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# Fluvial Geomorphology of the Sand Bed Milk River, Northern Montana

by

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## *ABSTRACT*

The Milk River, the southernmost waterway in Alberta, displays a classic meandering pattern for the majority of its course across the province. However, shortly after entering Montana an anomalous transition to braiding occurs. The most obvious expression of a rivers adjustment to changes in the controlling variables is an alteration to the channel pattern. Contrary to the accepted paradigm channel slope is slightly lower in the braided reach versus the meandering. At the morphological transition a dramatic reduction in bank strength occurs as the silt-clay content drops from 65% in the meandering reach to 18% in the braided. Channel widening produces an inefficient channel where roughly the same stream power is applied over a wider channel (≈50 versus 100 m). Therefore, braiding on the Milk River is caused by local incompetence from a drop in the available stream power due to channel widening induced by comparatively weak channel banks.

## *ACKNOWLEDGEMENTS*

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## CHAPTER 1 – OVERVIEW

### *INTRODUCTION*

As the Milk River crosses southern Alberta it displays a classic meandering channel pattern (Fig. 1). However, shortly after entering Montana a seemingly inexplicable morphological transition occurs. The channel type changes instantly to a chaotic braided pattern characterized by mid-channel bars dividing flow into multiple channels (Fig. 2). This sudden change in channel pattern is an anomalous feature on the landscape of northern Montana. The focus of this study is to determine the causative mechanisms for this morphological transition.

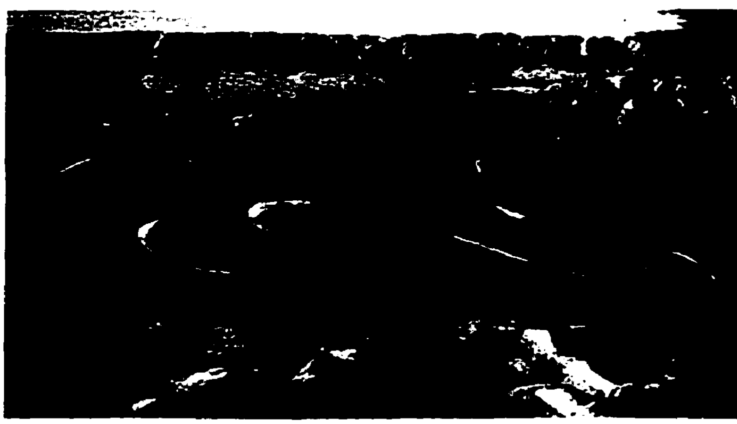

**Figure 1 – Typical meandering reach along the Milk River, southern Alberta - northern Montana.**

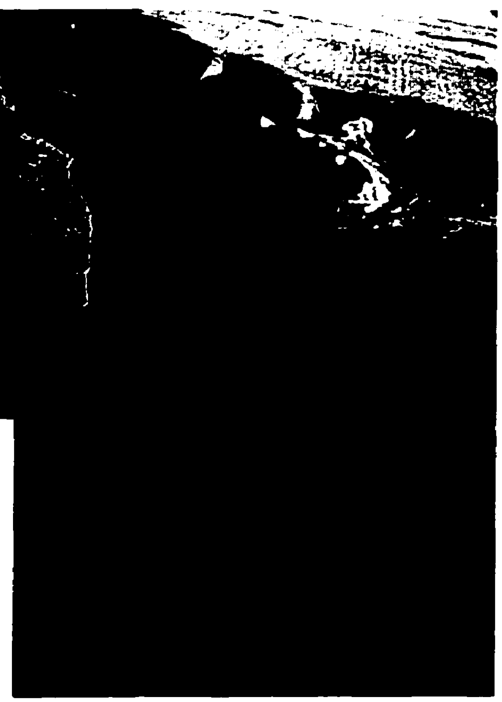

**Figure 2 – Braided reach of the Milk River, northern Montana.**

Rivers are among the most pervasive geomorphic agents currently acting on the surface of the earth. They serve as conduits through which the products of erosion are transmitted from source areas to sedimentary sinks. It has been estimated that rivers deliver yearly between 16 - 20 gigatons ($10^6$ tonnes) of sediment, 80% in solid form and 20% in dissolved form, to the oceans (Milliman and Syvitski, 1992; Ludwig and Probst, 1998). Rivers not only transport the products of erosion but they themselves can erode the landscape. However, the influx of eroded sediment sometimes exceeds the sediment transport capability of the river and new landforms are created through deposition. Rivers attempt to maintain a dynamic equilibrium whereby they transport the water and sediment load provided from upstream sources without undergoing significant morphological alterations. Four main variables act in concert to govern channel morphology. Rivers function as conduits for the movement of sediment and water. This discharge, along with the slope of the valley upon which the river flows, and the composition of the channel boundary materials represents the major variables controlling river morphology. Variations in the balance of these variables will elicit a response in one or more of the dependent variables such as channel pattern, sinuosity, channel slope, width, depth, velocity and channel roughness.

*CHANNEL PATTERNS*

Channel pattern is one of the most obvious expressions of a rivers adjustment to changes in any of the independent variables. In planview alluvial rivers can have a myriad of forms, but only various end members have been identified (Leopold and Wolman, 1957; Miall, 1977; Nanson and Knighton, 1996). The primary subdivision is into single channel and multi - channel forms. Miall (1977) used the number of channels and their sinuosity to arrive at a 4-fold classification of river morphology (Fig. 3). Single channel systems are divided into straight and meandering channels. Straight channels are relatively rare and often

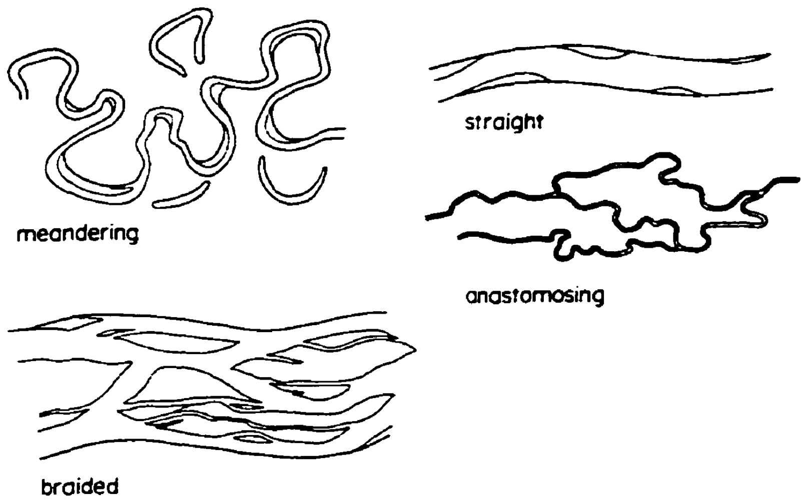


**Figure 3 - Four division channel classification based on the number of channels and sinuosity (Miall, 1977).**

limited to low gradient settings such as deltas (i.e. the lower course of the Mississippi River). Meandering rivers are the most common channel pattern and can be found all over the world. Leopold (1994) surveyed river valleys in the northwestern United States and found that meandering rivers occupied 90% of the total valley length. In multi – channel systems the terms braided and anastomosed were treated as synonymous for many years (Leopold and Wolman, 1957, Leopold *et al.*, 1964). However, Smith (1973, 1983, 1986) demonstrated that anastomosed rivers differ from braided rivers in numerous ways. Perhaps the most important difference lies in the characteristic degree of stability of each system. Channels and bars are transient features in braided systems and can move on the order of minutes to hours (Church, 1972; Smith, 1974; Hein and Walker, 1977). In comparison, the vegetated levees of anastomosing systems can remain stable for hundreds of years resulting in significant lateral stability. However, these channel patterns represent only the end members of a morphological continuum.

*Research Objectives*

As a discipline, geography attempts to explain the causal mechanisms for spatial differences in human and physical phenomena. Finding the reason why the Milk River suddenly changes from meandering to braided represents a fundamental geographical and geomorphological question. This study will endeavor to discuss and answer the following:

(1) Describe the physical characteristics of both the meandering and braided reaches of the Milk River.

(2) Determine if irrigation improvements installed on the Milk River in 1917 and 1939 are responsible for the morphological transition.

(3) Identify the factor(s) responsible for the morphological transition on the Milk River.

Explanations why a river displays a particular morphology are as varied as the patterns themselves. It is important to understand changes in river styles because such changes indicate differences in one or more of the independent variables. It is of increasing importance to be able to predict how a river responds to alterations of these variables for river engineers, planners and ecologists. Rivers long ago provided the cradle for civilization and today still support hundreds of millions of people. It is this pressure which leads to the manipulation of rivers both directly through engineering works, and indirectly through climate change. The Milk River presents an opportunity to improve our understanding of the factors important in causing downstream changes in channel morphology.

# CHAPTER 2 – PHYSICAL CONTROLS ON RIVER CHANNEL MORPHOLOGY

## *INTRODUCTION*

Research of morphological channel transitions lies at the heart of fluvial geomorphology in that it involves identifying the fundamental variables controlling river behavior. Changes in channel pattern have attracted the attention of fluvial geomorphologists for over a century. Davis (1889) was perhaps the first to identify braided rivers as a distinct channel pattern. However, given the qualitative nature of geomorphology at the time, rivers were described but detailed investigation of the underlying processes was not undertaken. Some early quantitative research involved extensive flume experiments which investigated the effects of varying discharge, bed material and slope on river patterns (Gilbert, 1917; Friedkin, 1945). With the change in direction of geomorphology in the 1950s and the seminal paper of Leopold and Wolman (1957), research became focused on identifying causal factors for different channel patterns. Many different theories explaining channel change have been presented but certain recurring themes can be identified.

## *IMPORTANT VARIABLES IN FLUVIAL GEOMORPHOLOGY*

The existence of similar river patterns on every continent indicates that certain physical controls dictate channel morphology. These can be divided into control (independent) and response (dependent) variables (Schumm and Lichty, 1965) when viewed over a graded timescale. The fundamental controlling variables are the discharge of water and sediment supplied from upstream areas as influenced by geology, base level, climate and topography. Other important controls on river morphology include valley slope, as well as composition and strength of the channel boundary. Changes in any of the controlling variables elicit adjustment by one or more of the response variables. One of the most dramatic adjustments is a change from one channel pattern to another. However, rivers can also delicately adjust characteristics such as width, depth, velocity, channel slope, channel pattern, sinuosity, bed grain size and roughness. It has been said that alluvial streams are the architects of their own geometry (Leopold, 1994). The challenge to fluvial geomorphology, and this study in particular, is unraveling the relative importance of each variable in a given situation.

### *Discharge Fluctuations*

Rapid fluctuations in discharge, whether short or long term, have been associated with braided rivers. Proglacial rivers, such as the Kicking Horse River in British Columbia, are characterized by large daily fluctuations in discharge (Smith, 1974). This can dramatically increase the sediment load through widespread bank erosion (Fahnestock, 1963). Sediment transport will also fluctuate with discharge. Stalled bedload pulses can act as the nucleus for the bar formation (longitudinal bars) necessary for channel braiding. Doeglas (1951) considered discharge fluctuation to be much more important than gradient or availability of sediment in producing a braided pattern. Long-term discharge fluctuations, such as the 100 year flood, have also been shown to contribute to braiding. The Cimarron River in Kansas experienced several large flood events during the 1930s. The increased width caused by flooding facilitated a conversion from a single to a multiple channel (braided) system. Narrowing and readjustment over the subsequent decades resulted in the river returning to a single channel pattern (Schumm and Lichty, 1963). Rapid increases in discharge are common in semi – arid to arid areas where flash floods can occur. The Gila River in eastern Arizona responded to a 1905 flood by increasing its width from 45 m to an average of 610 m. Like the Cimarron River, a slow recovery over 60 years led to infilling of the channel and a return to a meandering channel. However, other research, in particular flumes studies, has shown that braided patterns can be created with a constant discharge (Friedkin, 1945; Leopold and Wolman, 1957; Schumm and Khan, 1972; Hong and Davies, 1979; Ashmore, 1982; Germanoski and Schumm, 1993). Therefore, fluctuating discharge may not be a universal cause of braiding but can be important locally.

*Abundant Bedload*

The occurrence of mid – channel bars suggested to many early workers that braided channels form because the supply of sediment exceeds transport capability. This led to the common view that braided rivers were aggrading systems (Lane, 1957; Church, 1970; Smith, 1973). It was not until Rubey (1952) and Leopold and Wolman (1957) that the possibility of braided rivers being a valid dynamic equilibrium pattern was put forth. It is generally believed that braided rivers have significant portions of their sediment load transported as bedload. Schumm (1981, 1985) classified rivers as suspended load, mixed load, or bedload dominant. According to Schumm Bedload dominant streams could posses five different patterns, but the majority of these streams would display a braided morphology.

An abundance of bedload, whether supplied locally or from upstream, forms the bars which produce multiple channel braided rivers. There is either a lack of ability to transport the imposed load, or a lack of competence to remove the size of sediment supplied (Knighton, 1998). Examples exist where the introduction of large amounts of sediment exceed a rivers sediment transport capability and induces braiding. Schumm (1980) describes the Rangitata River on the South Island of New Zealand which, after exiting a gorge as a single channel, cuts into Pleistocene terraces. This rapidly introduces a large amount of sediment and induces braiding which persists across the Canterbury Plains. In northern Saskatchewan, Smith and Smith (1984) describe the meandering-to-braided conversion of the William River. For the majority of its course the William is a single channel meandering river. However, near Lake Athabasca the river passes through the Athabasca Sand Dunes. The actively migrating dunes increase bedload 40 times over a 27 km reach. The river's response is to increase width 5 times; a 10 times increase in the width – depth ratio and conversion from a single channel to a multi - channel sandy braided morphology.

Most discussions of braiding presume the presence of abundant bedload but sparse field data rarely provides unambiguous support of this concept (Smith and Smith, 1984). The importance of a large bedload component is questioned on the basis of bedload data from the gravel bed Tanana River near Fairbanks, Alaska (Burrows *et al., 1981)*. Bedload measurements made over a three-year period (1977 - 1979) show that bedload accounts for only one to one and a half percent of the total sediment transport (Burrows *et al.*, 1981). Despite this low bedload component, the Tanana River displays a classic braided morphology (D. Froese, pers. comm., 1999). The Tanana falls well short of Schumm's classification of bedload dominant streams (>11% bedload). The data for the Tanana River suggests that abundant bedload may not be necessary in the formation of gravel braided rivers.

*STEEP GRADIENT*

The presence of a steep gradient was one of the earliest factors noted as necessary for the occurrence of channel braiding. The classic studies of Leopold and Wolman (1957) and Lane (1957) concluded that braided rivers occur at channel slopes higher than those of meandering rivers given equivalent discharges. Data from both field and flume studies was used by Leopold and Wolman (1957) to show that multi - channel reaches have higher slopes than single channel reaches of similar discharge.

> "When streams of different patterns are considered in terms of hydraulic variables, braided patterns seem to be differentiated from meandering ones by certain combinations of slope, discharge and width – to – depth ratio." (Leopold and Wolman, 1957, p. 62)

As Figure 4 shows they plotted channel slope against bankfull discharge and found the equation:

$$s = 0.06Q_{bf}^{-0.44} \quad \text{(Imperial Units)}$$

$$s = 0.012Q_{bf}^{-0.44} \quad \text{(Metric Units)}$$

where: $s$ = channel slope
$Q_{bf}$ = bankfull discharge

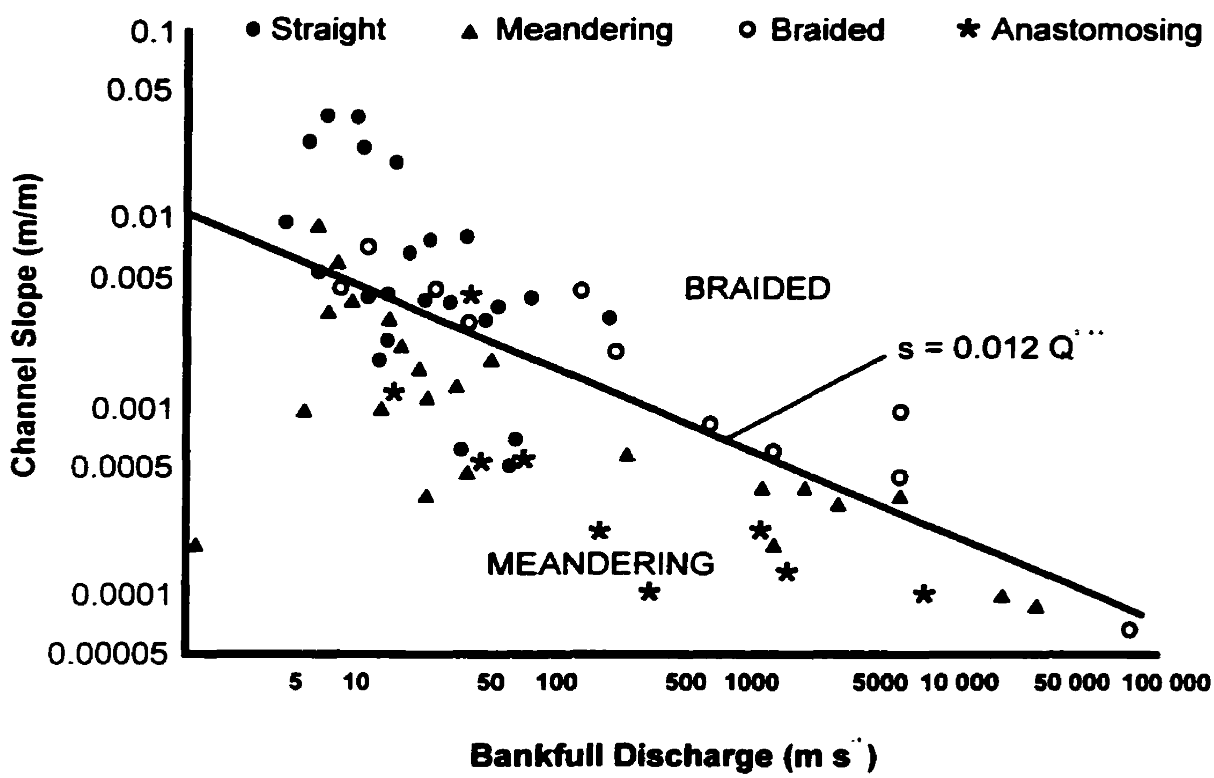


**Figure 4 – Channel pattern discriminated based on a slope-discharge diagram (modified from Leopold and Wolman, 1957).**

This equation differentiated meandering from braided channels on the basis of slope and discharge and has ever since been a central concept in studies of the controls on channel morphology. Independent of Leopold and Wolman (1957), the work of Lane (1957) arrived at similar conclusions but from a river engineering point of view (Lane, 1937, 1957). Lane described two styles of braiding: (1) The river is supplied with more sediment than it can transport causing overloading and aggradation; and (2) Steep slopes allow braiding without the river being aggrading. Lane (1957) produced a graph similar to that of Leopold and Wolman (1957) showing rivers plotted against slope and mean annual discharge. Braided channels occurred when:

$$s > 0.004Q_m^{-0.25}$$

where: $s$ = channel slope
$Q_m$ = mean annual flood

A fundamental problem with these explanations is the use of channel slope instead of valley slope. As pointed out by Richards (1982) channel slope is not an independent control because of its adjustment along with channel pattern. A variable with more explanatory capability would be valley slope which is independent of channel pattern. Schumm and Khan (1972) in a series of flume experiments found similar transitions from meandering-to-braided morphology but this time associated with increasing valley slope. Unlike the work of Leopold and Wolman (1957) and Lane (1957), Schumm and Khan (1972) found that flume river patterns did not necessarily exist along a smooth continuum, but could suddenly alter morphology from meandering-to-braided. Schumm (1981), in a discussion of his channel classification, re-emphasized the point that channel patterns may form a continuum but change abruptly at river - pattern thresholds.

Schumm (1973) synthesized his work and that of others into the concept of the geomorphic threshold. A threshold was defined as some critical parameter above which the geomorphic system suddenly changes. This forcing mechanism need not always be external (allocyclic or extrinsic) factors such as climate change, tectonic uplift/downdrop or any other change in base level. Changes within the system (autocyclic or intrinsic), such as increasing channel sinuosity, can push the system over a geomorphic threshold and induce cutoffs and a decrease in sinuosity. The suddenness of the meandering-to-braided transition on the Milk River suggests that some geomorphic threshold has been crossed.

Schumm and Beathard (1976) studied a meandering-to-braided transition on the Chippewa River in Wisconsin. The braided reach of this river plots below both the Leopold and Wolman (1957), and Lane (1957) threshold lines. This may indicate that the river is unstable and a slight change in any of the independent variables will instigate a return to a meandering pattern. The Rangitata River in New Zealand is a meandering river until it cuts into terrace deposits which increase the sediment load and convert the river to a braided pattern (Schumm, 1980). The Wairau River in New Zealand is a braided stream that plots very close to the Leopold and Wolman (1957) threshold line. Through the use of bank stabilization and training works the river is being converted to a more stable single thread pattern. The threshold concept does not necessarily agree with the spirit of the Leopold and Wolman (1957) paper which stresses that rivers form a continuum because the independent variables themselves exist on a continuum (see Knighton and Nanson, 1993 for a re-emphasis on the continuum). This is due to the geomorphic community's narrow focus on Figure 4 which suggests the presence of a channel pattern threshold. Thresholds no doubt exist but not all changes in channel pattern occur instantaneously.

Theoretical research has also shown the presence of a steep slope to be important to braiding. The stability analysis of Parker (1976) distinguished braiding from meandering on the basis of high width - depth ratio and slope. As the slope steepens the degree of braiding (i.e. number of channels) increases. The minimum stream power concept of Chang (1979, 1985) states that,

> "When multiple stable channel geometries and slopes are possible for a constant water discharge and sediment load, the channel geometry and plan configuration will be so adjusted along the valley slope that the stream power per unit channel length is a minimum for the river system." (Chang, 1985, p. 314)

Similar to Leopold and Wolman (1957) a plot of bankfull discharge versus slope was constructed. This diagram confirmed that braiding not only occurs at higher slopes but the degree of braiding also increases along with slope (Chang, 1985, p. 314).

The above papers emphasize that a steep slope is important to braiding but the reason for its importance is not discussed. Begin (1981) re–analyzed published data and found that braided rivers tend to have, on average, higher shear stress than is associated with highly sinuous meandering rivers. Any shear stress in excess of that needed to transport the imposed sediment load, must be expended in order for the stream to remain in dynamic equilibrium. The excess stress is often directed outward against the channel banks. This can result in channel widening until the excess shear stress is utilized. Widening produces an area of hydraulically less efficient flow where bars are deposited during waning discharge. Over large reaches with high gradients excess shear stress is constantly present and can maintain a wide channel and thus a braided pattern. If widening is critical for braiding then the composition and shear resistance of sediment to erosion of the channel perimeter must be important.

### *Composition and Erodibility of the Channel Perimeter*

The majority of the world's rivers are alluvial in nature, in that they flow through their own sediment or that deposited by a former river system. These deposits can range in size from gravel to clay and, therefore, impart different resistance characteristics to the channel bed and banks. Braided rivers are characterized by wider cross sections in comparison to single channel rivers of similar discharge. This suggests to many researchers that the resistance characteristics of the channel perimeter exert a strong control on river morphology. Erosion of channel banks is important for two reasons:

1. It is a potential source of bedload which can be used in the construction of channel bars,
2. Widening can decrease flow stability and increase the chances of areas of quiescent flow, thus enabling the formation of channel bars that would likely not form in a narrow channel.

Using a flume, Friedkin (1945) studied the various controls on river meandering. He found that highly resistant banks formed deep and narrow channel cross sections whereas easily eroded banks were wide and shallow. Friedkin (1945) stated that:

> "...this test clearly illustrates that a braided channel results when the banks are easily eroded."
> (Friedkin, 1945, p. 279)

The seminal paper of Schumm (1960) further examined the relationship between the composition of the channel perimeter and cross sectional geometry based on 69 locations in the American Midwest. The weighted mean percent silt - clay in the channel perimeter was used as a surrogate for bank strength; higher silt – clay content increases the cohesiveness and, therefore, resistance to erosion. Channels comprised predominantly of silt - clay were narrow and deep whereas those composed of low silt – clay, and thus a higher percentage of sand, were relatively wide and shallow. Schumm (1960) made no statements concerning morphology but braided rivers are typified by wide and shallow cross sections suggesting that they may be linked to areas of low bank strength. Schumm (1960) found that streams with sinuous channels have a narrow and deep cross section and a high percentage of silt – clay in the channel perimeter. The conclusion is that braided rivers occur in settings of low bank strength (low % silt - clay) and meandering in areas of higher bank strength (high % silt – clay) (Ferguson, 1972).

Theoretical stability analyses indicate that a critical factor in the formation of braided morphology is the channel width and/or width – depth ratio. Engelund and Skovgaard (1973) found that for a given hydraulic resistance and river depth, a river would be braided if it were above a certain threshold width. Below this width the river will remain stable and display a meandering morphology. Fredsøe (1978) conducted a continuation of this stability analysis in which it was shown that, depending on hydraulic conditions, a critical width – depth ratio existed above which a river tended to braid. Brotherton (1979) suggested that the critical factor in differentiating channel patterns is the relative ease of eroding and transporting bank materials. If bank erosion is more difficult than downstream transport, a river will remain straight; if erosion is easier than downstream transport a channel will widen and braid. The development of a meandering pattern lies somewhere in between. These theories support the assumption that highly erodible banks are a requisite condition for channel braiding because they permit widening that can induce instability and bar formation.

*Bank Vegetation*

Lane (1957) considered vegetation as one of eight variables affecting channel morphology. A frequently mentioned, but little studied component of bank strength, is the influence of riparian vegetation. The presence of large root mats in the channel bank can dramatically alter its erodibility. Smith (1976) found that well vegetated banks on the Alexandra River were 20 000 times more resistant to erosion than banks having similar sediment composition but without vegetation. It has been debated whether woody vegetation versus grasses imparts more resistive capability to the banks. Trimble (1997) found that grassed over banks in reaches of Coon Creek, Wisconsin were narrower and, thus, stored more sediment than adjacent forested reaches.

The Wood River in Idaho undergoes a meandering-to-braided to meandering transition which Mackin (1956) ascribes to vegetation change from woodland to grassland to woodland. Brice (1964) attributed a meandering to braided transition along the Calamus River in Nebraska as a change in bank erodibility because of differences in vegetal resistance. Conversion of the multi – channel Turandui River in New Zealand was brought about by the strategic placement of willows along the channel banks (Nevins, 1969). A natural analog is the spread of tamarisk on the Colorado Plateau (Graf, 1978). Tamarisk is a shrubby plant that colonizes freshly exposed sediment such as bars. This vegetation dramatically increases the resistance to flow and can therefore induce sediment deposition. On average channel width along the Green River was reduced 27% in response to the introduction of tamarisk in the 1880's. Rowntree and Dollar (1999) found a reduction in channel cross sectional area on the Bell River in South Africa where willow species were planted along the banks. Bank vegetation can either reduce bank erosion and/or induce sedimentation which leads to channel narrowing that can suppress development of braided morphology.

*Grazing (Bovine Bioturbation)*

The geomorphic impact of heavy grazing by cattle and other domesticated animals has been virtually ignored until recent work by Trimble (1994). Grazing cattle can weaken bank stability both mechanically through constant trampling, and by reducing the vegetation on the channel banks (Trimble and Mendel, 1995). Along Jenkins Creek in central Tennessee uncontrolled grazing caused six times as much bank erosion as the area protected from grazing (Trimble, 1994). The impact of cattle grazing depends not only on the amount of cattle but also the style of stream and composition of the banks. Myers and Swanson (1992) found particular stream types to be relatively immune even to heavy grazing. The role and potential impact of cattle grazing on channel morphology is poorly understood as the majority of studies have focused more on range management and water quality issues. Given the abundant evidence of heavy localized bank retreat in many streams morphological change induced by grazing is possible.

SUMMARY

The interaction and unique combination of the factors discussed above is responsible for the wide range of channel patterns. Discarding fluctuating discharge as a universal causative mechanism leaves flow strength, bank erodibility and the relative abundance of bedload as the main controls on channel pattern (Knighton and Nanson, 1993). The discharge and slope graph of both Leopold and Wolman (1957) and Lane (1957) can be thought of in terms of stream power. This is possible because discharge and slope are constituent elements of steam power. Therefore, stream power can be used as an indicator of flow strength. The following table lists the four main channel patterns and how the three controlling factors vary along an ordinal scale from low to high.

**Table 1 - Control Variables and Channel Pattern**

| Channel Pattern | Flow Strength | Bank Erodibility | Relative Sediment Supply Rate |
|---|---|---|---|
| Straight | Low | Low | Low |
| Meandering | Medium | Low/Medium | Low/Medium |
| Braided | High | High | Medium/High |
| Anastomosing | Low | Low | Medium/High |

In summary, braided rivers are generally thought to have higher flow strength, more erodible channel banks and a larger bedload component in comparison to meandering rivers. A goal of this thesis is to determine where the Milk River fits within this scheme.

## CHAPTER 3 – REGIONAL SETTING

### INTRODUCTION

Previous research along the Milk River in southeast Alberta has been directed primarily at describing the Quaternary and Holocene evolution of the area (Westgate, 1968; Barendregt, 1977, Kulig, 1996; Beaney, 1998). The work of Bradley (1982) focused on the impacts of different flow regimes on the recruitment capabilities of Plains Cottonwood (*Populus deltoides*). The first identification and description of the braided reach is found in Bradley (1982) but determination of the causal factors explaining its occurrence was outside the scope of her work.

