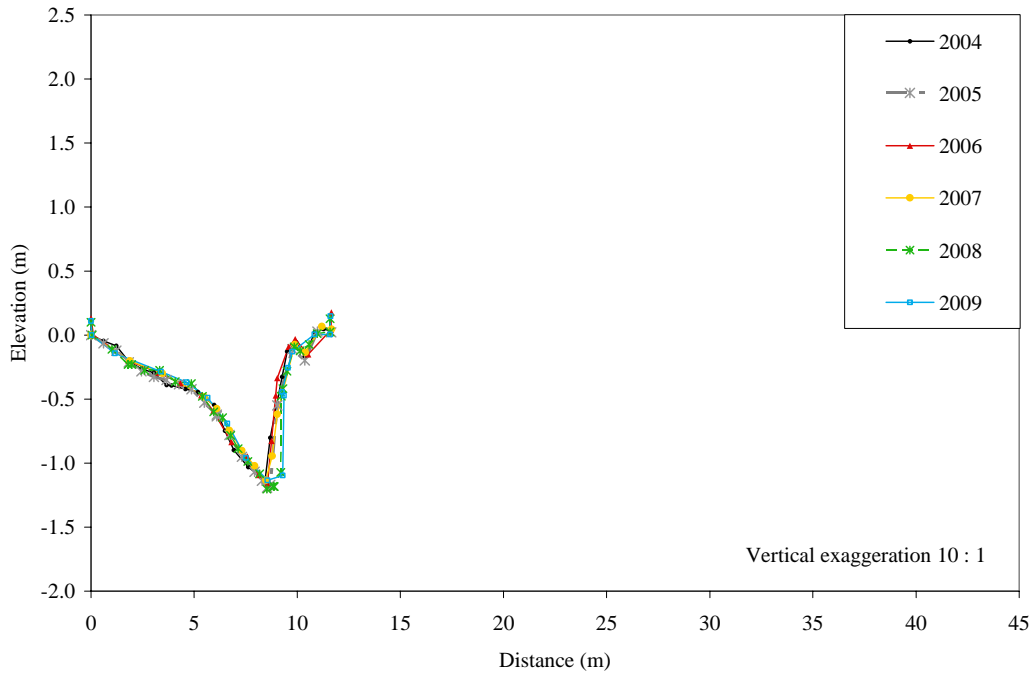
Figure A.86: Site 4, Cross section 3.0

APPENDIX

C

EROSION PIN DATA

Table C.1: Site 1 erosion pin data

xs	bank	upper/ lower	2006 protrusion of pin from bank(ft)	2007 protrusion from bank (ft)	2007 reset (ft)	2008 protrusion (ft)	2008 reset (ft)	2009 protrusion (ft)	2009 reset (ft)	WY 2007 Erosion (ft)	WY 2008 Erosion (ft)	WY 2009 Erosion (ft)
0.9	R	u	0.1	0.2	0.2	0.15	0.15	0.15	0.15	0.1	-0.05	0
0.9	R	l	0.25	0.06	0.06	0	0	0.17	0.17	-0.19	-0.06	0.17
1	R	u	0.25	0.15	0.15	0.15	0.15	0.06	0.06	-0.1	0	-0.09
1	R	l	0.14	0.75	0.75	0.71	0.63	0.91	0.91	0.61	-0.04	0.28
1.1	R	u	0.15	0.31	0.14	1.13	0.18	0.12	0.12	0.16	0.99	-0.06
1.1	R	l	0.06		0.06	0.6	0.25	0.7	0.58	-0.06	0.54	0.45
1.2	R	u	0.1	0.48	0.14	**2**	0.26	0.3	0.3	0.38	1.86	0.04
1.2	R	l	0.11	0.45	0.12	**2**	0.26	1.4	0.15	0.34	1.88	1.14
1.3	R	u	0.08	1.06	0.15	**2**	0.29	0.56	0.22	0.98	1.85	0.27
1.3	R	l	0.9	0.73	0.35	1.7	0.17	0.63	0.29	-0.17	1.35	0.46
1.4	L		0.2	0.15	0.15	0.18	0.21	0.11	0.11	-0.05	0.03	-0.1
2	L	u	0.22	0.29	0.29	**2**	0.17	**2**	0.34	0.07	1.71	1.83
2.1	R	u	0.1	0.19	0.19	0.15	0.15	0.1	0.1	0.09	-0.04	-0.05
2.1	R	l	0.3	0.07	0.07	0.04	0.04	0.12	0.12	-0.23	-0.03	0.08
2.1	L		0.13	**0.09**	**0.09**	0.1	0.1	0.16	0.16	-0.04	0.01	0.06
2.2	R	u	0.3	0.4	0.4	0.32	0.32	0.38	0.38	0.1	-0.08	0.06
2.2	R	l	0.32	0.26	0.26	0.23	0.23	0.3	0.3	-0.06	-0.03	0.07
3	R	u	0.22	0.23	0.23	0.75	0.31	**2**	0.1	0.01	0.52	1.69
3	R	l				**2**		0.36	0.06	0	2	0.36
2	L	l	-	-	-	-	-	-	0.24	-	-	-
	pin not found- totally out of bank											