### LOCATION AND REGIONAL PHYSIOGRAPHY

The Milk River drains 57 000 $km^2$ of southern Alberta, Saskatchewan and northern Montana (Fig. 5). The river begins in the Rocky Mountain foothills of

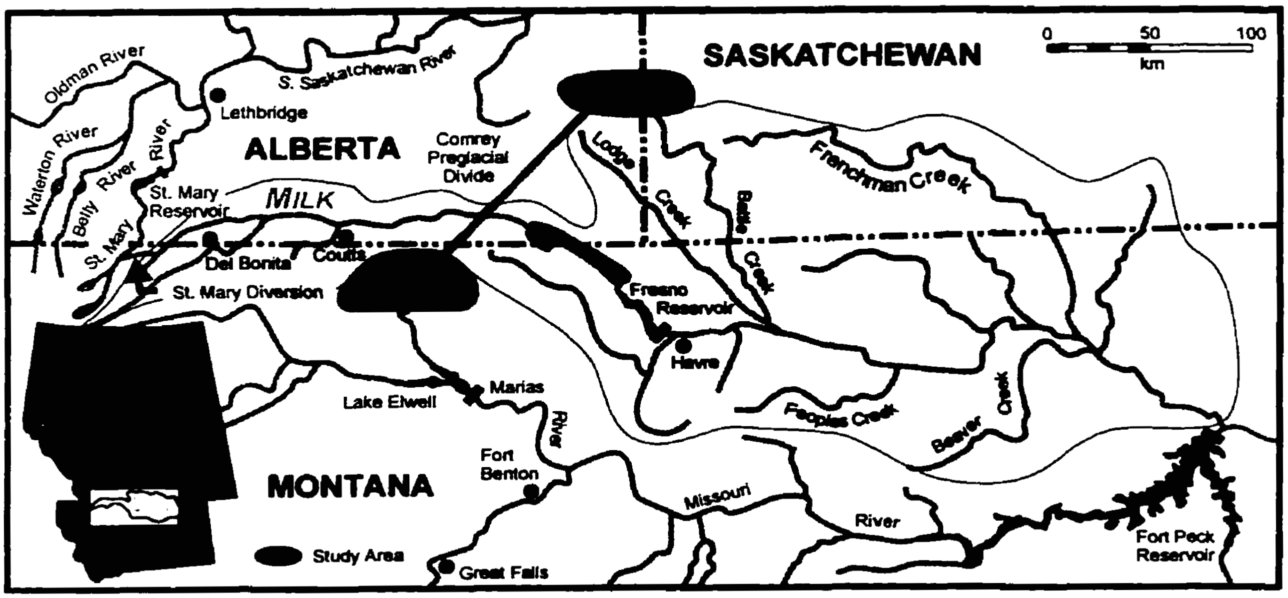


**Figure 5 - The Milk River drainage basin in Alberta, Saskatchewan and Montana.**

northern Montana and flows northeastward into Alberta. It crosses 180 km of southern Alberta before flowing back into Montana for the remaining 390 km. Below the Fort Peck Reservoir in east - central Montana, the Milk River joins the Missouri River and eventually empties into the Gulf of Mexico via the Mississippi River. Approximately 20 km west of Havre, Montana, the Milk River is impounded and forms the 35 km long Fresno Reservoir. The study area focuses on the final 28 km of river meanders in Alberta and the 50 km of meander and braid channels above the Fresno Reservoir (Fig. 6). As reported by Shaw and Kellerhals (1982)

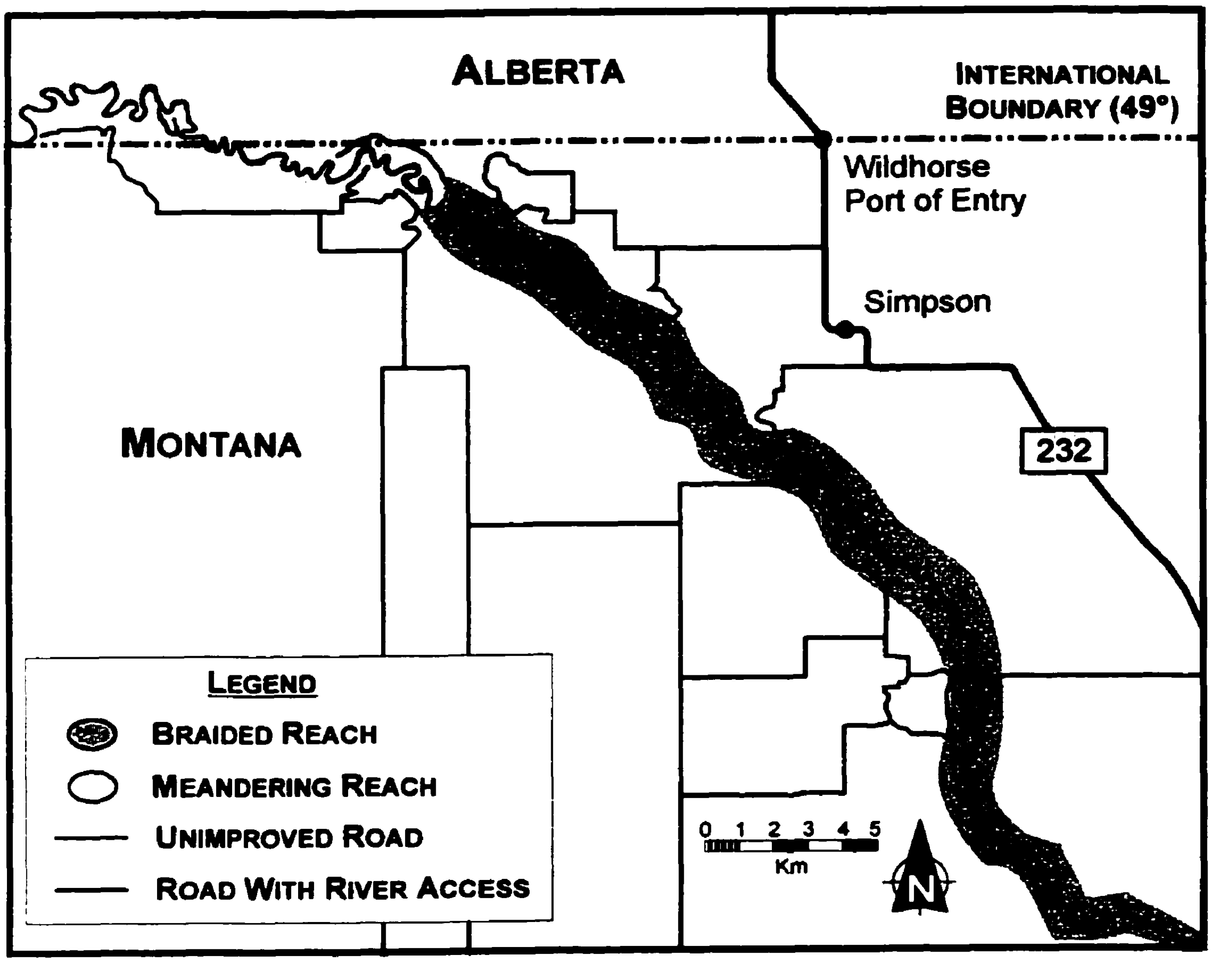


**Figure 6 - Study area showing the meandering and braided reaches of the Milk River.**

there is a sudden change in bed material from gravel (12 mm) to sand (0.5 mm) near the town of Milk River (Fig. 5). For the remainder of the river course, sand dominates the bed, with only isolated local bedrock or gravel outcrops.

The southeast corner of Alberta is within the Interior Plains physiographic province (Bostock, 1964). Pettapiece (1986) described this area as the Lost River Plain which is characterized by rolling topography covered by a thin blanket of morainal deposits with patches of exposed bedrock and localized heavily dissected topography. Barendregt (1977) further subdivided the area into seven distinct terrain units based on topography and elevation (Fig. 7).

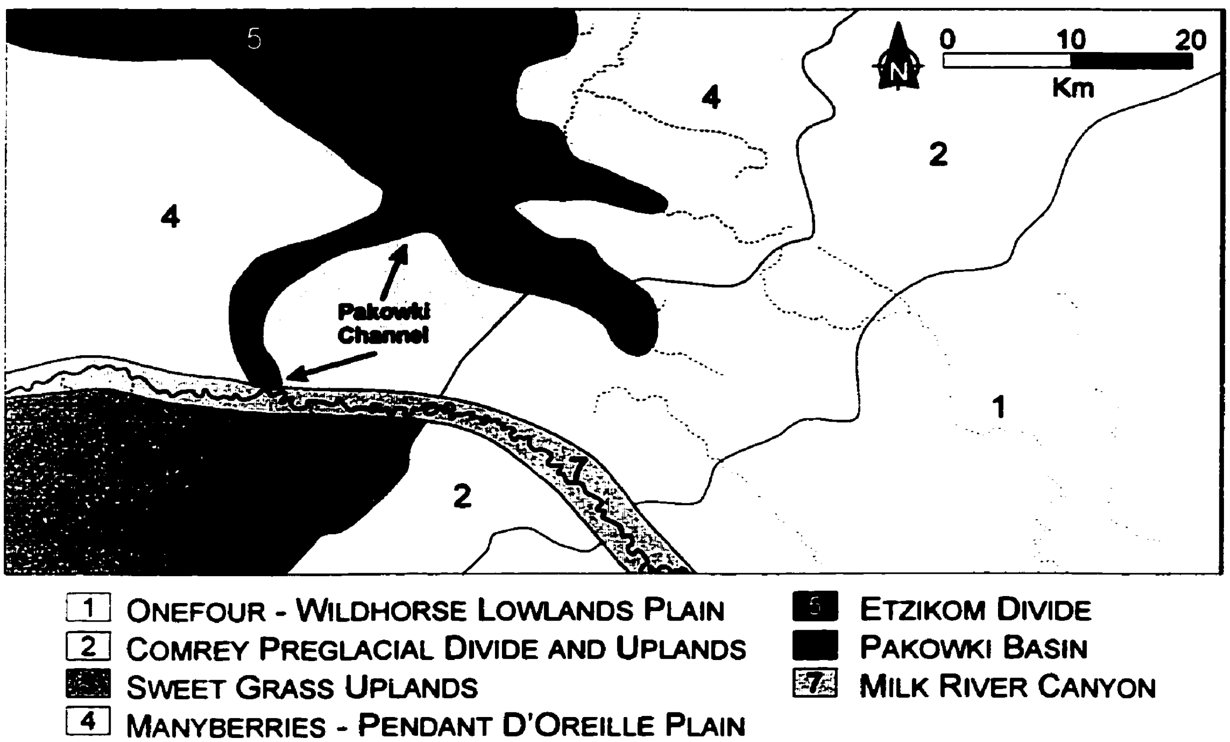


**Figure 7 - Physiographic units as identified by Barendregt, 1977.**

**Table 2 – Characteristics of the Seven Physiographic Units Identified By Barendregt 1977**

| Physiographic Region | Characteristics |
|---|---|
| Onefour – Wild Horse Lowlands Plain | Largest unit; thin veneer of mainly glaciofluvial deposits; relief seldom exceeds 2 to 3 m. |
| Comrey Preglacial Divide and Uplands | Little or no glacial sediments; large areas of scoured bedrock surfaces, flutings and drumlinoid forms; meltwater channels cut across this divide; relief exceeds 60 m. |
| Sweet Grass Uplands | Located on the slopes of the Sweet Grass Hills (igneous intrusive); thin veneer of till; flutings and drumlinoid ridges; relief varies from 2 to 8 m |
| Manyberries – Pendant D'Oreille | Morainal cover; hummocky to rolling topography; relief varies from 3 to 10 m. |
| Etzikom Divide | Thick end moraine; separates Pakowki drainage from the South Saskatchewan drainage. |
| Pakowki Basin | Structural low; sands, silts and clays from glacial lakes; internal drainage; relief seldom exceeds 2 to 3 m. |
| Milk River Canyon | Cut into Upper Cretaceous bedrock; extensive badland development on valley walls; valley floor covered with alluvium and colluvium. |

This study is concerned with the fluvial processes and landforms of the Milk River within the Milk River Canyon physiographic unit. The southeastern corner of Alberta and northern Montana is sparsely populated restricting vehicle access to this region to a single road in Alberta and Montana, and a few scattered 4-wheel drive trails.

### *Bedrock Geology*

Loading of the Canadian Prairies during uplift of the Canadian Rockies in Late Cretaceous times dramatically increased sediment accommodation space. Coupled with enhanced erosion rates facilitated from the increased relief a thick clastic sedimentary wedge was deposited into the Western Canadian Sedimentary Basin. During this period a series of shallow epicratonic seas covered the Interior

Plains of western Canada. This allowed an interfingering of marine and non - marine rock sequences, composed mainly of sandstones, siltstones and shales. The nomenclature used to describe bedrock differs between Alberta and Montana despite many of the formations being identical in composition. The Canadian name shall be presented, first followed by the American descriptor (AM superscript).

Stretching west from the Pinhorn Ranch (refer back to Fig. 5) the Pakowki/Clagett$^{AM}$ Formation outcrops along the lower portion of the valley walls. This Formation is a westward thinning sedimentary wedge of marine rock. It is composed primarily of dark grey shale and silty shale, with minor occurrences of grey sandstone. Outcrops of the Pakowki/Clagett$^{AM}$ Formation occur in minor fault blocks near the Fresno Dam. This formation is separated from the underlying Milk River/Eagle$^{AM}$ sandstone by a thin chert pebble conglomerate. The boundary with the overlying Foremost/Lower Judith River$^{AM}$ Formation is transitional (Barendregt, 1977).

Lithologic heterogeneity characterises the Foremost/Lower Judith River$^{AM}$ Formation. This eastward thinning sedimentary wedge is composed of siltstone, greenish grey mudstone and dark grey shale. Numerous coal seams and beds of brackish water mollusks are this formations most diagnostic features. The lower to middle portion of the Milk River valley walls are composed of this formation which is transitional with the underlying marine Pakowki/Clagett$^{AM}$ Formation and the overlying non – marine Oldman/Upper Judith River$^{AM}$ Formation (Barendregt, 1977).

Exposed along the upper portion of the Milk River valley is the world famous Oldman/Upper Judith River[AM] Formation. This formation contains one of the most significant collections of dinosaur fossils. Pale grey, coarse sandstone dominates this formation with minor amounts of grey siltstone, green and grey mudstone and dark grey to brown shales. The finer grained rocks become more common up - section. Bentonite is prevalent in the shales. Another diagnostic feature of this formation is the occurrence of concretionary ironstone beds that promote development of hoodoo like landforms (Barendregt, 1977).

One the most conspicuous feature on the landscape of southeastern Alberta and northern Montana is the Sweet Grass Hills. Evidence of these Tertiary laccolithic mountains can be seen in the valley sides of the Milk River valley. An igneous dike of early Tertiary age (approximately 50 Ma) is visible near the Eastern Crossing of the International Boundary. The later igneous intrusion of the Bearpaw Mountains in Montana produced faulting near the Fresno Dam that brought the Pakowki Formation to the surface. The area had been geologically quiet until onset of Pleistocene glaciation (Barendregt, 1977).

*QUATERNARY HISTORY*

Understanding of the sequence and pattern of glaciation in southeast Alberta has seen dramatic changes during the 1990s. Early and more recent work in southeastern Alberta (Westgate, 1968; Barendregt, 1977; Kulig, 1996) was driven by the theory that multiple glaciations had covered southern Alberta during the Pleistocene. Many researchers (Stalker, 1976; Westgate, 1968; Barendregt, 1977) have suggested that particular till units in southern Alberta predate the classical Wisconsinan Period. Several decades of magnetostratigraphic work summarized by Barendregt and Irving (1998) demonstrate that glaciers covered the Interior Plains only during the Brunhes Chron (0.78 Ma to present, roughly the Wisconsinan Period). This does not preclude the possibility of multiple glaciations in southeast Alberta but suggests that none predate the Wisconsinan. Kulig (1996) reinterpreted Westgate (1968) and proposed a 5 - stage sequence of glaciation in the region. Differing from earlier research, Kulig (1996) did not identify any deposits of pre – Late Wisconsinan age. Current research (Young *et al.*, 1994; Jackson *et al.*, 1996) indicates that the Edmonton area in central Alberta was only affected by a single Late Wisconsinan Laurentide glaciation. If this concept is correct multiple glaciations in southeast Alberta, which is both further from the ice centre and at a higher elevation than Edmonton, is difficult to envision. Further complicating the Quaternary interpretation of the area is the emergence of the subglacial megaflood hypothesis (Shaw, 1996; Rains *et al.*, 1993; Beaney, 1998). The proximity of this region to the ice margin and its possible location on a megaflood pathway is thought to be responsible for the complexity of the Quaternary history.

The precise order and extent of glaciation is not directly related to the study of channel patterns of the Milk River. However, the preglacial drainage network of southern Alberta and northern Montana was considerably different than that of today. As Figure 5 shows the Comrey Preglacial drainage divide extended between the Cypress Hills on the Alberta/Saskatchewan border and the Sweet

Grass Hills in Montana. This routed the preglacial Milk River northeast into the preglacial South Saskatchewan River. Streams southeast of the divide discharged into the preglacial Missouri River valley, thought to be located near Havre, Montana (Williams and Dyer, 1930; Stalker, 1961; Barendregt, 1977). Explanations for how the preglacial Milk River in Alberta cut across the Comrey Preglacial Divide involves both a traditional explanation and a more radical hypothesis.

Westgate (1968), Barendregt (1977) and Kulig (1996) all invoke an ice marginal setting to explain how ice forced the Milk River to cut across the Comrey Preglacial Divide (Fig. 8). During deglaciation meltwater from southern Alberta

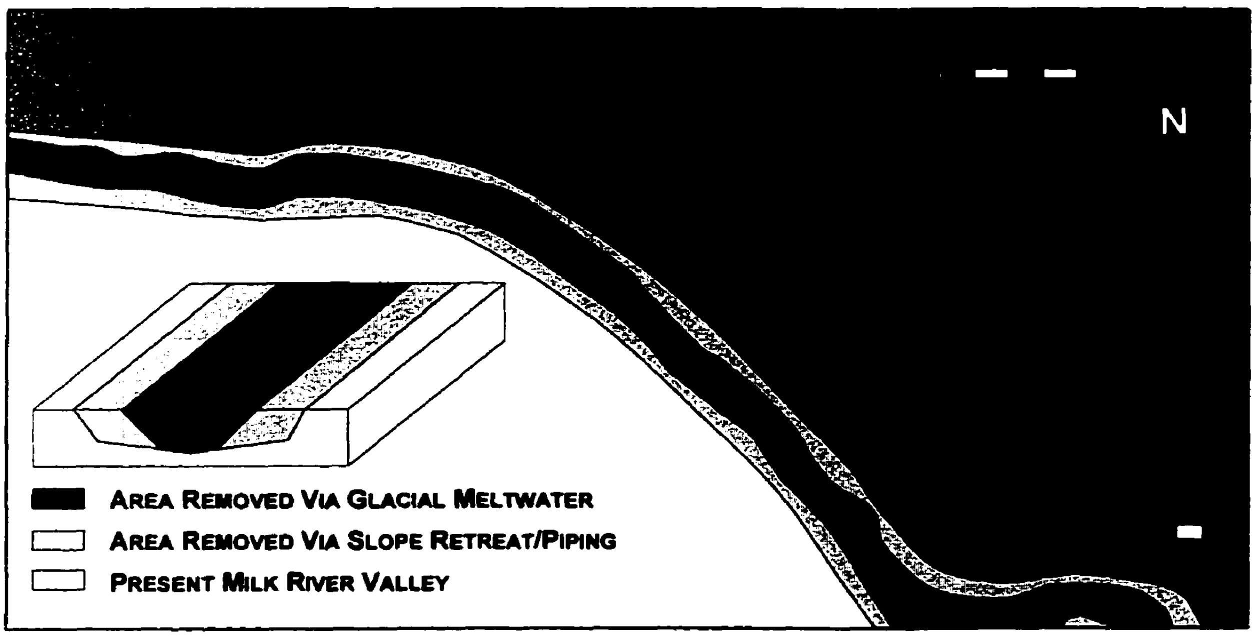


**Figure 8 - Hypothetical situation required for the Milk River valley to have formed in an ice marginal setting.**

was diverted along the margin of the retreating Laurentide ice sheet. This meltwater overtopped the divide and downcut into the friable bedrock thus connecting the Milk River with a minor channel on the Montana side of the divide.

This channel joined the preglacial Missouri River valley five kilometres west of Havre. The new Milk River channel was latter modified by drainage from Glacial Lake Pakowki which connects via the Pakowki Channel (Fig. 7).

The alternative explanation for how the Milk River overtopped the Comrey Preglacial Divide involves a large Wisconsinan subglacial megaflood (Beaney, 1998). As Figure 9 shows the proposed subglacial megaflood pathways

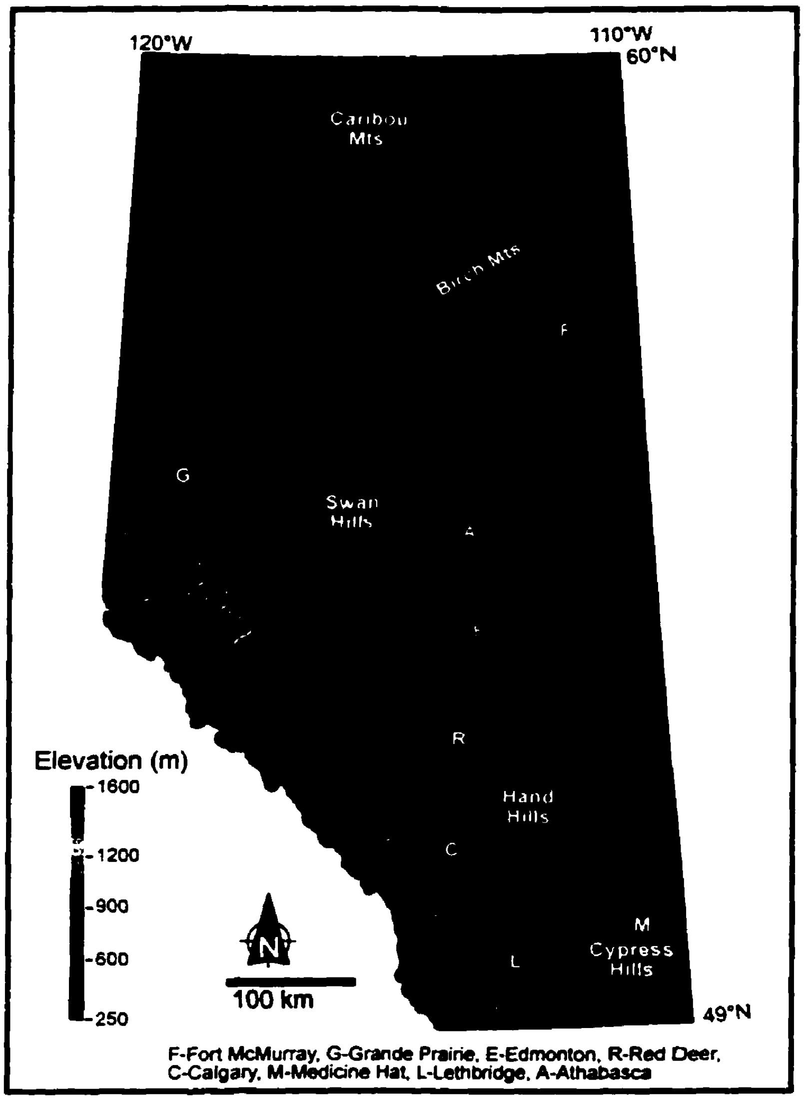


**Figure 9 – Sub-glacial megaflood pathways through Alberta (from Rains et. al., 1993).**

of Alberta converge in southeast Alberta and exit between the Sweet Grass and Cypress Hills (Rains et al., 1993). Barendregt (1977) postulates that ice thickness in the area was roughly 680 m. This would provide a large hydraulic head which could pressurize fluid at the base of the glacier and enable it to flow uphill against the regional slope. An initial subglacial sheetflood roughly 80 km wide and 30 m deep would have passed over the area. As discussed elsewhere (Walder, 1982; Shoemaker, 1992) sheetfloods are unstable and would quickly break down to channelised flow. These flows may be responsible for the Sage Creek, Lost River and Milk River valleys whereas the sheetflood generated the ripple like landforms present across the top of the divide (Fig. 10). Arguments supporting this

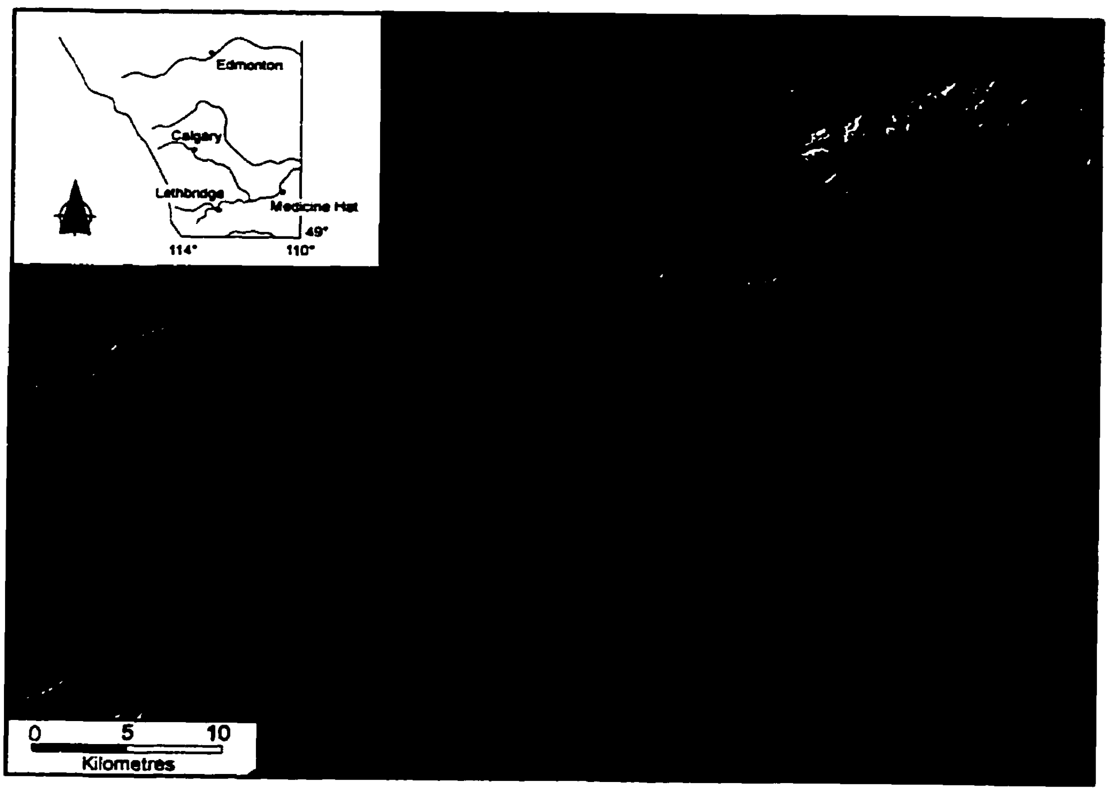


**Figure 10 – Hill shaded relief model of the Alberta portion of the study area. Note the ripple waveforms straddling the Comrey Preglacial divide (from Beaney, 1998).**

hypothesis are the additional channels (Sage Creek and Lost River located northeast of the Milk River) cutting across the divide. These are located in the middle of the divide where ice may have been located when the Milk River valley formed. These channels also occupy topographically higher positions on the divide. Given the possible location of the ice margin, the Milk River would have formed first and presumably captured a majority of the runoff from southern Alberta. This piracy would leave little water to cut the other large channels across the divide. A subglacial origin would enable formation of these channels simultaneously.

A polygenetic origin where the original formation of the channels was subglacial, and subsequent subaerial events acted as modifiers is a likely scenario. No matter what mode of formation, the evolution of the Milk River valley continues to this day, due to dynamic fluvial and slope processes.

### *Hydrology*

The Milk River is the northernmost tributary of the Mississippi River system. It rises on the Eastern Slopes of Montana before flowing across southern Alberta. After returning to Montana it travels eastward joining the Missouri River below Fort Peck Reservoir (refer back to Fig. 5). The Milk River receives little input of water along most of its course across Alberta and Montana. Small ephemeral tributaries, originating either in the Sweet Grass Hills to the south, or the Milk River Ridge to the north, join the river east of the town of Milk River. In Alberta, the large Pakowki Channel and Lost River both contain small ephemeral streams which contribute little discharge to the river. Above the Fresno Reservoir in Montana, the only contribution comes from small ephemeral streams. Below the town of Havre several tributaries from the Cypress Hills in Alberta and Saskatchewan join the Milk River.

For much of its course the Milk River drains semi – arid land where water is at a premium. Natural runoff can become very low during late summer and winter. For this reason discharge has been augmented to provide better irrigation potential. In 1917, a diversion canal was completed near Babb, Montana, to direct water via a cross - valley siphon pipe from the St. Mary River into the North Fork of the Milk River. In 1939 the Fresno Dam and 35 km long reservoir were completed primarily for irrigation water storage and flood protection for Havre (Fig. 5; Straus, 1948). The effectiveness of the Fresno Reservoir is declining as a 1978 sediment survey demonstrated that 20% of the original capacity had been lost. Over the intervening 20 years a further 10% has been infilled (US Bureau of Reclamation, 1984). The upriver diversion resulted in a threefold increase in mean monthly flows from May to September. However, the diversion has had little effect on peak flows through the study areas (Bradley, 1984). The majority of the basin is below the siphon which allows accumulation of a significant portion of the peak flow independent of the diversion (Bradley and Smith, 1984).

Typical of most rivers in Alberta, the Milk River displays a wide variety of discharges around the mean (Fig. 11). Today the peak discharge occurs much later than prior to the diversion. The pre - diversion peak occurred in late March/early April; while the post - diversion peak has shifted to a more traditional late May/early June peak. This demonstrates the management scheme of the

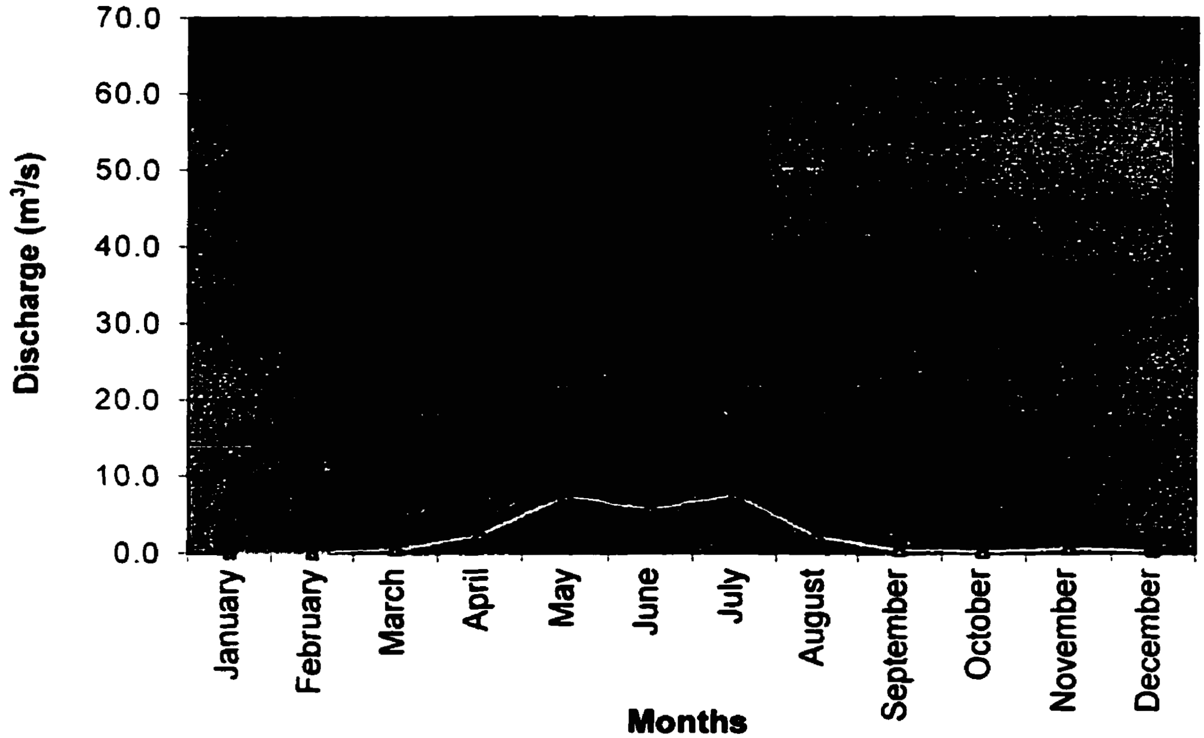


**Figure 11 – Milk River hydrograph at Eastern Crossing for the mean, maximum, minimum and pre - diversion monthly discharges. Mean hydrograph for the Milk River station is also shown.**

diversion which begins siphoning flow from the St. Mary River in late April/early May when natural flow begins to decline. In eight years of data, prior to the diversion, the river had discharges below one $m^3/s$ six times in July, August and September. In the 73 years following the diversion, the same months had discharges below one $m^3/s$ only three times. Discharge is increased during the low flow summer months when downstream irrigation requirements are the greatest. As Figure 11 shows, the mean discharge of the Milk River at Milk River and the Eastern Crossing gauging stations are virtually identical despite the fact they are separated by approximately 120 km.