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		pin not found; no apparent erosion, possible deposition									

Table C.2: Site 2 erosion pin data.

xs	bank		2006 pin protrusion (ft)	2007 pin protrusion	2007 reset	2008 pin protrusion	2008 reset	2009 pin protrusion	2009 reset (ft)	WY 2007 Erosion (ft)	WY 2008 Erosion (ft)	WY 2009 Erosion (ft)
0.8	r	u	0.19	0.12	0.12	0.61	0.18	0.35	0.13	-0.07	0.49	0.17
0.8	l		0.29	0.05	0.05	0.05	0.05	.	.	-0.24	0	
0.9	R	u	0.11	0.26	0.06	0.66	0.12	.	.	0.15	0.6	
0.9	R	l	0.11	0.48	0.24	0.82	0.21	1.5	0.1	0.37	0.58	1.29
1	R		0.15	0.52	0.13	0.59	0.33	1.27	0.8	0.37	0.46	0.94
1	R		0.21	0.62	0.13	1.58	0.81	1.21	0.13	0.41	1.45	0.4
1.1	R	u	0.15	0.6	0.15	1.17	0.13	0.85	0.15	0.45	1.02	0.72
1.1	R	l	0.12	0.5	0.19	0.91	0.14	1.12	0.15	0.38	0.72	0.98
1.2	R	u	0.18	0.05	0.05	2	0.46	1.61	0.2	-0.13	1.95	1.15
1.2	R	l	0.6	2	0	2	0.13	0.47	0.25	1.4	2	0.34
1.3	R	u	0.07	1.36	0.32	2	0.1	2	0.19	1.29	1.68	1.9
1.3	R	l	.	.	.	.	.	.	0.1		.	.
1.4	R		0.16	0.84	0.18	0.18	0.18	0.95	0.95	0.68	0	0.77
2	L		0.11	0.3	0.3	0.3	0.3	2	0.22	0.19	0	1.7
2.1	L	u	0.33	0.16	0.16	0.13	0.13	0.19	0.19	-0.17	-0.03	0.06
2.1	L	l	0.25	0.18	0.18	0.24	0.24	0.3	0.3	-0.07	0.06	0.06
2.2	L	u	0.19	0.73	0.11	0.41	0.09	1.14	0.32	0.54	0.3	1.05
2.2	L	l	0.14	0.56	0.1	0.92	0.12	0.65	0.12	0.42	0.82	0.53
2.3	L		0.23	0.3	0.3	2	0.17	.	.	0.07	1.7	.
2.4	L		0.24	0.27	0.27	0.22	0.14	0.26	0.08	0.03	-0.05	0.12
2.4	R	l	0.15	0.15	0.15	0.15	0.15	0.2	0.09	0	0	0.05
2.5	L		0.17	0.15	0.15	0.18	0.18	0.15	0.15	-0.02	0.03	-0.03
3	L		0.24	0.21	0.21	0.32	0.17	0.2	0.2	-0.03	0.11	0.03
3	R	u	0.18	0.12	0.12	0.12	0.12	0.07	0.07	-0.06	0	-0.05
3	R	l	0.18	0.12	0.12	0.12	0.12	0.12	0.12	-0.06	0	0