Over 91 years of records, the Eastern Crossing hydrograph station has had three locations (Fig. 12). The current station is located at the Aagesson Ranch,

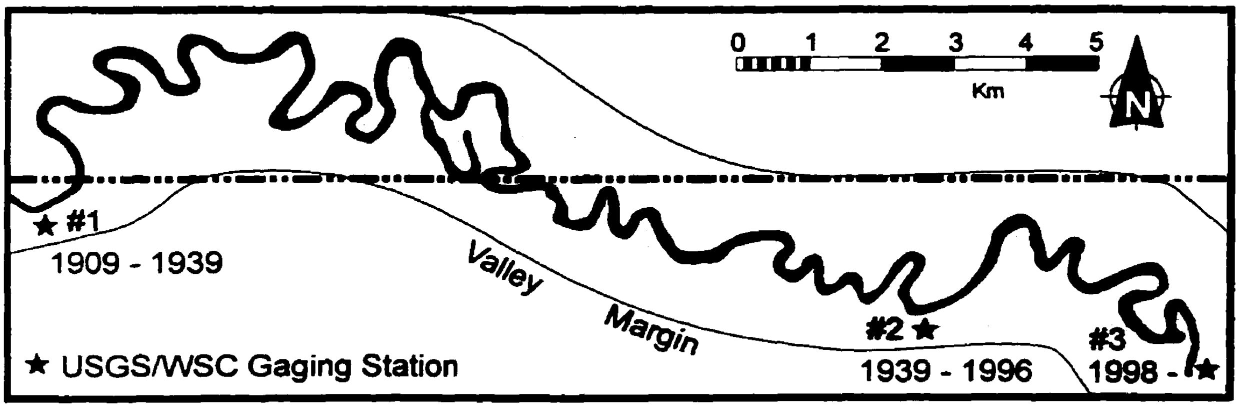


**Figure 12 – Location of the Eastern Crossing gauging station for the period 1909-1999.**

14 km downriver from the original station at the mouth of Kennedy Coulee. Don Bischoff (Pers. commun. 1998), United States Geologic Survey (USGS) hydrologic technician, confirmed that measurements at all three stations can be taken as identical given no significant tributary input and minimal output between the stations. An important characteristic of prairie rivers, of which the Milk River is a typical example, is the occurrence of pronounced discharge peaks in March and April. The majority of these events are from ice jams near the gauging station. As Table 3 shows ice jam events are a common occurrence on the Milk River and can have impacts on both the channel and the landscape surrounding it.

**Table 3 – Interpreted Mechanical Ice Breakup Events at the Eastern Crossing Gauging Station (From Smith and Pearce, in press)**

| Year | Mechanical Breakup Q | Date | Year | Mechanical Breakup Q | Date |
|---|---|---|---|---|---|
| [illegible] | 56.9 | April 06 | [illegible] | 47.9 | April 07 |
| [illegible] | 52.7 | April 14 | [illegible] | 102.0 | April 2 |
| [illegible] | 30.3 | April 09 | [illegible] | 50.1 | March 25 |
| [illegible] | 49.6 | March 24 | [illegible] | 115.0 | March 22 |
| [illegible] | 138.0 | April 09 | [illegible] | 41.9 | March 23 |
| [illegible] | 112.0 | April 22 | [illegible] | 303.0 | April 9 |
| [illegible] | 50.1 | April 14 | [illegible] | 195.0 | March 24 |
| [illegible] | 49.8 | April 24 | [illegible] | 85.0 | March 06 |
| [illegible] | 56.6 | March 24 | [illegible] | 120.0 | April 13 |
| [illegible] | 153.0 | March 24 | [illegible] | 142.0 | March 19 |
| [illegible] | 85.0 | March 30 | [illegible] | 59.2 | March 21 |
| [illegible] | 51.5 | April 25 | [illegible] | 204.0 | March 27 |
| [illegible] | 95.7 | April 18 | [illegible] | 175.0 | March 8 |
| [illegible] | 80.7 | April 13 | [illegible] | 148.0 | April 14 |
| [illegible] | 54.1 | April 12 | [illegible] | 283.0 | Feb. 27 |
| [illegible] | 60.6 | March 19 | [illegible] | 44.5 | April 06 |
| [illegible] | 39.9 | March 5 | [illegible] | 39.6 | March 29 |
| [illegible] | 57.2 | April 04 | [illegible] | 113.0 | March 26 |
| [illegible] | 93.7 | March 30 | [illegible] | 45.3 | March 9 |
| [illegible] | 246.0 | March 23 | [illegible] | 283.0 | March 4 |
| [illegible] | 132.0 | April 19 | [illegible] | 339.8 | March 13 |
| [illegible] | 53.2 | April 19 | [illegible] | 255.0 | March 22 |
| [illegible] | 270.0 | March 31 | [illegible] | 89.9 | |

### *Characteristics of the Milk River Valley*

The gently rolling landscape of southern Alberta is scarred in many places by deep valleys formed in response to glaciation. What sets the Milk River valley apart from many of these other coulees is the presence of a significant perennial waterway. The activity of the Milk River, as well as the valley slopes, has produced a dynamic landscape and a suite of landforms unique in southern Alberta.

*Valley Characteristics*

In certain locations the Milk River valley approaches canyon-like dimensions (Beaty, 1990). The most dramatic location being where the river crosses the Comrey Preglacial Divide, known locally as the Comrey Breaks. Here, the valley dimensions are at a maximum (depth of 150 m and width of 1500 m), and badland development is the most pronounced. Both above and below this reach in the meandering section, the valley sides remain heavily dissected with an average valley depth of 75 m and width of 951 m. Below the morphological transition the valley becomes shallower (47 m), narrower (701 m) and less dissected.

The bedrock exposed along the valley walls of the Milk River generally has a high rate of erosion. As discussed earlier, the Late Cretaceous bedrock outcropping in the valley is mainly sandstones, siltstones and shales. Like most other Upper Cretaceous formations, this bedrock is poorly indurated and highly susceptible to erosion. Shrink – swell clays, predominantly montmorillonite, are present in the bentonitic beds which are common in the Oldman and Foremost formations. The absence of any major glacial drift appears important in allowing enhanced erosion not only along the Milk River valley (Barendregt, 1977) but also the Red Deer River in Dinosaur Provincial Park (Bayrock and Broscoe, 1972). The calcium carbonate present in the tills acts as a cementing agent making them more indurated. The bedrock also lacks this cementing agent and instead has large amounts of sodium sulphate which acts as a dispersent (Barendregt, 1977). High erosion rates result in sparse vegetation on the slopes. Along the Milk River valley, short but intense periods of rainfall are separated by long periods of drought

(Barendregt and Ongley, 1977). This climatic regime is common to the majority of badlands on the Great Plains. The above factors have combined to produce 260 km$^2$ of classical badland topography, as well as areas of heavily dissected valley walls (Fig. 13). The shape of the valley walls depends largely on the local

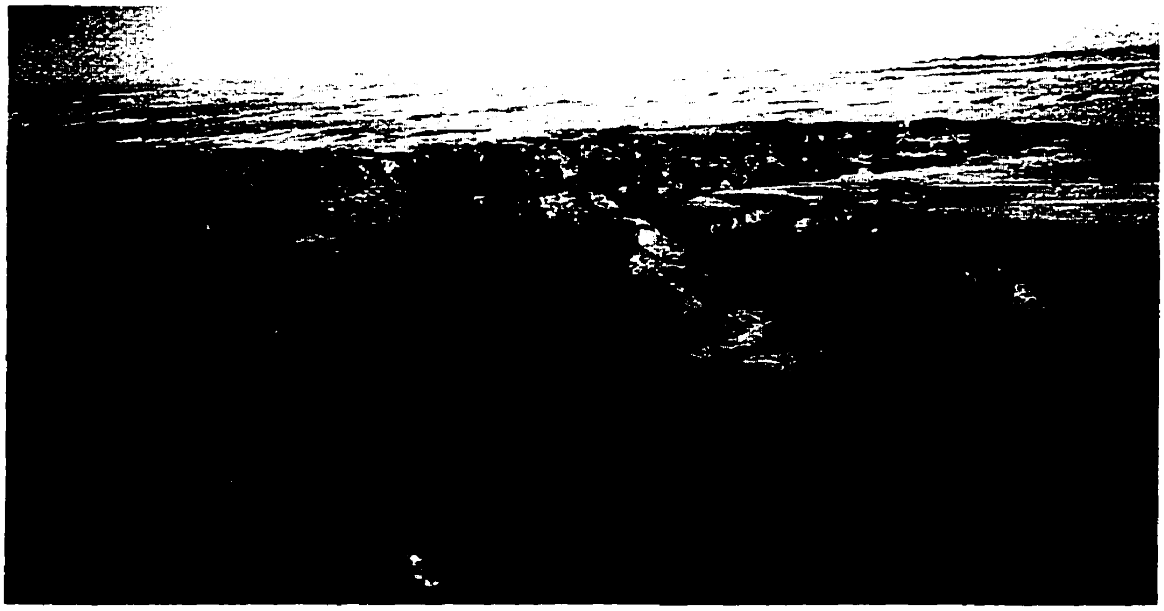

**Figure 13 – Areas of heavily dissected badland topography along the Milk River canyon, southern Alberta.**

bedrock lithology. Bedrock scarps range in slope from 35° in bentonitic shales to 70° in sandstone (Barendregt, 1977). Near the Comrey Breaks approximately 600 m of postglacial widening is attributed to slope retreat and piping. Of these processes piping is easily the most important contributing over 90% of the postglacial widening (Beaty and Barendregt, 1987). In the badland sections Barendregt and Ongley (1977) measured an average scarp retreat of 0.62 cm/yr for a two-year period (1975 - 1977). This is comparable to rates measured by Campbell (1977) along the Red Deer River 200 km to the north. Over a summer period Barendregt and Ongley (1977) estimated 111 x 10$^3$ tonnes of sediment are delivered to the valley bottom through piping and slope wash.

Valley wall morphology in the braided reach is dramatically different from the heavily dissected meandering reach. Despite similar bedrock lithology, climate and a scarcity of significant glacial drift, the development of heavily dissected or badland topography is largely absent. Localized areas of badland topography occur but the majority of the valley walls are more gentle in slope and vegetated (Fig. 14). Badland topography briefly reemerges near the city of Havre in an area known locally as the Milk River badlands.

**Figure 14 – Gentle and well vegetated slopes along the braided reach of the Milk River, northern Montana.**

*Valley Bottom and Floodplain Characteristics*

Material removed from hillslopes is usually transported only short distances before being deposited at the foot of the slope. The variability in slope morphology between the meandering and braided reaches has led to differences in valley bottom sediments. In the meandering reach, Barendregt (1977) defined these areas adjacent to the valley walls as glacis[1]. The zone beside the valley margin is a debris transporting surface termed an erosion glacis (pediment). It ranges from 5 to 20° in slope and is seldom greater than 500 m wide. This feature then grades into a gently inclined (0.5 – 5°) accumulation glacis which resembles a series of coalescing alluvial fans (bajada). As the Milk River meanders across the valley bottom it often cuts into an accumulation glacis whose stratigraphy reveals numerous fine grained deposits topped by a paleosol (Fig. 15). These paleosols

**Figure 15 – Internal stratigraphy of an accumulation glacis showing numerous fine-grain slope deposits suggesting periods of hillslope activity, followed by stability and soil formation as indicated by the paleosols.**

indicate periods of hillslope stability allowing soil formation that are then interrupted by instability leading to aggradation. Accumulation glacis are composed of sands, silts and clay lenses which grade into lacustrine like clays near the lower end of the glacis (Barendregt, 1977). Pipes, which carry sediment directly to the river or

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[1]A glacis is a gently sloping planar surface formed as a result of scarp retreat. It differs from a pediment in that it forms quickly in soft materials and serves a store for sediment. Pediments are developed in hard crystalline rock and develop very slowly (Barendregt, 1987).

deposit it on the glacis, are present beneath the glacis surface. Collapse of these pipes gives rise to many of the gulleys on both the scarp and valley bottom.

The relative stability of hillslopes in the braided reach means that such hillslope deposits are sporadic and for the most part absent. Localized coulee development in the braided reach produces a similar suite of landforms but they are subdued, both in extent and form, in comparison to the meandering reach. A generalized valley cross-section of the two areas is shown in Figure 16.

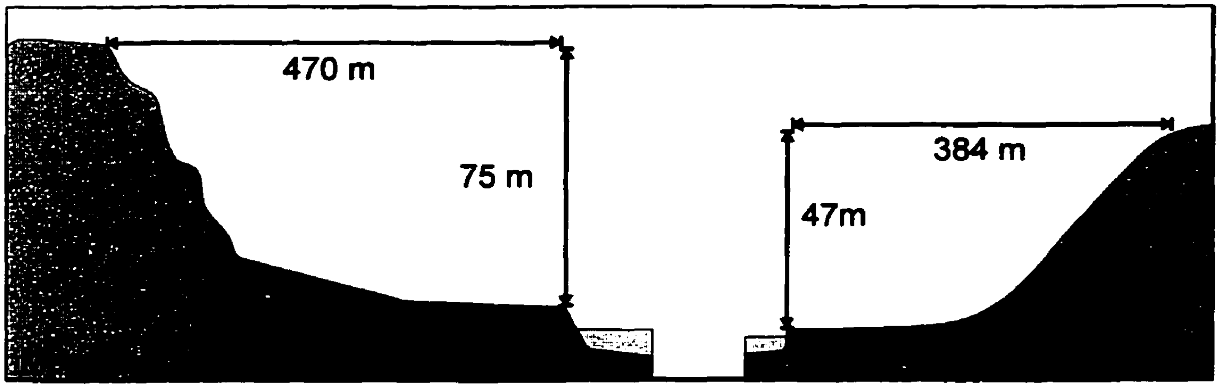


**Figure 16 – Cross section of slope morphology in the meandering and braided reaches. Note the deeper, wider and steeper cross section in the meandering versus the braided reach.**

Barendregt (1977) prepared a general surficial geology map for the southeast corner of Alberta at a scale of 1:20 000. Owing to the complexity of the valley bottom, this area was mapped at a scale of 1:5 000. Mapping shows that the valley bottom is composed predominantly of hillslope (erosional and accumulation glacis) deposits. Active (hillslope) slopewash processes often bury any fluvial channel deposits. Modern fluvial deposits are scarce and generally isolated to recent point bar sediments. The remainder of the floodplain is composed of possible terrace deposits. Barendregt (pers. comm., 1999) reports less than 3 m of fill along most of the meandering reach in Alberta. No detailed surficial geology map exists for the study area in Montana. Given the lack of active slope deposits on the valley bottom, it is postulated that the majority of the sediments are fluvial in origin.

*Biogeographical Characteristics*

Previous work of Bradley (1982) identified vegetation patterns displayed along the Milk River. Upland and stable valley slopes are characterized by native mixed grasses dominated by spear grass (*Stipa comata*) and blue grama (*Bouteloua gracilis*). The uplands in Canada are composed largely of native species whereas the American side is cultivated for dry land farming. Heavily dissected slopes have sparse vegetation that is dominated by deep-rooted shrubs such as greasewood (*Sarcobatus vermiculatus*), rabbit – brush (*Chrysothamnus nauseosus*) and long – leaved sage (*Artemesia longifolia*). Stable slopes have greater vegetation cover dominated by mixed grasses as well as slender wheat grass (*Agropyron trachycaulum*) and Plains muhly (*Muhlenbergia cuspidata*). Moving from the slopes to the more gentle glacis surfaces results in a switch to sagebrush (*Artemesia cana*) flats with mixed grasses (*Stipa comata, Bouteloua gracilis, Agropyron spp.*). Where undisturbed the braided reach displays a similar vegetation pattern to that of the glacis surfaces. However, grazing impacts have caused a decrease in spear grass and an increase in blue grama as well as prickly pear cactus (*Opuntia polyacantha*). Common on the braided reach are saline flats with wire rush (*Juncus balticus*), salt grass (*Distichilis stricta*) and alkali cord grass (*Spartina gracilis*).

The relative absence of mature Plains cottonwood (*Populus deltoides*) on the braided reach versus the large woodlands on the meandering reach is the most obvious change in vegetation distribution (Fig. 17). Numerous cottonwood

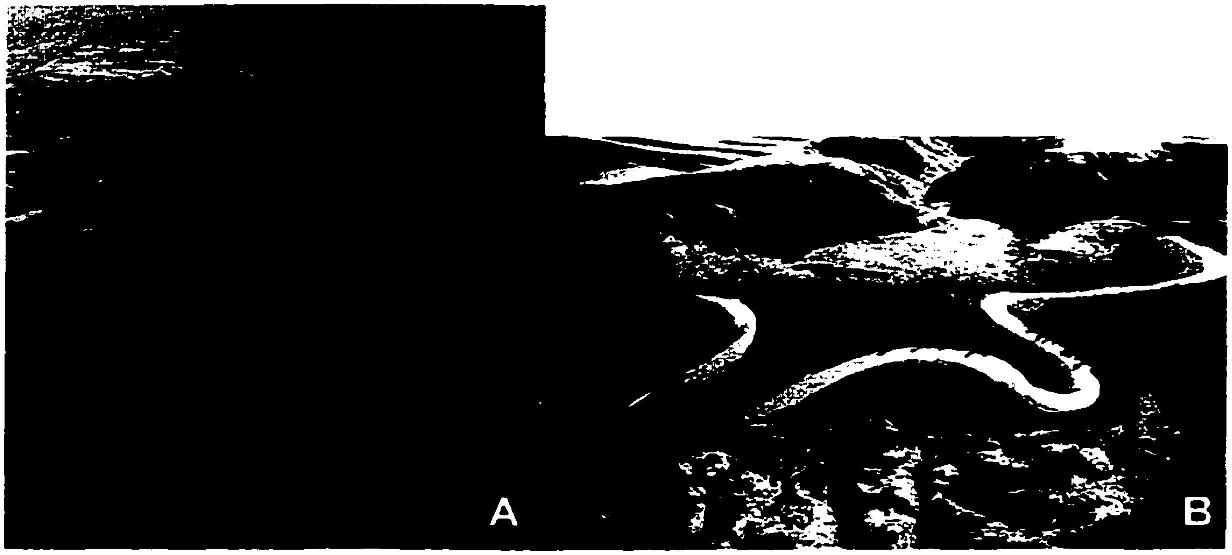


**Figure 17 – Complete absence of cottonwood forest in the braided reach (17A) versus the mature cottonwood forest along the meandering (17B).**

seedlings and sandbar willow (*Salix interior*) colonize active point bars in the meandering reach. The number of suitable recruitment sites in the braided reach is dramatically reduced and therefore considerably less cottonwood and willow are established. In the meandering reach the woodlands are highly variable in terms of density, age, height of the canopy and structure and composition of the understory. There are very few cottonwoods greater than 10 years old in the braided reach. Most of the trees less than 10 years old have been damaged by river ice drives and jams which does not allow many trees to reach maturity (Smith and Pearce, in press).

# CHAPTER 4 – DATA COLLECTION METHODOLOGY

## INTRODUCTION

Fieldwork was undertaken in July and August, 1998 with the goal of gathering characteristics useful in distinguishing the geomorphic nature of the meandering and braided portions of the Milk River. Channel slope was measured along the lower 28 km of the meandering reach, the entire 47 km of the braided reach, and the upper 3 km of the backwater reach of Fresno Reservoir. Geometry of the channel cross section was measured at 10 sites in the meandering reach, 11 sites in the braided and 3 sites in the backwater area. Sediment grab samples gathered in the field were later analyzed for grain size in the soil laboratory at the University of Calgary. Topographic maps and aerial photographs enabled measurement of valley characteristics as well as broad changes in river morphology.

## FIELD METHODS

Gathering the data necessary for construction of the slope profile constituted the majority of the field season. Of the 8 weeks in the field, 6 were spent collecting slope data and the remaining 2 weeks were used for measuring the channel cross sections, and collecting miscellaneous information.

### *Slope Surveying and Width Measurements*

A detailed survey of the channel slope of the Milk River was undertaken to assess changes in slope between the different channel morphologies. An Auto Laser Leveller was used to survey elevation information (Fig. 18). This instrument sends out an infrared beam at a constant level. A stadia rod equipped with a

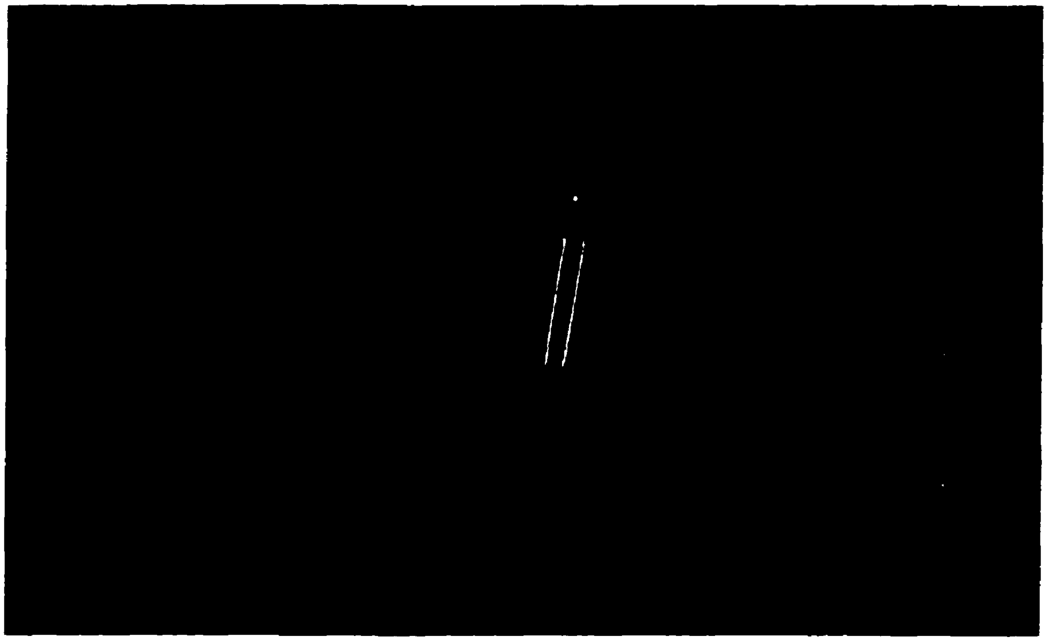

**Figure 18 – Auto Laser Leveller used for surveying channel slope and cross-sectional characteristics.**

sensor is then used to detect the infrared beam and provide the elevation of that location. For the upper 3 km of the backwater area, 47 km of the braided reach and the lower 9 km of the meandering reach a 50 m spacing was used for gathering information[2]. Separation spacing was determined using a Bushnell Laser Range Finder with a ± 1 m accuracy and a calibrated wheel. In the upper 19 km of the meandering reach the 50 m spacing was abandoned in favor of a cross – neck method. As Figure 19 shows elevation data was gathered on the upstream and downstream side of a neck. Channel distance was then measured between these two points. Each day's measurements were tied together with the final result being a 78 km continuous slope profile.

[2] Various locations made a 50 m spacing impossible so a larger spacing was used.

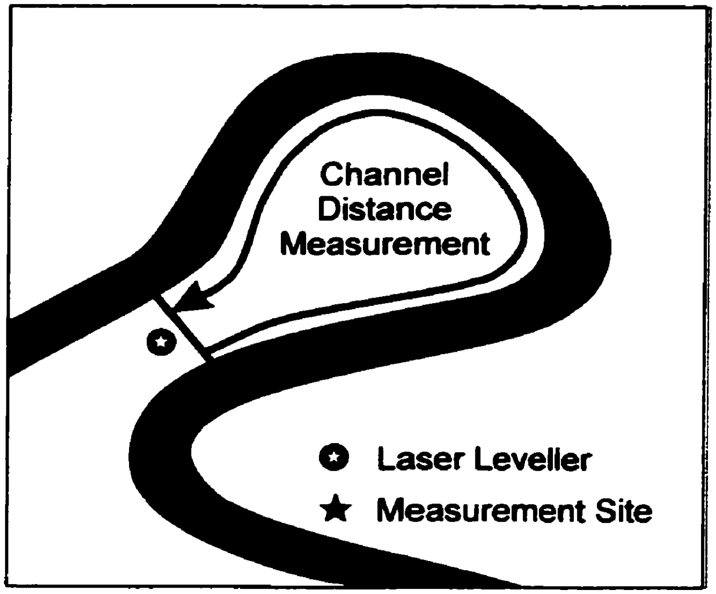


**Figure 19 – Cross neck method of gathering channel slope data in the meandering reach.**

At the same time slope measurements were made the active channel width from vegetated bank to vegetated bank was measured. The Bushnell Laser Range Finder was used to acquire this data. Width values were collected at every location a slope measurement was made as well as every 50 m throughout the entire meandering section. This resulted in 1454 individual measurements of river width.

*Channel Cross Sections*

Characterizing the geometry of the various reaches necessitated surveying numerous cross sectional profiles. Three cross sections were surveyed in the backwater reach, 11 in the braided and 10 in the meandering. The locations of the cross sections in the backwater and braided reaches are shown in Figure 20. Given the uniformity of the backwater area the location of a cross section was based mainly on finding a site suitable for setting up the equipment. Width variability in the braided reach made the selection of a suitable cross section

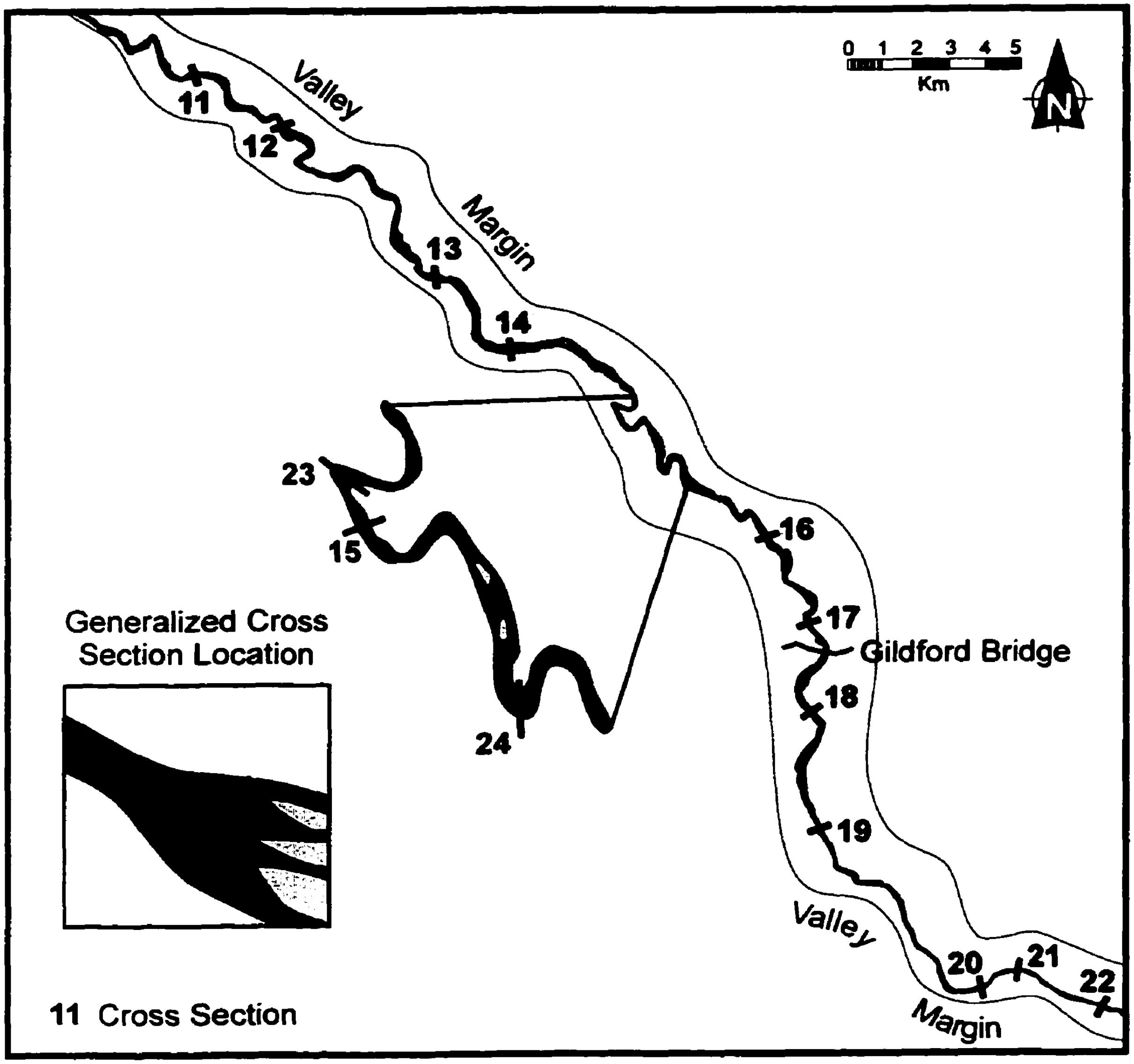


**Figure 20 – Cross section sampling locations in the braided reach. Inset shows the general location used for cross sectional measurements.**

problematic. Discussions with Dr. N.D. Smith (pers. commun, 1998), University of Nebraska, indicated that sites downstream of constrictions, but above the sub - aerial bars would be best because the bars would ultimately be removed from any cross sectional profiles measured in their presence (Inset Fig. 20). Figure 21 shows the location of the 10 sampling sites in the meandering reach. Cross

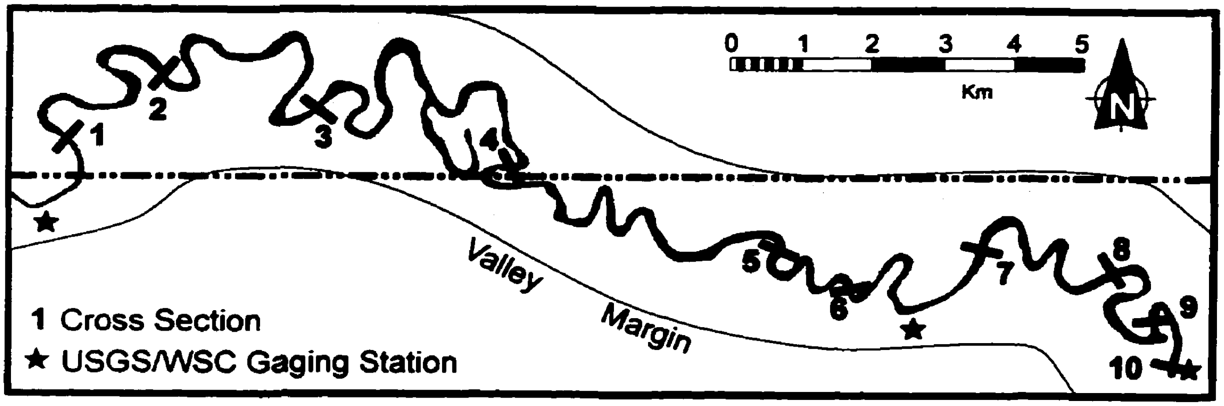


**Figure 21 – Cross section sampling locations in the meandering reach.**

sections were located on the inflection or cross over points between meander loops where over deepening from scour would be minimized (Ostkerkamp, 1979).

Cross sectional form was characterized using the Auto Laser Leveller. With the leveller located on a bank, measurements of the channel bed were taken any time significant changes were observed. Care was exercised to take measurements at the same location on the bedforms (midway between the trough and crest on a dune). The number of measurements acquired depended on the complexity of the channel bed. The type of bedform was also noted during this survey.

At each cross section, samples of the sediment constituting the channel perimeter were collected. In order to characterize the channel bottom samples representing 10% of the bed were collected (i.e. 100 m wide channel = 10 samples every 10 m). Sample collection followed the methodology of Smith (1970, 1971) and Osterkamp (1979). The upper 10 cm of bed material at each sampling site was collected and returned to the laboratory at the University of Calgary for further analysis. Bank material samples were collected from both the left and right bank.

The outer layer was removed ensuring collection of true bank material. Composite samples (water line, mid - way and upper) of the bank were collected to ensure equal representation (Osterkamp, 1979).