Table C.3: Site 3 erosion pin data

xs	bank		2006 reset (ft)	2007 protrusion from bank (ft)	2007 reset (ft)	2008 protrusion from bank (ft)	2008 reset (ft)	2009 protrusion from bank (ft)	2009 reset (ft)	WY 2007 Erosion (ft)	WY 2008 Erosion (ft)	WY 2009 Erosion (ft)
1	L	u	0.24	0.2	0.2	-	-	0.1	0.1	-0.04		
1	L	l	0.24	0.3	0.3	-	-	0.55	0.22	0.06		
1.1	R	u	0.19	0.29	0.29	0.27	0.22	0.23	0.23	0.1	-0.02	0.01
1.1	R	l	0.26	0.43	0.15	0.3	0.3	0.41	0.2	0.17	0.15	0.11
1.2	R	l	0.16	0.15	0.15	**0.15**	**0.15**	0.12	0.12	-0.01	0	-0.03
1.2	R		0.47	0.19	0.19	**0.19**	**0.19**	**0.19**	.	-0.28	0	0
1.3	R	u	0.2	0.2	0.2	1.16	0.3	0.72	0.13	0	0.96	0.42
1.3	R	l	0.38	0.13	0.13	2	0.4	1.5	0.09	-0.25	1.87	1.1
1.4	R	u	0.25	1.1	0.22	1.14	0.89	2.1	0.19	0.85	0.92	1.21
1.4	R	l	0.24	0.8	0.29	1.93	0.8	1.36	0.51	0.56	1.64	0.56
1.5	R	u	0.15	0.39	0.11	**2**	0.26	**2**	0.42	0.24	1.89	1.74
1.5	R	l	0.26	0.41	0.18	**2**	0.28	**2**	0.26	0.15	1.82	1.72
1.6	R	u	0.18	0.56	0.18	1.42	0.19	**2**	0.16	0.38	1.24	1.81
1.6	R	l	0.11	.			1.02	0.19	**2**	0.25		1.02	1.81
2	L		0.29	0.12	0.12	**0.12**	**0.12**	**0.12**	.	-0.17	0	0
2	L			0.1	0.1	**0.1**	**0.1**	**0.1**	.	0.1	0	0
2	R		0.19	0.3	0.3	0.92	0.92	1	0.6	0.11	0.62	0.08
2.1	R	u	0.11	0.85	0.17	.	.	**2**	0.1	0.74		
2.2	R	u	0.24	0.19	0.19	0.23	0.23	0.27	0.27	-0.05	0.04	0.04
2.2	R	l	0.2	0.2	0.2	0.44	0.44	0.55	0.55	0	0.24	0.11
3	R	u	0.16	0.18	0.18	0.19	0.19	0.22	0.22	0.02	0.01	0.03
3	R	l	0.15	0.16	0.16	-	.	.	.	0.01		
3.1	R	u	0.15	0.15	0.15	0.23	0.23	0.23	0.23	0	0.08	0
3.1	R	l	0.17			0.15	0.15	0.25	0.25	-0.17	0.15	0.1
		pin not found- totally out of bank										
		pin not found; no apparent erosion, possible deposition										

Table C.4: Site 4 erosion pin data

xs	bank	upper/lower	2006 protrusion of pin from bank(ft)	2006 reset (ft)	2007 protrusion from bank (ft)	2007 reset (ft)	2008 protrusion (ft)	2008 reset (ft)	2009 protrusion (ft)	2009 reset (ft)	WY 2007 Erosion (ft)	WY 2008 Erosion (ft)	WY 2009 Erosion (ft)
0.9	R	u	0.1		0.2	0.2	0.15	0.15	0.15	0.15	0.1	-0.05	0
0.9	R	l	0.25		0.06	0.06	0	0	0.17	0.17	-0.19	-0.06	0.17
1	R	u	0.25		0.15	0.15	0.15	0.15	0.06	0.06	-0.1	0	-0.09
1	R	l	0.14		0.75	0.75	0.71	0.63	0.91	0.91	0.61	-0.04	0.28
1.1	R	u	0.15		0.31	0.14	1.13	0.18	0.12	0.12	0.16	0.99	-0.06
1.1	R	l	0.06		-	0.06	0.6	0.25	0.7	0.58	-0.06	0.54	0.45
1.2	R	u	0.1		0.48	0.14	**2**	0.26	0.3	0.3	0.38	1.86	0.04
1.2	R	l	0.11		0.45	0.12	**2**	0.26	1.4	0.15	0.34	1.88	1.14
1.3	R	u	0.08		1.06	0.15	**2**	0.29	0.56	0.22	0.98	1.85	0.27
1.3	R	l	0.9		0.73	0.35	1.7	0.17	0.63	0.29	-0.17	1.35	0.46
1.4	L		0.2		0.15	0.15	0.18	0.21	0.11	0.11	-0.05	0.03	-0.1
2	L	u	0.22		0.29	0.29	**2**	0.17	**2**	0.34	0.07	1.71	1.83
2.1	R	u	0.1		0.19	0.19	0.15	0.15	0.1	0.1	0.09	-0.04	-0.05
2.1	R	l	0.3		0.07	0.07	0.04	0.04	0.12	0.12	-0.23	-0.03	0.08
2.1	L		0.13		**0.09**	**0.09**	0.1	0.1	0.16	0.16	-0.04	0.01	0.06
2.2	R	u	0.3		0.4	0.4	0.32	0.32	0.38	0.38	0.1	-0.08	0.06
2.2	R	l	0.32		0.26	0.26	0.23	0.23	0.3	0.3	-0.06	-0.03	0.07
3	R	u	0.22		0.23	0.23	0.75	0.31	**2**	0.1	0.01	0.52	1.69
3	R	l					**2**		0.36	0.06	0	2	0.36
2	L	l	-	-	-	-	-	-	-	0.24	-	-	-
		pin not found- totally out of bank											
		pin not found; possible deposition											

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