A limited suspended sediment sampling program was initiated in order to identify any relative changes in load. A USGS DH – 59 depth integrating sampler was used to gather samples. The sampler was lowered and raised at a constant rate (Locking, 1983). In the braided section, samples were collected in the main channels which were identified using the cross section data. Two samples were collected at each of the cross sections in the backwater and meandering reaches. All samples were stored in airtight jars and returned to the University of Calgary for analysis.

*Discharge*

Because of the Milk River's stature as an international waterway, discharge records for the Eastern Crossing gauging station extend back to 1909. As mentioned previously the USGS considers values from the current station (refer back to Fig. 12) to be equal to those of the previous two stations upriver in the meandering reach. Changes in discharge downstream to the Fresno Reservoir are also thought to be insignificant. Therefore, daily discharge obtained from the USGS for 1998 (http://waterdata.usgs.gov/nwis-w/MT/?statnum=06135000) can be used for the particular day a cross section was measured. Monthly means and extremes for all the gauging stations in Alberta were obtained from the Water Survey of Canada.

Three separate methods for determining bankfull discharge were used in the meandering reach. The stage-discharge relationship at the current gauging station could not be used as it has yet to experience a bankfull event. Therefore, the stage-discharge graph is incomplete and extrapolation is plagued with errors. Two of the three indirect methods take advantage of direct measurements of the bankfull channel dimensions whereas the third uses the size of the drainage basin and a pre-established relationship to determine bankfull discharge. The following equations were used in determining the bankfull discharge:

*Manning's Formula*

$$Q_{bf} = \frac{A \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{2}}}{n}$$

where:
$Q_{bf}$ = bankfull discharge
A = bankfull area
R = bankfull hydraulic radius
S = channel slope
n = Manning's roughness coefficient (0.025)

The Manning's equation takes advantage of the fact that velocity is strongly related to flow resistance. The equation indirectly determines velocity and by incorporating channel dimensions into the equation allows calculation of discharge.

*Osterkamp – Hedman Formula (1982)*

$$Q_{bf} = 0.32W^{1.51} \quad and \quad Q_{bf} = 0.029W^{1.18}G^{-0.49}$$

where:
$Q_{bf}$ = bankfull discharge
W = bankfull width
G = channel gradient

This method assumes that the size and shape of the channel cross section is the integrated resultant of all discharges, water and sediment, conveyed by that channel. Therefore, a relationship can be constructed between channel dimensions and discharge. The above relationship was constructed from a data set consisting of rivers from the Missouri River drainage basin of which the Milk River is a part. Some of the data came from the Milk River so this relationship is directly applicable to this study.

*Drainage Basin Relationship (Upper Salmon River, Idaho) – Emmett (1975)*

$$Q_{bf} = 0.42 A_d^{0.69}$$

where: $Q_{bf}$ = bankfull discharge
$A_d$ = drainage basin area

As the size of the drainage basin increases so should the water discharge. This method relies on this relationship. By using the discharge at numerous gauging stations and the size of the basin a relationship between drainage basin area and discharge may be created.

Bankfull channel dimensions were surveyed at three locations near the present gauging station. These measurements were combined to arrive at average bankfull channel dimensions. These dimensions were then used in the first two equations. Drainage basin area, excluding areas of internal drainage, was obtained from Water Survey of Canada records. The equation used in the drainage basin area discharge determination was constructed for the Salmon River in Idaho (Emmett, 1975). Although the Upper Salmon River of central Idaho and the Milk River are not directly comparable in terms of drainage basin characteristics the strength of this equation is that over 30 bankfull discharge measurements were used in its construction. The relationship between drainage basin area and bankfull discharge determined for the Salmon River had a very strong correlation of 0.8729. Independent corroboration from the other two equations will help confirm the validity of this equation.

### LABORATORY METHODS

The main laboratory task involved grain size analyses of the sediments composing the channel perimeter. Determination of the suspended sediment content was also undertaken. Broad morphological characteristics of the valley and river that were impractical to measure in the field were obtained from topographic maps and aerial photographs.

*Grain Size Analysis*

Sediment samples collected in the field were dried in preparation for grain size analysis. Sixty-nine samples were analyzed, 25 bed material samples and 44 bank samples. The grain size of the sediment was based on the phi ($\phi$) scale where $\log_2$ is used for the upper and lower class boundaries (Krumbein, 1936; Folk, 1974).

The bed material was first split using equal sized samples and then combined to get one sample representative of the bed at that cross section (Dr. N.D. Smith, pers. commun, 1998). Since the dominant grain size of the bed material was sand (>4.0 phi), a series of sieves at ½ phi intervals were used. The sieve stack was placed in the Ro – Tap Shaker for 10 minutes. The grain size distribution was determined using the percentage weight of each phi size compared to the original weight of the sample (Folk, 1974). The cumulative weight percentage of each phi size was then plotted versus phi size. The resulting curve enables determination of the mean, mode and sorting index for each sample (Folk, 1974).

With regards to the bank samples, the amount of silt – clay present was of primary interest. Determination of the fine fraction (< 4.0 phi) was accomplished using hydrometer analysis (McKeague, 1981). Sediment samples were air dried, split and weighed to 40.0 grams. These samples were then pre – treated with hydrogen peroxide ($H_2O_2$) in order to destroy any organic material bonds. Samples were also dispersed with a Calgon solution to destroy any grain to grain bonds. The samples were then agitated into suspension and placed in a one liter cylinder. The density of the sample was measured at times representing one phi intervals from 30 seconds (approximately 4.0 phi) to 1080 minutes (18 hours). The percentage of sand, silt and clay was then calculated.

Suspended sediment concentrations were determined using the Millipore Filtration System. Each sample was filtered using Millipore filter paper. This ensured particles greater than 1.2 μm in size were retained. The extracted water was measured for volume (in milliliters) whereas the sediment was measured for its weight (in milligrams). When combined this gives the concentration in mg/ml. Concentration readings by convention are in mg/L so depending on the volume of the sample a correction factor was applied to adjust the volume upwards to one liter. For example, 10 mg/500 ml would be double to get 20 mg/L.

*Topographic Map and Aerial Photograph Work*

The impracticality of directly measuring characteristics such as valley width and depth necessitated the use of topographic maps and aerial photographs. In order to harmonize these measurements between the different media, a common location was selected as the starting point. The morphologic transition was used, as it is easily identified on both the map and photos. For the entire study area cross sections were established every kilometre starting at the transition point. At each of these sections width of the valley bottom as well as valley depth was measured from the maps. Using the photos allowed river sinuosity of each one kilometre section to be calculated. The 1992 photos (USDA – FSA Aerial Photography Field Office, Salt Lake City, Utah) enabled linkage of the channel slope data and the sinuosity data because little dramatic morphologic change has occurred over the intervening six years.

### *Local Knowledge*

An invaluable source of knowledge for the study area is the people whose survival depends on the land and river. The local ranchers and farmers are intimately tied to the Milk River as it is the only surficial water source in the area. Discussions with various families (Aageson, Greytak and Meland) who have lived in the area for generations provided details on past river conditions.

## *CHAPTER 5 – PHYSICAL CHARACTERISTICS OF THE MILK RIVER*

### *INTRODUCTION*

The three dimensional form of a river is described by the channel geometry. As discussed earlier certain control variables interact to produce the channel geometry displayed by a given river. The control variables, which will be described for the meandering and braided reaches of the Milk River, are:

1. *Hydraulic Characteristics* – bankfull discharge as well as stream power and shear stress.
2. *Sediment Discharge* – suspended load and bedload.
3. *Composition of the Channel Perimeter* – grain size of the channel bed and banks as well as the type of riparian vegetation.
4. *Valley Slope* – the gradient of the Milk River valley.

As described by Knighton (1998) channel geometry possess four degrees of freedom (or response variables), which can adjust to changes in the controlling variables. The variables of adjustment are:

1. *Cross - Sectional Form* – characterized by the shape (width/depth ratio) and cross - sectional area of the channel
2. *Bed Configuration* – the grain size of the bed, whether it is composed of gravel or sand. The Milk River possesses a sand bed throughout. The bed was sculpted in dunes along the entire study reach.
3. *Planimetric Geometry* – the channel pattern when viewed from above.
4. *Channel Slope* – the gradient of the water surface at the reach and longitudinal scales.

The sampling program undertaken enables characterization of both the controlling variables as well as the response variables for both the meandering and braided reaches of the Milk River.

### *Control Variable - Hydraulic Characteristics*

It is through the interaction of flowing water with its surrounding environment that fluvial landforms are created and destroyed. It is important to know how much water can flow through a channel before overtopping the banks and spreading out on the floodplain. This bankfull discharge is often called the channel – forming discharge. It is also crucial to gain an understanding of the amount of work the river can perform through the use of stream power equations. This helps determine whether a stream is actively moving or depositing sediment.

#### *Bankfull Discharge*

Bankfull discharge was determined for both the meandering and braided reaches. Three separate calculations were used in the meandering reach. The following table outlines the bankfull discharge values obtained using the three different approaches:

**Table 4 – Bankfull Discharge Values in the Meandering Reach**

| Method | Bankfull Discharge ($m^3/s$) |
|---|---|
| Drainage Basin | 155.55 |
| Osterkamp - Hedman | 158.20 |
| Manning's Formula | 146.72 |

As Table 4 illustrates there is good agreement between the three different approaches. This provides confidence in using 154 $m^3/s$ as the value of bankfull discharge in the meandering reach.

In the braided reach the Manning's equation was employed using the bankfull channel dimensions as input values. Bankfull discharge was calculated for each of the nine cross – sections in order to produce an average value. The bankfull discharge for the braided reach was calculated to 124 $m^3/s$ which is 20% less than the 154 $m^3/s$ observed in the meandering reach.

*Stream Power*

As water flows through a river channel it possesses the ability to do work. One way of quantifying this is through the use of the stream power equation. This equation has several forms which allow it to show the potential for doing work, and also how effective the river is at utilizing the available power. The following three formulae for calculating stream power were used:

| *Maximum Stream Power Per Unit Length* | *Stream Power Per Unit Length* | *Stream Power Per Unit Area* |
|---|---|---|
| $\Omega_p = \gamma Q s_v$ | $\Omega = \gamma Q s$ | $\omega = \gamma Q s / w$ |

where: $\gamma$ = specific weight of water
$Q$ = discharge
$s_v$ = valley slope
$s$ = channel slope
$w$ = channel width

The calculation of the maximum stream power per unit length uses the valley slope which is the steepest gradient that the channel could assume and thus represents the maximum amount of work that could be performed. The stream power per unit length formula expresses the amount of stream power that is available for a given length of channel. Stream power per unit area is a measure of how much energy is available at the channel bed.

The following table outlines the values for each stream power equation in each of the three morphological zones:

**Table 5 – Stream Power Values in the Three Morphological Zones**

| Morphology | Maximum Stream Power Per Unit Length | Stream Power Per Unit Length | Stream Power Per Unit Area |
|---|---|---|---|
| Meandering | 164.12 | 77.24 | 1.73 |
| Braided | 95.15 | 72.94 | 0.70 |
| Backwater | 34.03 | 33.76 | 1.09 |

The maximum stream power per unit length values are very different in each of the three zones. The greatest value is that of the meandering reach at 164.12 $N{\cdot}s^{-1}$. In the braided reach the value drops to 95.15 $N{\cdot}s^{-1}$ which represents a 42% reduction from the meandering value. By far the lowest value is 34.03 $N{\cdot}s^{-1}$ which is found in the backwater reach. The stream power per unit length is very similar in two of the three morphological zones. The highest value of 77.24 $N{\cdot}s^{-1}$ is found in the meandering reach but this value is only 6% higher than the 72.94 $N{\cdot}s^{-1}$ measured in the braided reach. Once again the backwater reach is much lower at 33.76 $N{\cdot}s^{-1}$. Unique values of stream power per unit area were measured for each of the three morphologies. The highest value was again found in the meandering reach at 1.73 $N{\cdot}m^{-1}\ s^{-1}$. The lowest value of 0.70 $N{\cdot}m^{-1}\ s^{-1}$ was found in the braided reach. This represents a 60% reduction in the stream power per unit area. The backwater value was intermediate to the two values at 1.09 $N{\cdot}m^{-1}\ s^{-1}$.

*Control Variable - Sediment Transport*

As mentioned earlier, rivers serve as conduits through which the products of erosion are transported from source areas to sedimentary sinks. The load carried by a river can be divided into three components (Knighton, 1998):

(1) Dissolved Load – materials transported in solution, i.e. $Ca^{2+}$, $Mg^{2+}$, $HCO_3^-$, $SiO_2$.

(2) Wash Load – composed primarily of particles finer than those of the channel bed (< 0.062 mm). Usually transported directly through the system and deposited in a sedimentary sink such as a lake, reservoir or ocean.

(3) Bed-Material Load – includes all particles found in significant quantities on the channel bed and lower banks (> 0.062 mm).

Two main types of load, suspended and bedload, compose the majority of the sediment in transport. The distinction between these transport mechanisms is fuzzy as changing flow conditions can quickly move a grain from bedload to suspended load. Bed-material load moves predominantly as bedload, where particles roll, slide or saltate along the channel bed at velocities less than those of the surrounding flow. Wash load moves primarily as suspended load where smaller particles are supported in the water column by turbulent eddies (Gomez, 1991; Knighton, 1998). The following sections will discuss the quantities of both suspended load and bedload on the Milk River.

*Suspended Sediment Load*

In 1805 the American explorer Captain Merriweather Lewis named the Milk River as he passed through the area on his expedition to discover the Pacific Ocean. One of his journal entries reads as follows,

> "The water of this river possesses a peculiar whiteness, being about the color of a cup of tea with the admixture of a tablespoonful of milk."
> *Captain Merriweather Lewis, 1805*

The inference of Captain Lewis that the Milk River has a high sediment load is borne out by modern suspended sediment sampling programs active along the Milk River.

Suspended sediment load in the Milk River displays two significant trends, one of which is displayed in Figure 22. There is a dramatic increase in suspended

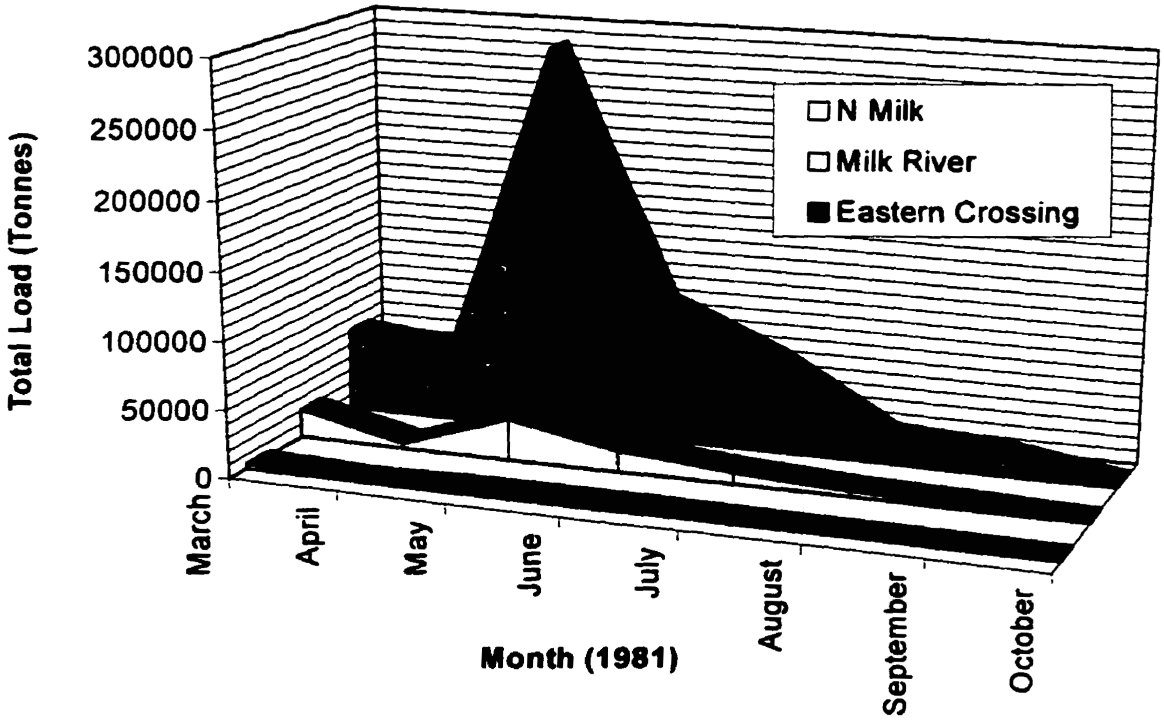


**Figure 22 – Suspended load values at three stations along the Milk River. The North Milk River station is the furthest upstream.**

sediment load from the upper to the lower reaches of the Milk River within Alberta. An example can be seen in this figure where sediment discharge in May at the North Milk River gauging station was 2 500 tonnes, 31 000 tonnes at the town of Milk River and 287 000 tonnes at the Eastern Crossing gauging station. A similar trend is observed in data collected during the summer of 1998 (Fig. 23). From the town of Milk River to the Eastern Crossing gauging station there is an 8½ - fold increase in daily suspended sediment load from 97 to 825 tonnes. Both Figure 22 and 23 demonstrate that the largest increase in suspended sediment load occurs between the town of Milk River and the Eastern Crossing. It is also

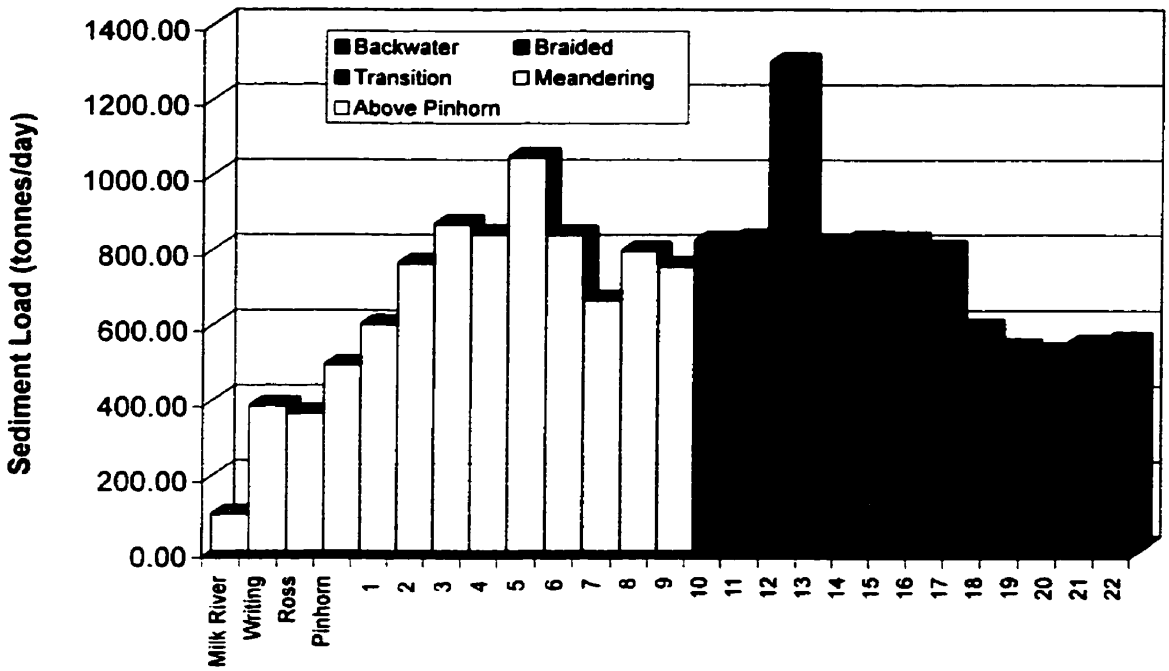


**Figure 23 – Sediment concentration values measured from the gauging station at the town of Milk River to the Eastern Crossing gauging station.**

observed in Figure 23 that after increasing from the town of Milk River, the suspended sediment load becomes roughly constant near cross section #2 and remains relatively stable until the Fresno Reservoir impounds the Milk River.

The second major trend is the tendency for suspended sediment load to decrease throughout the year in spite of flows remaining relatively constant. For example, at the town of Milk River from April to May, 1982 the sediment discharge decreased from 87 000 to 22 000 tonnes despite a slight increase in mean monthly flow from 20.5 to 20.7 $m^3/s$. The suspended sediment load on June 23, 1981 at the Eastern Crossing gauging station was 1 878 tonnes with a discharge of 22.8 $m^3/s$. A month later on July 24 the load was roughly two thirds less (685 tonnes), yet the discharge was only 6% lower (21.4 $m^3/s$). This suggests the presence of a hysteresis effect where flows in the spring flush the system of sediment that had accumulated during lower flows in the fall and winter of the previous year. This deprives later flows of a sediment source and produces lower suspended sediment loads given the same discharge.

*Bedload*

Bedload transport ranges widely both temporally and spatially and is therefore one of the most difficult aspects of fluvial system to characterize. A very limited dataset on bedload discharge at the Eastern Crossing gauging station is available (Spitzer, 1988). A Helley – Smith bedload sampler was used to directly sample the bedload discharge. Table 6 presents the bedload discharge, streamflow discharge and suspended sediment discharge for three measurements acquired in 1976.

**Table 6 – Bedload Discharge at the Eastern Crossing Gauging Station**

| Date 1976 | Streamflow Discharge ($m^3/s$) | Bedload Discharge (tonnes/day) | Suspended Sediment Discharge (tonnes/day) | Bedload as a Percentage of Suspended Load |
|---|---|---|---|---|
| Jul. 14 | 22.1 | 50 | 2080 | 2.4 |
| Aug. 25 | 20.0 | 80 | 2010 | 4.0 |
| Aug. 26 | 18.0 | 45 | 2250 | 2.0 |

This data suggests that bedload is a small component (less than 5%) of the total sediment discharge along the Milk River.

*Control Variable - Composition of the Channel Perimeter*

Samples of the sediment composing both the bed and bank of the Milk River were analyzed for grain size and degree of sorting.

*Bed Material*

Twenty-three cross sections were sampled in order to characterize the grain size and degree of sorting along the Milk River. Ten samples were located in the meandering reach, nine in the braided, three in the backwater area and one near the morphological transition. Figure 24 is a plot displaying the cumulative grain size curve of each cross section versus the grain size of the sediment. Appendix 1

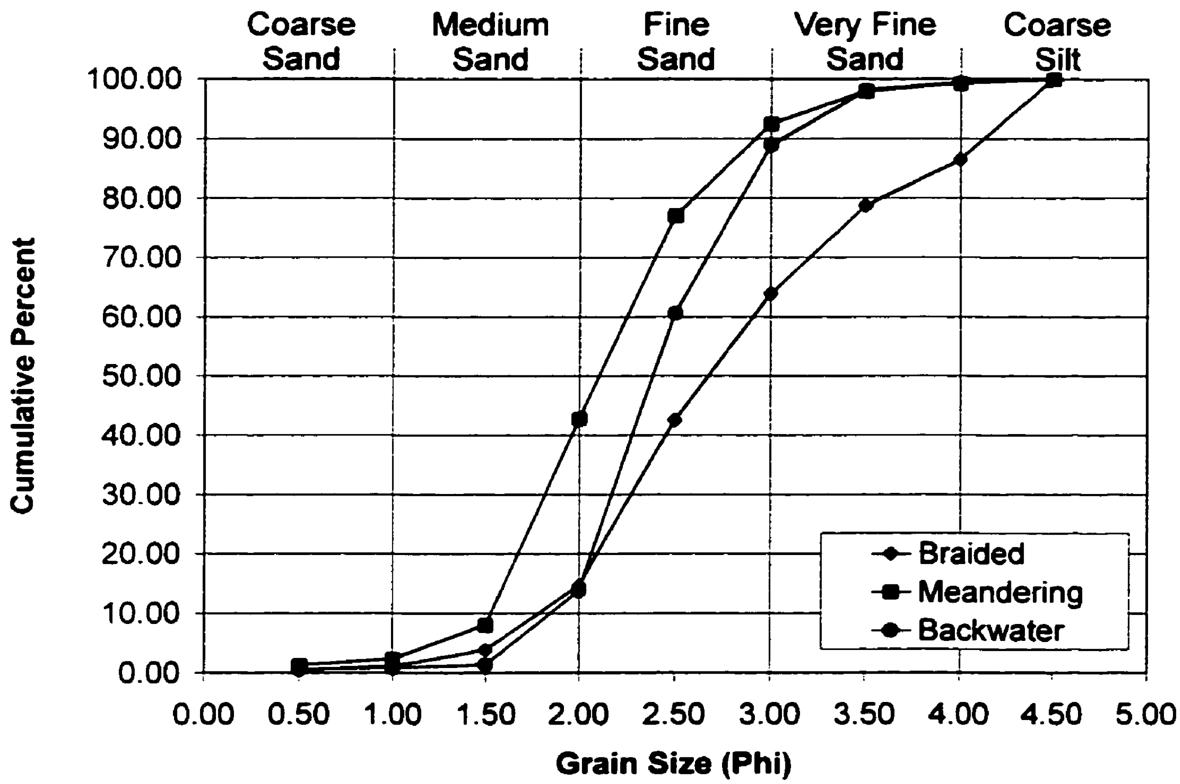


**Figure 24 – Average cumulative grain size plots from each of the three river morphologies.**

contains a plot identifying the individual samples as well as the raw data from which the graphs were constructed. From the cumulative grain size curves of Figure 24 the graphical mean was calculated according to the formula (Folk, 1974):

$$M_z = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

From the same curves the inclusive graphic standard deviation, a measure of sorting, was calculated using the following formula (Folk, 1974):

$$\sigma_I = \left(\frac{\phi 84 - \phi 16}{4}\right) + \left(\frac{\phi 95 - \phi 5}{6.6}\right)$$

The graphical mean and the sorting index for each sample are given in Table 7.

**Table 7 – Graphical Mean and Sorting Index For Each Bed Material Sample**

| Cross Section | Mean ($M_z$) ($\phi$) | Sorting ($\sigma_I$) | River Morphology |
|---|---|---|---|
| 1 | 2.08 | 0.55 | Meandering |
| 2 | 2.31 | 0.64 | Meandering |
| 3 | 2.10 | 0.51 | Meandering |
| 4 | 2.16 | 0.64 | Meandering |
| 5 | 1.97 | 0.52 | Meandering |
| 6 | 2.12 | 0.60 | Meandering |
| 7 | 2.12 | 0.51 | Meandering |
| 8 | 2.32 | 0.52 | Meandering |
| 9 | 2.19 | 0.59 | Meandering |
| 10 | 2.00 | 0.51 | Meandering |
| 11 | 2.32 | 0.53 | Transition |
| 12 | 2.75 | 0.89 | Braided |
| 13 | 2.84 | 0.93 | Braided |
| 14 | 2.65 | 0.85 | Braided |
| 15 | 2.94 | 0.97 | Braided |
| 16 | 2.92 | 0.81 | Braided |
| 17 | 2.95 | 0.86 | Braided |
| 18 | 2.91 | 0.90 | Braided |
| 19 | 2.85 | 0.89 | Braided |
| 20 | 2.64 | 0.69 | Braided |
| 21 | 2.32 | 0.47 | Backwater |
| 22 | 2.41 | 0.43 | Backwater |
| 23 | 2.55 | 0.50 | Backwater |
| | | | |
| Average | 2.14 | 0.56 | Meandering |
| Average | 2.83 | 0.87 | Braided |
| Average | 2.43 | 0.46 | Backwater |

The three major morphological zones (meandering, braided and backwater) along the Milk River each display a unique combination of mean grain size and degree of sorting (Fig. 25). In comparison to the samples from the meandering

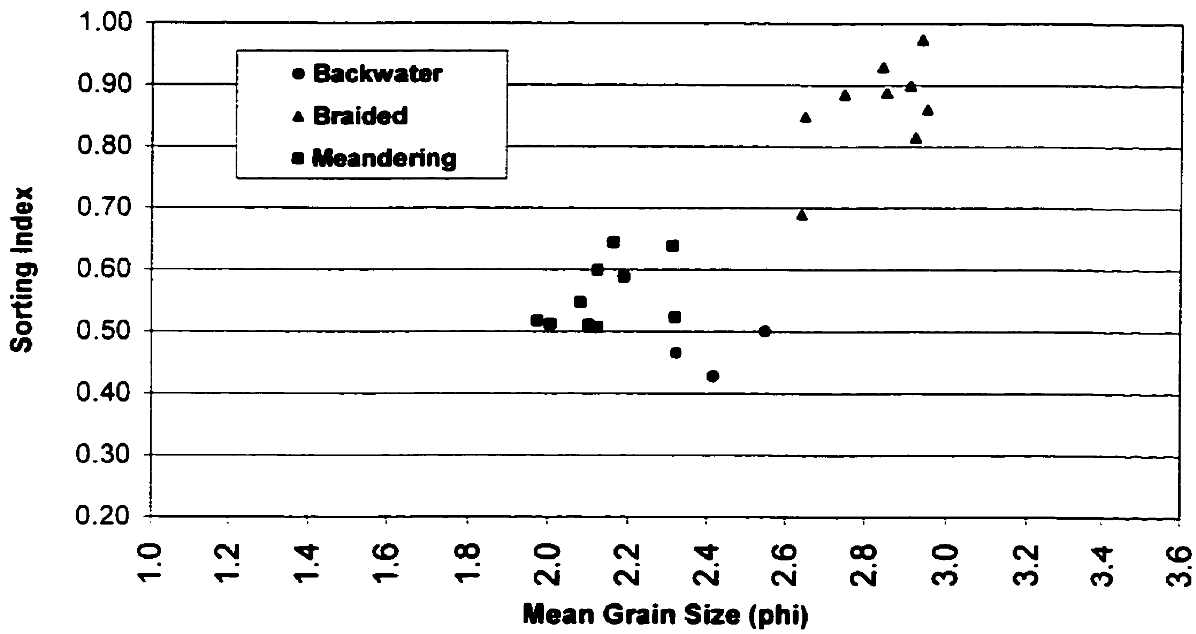


**Figure 25 – Plot of mean grain size versus sorting index.**

reach, bed material from the braided reach is finer and more poorly sorted. The grain size of the backwater area falls between the meandering and braided reaches and displays the best sorting of the three morphologies.

A verbal classification scale (Table 8) describing the degree of sorting was derived from the testing of numerous samples from a wide variety of sedimentary environments (Folk, 1974).

**Table 8 - Classification Scale For Sorting (σI)**

| | | | |
|---|---|---|---|
| Under 0.35 ϕ | Very Well Sorted | 1.0 – 2.0 ϕ | Poorly Sorted |
| 0.35 – 0.50 ϕ | Well Sorted | 2.0 – 4.0 ϕ | Very Poorly Sorted |
| 0.50 – 0.71 ϕ | Moderately Well Sorted | Over 4.0 ϕ | Extremely Poorly Sorted |
| 0.71 – 1.0 ϕ | Moderately Sorted | | |

Bed material in each of the three different morphologies displays a distinct degree of sorting. The poorest sorting is found in the braided reach where the bed is described as moderately sorted (0.87ϕ). Sediment composing the bed in the meandering reach is better sorted and is classed as moderately well sorted (0.56ϕ). Bed material in the backwater reach is well sorted (0.46ϕ) and is the best sorted of the three morphologies.

When comparing the mean grain size of each zone the difference is small with each mean falling in the fine sand phi range (2 – 3 ϕ). However, as Figure 26

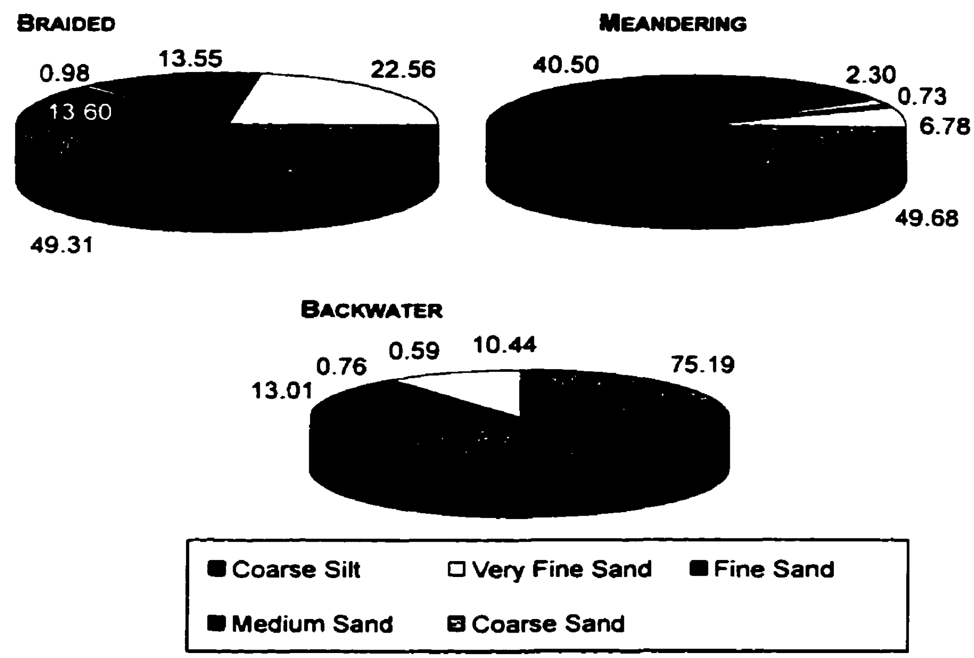


**Figure 26 – Size distribution of bed material in each of the three morphological zones. Numbers represent percentage of the bed material for a given size class.**

shows the combination of size classes in each morphological reach is distinct. The braided reach has considerably more coarse silt (13.55%) than either the meandering (0.73%) or the backwater reach (0.59%). A similar trend is observed with very fine sand where the braided reach has 22.56% versus 6.78% in the meandering and 10.44% in the backwater reach. The fine sand component, in which the mean grain size of all three reaches falls, is the largest constituent of each sample. The fine sand component constitutes nearly half of the bed material (49.31% braided versus 49.68% meandering) within the braided and meandering reaches. In the backwater reach fine sand comprises three-quarters of the bed material (75.19%). In both the braided (13.60%) and the backwater (13.01%) reaches, medium sand is a relatively minor constituent of the bed material. However, it makes up 40.50% of the bed material in the meandering reach. Coarse sand is a negligible component of each reach (0.98% braided, 2.30% meandering and 0.76% backwater). In summary, 36.11% of the braided bed material is composed of fine particles (coarse silt and very fine sand) in comparison to 7.52% in the meandering and 11.03% in the backwater reach. The coarser grains (fine and medium sand) make up 92.48% of the meandering and 88.97% of the backwater reach versus 63.89% in the braided. Therefore, despite similar graphical mean grain size it can be observed that each morphology has a unique size distribution of bed material.

*Bank Material*

The sedimentary composition of the channel perimeter is characterized using 44 bank samples representing 22 cross section locations. Samples from the left and right bank are amalgamated to give a single value for each location (Appendix 2 contains the left and right bank values). Figure 27 shows three distinct populations with the backwater reach having the highest average silt – clay content

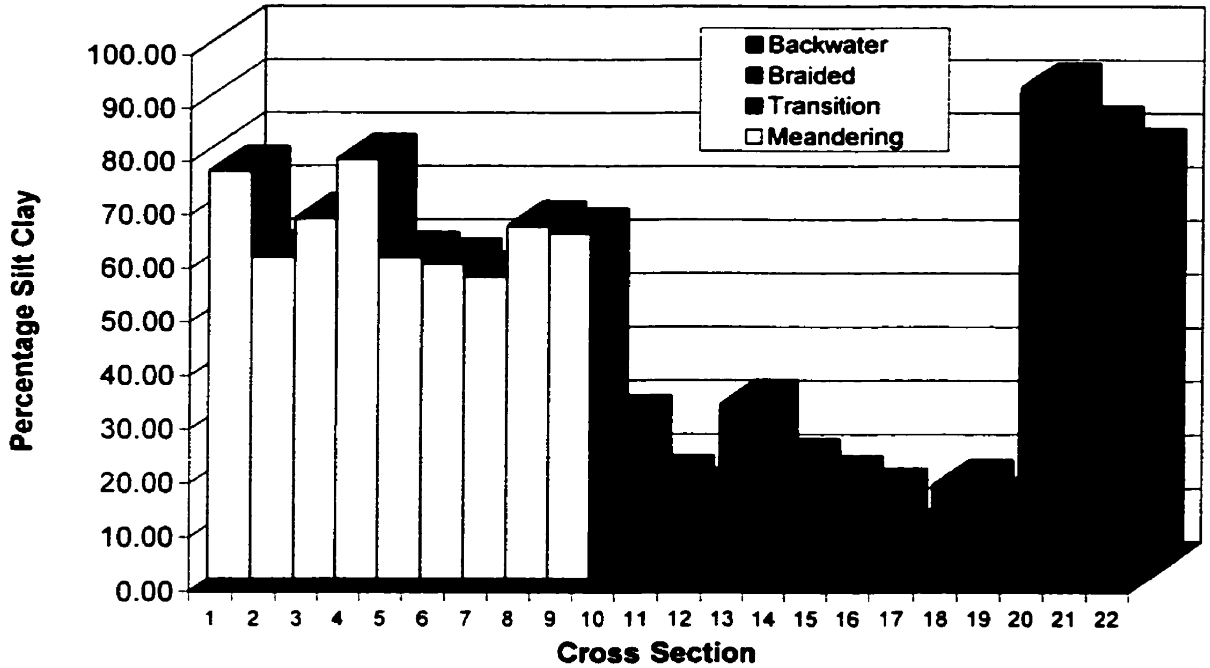


**Figure 27 – Downstream change in the percentage of silt-clay composing the channel banks along the Milk River.**

followed by the meandering and finally the braided reach. The backwater reach averaged 84.92% with a range from 79.46% to 91.70%. Silt – clay values in the meandering reach averaged 65.17% ranging from 56.32% to 78.28%. In the braided reach values ranged from 8.27% to 32.46% with an average of 18.03%.

*CONTROL VARIABLE – VALLEY SLOPE*

The slope of the valley upon which a river flows is an important variable in fluvial geomorphology. Values of valley slope for the Milk River are presented in Figure 28. On average the valley slope within the meandering reach is roughly twice that of the braided (113 cm/km versus 59 cm/km). However, within each reach there are two anomalous zones of lower than average valley slope. Between stations 67 575 and 65 875 m within the meandering reach, the valley slope averages 79 cm/km which is 70% of the reach average. In the braided reach the valley slope averages 150% higher than the reach average (88 cm/km versus 59 cm/km) between stations 26 150 and 22 350 m.

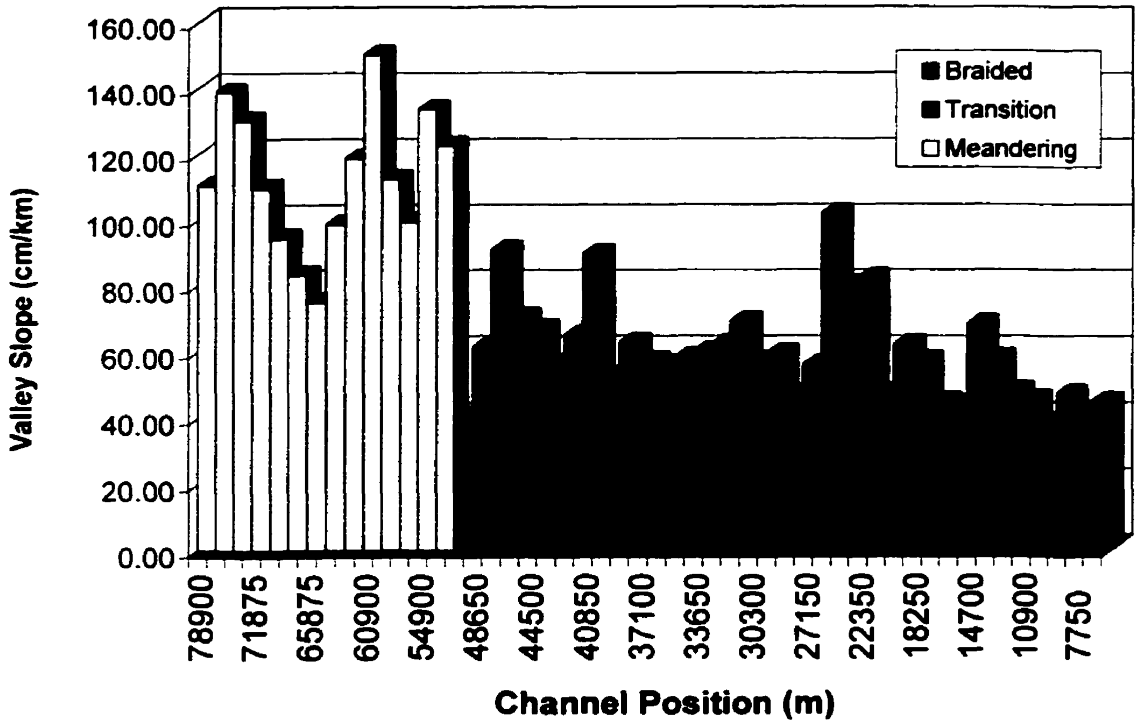


**Figure 28 – Downstream change in valley slope values along the Milk River.**

*RESPONSE VARIABLE - CROSS SECTIONAL FORM*

There is a dramatic change in cross sectional form concomitant with changes in river morphology. The meandering and backwater reaches are similar in nature in that they resemble a canal whereas the braided cross section consists of multiple channels (Fig. 29). The trend apparent in the cross sections is that those of the meandering and backwater reaches are uniform in shape whereas in the braided reach they are more chaotic.

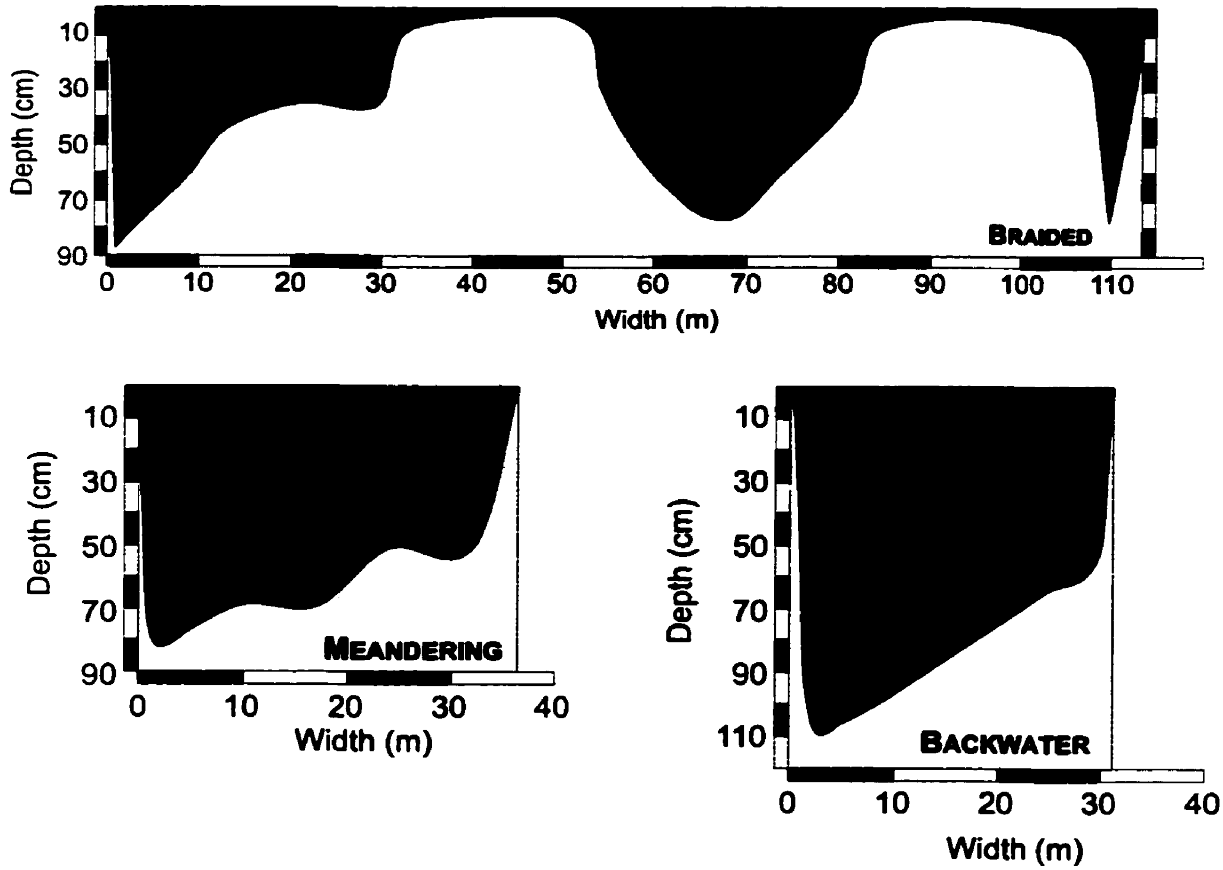


**Figure 29 – Typical cross section from each of the morphological zones observed along the Milk River.**

*Channel Width and Depth*

Each of the three morphological zones possesses a unique combination of average width and the amount of scatter about the mean. As Figure 30 shows the

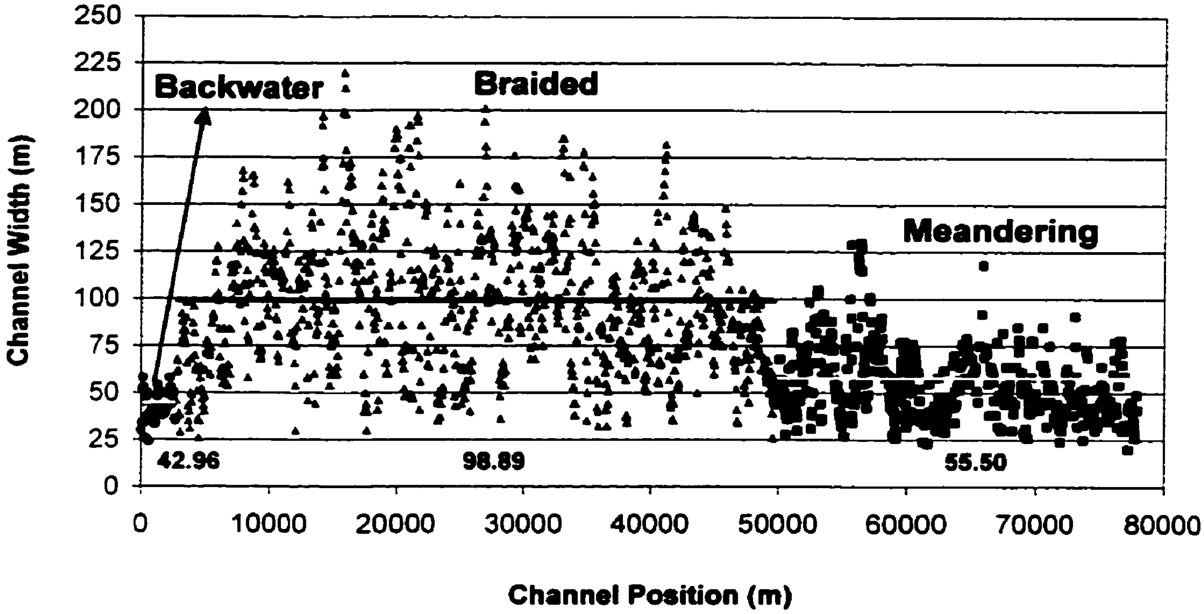


**Figure 30 – Variability in terms of channel width in the three morphological zones along the Milk River. Mean values are listed numerically below the graph and also denoted with a line cutting through each data set.**

meandering reach is tighter in its distribution of width values than is the braided reach, but the tightest distribution is found in the backwater reach. The following table highlights the important channel width characteristics along the Milk River:

**Table 9 – Channel Width Values Along the Milk River**

| Morphology | Number of Observ. | Mean Channel Width (m) | Standard Deviation | Min | Max | Range |
|---|---|---|---|---|---|---|
| Meandering | 460 | 55.50 | 19.50 | 20.00 | 130.00 | 110.00 |
| Braided | 940 | 98.89 | 36.80 | 26.00 | 220.00 | 194.00 |
| Backwater | 54 | 42.96 | 8.10 | 24.00 | 58.00 | 34.00 |

Of the three morphological zones, the largest average width is observed in the braided reach whose value of 99 m is roughly double the 56 m averaged in the meandering reach. The narrowest zone is the backwater reach whose value of 43 m is only 43% of the braided reach (see Appendix 3 for individual width measurements). The most variable of the three morphologies as expressed by the standard deviation, a measure describing the deviation of a typical value from the mean, is the braided reach, followed by the meandering and backwater reaches. This reinforces the trend mentioned earlier that the meandering and backwater reaches are more uniform than the braided.

Average channel depth values are also different for each of the three morphologies. The shallowest channel pattern is the braided at 0.36 m. The deepest is the backwater at 0.76 m with the meandering having a depth of 0.54 m.

The width and depth values can be combined to produce the width/depth ratio which is a surrogate measure of channel shape. That is, a high width/depth ratio indicates a wide and shallow channel whereas a low width/depth value is indicative of a deep and narrow channel. Figure 31 depicts the width/depth values

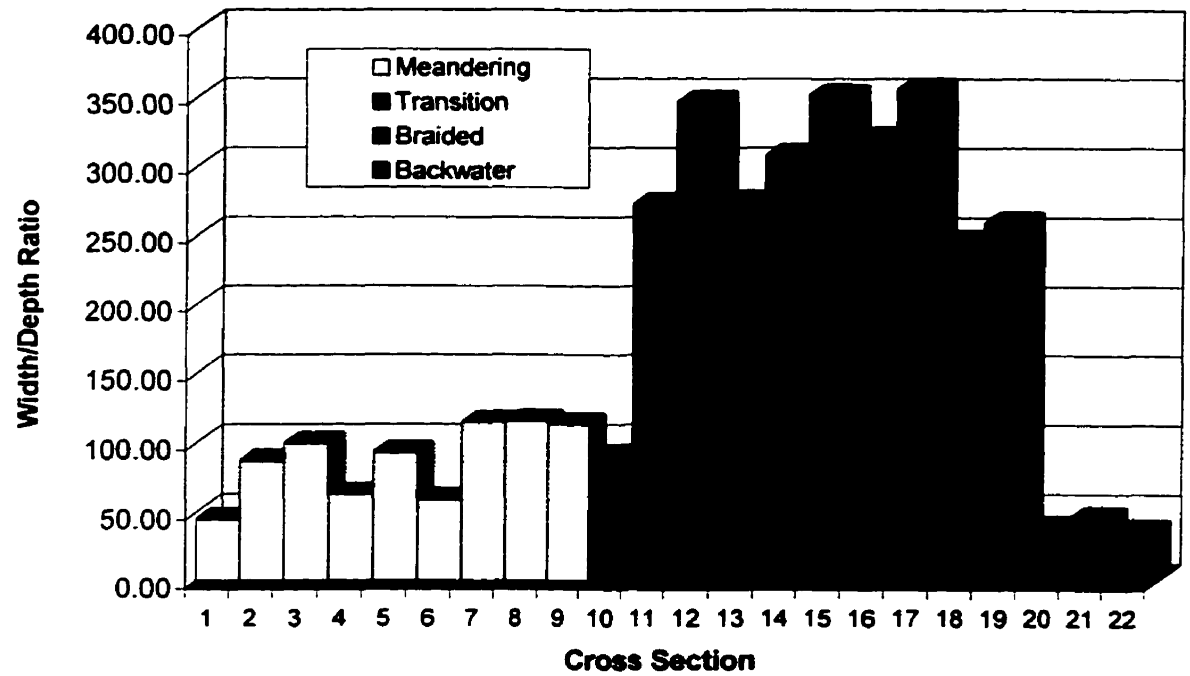


**Figure 31 – Downstream change in the width/depth ratio observed in each of the three morphological zones.**

measuring along the Milk River. The largest width/depth values are in the braided reach with an average of 304. The smallest width/depth values are in the backwater reach with an average of 41. The meandering reach is intermediate but its average value of 88 is closer to the backwater value. These width/depth values indicate that each of the three morphological zones is unique from one another.

*Cross Sectional Area*

Knowledge of channel width and depth allows calculation of cross sectional area. The meandering and backwater cross sections have values very similar to one another at 24 and 23 $m^2$, respectively. A cross section in the braided reach is on average 32% larger than the meandering with an area of 36 $m^2$.

*RESPONSE VARIABLE - PLANIMETRIC GEOMETRY*

When viewed from overhead one of the most obvious expressions of channel pattern is the degree of sinuosity. An aerial view also enables characterization of the width and depth of the Milk River valley. The following sections will present these measurements.

*Sinuosity*

Channel sinuosity, a ratio relating channel distance to valley distance, is presented in Figure 32. A dramatic difference can be seen between the

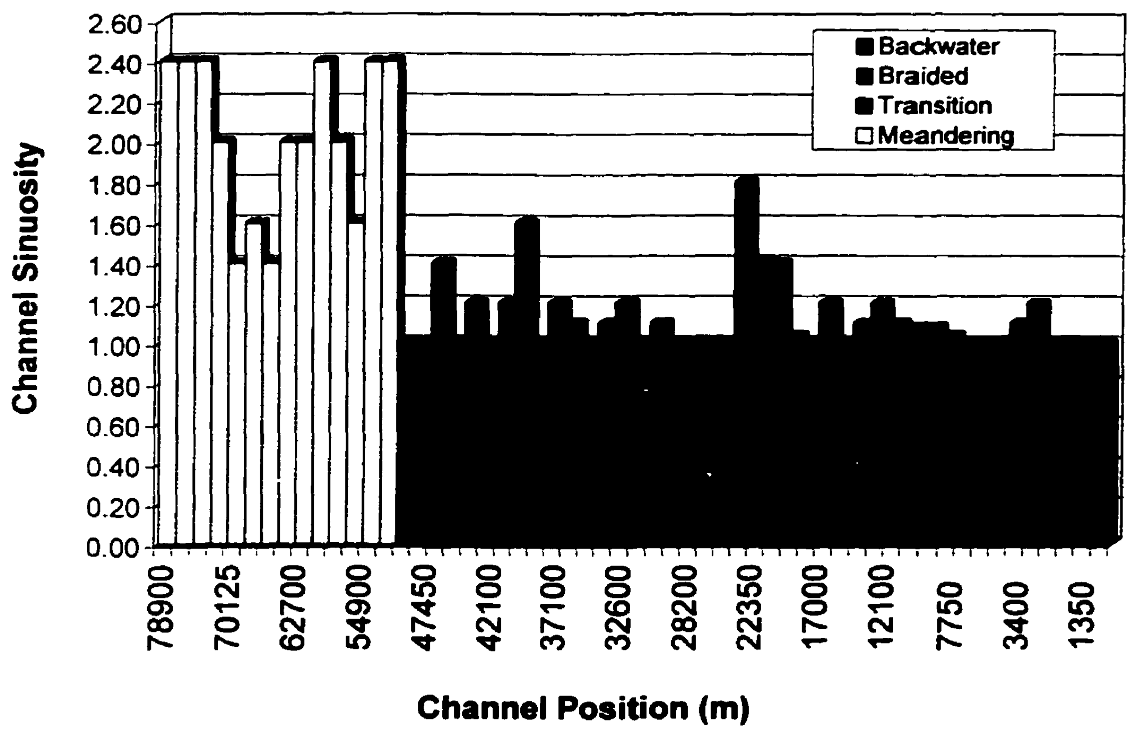


**Figure 32 – Channel sinuosity values observed along the Milk River.**

meandering and braided reaches. Sinuosity in the meandering reach averages 2.03 versus only 1.13 for the braided reach. In other words, for every one kilometre of straight-line distance in the meandering reach the river adds an additional 1 030 m of channel distance to its course. In the braided reach only

130 m of additional channel distance is added. There are anomalous sections within each reach of the study area. For example, from 71 125 to 65 875 m in the meandering reach the sinuosity drops to 1.47. In the braided reach from 26 150 to 22 350 m the sinuosity is 35% above the reach average (1.53 vs. 1.13). The channel sinuosity averages 1.00 indicating a straight channel course in the backwater reach.

*Valley Geometry – Width and Depth*

The width and depth of the Milk River valley is presented in Figure 33 and 34 respectively. Both valley width and depth were measured every one kilometre from the meandering – to – braided transition (49 650 m). These locations were then converted to channel distances (in metres).

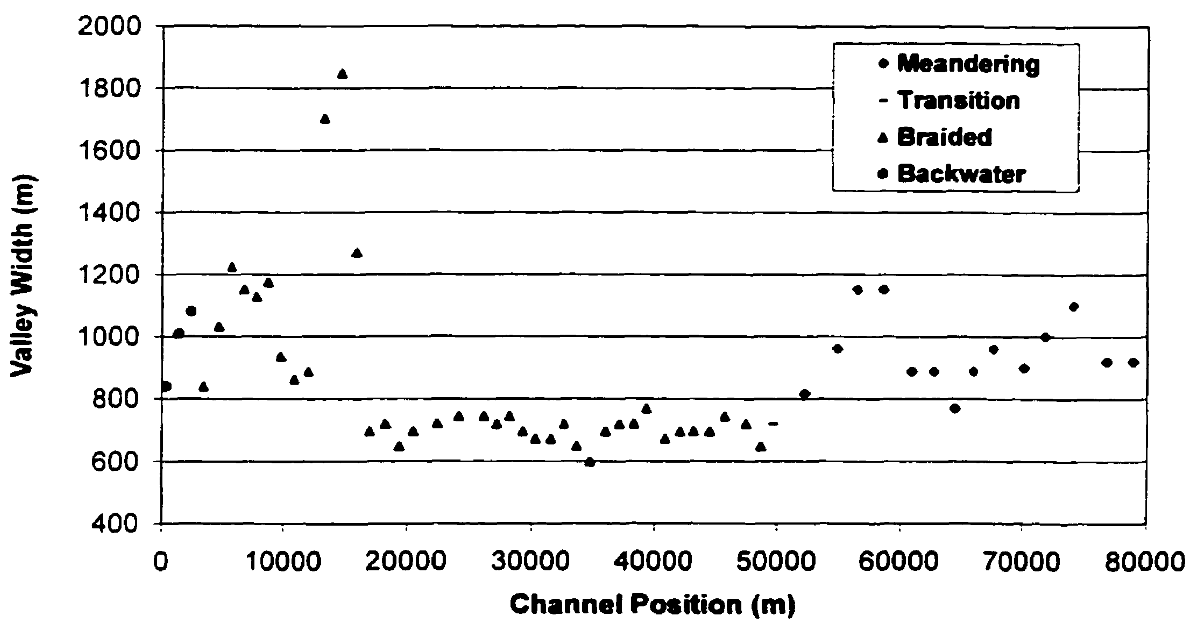


**Figure 33 – Valley width values along the Milk River.**

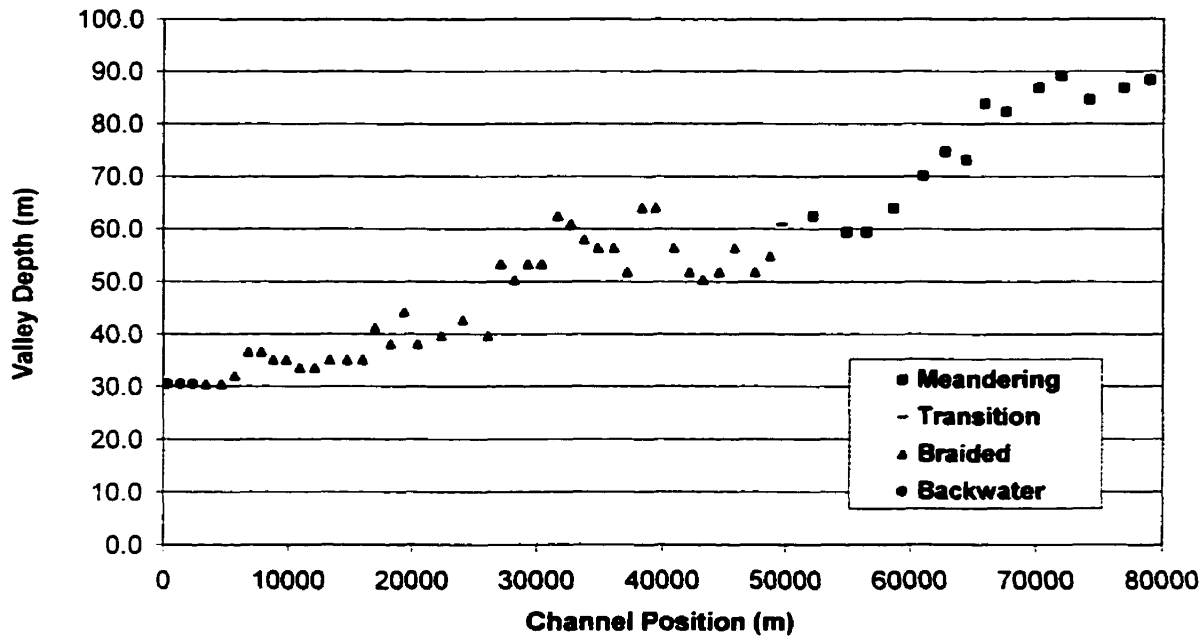


**Figure 34 – Valley depth values along the Milk River.**

There are four valley width zones along the Milk River, one in each of the meandering and backwater reaches, and two in the braided. Within the meandering reach the width of the valley averages 951 m. In Figure 33 the valley width values are widely scattered with a standard deviation from the mean of 116 m. In the braided reach from 48 650 to 17 000 m the valley width drops by over 250 m to a value of 701 m. The values are also much more constant with a standard deviation of only 38 m. The final 12 250 m of the braided reach from 15 950 to 3400 m has a widely scattered distribution. The average valley width is the largest of the four zones at 1172 m and also has the largest standard deviation at 319 m. Average valley width in the backwater reach is 976 m.

There are five zones of valley depth along the Milk River, two in both the meandering and braided reaches and one in the backwater reach (Fig. 34). The first zone in the meandering reach from 78 900 to 65 875 m has an average valley depth of 86 m. The next zone from 64 395 to 49 650 m is one where the valley depth is slowly declining as indicated by the 66 m average. The overall average valley depth of the meandering reach is 75 m. The first zone in the braided reach from 48 650 to 27 150 m has an average valley depth of 56 m and shows no increasing or decreasing tendencies. The final zone in the braided reach from 26 150 to 3400 m displays a slowly declining valley depth which averages 36 m. The average valley depth for the braided reach, including all values from both zones is 47 m. The valley depth averages 31 m within the backwater reach. The overall trend is for valley depth to decline in a downstream direction.

*RESPONSE VARIABLE – CHANNEL SLOPE PROFILE*

The longitudinal profile displayed in Figure 35 was compiled from over 1 400 individual channel elevation measurements and is partitioned into the three main

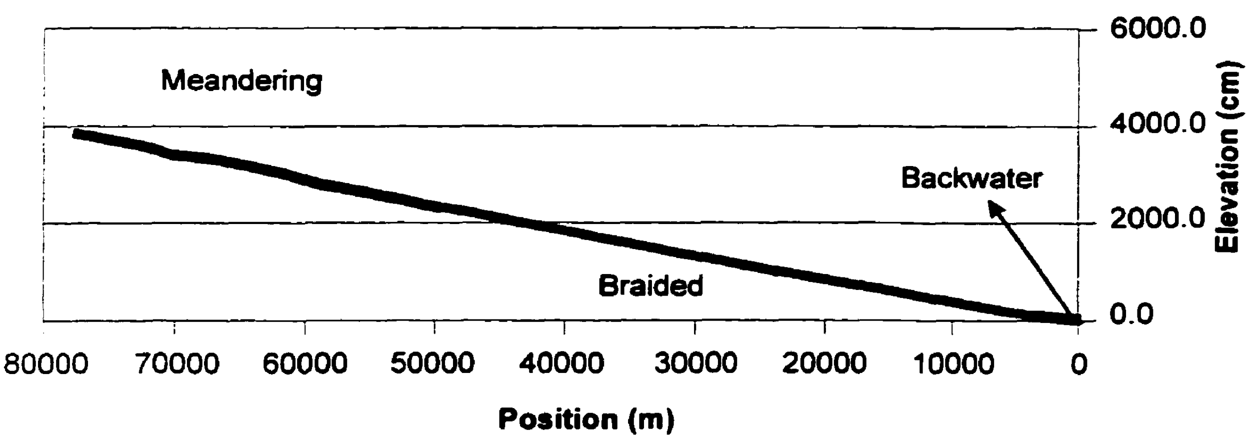


**Figure 35 – Longitudinal profile of the Milk River in the study area.**

Milk River morphological zones of meandering, braiding and backwater (raw slope data can be found in Appendix 3).

The elevation measurements, when combined with horizontal distance, provide data on the channel slope of each zone which is presented in Table 10.

**Table 10 - Channel Slope of the Three Morphological Zones Along the Milk River**

| Morphology | Number of Observ. | Mean Channel Slope (cm/km) | Standard Deviation | Min | Max | Range |
|---|---|---|---|---|---|---|
| Meandering | 460 | 54.75 | 13.19 | 18.00 | 98.60 | 80.60 |
| Braided | 940 | 48.34 | 7.64 | 22.80 | 67.10 | 44.30 |
| Backwater | 54 | 30.50 | 4.88 | 23.70 | 39.70 | 16.00 |

The steepest channel slope is found in the meandering reach, whereas the lowest is in the backwater reach. Channel slope in the braided reach is intermediate the other zones but is only 6.41 cm/km less than the meandering reach (meandering channel slope is 13% steeper than the braided). The values of standard deviation reflect the range of observed channel slope values.

Figure 36 is a plot demonstrating the variability of the channel slope in each of the three morphological zones. The most obvious feature in the meandering reach are the three large peaks, two above and one below the mean. The peaks above the mean at approximately 60 000 and 72 000 m are 34.55 and 32.55 cm/km greater than the mean whereas the peak below the mean near 68 000 m is 26.55 cm/km less than the mean. This is more than double the standard deviation of 13.19 observed over the meandering reach as a whole.

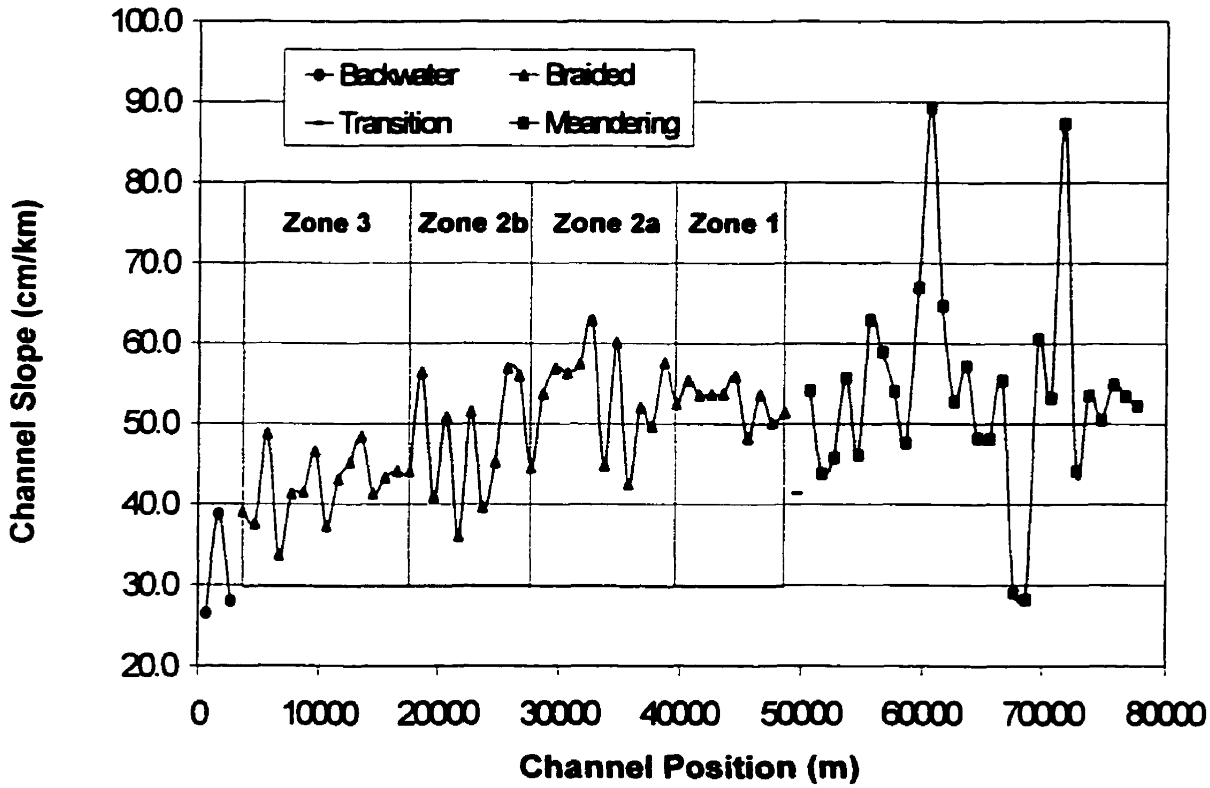


**Figure 36 – Variability in channel slope observed in each of the three morphological zones along the Milk River.**

Two separate patterns within the braided reach, one based on changes in the channel slope and the other on its oscillatory nature, can be observed (Figure 36). The upper 21 000 m of the braided reach from 48 650 to 27 650 m features a stable slope which is above the reach average. The remaining 24 000 m from 27 650 to 3 650 m displays a slowly declining slope, which is below the reach average. Superimposed on this trend is the oscillating pattern observed in the average channel slope values. From 48 650 to 39 650 m the channel values oscillate over a relatively small range in comparison to other regions in the braided reach. The greatest degree of oscillation is observed from 39 650 m to 17 650 m whereas an intermediate level of oscillations is present from 17 650 to 3 650 m.

When combined these different trends produce the four unique zones presented in Table 11.

**Table 11 - Characteristics of the Four Slope Zones Within the Braided Reach**

| Zone | Location (m) | Channel Slope (cm/km) | Relative Oscillation Magnitude | Oscillation Range (cm/km) |
|---|---|---|---|---|
| 1 | 48 650 – 39 650 | 53.4 | Low | 7.7 |
| 2 | 39 650 – 27 650 | 53.3 | High | 20.4 |
| 3 | 27 650 – 17 650 | 47.5 | High | 20.8 |
| 4 | 17 650 – 3 650 | 43.0 | Medium | 15.1 |

Thick vegetation growth along the backwater reach made acquisition of more than 2 650 m of data impossible. This distance does not allow identification of any significant downriver trends in channel slope.

# CHAPTER 6 – CAUSES OF CHANNEL PATTERN CHANGE ON THE MILK RIVER

## INTRODUCTION

As the previous chapter illustrated various control and response variables change at the morphological transition, while others remain constant. This chapter will assess which variables are responsible for channel change along the Milk River. Addressing the following objectives is the goal of this study:

(1) Describe the physical characteristics of both the meandering and braided reaches of the Milk River.

(2) Determine if irrigation improvements installed on the Milk River in 1917 and 1939 are responsible for the morphological transition.

(3) Identify the factor(s) responsible for the morphological transition on the Milk River.

The four potential causes of braiding discussed earlier (Chapter 2) will be analyzed as possible causes of channel change along the Milk River.

## BRAIDING AND THE MILK RIVER – FLUCTUATING DISCHARGE

This mechanism has been noted for many braided rivers which occur in proglacial settings (i.e. Fahnestock, 1963; Doeglas, 1951). The instability in the hydrograph is thought to lead to instability in the channel sediments, which makes them susceptible to erosion and deposition in the form of mid - channel bars. However, numerous researchers have been able to create braided rivers in flumes with constant discharge (i.e Friedkin, 1945; Leopold and Wolman, 1957; Schumm and Khan, 1972; Hong and Davies, 1979; Ashmore, 1982; Germanoski and Schumm, 1993). This suggests that an unstable hydrograph can be locally important but is not a universal cause of braiding.

A large flood event can also dramatically widen a river and cause the onset of braiding. Examples of this include the Cimarron River in Kansas (Schumm and Lichty, 1963) and the Gila River in Arizona (Burkham, 1972) but a gradual return to a single channel pattern usually follows. The flood that initiated widening along the Cimarron River in Kansas was measured at 3 399 $m^3/s$. The mean annual flood along this river is approximately 137 $m^3/s$. Thus, the flood that altered the channel morphology was 24.73 times larger than the normal flood. On the Gila River there was a series of large flood between 1905 – 1917 which initiated widening and the conversion of the channel pattern to braiding. The largest of these floods was 4 248 $m^3/s$ in comparison to the mean flood of roughly 212 $m^3/s$. Therefore, the major flood that was in part responsible for dramatically widening the Gila River and instigating a change in channel pattern was 20.00 times the normal flood. A survey of the discharge records along the Milk River extending back to 1909 revealed that the largest flood (not including ice jams) was 211 $m^3/s$. The mean annual flood is 32 $m^3/s$ indicating that the largest flood on record is only 6.59 times larger than the mean annual flood. This suggests that extreme floods, such as those that have affected the Cimarron and Gila rivers, have not significantly impacted channel morphology along the Milk River.

One of the largest floods on record along the Milk River occurred in June of 1953. The average discharge peaked at 198 $m^3/s$. However, examination of the 1939 and 1960 aerial photographs shows little change during this period (Fig. 37).

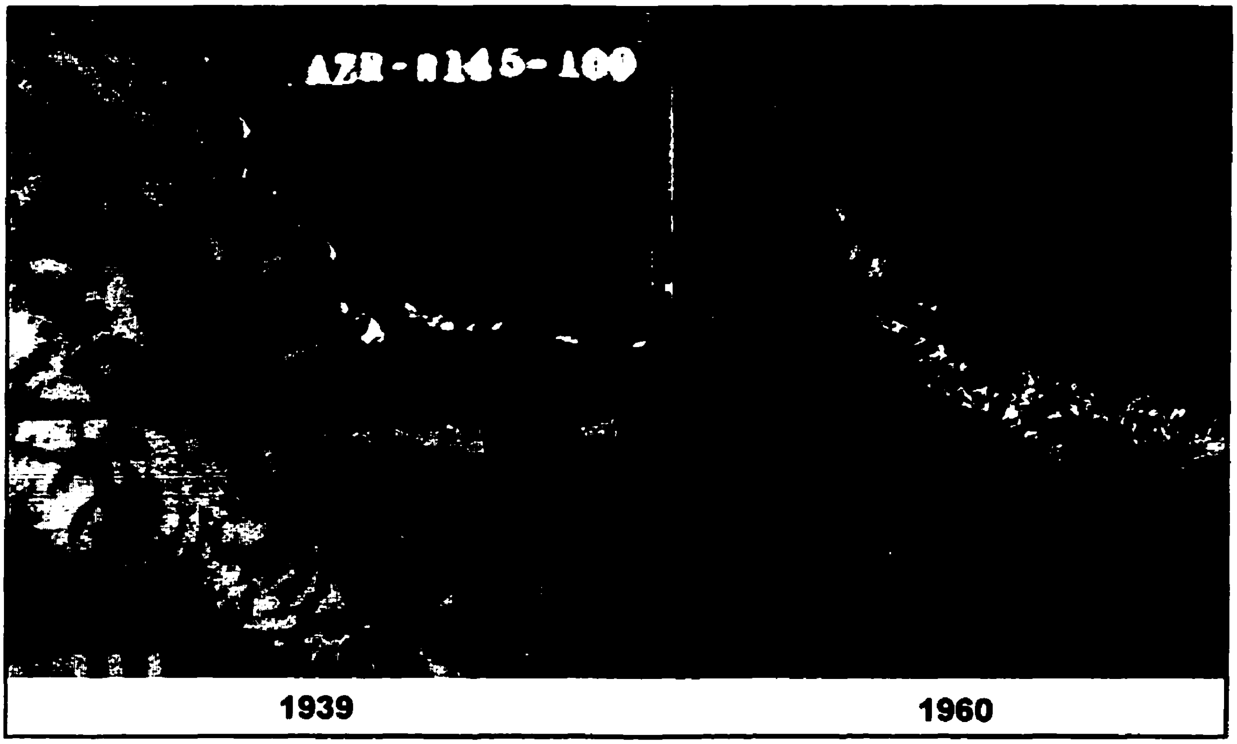


**Figure 37 – Aerial photographs showing little morphological change in the braided reach between 1939 and 1960. Arrows highlight areas of little to no lateral migration suggesting long-term stability of the Milk River.**

If the flood had any impact on the channel the modifications were repaired in just 10 years. A comparison of the 1960 and 1991 aerial photographs also shows very little change; so it would appear that the 1952 flood had very little impact on channel morphology in the braided reach.

The hydrograph on the Milk River, both in the short and long term, has been stable. The discharge remains almost constant from late April to early October while the St. Mary diversion is in operation. There are no large floods, from the hydrologic records or the photographs, that appear to have caused dramatic channel widening. Therefore, instability of the hydrograph, whether it be short or long term, does not appear to be the cause of braiding along the Milk River.

*BRAIDING AND THE MILK RIVER – ABUNDANT BEDLOAD*

The prevalence of channel bars has led many researchers to suggest that braided rivers have greater bedload transport than meandering rivers (Schumm, 1981, 1985). This idea is contradicted on the Tanana River in Alaska which is a classic gravel bed braided river yet possesses a very low proportion of bedload (i.e. less than 5%). Knighton, 1998 states that,

> "The availability of large amounts of sediment, supplied either from upstream or locally (notably the channel banks), is regarded as a necessary condition for braiding. Braiding may result from either a lack of capacity to transport the amount of bed material supplied, or a lack of competence to remove the size of sediment supplied."
> (Knighton, 1998, p. 231)

Perceptually an abundant bedload implies that the river receives inputs of sediment, either from local bank erosion or tributary input, which exceeds its ability to transport the imposed bedload. In regards to the Milk River what must be emphasized from Knighton's above statement is that "braiding may result from either *a lack of capacity to transport the amount of bed material supplied...*" This suggests that the river need not be overloaded by inputs of new sediment. Any change in the conditions required for bedload movement that decreases the rivers ability to transport the supplied bedload could initiate braiding. If, for example, a river is transporting 100 tonnes of sediment and conditions change and it can now only transport 50 tonnes the other 50 tonnes must enter storage, perhaps in the form of channel bars.

As discussed in the previous chapter there is limited bedload data for the Milk River. This data suggests that bedload accounts for less than 5% of the sediment transported by the river. It would, therefore, appear that an abundant bedload, in the traditional sense of large inputs such as those Schumm (1980) observed on the Canterbury Plain in New Zealand, is not responsible for braiding on the Milk River. However, as will be discussed later there is a change in the amount of stream power available between the meandering and braided reaches. This therefore implies a change in the ability of the river to transport bedload. Any decrease in bedload transportability may manifest itself in the deposition of channel bars.

*BRAIDING AND THE MILK RIVER – STEEP GRADIENT*

The oft quoted relation of Leopold and Wolman (1957), Lane (1957) and Schumm and Khan (1972) states that given the same discharge a braided river will have a higher slope than a meandering river. In other words, should a river suddenly increase its slope for whatever reasons the river morphology may change from meandering-to-braided. Figure 38 is the diagram from which the Leopold and Wolman (1957) channel pattern discriminator was created. When the values from

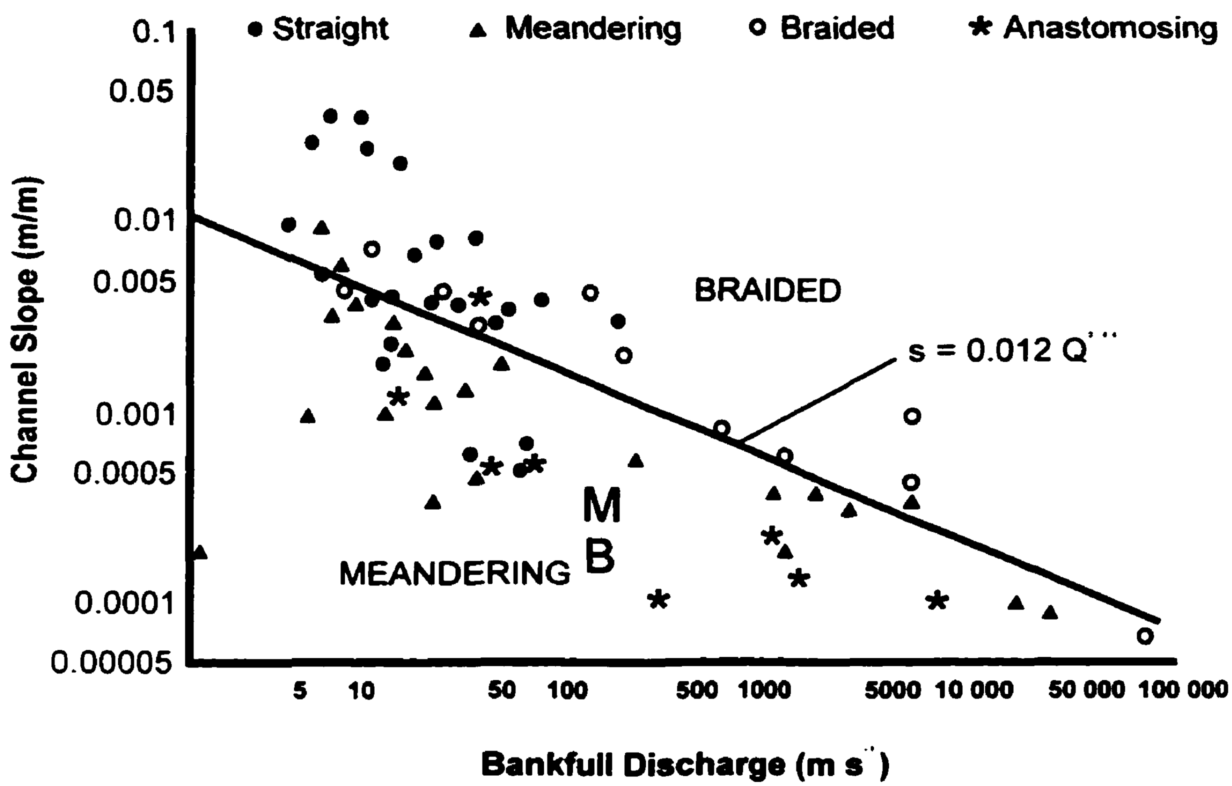


**Figure 38 – Leopold and Wolman (1957) channel slope – bankfull discharge graph used in the discrimination of meandering and braided channel patterns. M and B denote the position of the meandering and braided portions of the Milk River respectively.**

the meandering reach of the Milk River is plotted on this graph it is clearly in the meandering zone as identified by Leopold and Wolman (1957). However, the channel slope and bankfull discharge values for the braided reach also fall in the meandering zone. This clearly demonstrates that the relationship derived by Leopold and Wolman (1957) does not correctly predict channel pattern along the Milk River. Similarly, the Lane (1957) relationship predicts that the channel slope in the braided reach should be over three times as high as it actually is and therefore fails to correctly predict channel pattern on the Milk River. Given that the channel slope in the braided reach is marginally lower (48.34 cm/km) than that of the meandering reach (54.75 cm/km), it would seem safe to rule out a high channel slope as the cause of braiding on the Milk River.

The concept of a steeper channel slope in a braided reach is connected to the idea that braided rivers have abundant bedload. Given that bedload transport is energy intensive, a steep channel slope is often a prerequisite in order to have the necessary stream power for bedload movement. However, braiding on the Milk River occurs in a situation opposite that of the accepted concept of high stream power braiding. The situation on the Milk River suggests the possibility of low stream power braiding.

*BRAIDING AND THE MILK RIVER – COMPOSITION AND ERODIBILITY OF THE CHANNEL PERIMETER*

Of the major response variables, the composition of the channel perimeter shows significant change between the meandering and braided reaches. Each of the three different morphological reaches, meandering, braided and backwater, posses a unique average silt-clay content (refer back to Figure 27).

The highest silt-clay content of the three morphologies is in the backwater reach at 84.92%. This is the result of the interaction between the Milk River and the Fresno Reservoir. As the channel enters the reservoir it changes morphology in response to the change in channel slope (Fig. 39). In the braided reach the channel slope is 48.34 cm/km. The influence of the Fresno Reservoir instigates a

**Figure 39 – Backwater reach of the Milk River immediately above the Fresno Reservoir.**

reduction in channel slope in the backwater reach to 30.50 cm/km, a drop of 37% from the braided reach. This is because of the rise in base level brought about by construction of the Fresno Dam. In order to match the new base level, which is the top of the dam spillway, the river must aggrade, thereby reducing its channel slope (Fig. 40). This change is in line with adjustments predicted by Leopold and

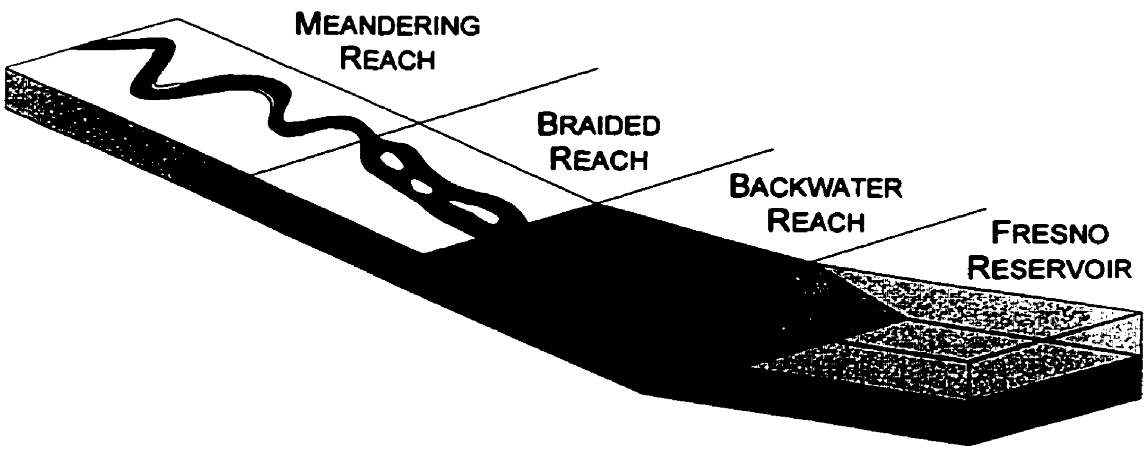


**Figure 40 – Effect on channel morphology of the rise in base level introduced by the Fresno Reservoir and Dam.**

Bull (1979) and Leopold (1993), which state that upon entering a reservoir there should be roughly a halving of channel slope. After rapid aggradation to the new base level the Milk River attempts to maintain a dynamic equilibrium in the backwater reach through changes in channel morphology. The most obvious difference from the braided reach is the change in width. The channel undergoes a 56% reduction in width from an average of 99 m in the braided reach to 43 m in the backwater. This reduction in width results in a decrease in channel cross sectional area of 34% from 35 $m^2$ in the braided reach to 23 $m^2$ in the backwater. This reduction in cross sectional area leads to an increase in overbank events as the channel can no longer contain as much water. These overbank events allow the suspended sediment laden waters of the Milk River to deposit part of the load in the form of silt-clay rich channel levees. The levees along the backwater reach are prominent and resemble those of anastomosing rivers such as the Columbia River in British Columbia in that they are very pronounced and contain very little sand. Another adjustment by the river to the reduction in channel slope is an alteration in the style of bedforms. There is a change from dunes to ripples which represents a reduction in channel boundary friction and thus increases the rate at which water and sediment may pass through a given reach (Leopold and Bull, 1979).

The difference in silt-clay content between the meandering and braided reaches is very pronounced. There is 47.14% less silt-clay in the channel banks of the braided reach (18.03%) versus those of the meandering reach (65.17%). This dramatic reduction in the presence of cohesive silt-clay in the braided reach is a critical factor affecting channel morphology. The change in the composition and erodibility of the channel banks may be a major cause of the meandering-to-braided transition on the Milk River.

*What is Causing Channel Pattern Change on the Milk River?*

A common characteristic of braided rivers is their greater width in comparison to meandering rivers of similar discharge. In order for river widening to occur, the channel perimeter must be relatively easy to erode. Erosion of the channel banks also introduces sediment to the river which can potentially overwhelm its transport capacity and lead to the temporary storage of sediment in the form of mid - channel bars. It is dissection of these bars at lower flows which gives a sand bed river a braided appearance (Smith, 1971).

Bank strength is usually measured in terms of the percentage of silt – clay in the bank sediment. Along the Milk River, this is the one braiding causative mechanism which changes significantly. As described in Chapter 5 the banks in the meandering reach are cohesive because they are composed of, on average, 65.17% silt-clay content. This high percentage of silt-clay increases bank strength and helps prevent widespread lateral erosion (Schumm, 1960). In the braided reach the banks have only 18.03% silt-clay. Therefore, the banks in the braided reach have over 72% sand and small pebbles versus only 35% sand in the meandering reach. The Hjulström curve (Hjulström, 1935) demonstrated that the easiest particles to entrain are sand grains roughly 0.1 mm in size. The majority of the sand composing the banks of the braided reach averages 0.15 mm in size. Silt and clay particles are much more difficult to entrain because they possess grain to grain cohesion that is essentially absent in sandy sediments.

The impact of the channel widening facilitated by the decreased bank strength in the braided reach is best demonstrated in terms of stream power. Figure 41 shows the unit length stream power in the meandering and braided reaches. Differences between the two are negligible as evidenced by the average

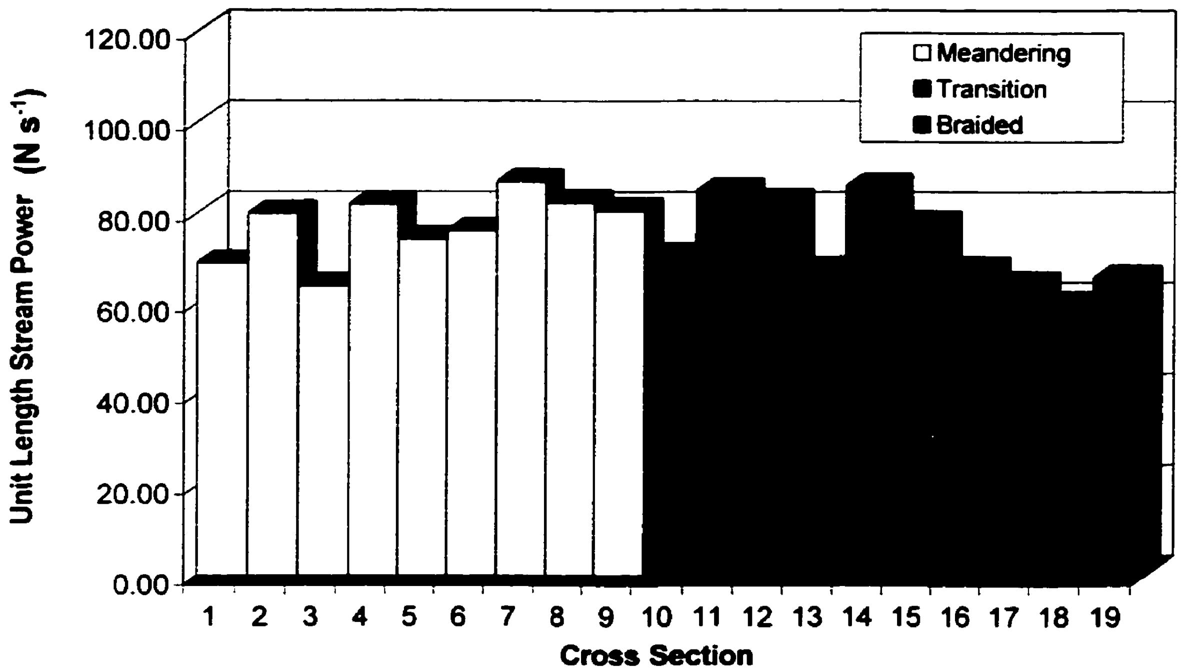


**Figure 41 – Unit length stream power in the meandering and braided reaches.**

values, 77.24 $N{\cdot}s^{-1}$ in the meandering reach versus 72.94 $N{\cdot}s^{-1}$ in the braided reach. This represents only a 6% drop between the reaches. The similarity in these values can be explained by the similarity of the values used to calculate unit length stream power ($\Omega$). The equation is:

$\Omega = \gamma Qs$ where: $\gamma$ = specific weight of water
Q = discharge
s = channel slope

Neither the specific weight of water, nor the discharge differs between the meandering and braided reaches. The only variable in the stream power equation that shows any change is the channel slope value. However, that change is negligible as there is only a 6.41 cm/km reduction in channel slope from the meandering to braided reach and, thus, not a significant change in unit length stream power. This measure represents the total amount of power available for work (Graf, 1988). The unit length stream power can be thought of as the raw power that can be used to perform tasks such as bedload movement, bank erosion, etc. However, in much the same manner that the power created by a car engine is not the same amount of power that reaches the wheels, the unit length stream power that reaches the channel boundary is dampened through friction with the channel perimeter. The power per unit width, which changes significantly between the meandering and braided reaches, is shown in Figure 42.

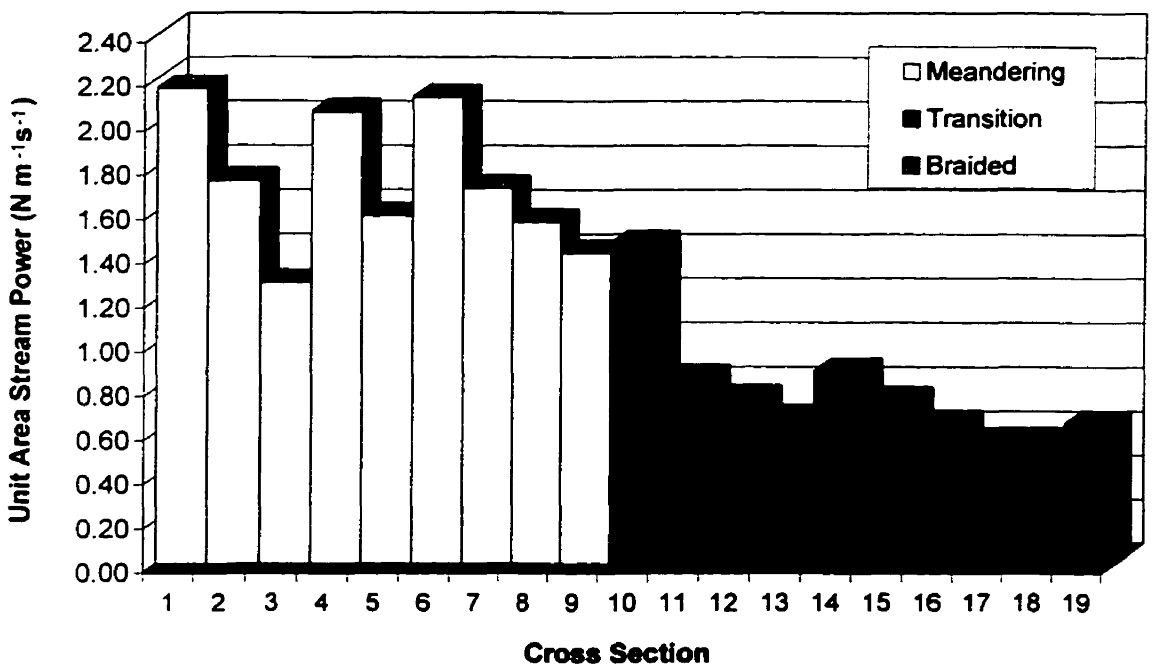


**Figure 42 – Unit area stream power in the meandering and braided reaches.**

The equation for calculating unit area stream power ($\omega$) is:

$\omega = \gamma Qs/w$ where: $\gamma$ = specific weight of water
$Q$ = discharge
$s$ = channel slope
$w$ = channel width

These values represent how effectively the total stream power is applied to the channel boundary (Graf, 1988). In the meandering reach the unit area stream power averages 1.73 $N \cdot m^{-1}\ s^{-1}$ while in the braided the average is 0.70 $N \cdot m^{-1}\ s^{-1}$. This represents a 60% reduction in the unit area stream power from the meandering to braided reaches. This dramatic decline in how effectively the stream power is applied to the channel boundary is due to the 78% increase in channel width from 56 m in the meandering reach to 99 m in the braided reach.

How does the dramatic decrease in unit area stream power effect the braided reach? One of the least obvious manifestations of the decrease in unit area stream power in the braided reach is found on the channel bed. As Figure 25 and 26 show there is a sudden decline in the mean grain size and sorting index of the channel bed material. In the braided reach the mean grain size is 2.83$\phi$, or 0.155 mm. This represents a 33% reduction from the 2.14$\phi$, or 0.230 mm mean grain size of the meandering reach. The sorting index shows a change from moderately well sorted bed material in the meandering reach to moderately sorted in the braided. As Figure 26 demonstrates there is a considerable difference in the composition of the bed material in the two reaches. Only 7.52% of the bed in the meandering reach is composed of coarse silt and very fine sand. In the braided reach the same grain sizes make up 36.11% of the bed. The majority (90.18%) of the bed material in the meandering reach is composed of medium and fine sand. These same grain sizes represent only 62.91% of the bed material in the braided reach. The majority of this difference is because of a 26.90% decrease in the amount of medium sand in bed of the braided reach. Thus, the meandering bed has less fine material and is composed predominantly of medium and fine sand. The braided reach has a much greater fine fraction and considerably less medium sand.

The sudden reduction in the unit area stream power at the transition can explain the change in the composition of the bed material. The channel cross section in the braided reach becomes much less organized compared to that of the meandering reach (Figure 29). As multiple channels emerge in the braided reach these channels become the areas where the majority of the stream power is applied. In the meandering reach the cross section is more uniform and thus the stream power is applied more evenly across the bed. The uneven application of stream power in the braided reach leads to areas of relatively quiescent flow where less stream power is available for the transport of bed material. This results in the deposition of finer grained material in the braided reach, that for the most part, remains in transport in the meandering reach. It is deposition of this finer material that lowers the mean grain size and leads to a poorer sorting index in the braided reach.

In order to test for the existence of a relationship between bank strength and channel pattern, regression analysis was performed. This allows testing of the hypothesis that bank strength influences channel pattern. It also enables identification of the strength of any relationship that exists between the variables. Each run used width/depth ratio as a surrogate for channel pattern as both the meandering and braided reaches possess a very distinct width/depth value. The first run used width/depth ratio as the dependent variable and the percent silt-clay in the banks as the independent variable. Width/depth ratio was again used as the dependent variable in the second run but this time the independent variable was the unit area stream power.

A scatterplot of percent silt-clay in the banks versus width/depth ratio is given in Figure 43. It can be seen that two separate populations exist, one for each of

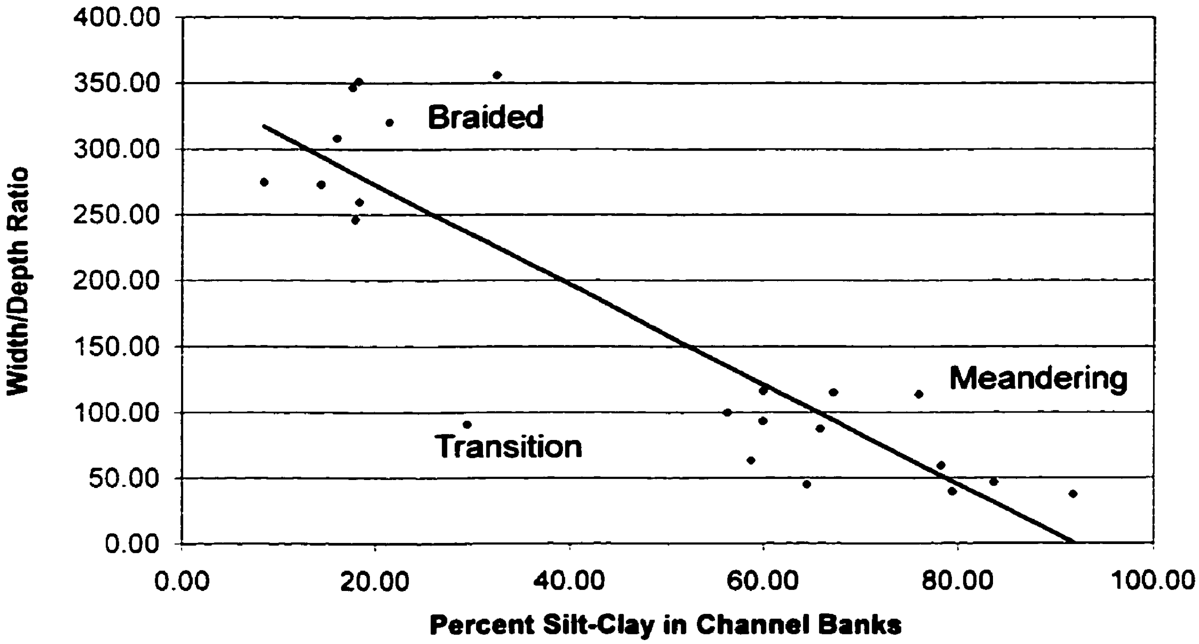


**Figure 43 – Scatterplot of percent silt-clay in the banks versus the width/depth ratio.**

the meandering and braided reaches. When the values at the morphological transition are included the correlation coefficient ($r^2$) for this relationship is 0.7673. This implies that 76.73% of the width/depth ratio can be explained by variations in the silt-clay content of the banks. If the transition values are excluded the $r^2$ value jumps to 0.8375. This difference is due to the fact that the sampling location at the transition possesses a meandering morphology yet the percent silt-clay values are transitory between the values observed in the two reaches. Thus, 83.75% of the variation in width/depth ratio and, therefore, channel pattern can be explained by the percent silt-clay in the channel banks.

The scatterplot of unit area stream power versus the width/depth ratio is shown in Figure 44. Once again the meandering and braided reaches present

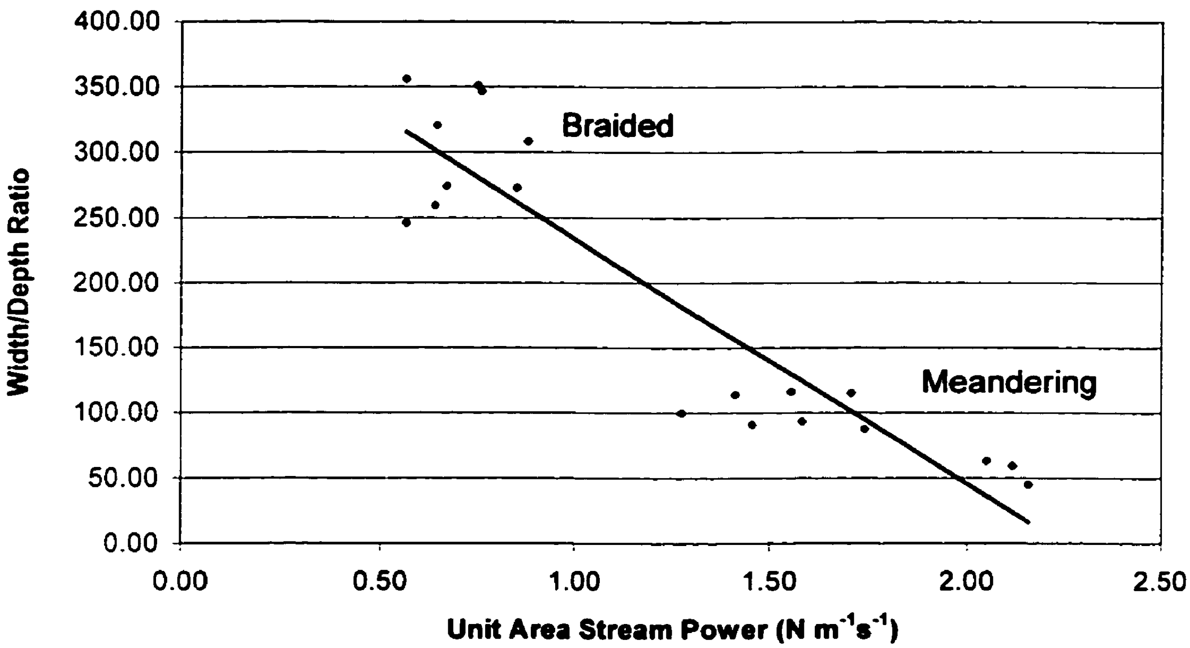


**Figure 44 – Scatterplot of unit area stream power versus the width/depth ratio.**

themselves as two separate populations. The exclusion of the values at the morphological transition does little to change the strength of the relationship. The difference represents only a 0.2% change. The $r^2$ value for this relationship is

0.8449. This suggests that 84.49% of the width/depth ratio can be explained by variations in the unit area stream power.

What do these regression coefficients suggest about channel pattern change on the Milk River? The relationship displayed in Figure 43 demonstrates that as the percent silt-clay in the channel banks decreases the width/depth ratio of the river increases. That is, the lower the silt-clay in the banks, and therefore the less resistant to erosion, the wider and shallower the river becomes. The relationship between unit area stream power and width/depth ratio suggests that as the unit area stream power declines at the transition the rivers width/depth ratio increases.

*How Did Braiding Begin and How Does It Continue?*

The above regression relationships suggest both an initiating and a perpetuating mechanism for braiding on the Milk River. When the Milk River established its channel pattern it adjusted to the materials constituting the channel perimeter. Near the transition point where the banks become much less cohesive the river was able to widen its channel. This widening occurred as the circulatory cells in flowing water interacted with the relatively weak channel banks. Channel widening continued until it reached a point where the shear stress exerted by the flow was no longer greater than the shear strength of the banks.

This increased width is responsible for the 60% drop in unit area stream power. The river no longer possesses the same ability to transport material as in the meandering reach. The reduction of stream power in the braided reach leads to areas of local incompetence where sediment transport becomes impractical and bar formation is initiated. During the spring freshet, the ability of the river to transport sediment will be greater but as the flow begins to wane a portion of the sediment must be deposited in the form of transverse bars. As the flow continues to wane these bars are dissected and the braided morphology arises.

As discussed by Ferguson (1987) the position of the threshold line on the Leopold and Wolman (1957) slope-discharge graph should shift with changes in the composition of the channel perimeter. As Figure 45A demonstrates, strong channel banks will have a higher meandering-to-braided threshold than weak

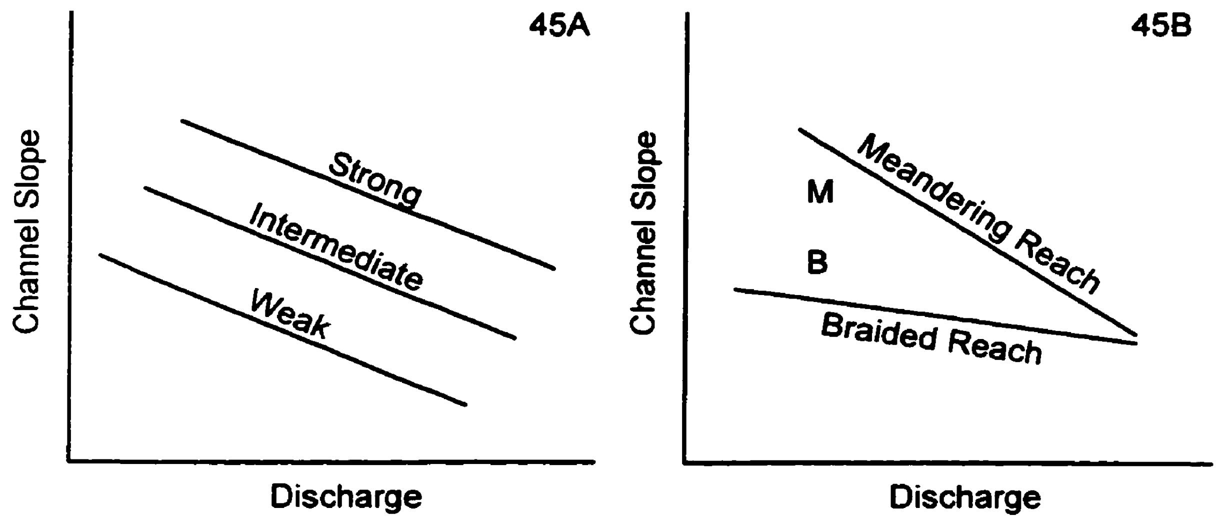


**Figure 45 – (A) Shift in the meandering-to-braided threshold because of changes in bank strength. (B) Possible situation on the Milk River where the downward shift in the threshold due to the reduction in bank strength results in the braided reach plotting above the line in the braided zone.**

channel banks. Therefore, if two different rivers have identical discharge and slope but the composition of the channel banks changes the stream power required to initiate channel braiding will change. For example, on the Milk River the channel banks in the meandering reach are cohesive and, thus, require a high stream power to initiate the channel widening necessary for braiding. The strength of the banks is preventing the Milk River from crossing the meandering-to-braided threshold. Given that the discharge and slope are almost unchanged in the braided reach the unit length stream power is virtually identical. What has changed is bank strength, which is much lower in the braided reach. Thus, there has been a downward shift in the meandering-to-braided threshold line (Fig. 45B). This shift is enough that the braided reach plots above the line and the channel pattern has converted from meandering-to-braided.

*ABNORMALITIES OF THE MILK RIVER*

Despite the low silt-clay content of the banks in the braided reach they are stable and not actively eroding. Discussion with local ranchers suggests that over most of the braided reach less than two metres of movement has occurred over the past 50 years. This is contradictory with many papers which suggest that channel banks in braided rivers are actively shifting as the river migrates across the valley bottom. The earliest aerial photographs from 1939 show the braided reach to be in almost the exact same position as today (refer back to Fig. 37). Unlike the gravel bed rivers on the Canterbury Plain in New Zealand, which often cut into Pleistocene terraces and dramatically increase their sediment load, the braided reach of the sandy Milk River does not appear to add significant amounts of sediment through bank erosion. The Canterbury rivers often braid below these terraces which suggests that the input of fresh gravel has overloaded the rivers transport capability. Smith and Smith (1984) found a similar situation on the sandy William River in northern Saskatchewan where inputs from a dune field increased bedload 40-fold and led to an overloading of the river transport capability and a braided morphology. The braiding of the Milk River is due to a decrease in transport efficiency as opposed to a direct overloading of sediment transport such as that occurring on the William River or the Rangitata River in New Zealand.

The stability of the channel banks and more or less constant location of the channel suggests that the braided reach is in a graded state. Graded in this study implies that significant aggradation or degradation is not taking place and the vertical position of the river is constant. Bridge piers from a 1910's era bridge are still observable in the braided channel. Discussions with local ranchers indicate that the piers have remained exposed to the same degree since at least the 1950s (Don Greytak, pers. commun., 1998). If rapid aggradation was occurring a narrower channel and pronounced levees would be expected as overbank events become more common. This morphological reaction is occurring in the backwater area where the Milk River is undergoing aggradation. In the braided reach topographic surveys failed to reveal any levee development. It is speculated that the river is not aggrading as the excess sediment is stored in channel bars. The braided reach has a series of flow constriction and expansion points (Fig. 46). The

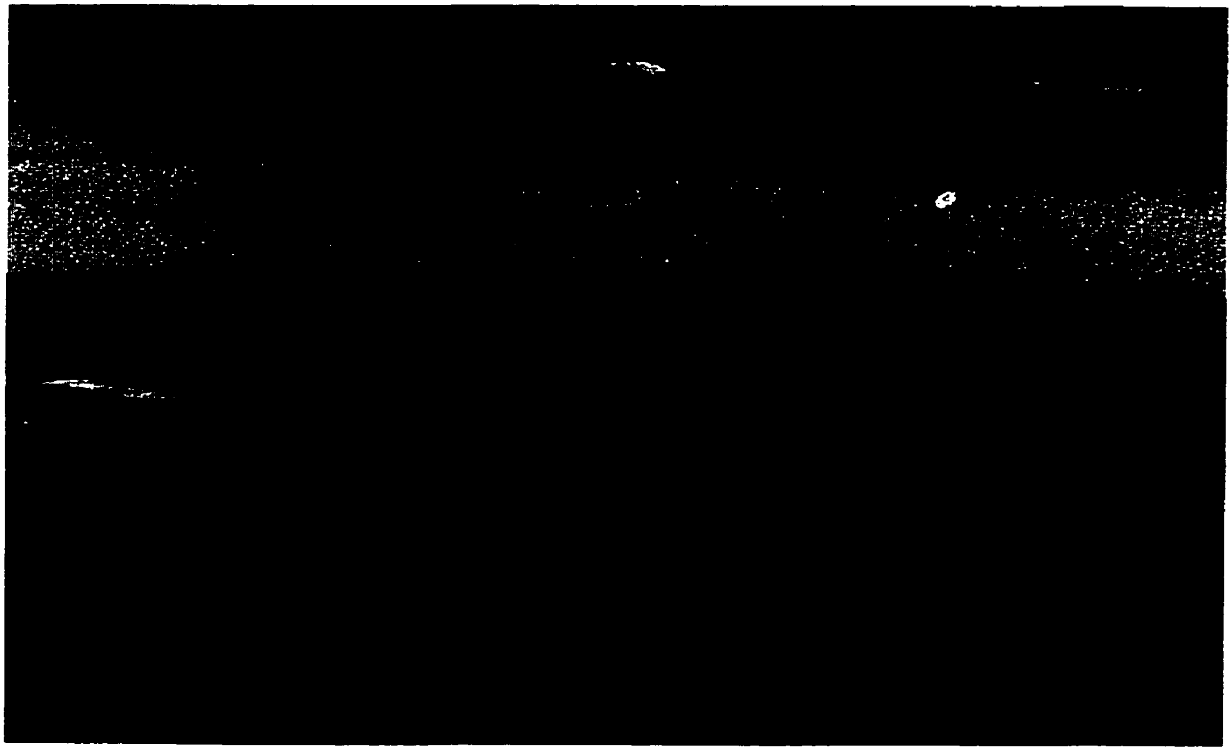

**Figure 46 – Flow constriction and expansion along the Milk River. Deposition occurs in the expansion zones as the flow loses competence and deposits excess sediment in the form of mid-channel bars.**

expansion zones act as temporary sediment sinks where bars are deposited as flow wanes from the spring flood. In the next year the spring flood flushes this sediment down to the next expansion zone. It make take a grain of sand 40 or 50 years to make it through the braided reach but it is not entering long term storage in an aggrading floodplain.

The long-term stability of the river is supported by the valley margin. In the meandering reach scallops in the soft bedrock point to the fact that the river has actively migrated in the past (Fig. 47). This migration has resulted in erosion of the

**Figure 47 – Meander scars along the valley margin serve as evidence of active lateral migration of the Milk River.**

valley margin and along with badland processes has widened the valley to an average of 951 m in the meandering reach. In the braided reach the valley margin is straight and shows no indication of extensive river migration in the past (Fig. 48).

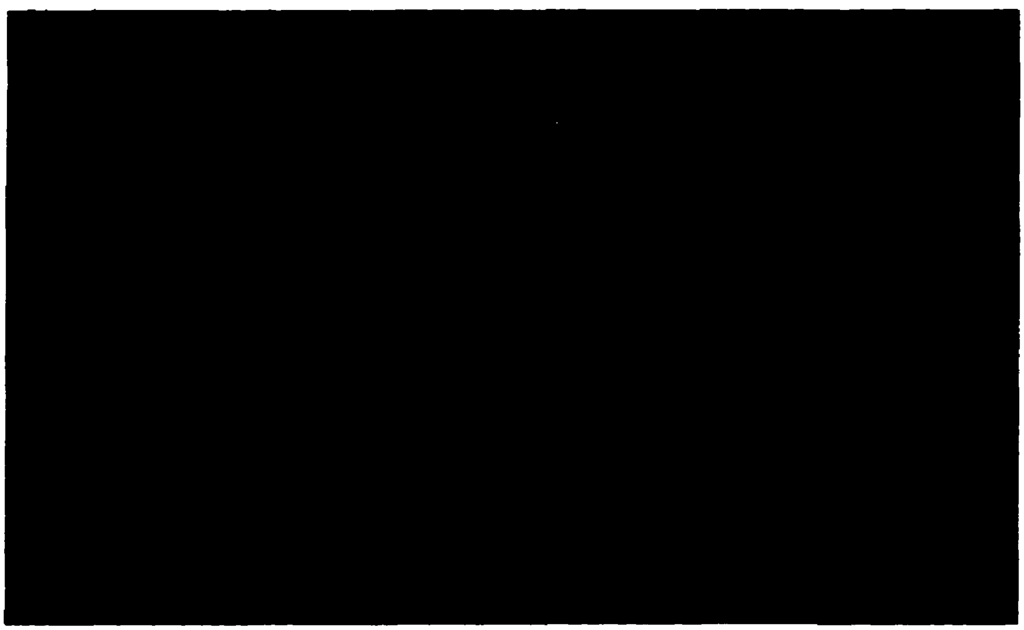

**Figure 48 – The relatively uniform valley margin in the braided reach suggests little lateral migration of the Milk River in the braided reach.**

The valley is much narrower, averaging 701 m. It has been estimated by Beaty and Barendregt (1987) that as much as 600 m of post-glacial widening has occurred in the canyon section in Alberta which is over 1.5 km wide. This represents nearly a one third increase in valley width by Holocene slope and fluvial processes. A 33% increase in valley width through slope processes, piping and river migration in the 701 m wide braided valley would produce a valley width of 933 m which is comparable to the width of the valley in the meandering reach. This suggests that long term stability in the braided reach has existed since deglaciation. Active migration of the river in the braided reach is limited by the decrease in unit area stream power. The river is expending the majority of its stream power on transporting the imposed sediment load and does not possess the necessary stream power to migrate back and forth across the floodplain. This maximization of stream power helps explain why there is no active bank erosion and why the river position has changed little over the past 60 years.

The stability of the banks also points to the ineffectiveness of cows as an agent of channel change. Typical channel banks in the braided reach are vertical and average roughly 0.7 m in height. Over the 40 km of braided channel that was surveyed a cow was never observed to use an area with such steep banks. Cattle congregated at low spots in the banks which resembled pseudo point bars. At these locations banks were non - existent and cattle had easy access to water. Large-scale bank degradation by cattle seems unimportant as 95% of the banks observed along the braided reach were covered with a thick mat of grass.

Apart from the morphological differences between the two reaches the most obvious difference is the change in vegetation. The cottonwood forest and associated shrub communities of the meandering reach give way to open grassland in the braided reach. The sparseness of cottonwood trees and shrubs along the braided reach can be attributed to three main mechanisms. First, in the braided reach suitable recruitment sites are fewer than in the meandering area. A bar in the braided reach may be stable for a year or two and thus any vegetation that does establish will be washed away in the next flood. Through the process of point bar deposition and river migration the recruitment sites on point bars in the meandering reach are more stable and have a better chance at supporting vegetation than does the unstable bars of the braided reach. Second, the pseudo point bar areas in the braided reach where vegetation does have a chance at establishment are the areas preferred by cattle for watering. The vegetation of young cottonwoods and shrubs is high in nutrients and will be preferentially grazed by cattle. Access to the valley bottom in the meandering reach is difficult because of the steep slopes whereas the gentle slopes of the braided reach allow easy access. Third, any vegetation that becomes established and survives grazing by cattle will likely be destroyed by ice drives and floes (Smith and Pearce, in press). As mentioned above there are numerous constriction and expansion zones along the braided reach. Ice appears to pile up at these constrictions enabling it to get out of the channel with high frequency. All along the braided reach numerous shrubs and young cottonwoods were observed bent and broken. Historic photos, such as Figure 49, of ice jams since the 1910's have shown ice from valley margin

**Figure 49 – Ice jam covering the approximately 700 m wide valley floor in an area now flooded by the Fresno Reservoir.**

to valley margin (valley is approximately 700 m wide). A 1996 ice jam near the Guilford bridge, as seen in Figure 50, sheared off two power poles some 250 m

**Figure 50 – Ice blocks scattered over 200 m from the channel after the 1996 ice jam event at the Guillford bridge.**

from the channel (Gary Meland, pers. commun., 1998). A 5-year-old cottonwood seedling stands little chance of survival against these odds. These factors prevent the establishment of significant vegetation communities in the channel which can act as sediment traps and initiate channel narrowing.

*WHY IS THE BANK STRENGTH DIFFERENT BETWEEN THE REACHES?*

If, as the regression analysis suggests, changes in bank strength are responsible for channel pattern change along the Milk River it is important to assess why the change in bank strength occurs. The fluvial morphological transition coincides with a change in slope morphology. As Figure 13 demonstrates the valley slopes in the meandering reach possess classic badland morphology. This differs drastically with the valley slopes along the braided reach which, are for the most part gentle in profile and completely vegetated (Fig. 14). This implies that sediment delivery to the valley bottom is dramatically different between the meandering and braided reaches. As Barendregt and Ongley (1977) reported piping and slopewash are the main processes active in the Milk River badlands. These processes eroded the soft Late Cretaceous bedrock and deliver large amounts of sediment to the valley bottom. The composition of this sediment reflects the composition of the bedrock in that fine materials dominate as shales are more prevalent than sandstone in exposures along the valley slopes. As described in Chapter 3 the surficial geology map of the Milk River valley prepared by Barendregt (1977) shows that the majority of the valley bottom is covered with hillslope deposits (glacis or pediments). The modern fluvial deposits are largely restricted to the active point bar surfaces. For the most part the hillslope deposits are fine grained materials with the inter-fingering of the occasional sand bed. Thus, through the active slope process of the badland-dominated meandering reach, a large amount of fine grained deposits are introduced to the valley bottom. It is these deposits through which the Milk River must travel. The downstream change in suspended sediment concentration supports this argument in that there is a tremendous increase in load above the morphological transition. However, downstream of this point the suspended load changes very little suggesting that there is little contribution of fine grained material from the surrounding valley slopes in the braided reach (refer back to Fig. 23). It is the comparatively stable slope morphology of the braided reach which suppresses the introduction of fine material to the valley bottom. Unlike the meandering reach, whose valley bottom slopes gradually towards the Milk River because of the glacis (pediment) surface, the braided reach has more of a canal-like appearance (Fig. 16). The only surficial geology map of the area is that of Alden (1932) which shows the entire valley floor to be covered with alluvium. This alluvium is composed almost entirely of sand.

It is also postulated that the calculated bankfull discharge of the braided reach is too low. Bankfull discharge was determined using the cross sectional geometry. In the meandering reach bankfull discharge is 154 $m^3/s$ and drops to 124 $m^3/s$ in the braided. However, as Figure 51 shows channel bars occupying the braided channel significantly decrease the cross sectional area (N.D. Smith,

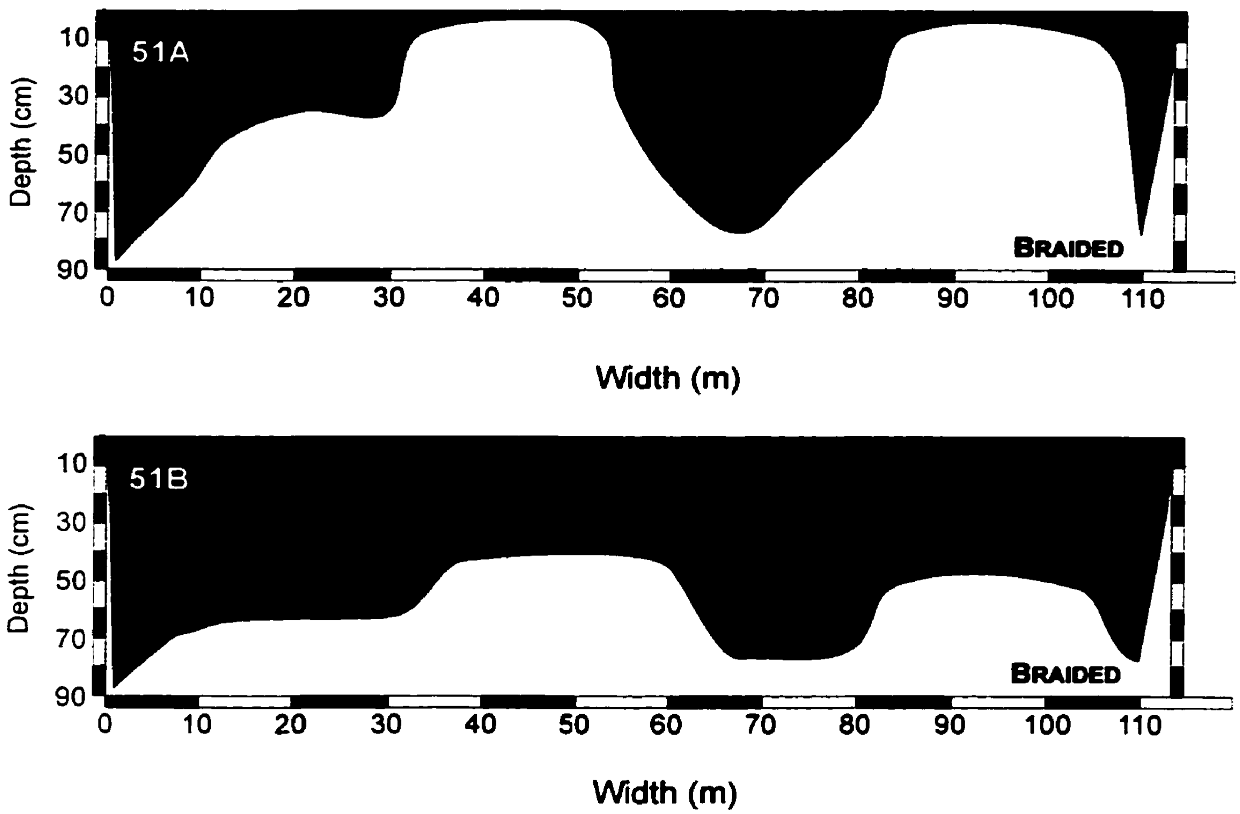


**Figure 51 – Braided channel cross section. Bars occupy a large portion of the low flow cross section. During high flow events significant portions of the bars will be in transport, thus increasing the channel capacity and bankfull discharge.**

pers. commun., 1998). The increased stream power provided by bankfull, or near bankfull discharge should be capable of mobilizing large parts of these bars. If, during these floods, even half of the bars are in motion channel capacity increases significantly. Also, removal of a portion of the bars reduces form roughness, which would enable more water to pass through the cross section. This increase in bankfull channel capacity raises the bankfull discharge to 189 $m^3/s$ in the braided reach, which is 23% greater than the meandering reach. Floods of this magnitude are rare on the Milk River, occurring only twice in the past 100 years. This would suppress the introduction of fine material to the floodplain through overbank events. Meanwhile, overbank events in the meandering reach are more common which leads to the introduction of fine material to the floodplain through flood deposits and helps to reinforce the trend. Thus, through a unique combination of slope and fluvial processes the channel banks of the meandering reach are rich in silt-clay, whereas those of the braided reach are composed primarily of sand.

The cause of the change in the valley morphology is not due to differences in bedrock lithology as the same bedrock visible at the international boundary is exposed 50 km to the south at Havre. The most obvious difference is the change in valley orientation. The meandering reach is oriented primarily east to west whereas the braided reach is approximately north-south. This change in orientation, along with the direction of the prevailing wind might prevent the development of the coulees characteristic of badland topography along the braided reach. The importance of wind to coulee formation was described by Beaty (1975) for an area around Lethbridge in southern Alberta. The windward side of valleys transverse to the prevailing wind were more prone to coulee development because of drier surfaces which support less vegetation and therefore are more susceptible to erosion.

### *Will the Braided Reach Convert to a Meandering River?*

As described earlier the difference in valley width strongly suggests that the braided reach of the Milk River has been in existence for an extended period of time. However, in certain locations in the braided reach the thalweg ricochets back and forth across the channel. It appears as though the river is attempting to assume a meandering pattern. Conversion to a meandering pattern would first require a reduction in channel width to dimensions similar to those of the meandering reach. This is necessary because, as described above, sediment transport cannot be maintained in a 100 m wide channel. In order to instigate a reduction in width a stabilizing mechanism, such as vegetation, must invade the channel bars. This process has been observed in numerous settings in the western United States. The conversion of channel bars to floodplain was observed by Graf (1978) on the Green River in southern Utah where the invasion of tamarisk stabilized the bars and led to a 27% reduction in width of the river. A similar mechanism of vegetation stabilization and channel narrowing was observed along both the Cimarron River in Kansas (Schumm and Lichty, 1963) and the Gila River in Arizona (Burkham, 1972). As described earlier there are three vegetation suppression mechanisms operating along the braided reach of the Milk River. The lack of sites stable for long enough periods to allow successful establishment, grazing by cattle, and river ice all act to prevent channel narrowing through stabilization by vegetation. The repetitive action of river ice is perhaps the main mechanism (Smith and Pearce, in press) and is what separates the Milk River from the examples above as these rivers are located in areas where river ice processes are low to non-existent.

If the Milk River somehow manages to reduce its channel width it then must increase its sinuosity from the average of 1.13 observed in the braided reach. The following formula is an alternative approach to calculating channel sinuosity using the valley and channel slope and enables prediction of what channel slope would be required for a variety of sinuosity values:

$P = Sv/Sc$ where: $S_v$ = valley slope
$S_c$ = channel slope
P = sinuosity

Using this formula the calculated sinuosity of the braided reach is 1.22 versus the measured value of 1.13. In the meandering reach the formula yields a sinuosity value of 2.06 versus the measured value of 2.03. This suggests that this formula is applicable to the Milk River. Therefore, reworking this formula ($Sc = Sv/P$) allows calculation of the channel slope given a particular valley slope and sinuosity. Given the braided reaches valley slope of 59.00 cm/km and a sinuosity of 2.00 the resulting meander channel slope would be 29.5 cm/km. Reducing the sinuosity to 1.50, which is Leopold and Wolman's (1957) minimum for a meandering river, would produce a channel slope of 39.3 cm/km. These values are 46% and 28%, respectively, below the 54.75 cm/km average channel slope of the meandering reach. Using the average discharge and width of the meandering reach along with these computed channel slopes allows calculation of the unit length and unit area stream power generated by this new meandering channel. The unit length stream power is 44.52 $N \cdot s^{-1}$ and 55.92 $N \cdot s^{-1}$ for the channel with a slope of 29.5 cm/km and 39.3 cm/km, respectively. These values are 42% and 28% below the average calculated for the meandering reach. The calculated unit area stream power for the 29.5 cm/km channel is 0.80 $N \cdot m^{-1} s^{-1}$ and 1.03 $N \cdot m^{-1} s^{-1}$ for the 39.3 cm/km channel. The 29.5 cm/km channel is 54% below the meandering reach average whereas the 39.3 cm/km is 40% lower. This supports the hypothesis that the braided channel pattern on this portion of the Milk River is the equilibrium pattern given that a meandering channel in this area, at a sinuosity of 1.50 or 2.00, does not posses the stream power necessary to maintain sediment transport.

The importance of valley slope to channel sinuosity was demonstrated through the work of Ouchi (1985). Both in a flume study zand in the field, it was shown that in a region of tectonic activity those areas that became steeper responded by increasing channel sinuosity in an attempt to off set the increase in valley slope. In the areas where valley slope diminished the river adjusted by assuming a straighter course in order to maximize the available power. Although tectonically stable the Milk River displays a similar response. In the meandering reach where the valley slope is almost double that of the braided reach the river has responded by increasing its sinuosity to an average value of 2.03. The lower valley slope of the braided reach has necessitated a straighter course as the Milk River attempts to maximize the available stream power. This can be seen in the values for maximum stream power per unit length, which instead of channel slope uses valley slope to determine the maximum stream power the river could expend. The meandering reach has a value of 164.12 $N \cdot s^{-1}$ versus 95.15 $N \cdot s^{-1}$ in the braided. Through adjustments in the channel sinuosity and, therefore, the channel slope, these values are greatly reduced in terms of stream power per unit length. The stream power per unit length in both reaches, as discussed above, is similar at 77.24 $N \cdot s^{-1}$ in the meandering and 72.94 $N \cdot s^{-1}$ in the braided. Thus, the meandering reach is operating at only 47% of its capacity in terms of the maximum available stream power. The braided reach, on the other hand, is operating at close to 77% of its maximum stream power capacity. Thus, the braided reach has little ability to increase its sinuosity because this would reduce its stream power and lead to a drastic inequity with the meandering reach.

*IS THE 1917 AND 1939 HUMAN MODIFICATIONS CAUSING CHANNEL BRAIDING?*

Given that the Milk River flows through semi-arid land, it has long been used as a source of irrigation waters. However, because of the aridity in the region the river would often run dry in the later parts of the summer prior to 1917. This was the impetus behind the 1917 diversion which takes water from the St. Mary River in order to augment flow in the Milk River. Furthering the goal of improved irrigation the Fresno Dam and Reservoir were built in 1939 to provide a constant source of water for irrigation east of Havre.

Evidence of the state of the river prior to 1917 comes mainly from various maps and local farmers whose families have lived in the region for several generations. The Kremlin Quadrangle topographic map of 1906 shows the area around Saddle Butte, which today is the area of the delta building into the Fresno Reservoir. As Figure 52 shows the Milk River in this area is depicted as wide and low in sinuosity. A much smaller scale map produced for planning purposes in

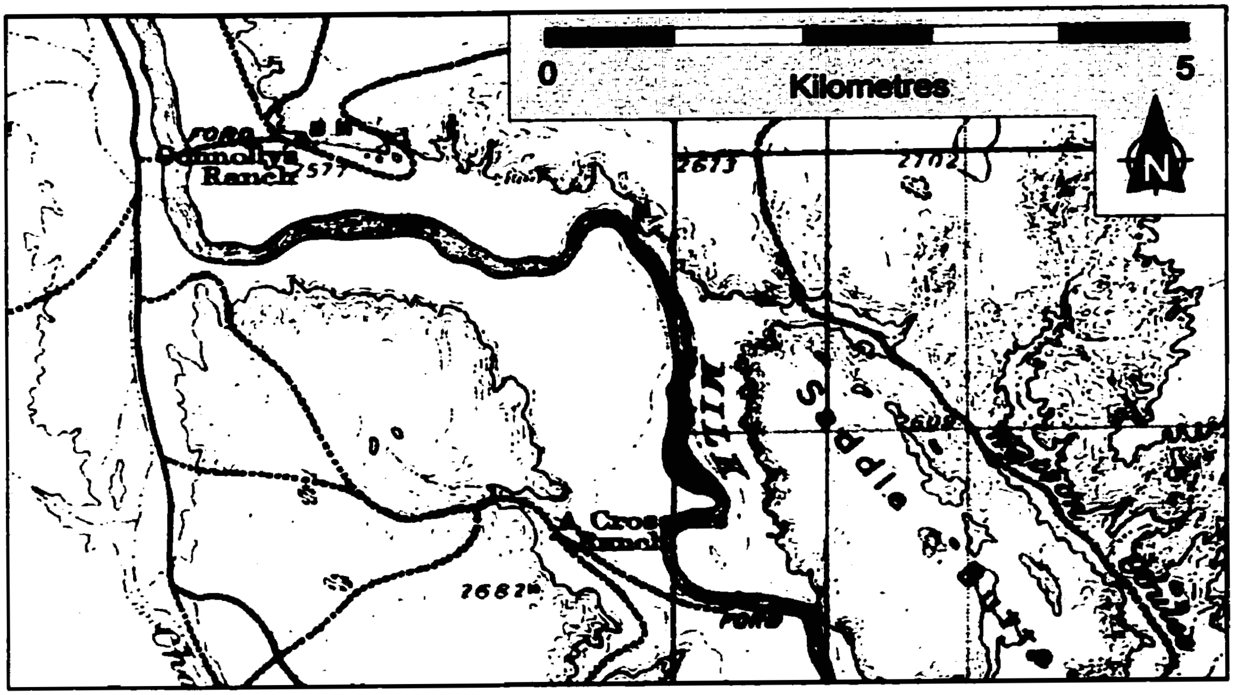


**Figure 52 – A portion of the 1906 Kremlin Quadrangle depicting a wide and low sinuosity course for the Milk River.**

1920 shows the entire Milk River drainage basin as surveyed from 1898-1917. Of interest is the area near the Eastern Crossing (Fig. 53). Above the International

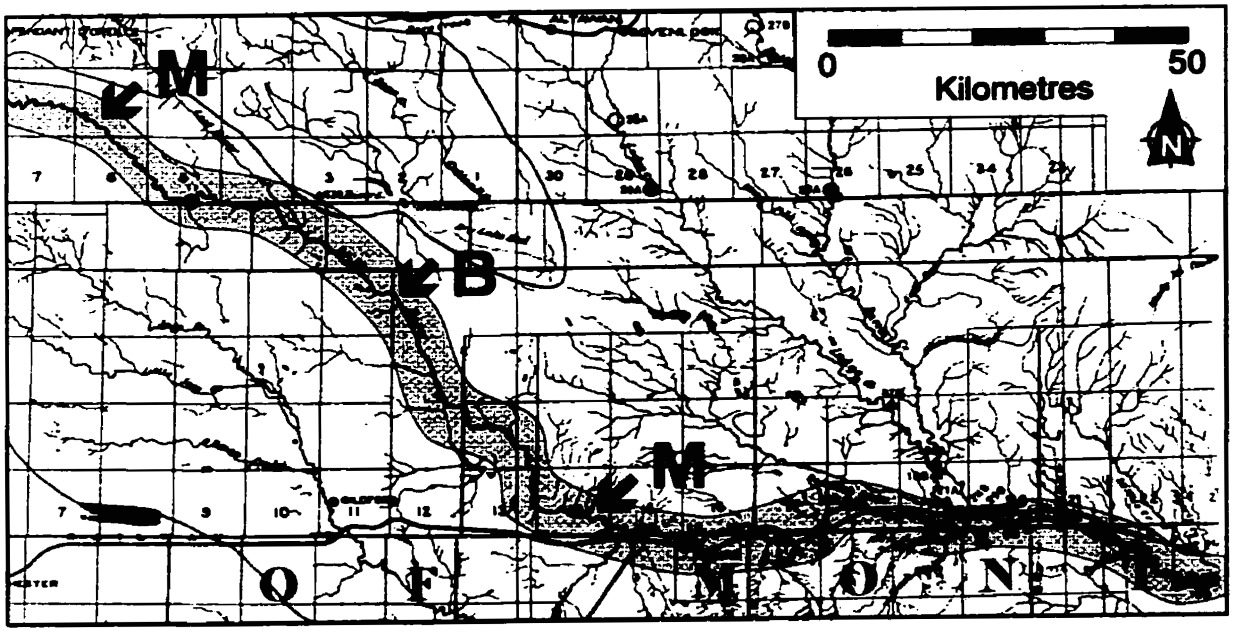


**Figure 53 – Small scale map of the area around the Eastern Crossing showing the much straighter braided reach in comparison to the sinuous channel both above and below.**

Boundary the map shows the Milk River as very sinuous. However, below the boundary the river is shown to be straight until the area where it again turns to the east and returns to a sinuous course. The final line of evidence from maps comes from cadastral maps surveyed in 1911 which show a wide and low sinuosity course for the Milk River. Discussions with local farmer Gary Meland, whose great grandfather settled in the area in the early 1900's, indicates that the Milk River of today looks very similar to the Milk River of the 1910's.

Did construction of the Fresno Dam and Reservoir in 1939 instigate adjustments along the Milk River that led to formation of the braided reach? If this was the case the braided morphology should extend directly to the delta front in the form of a braid delta. However, it has been shown that the backwater reach possesses a distinct morphology from the braided reach. Also, aerial photographs from the fall of 1939 before the Fresno Reservoir began to fill show that the braided morphology extended to the area where the Fresno Dam was constructed (Fig. 54). As described previously the Milk River's response to the Fresno Reservoir has been significant channel narrowing and straightening.

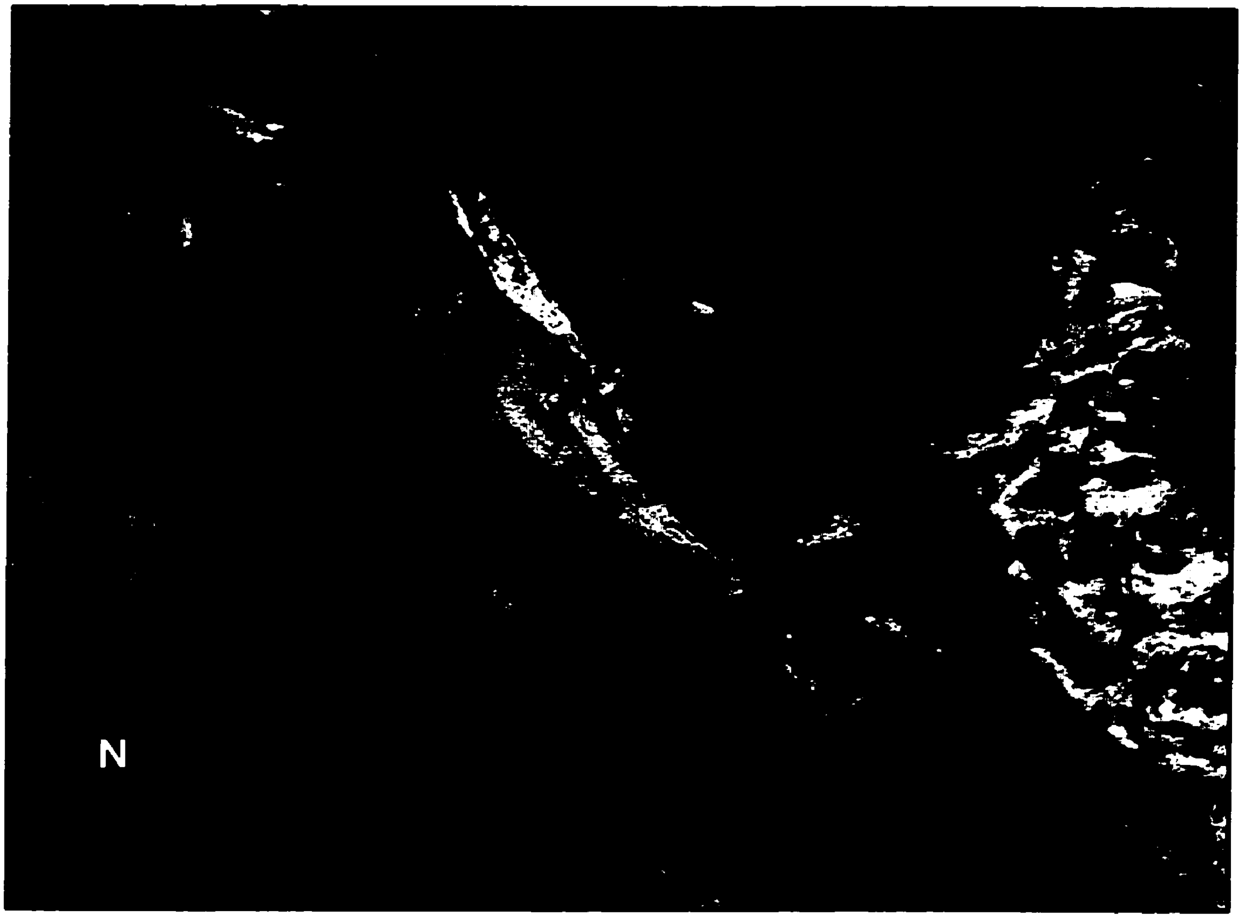


**Figure 54 - Milk River displaying braided morphology in the area of the present day Fresno Reservoir.**

Therefore, it would appear that the construction of the St. Mary diversion in 1917 and the Fresno Dam and Reservoir in 1939 are not the cause of braiding on the Milk River. The braided morphology is a natural reaction to changes in the controlling variables.

## CHAPTER 7 – CONCLUSION

The Milk River is a unique river in that its morphological transition is not accompanied by the change in variables often described in the literature. There is no obvious influx of sediment from a tributary source, the channel slope is not higher in the braided reach nor is the channel constantly shifting across the valley bottom. The majority of braided rivers occur in high stream power settings where the channel slope is high enabling significant bedload transport. However, the Milk River represents a case of braiding due to lower unit area stream power.

***Research Objective #1*** - Describe the physical characteristics of both the meandering and braided reaches of the Milk River.

The meandering reach of the Milk River is characterized by its high sinuosity (2.0) and comparatively low width/depth (88) ratio. The average channel slope of this reach is 54.75 cm/km. Cohesive channel banks with an average silt-clay content of 65.17% are found in the meandering reach. The unit area stream power which uses the average channel width of 56 m is 1.73 $N{\cdot}m^{-1}\ s^{-1}$.

A wide and shallow cross section, as indicated by the width/depth value of 304, is the dominant characteristic of the braided reach. Over the braided reach the river assumes a low sinuosity course (1.13). An important difference from the meandering reach is the lower channel slope of 48.34 cm/km. Whereas the channel banks in the meandering reach are largely composed of cohesive silt-clay, the banks of the braided reach are mainly sand with a silt-clay content of only 18.03%. The larger channel width of the braided river (99 m) in combination with the lower channel slope produces a much lower unit area stream power of only 0.70 $N \cdot m^{-1} s^{-1}$.

***Research Objective #2*** - Determine if irrigation improvements installed on the Milk River in 1917 and 1939 are responsible for the morphological transition.

One of the most pervasive geomorphic agents of the past few centuries, humans, have had major impacts on the Milk River. However, neither the 1919 diversion of the St. Mary River nor the 1939 construction of the Fresno Dam and Reservoir is directly responsible for the braided morphology of the Milk River. Historic maps, photographs and eyewitness accounts all describe the braided reach of today as similar to that prior to the modifications.

***Research Objective #3*** - Identify the factor(s) responsible for the morphological transition on the Milk River.

Of the four major mechanisms thought to cause braiding only one shows any significant change between the meandering and braided reaches of the Milk River.

(1) Discharge variability, both in the long and short term, is not of importance on the Milk River as the St. Mary diversion provides a constant supply of water. There also have been no extreme floods on the river since 1909 that could have induced large scale channel widening.

(2) In many braided rivers an abundant bedload, introduced from either local bank erosion or tributary input, exceeds the sediment transport capability of a river and leads to a braided morphology. This is not the case on the Milk River as there is no tributary input and the channel banks along the braided reach are very stable. A decrease

in the unit area stream power in the braided reach in comparison to that of the meandering reach leads to a reduction in the ability of the river to transport the imposed sediment load. Thus, instead of being overwhelmed by an influx of sediment the Milk River is overwhelmed because of a decrease in the available stream power necessary for sediment transport.

(3) The presence of a high stream power is the longest standing concept on the cause of channel braiding. The seminal paper of Leopold and Wolman (1957) ingrained this theory into the minds of many fluvial geomorphologists. However, the Milk River does not conform to this notion, as the channel slope of the braided reach is marginally lower than that of the meandering reach.

(4) The composition of the channel perimeter through which a river flows is a critical element in fluvial geomorphology. The channel boundary in the meandering reach is composed predominantly of cohesive silt-clay while the braided reach is dominated by fine sand. The cohesive channel banks in the meandering reach prevent large scale widening which could break down the helicoidal circulation currents necessary for maintenance of a meandering pattern. However, in the braided reach the sandy channel banks enabled widening and an almost doubling of the channel width. This widening, coupled with lower channel slope, reduces the unit area stream power of the braided reach to a level half that of the meandering. This reduction in available power is what leads to the inability of the Milk River to

transport the entire imposed sediment load. This promotes development of channel bars as the river deposits the sediment which it can no longer transport. Dissection of these bars as flow wanes produces the braided channel pattern.

The majority of the braided rivers described in the literature have a gravel bed where a high slope is required for bedload movement. The Milk River, on the other hand, is a sand bed river where sufficient power for the movement of sand is almost always present. Where the channel banks switch from cohesive silt-clay to fine sand the stream power changes and, thus, the sediment transport capability of the Milk River. The reduction in unit area stream power brought about by the increased width of the braided reach promotes deposition of part of the rivers sediment load. The majority of braided rivers possess excess stream power, which is used to erode the channel perimeter and introduce new sediment. This sediment eventually exceeds the rivers sediment transport capability and the deposition of bars results. The Milk River, unlike most braided rivers, is an example of braiding brought about by a reduction in the stream power available for sediment transport. Thus, braiding on the Milk River occurs in a low stream power setting produced by the change in bank strength and the concomitant reduction in available stream power.

*FUTURE RESEARCH ALONG THE MILK RIVER*

As with most research projects the answer to one question often results in the creation of several new questions:

(1) What is the history of the braided reach in terms of aggradation and/or degradation? A geophysical program using electrical resistivity could be initiated at various locations along the valley floor to identify the depth of fill. This must be coupled with vibracoring to provide control for the resistivity but also to search for dateable materials or ash layers in order to provide temporal control.

(2) Given that the morphology of the river is intimately tied into the slope process active along its length, a better understanding of why the slope morphology changes would be useful.

(3) The bankfull discharge of sand-bed braided rivers is difficult to determine given the presence of channel bars. A detailed survey of numerous channel cross sections in the fall when flow is low, and then again the next spring during higher flows. This will enable determination of how much of the bars are mobilized during high flows.

(4) With a bigger picture in mind, other sand-bed braided rivers need to be studied to determine the controlling factors. Most work into the controlling factors of braided rivers has focused on gravel-bed rivers. The majority of the studies conducted on sand-bed braided rivers have focused on the sedimentology of the deposits and not necessarily attempted to answer the question why is the river braided here and meandering there?

## *REFERENCES*

Alden, W.C., 1932, Physiography and glacial geology of eastern Montana and adjacent areas: USGS Professional Paper, 133 p.

Ashmore, P. E., 1982, Laboratory modeling of gravel braided stream morphology: Earth Surface Processes and Landforms, v. 7, p. 21-225.

Barendregt, R. W., 1977, A detailed geomorphological survey of the Pakowki-Pinhorn area of southern Alberta [Ph.D. thesis]: Queen's University, 275 p.

Barendregt, R. W., 1987, Geomorphology of the Drumheller Badlands, in Jackson, L. E. Jr., and Wilson, M. C., eds., Geology of the Calgary Area: Calgary, Canadian Society of Petroleum Geologists, p. 89-95.

Barendregt, R. W., and Ongley, E. D., 1977, Piping in the Milk River Canyon, southeastern Alberta - a contemporary dryland geomorphic process: Erosion and Solid Matter Transport in Inland Waters, International Association of Hydrological Sciences Publication No. 122, p. 233 - 243.

Barendregt, R. W., and Ongley, E. D., 1979, Slope recession in the Onefour Badlands, Alberta, Canada: an initial appraisal of contrasted moisture regimes: Canadian Journal of Earth Sciences, v. 16, p. 224 - 229.

Barendregt, R. W., and Irving, E., 1998, Changes in the extent of North American ice sheets during the late Cenozoic: Canadian Journal of Earth Sciences, v. 35, p. 504-509.

Bayrock, L. A., and Broscoe, A. J., 1972, A quantitative study of badland erosion, Dinosaur Provincial Park, Alberta, *in* International Geological Congress, Montreal, PQ, p. 95-102.

Beaney, C. L., 1998, The subglacial geomorphology of southeast Alberta: evidence for subglacial meltwater erosion [M.Sc. thesis]: University of Alberta, 136 p.

Beaty, C. B., 1975, Coulee alignment and the wind in southern Alberta, Canada: Geological Society of America, v. 86, p. 119-128.

Beaty, C. B., 1990, Milk River in southern Alberta: a classic underfit stream: The Canadian Geographer, v. 34, no. 2, p. 171 - 174.

Beaty, C. B., and Barendregt, R. W., 1987, The Milk River Canyon, Alberta: Superposition and piping in a semi-arid environment, in Beus, S. S., ed., Rocky Mountain Section of the Geological Society of America - Centennial Field Guide: Boulder, Colorado, The Geological Society of America, p. 29-32.

Begin, Z. B., 1981, The relationship between flow-shear stress and stream pattern: Journal of Hydrology, v. 52, p. 307-319.

Bostock, H. S., 1964, A provisional physiographic map of Canada: Geological Survey of Canada Paper, map 64-35.

Bradley, C. E., 1982, Modified meandering river regimes - effects on Plains Cottonwood regeneration, Milk River valley, S.E. Alberta and N. Montana [M.Sc. thesis]: University of Calgary, 124 p.

Bradley, C. E., and Smith, D. G., 1984, Meandering channel response to altered flow regime: Milk River, Alberta and Montana: Water Resources Research, v. 20, no. 12, p. 1913 - 1920.

Brice, J., 1964, Channel patterns and terraces of the Loup Rivers in Nebraska: U.S. Geological Survey Professional Paper, p. 1-41.

Brotherton, D. I., 1979, On the origin and characteristic of river channel patterns: Journal of Hydrology, v. 44, p. 211-230.

Burkham, D. E., 1972, Channel changes of the Gila River in Safford Valley, Arizona: Geological Survey Professional Paper 655 - G.

Burrows, R. L., Emmett, W. W., and Parks, B., 1981, Sediment transport in the Tanana River near Fairbanks, Alaska: Water-Resources Investigations 81-20.

Campbell, I. A., 1977, Stream discharge, suspended sediment and erosion rates in the Red Deer River basin, Alberta, Canada: Erosion and Solid Matter Transport in Inland Waters, v. International Association of Hydrological Sciences Publication No. 122, p. 244-259.

Chang, H. H., 1979, Minimum stream power and river channel patterns: Journal of Hydrology, v. 41, p. 303-327.

Chang, H. H., 1985, River morphology and thresholds: Journal of Hydraulic Engineering, v. 111, no. 3, p. 503-519.

Church, M., 1970, Baffin Island sandurs; a study of Arctic fluvial processes [Ph.D. thesis]: University of British Columbia.

Church, M., 1972, Baffin Island sandurs; a study of Arctic fluvial processes: Bulletin 216, Geological Survey of Canada, p. 208.

Davis, W. M., 1889, The geographical cycle: Geographical Journal, v. 14, p. 481-504.

Doeglas, D. J., 1951, Meanderende en verwilderde rivieren; meandering and braided rivers: Geologie en Mijnbouw, v. 9, p. 297-299.

Emmett, W. W., 1975, The channels and waters of the upper Salmon River area, Idaho: U.S. Geological Survey Professional Paper, p. 116.

Engelund, F., and Skovgaard, O., 1973, On the origin of meandering and braiding in alluvial streams: Journal of Fluid Mechanics, v. 57, no. 2, p. 289-302.

Fahnestock, R. K., 1963, Morphology and hydrology of a glacial stream; White River, Mount Rainier, Washington: USGS Geological Survey Professional Paper, p. A1-A70.

Ferguson, R. I., 1972, Channel pattern and sediment type: Area, v. 5, p. 38-41.

Ferguson, R. I., 1987, Hydraulic and sedimentary controls of channel pattern, in Richards, K., ed., River Channels - Environment and Process, p. 129-158.

Folk, R. L., 1974, Petrology of sedimentary rocks: Austin, Texas, Hemphill Pub. Co., 182 p.

Fredsøe, J., 1978, Meandering and braiding of rivers: Journal of Fluid Mechanics, v. 84, no. 4, p. 609-624.

Friedkin, J. F., 1945, A laboratory study of the meandering of alluvial rivers, in Schumm, S. A., ed., River Morphology, p. 237-281.

Germanoski, D., and Schumm, S. A., 1993, Changes in braided river morphology resulting from aggradation and degradation: The Journal of Geology, v. 101, p. 451-466.

Gilbert, G.K., 1917, Hydraulic-mining debris in the Sierra Nevada: USGS Professional Papeer 105

Gomez, B., 1991, Bedload transport: Earth-Science Reviews, v. 31, p. 89-132.

Graf, W. L., 1978, Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region: Geological Society of America Bulletin, v. 89, p. 1491-1501.

Graf, W. L., 1988, Fluvial processes in dryland rivers, Springer Series in Physical Environment: New York, USA, Springer - Verlag, 346 p.

Hein, F. J., and Walker, R. G., 1977, Bar evolution and development of stratification in the gravelly, braided, Kicking Horse River, British Columbia: Canadian Journal of Earth Sciences, v. 14, no. 4, p. 562-570.

Hjulström, F., 1935, Studies of the morphological activity of rivers as illustrated by the River Fyris: Bulletin of the Geological Institute University of Uppsala 25, 221-527.

Hong, L. B., and Davies, T. R. H., 1979, A study of stream braiding: Geological Society of America Bulletin, v. 90, no. 12, p. 1839-1859.

Jackson, L. E., Jr., Little, E. C., Leboe, E. R., and Holme, P. J., 1996, A re-evaluation of the paleogeography of the maximum continental and montane advances, southwestern Alberta: Geological Survey of Canada, Current Research 1996-A, p. 165-173.

Knighton, A. D., 1998, Fluvial forms and processes - A new perspective: New York, New York, Arnold, 383 p.

Knighton, A. D., and Nanson, G. C., 1993, Anastomosis and the continuum of channel pattern: Earth Surface Processes and Landforms, v. 18, p. 613-625.

Krumbein, W. C., 1936, The use of quartile measures in describing and comparing sediments: American Journal of Science, v. 32, no. 188, p. 98-111.

Kulig, J. J., 1996, The glaciation of the Cypress Hills of Alberta and Saskatchewan and its regional implications: Quaternary International, v. 32, p. 53-77.

Lane, E. W., 1937, Stable channels in erodible material: American Society of Civil Engineering, Transactions, v. 63, p. 123-142.

Lane, E. W., 1957, A study of the shape of channels formed by natural streams flowing in erodible material: Missouri River Division Sediment Series 9, p. 106.

Leopold, L. B., 1993, Base level rise: Gradient of deposition: Israel Journal of Earth Science, v. 41, p. 57-64.

Leopold, L. B., 1994, A view of the river: Berkeley, California, University of California at Berkeley, 298 p.

Leopold, L. B., and Bull, W. B., 1979, Base level, aggradation, and grade: Proceedings of the American Philosophy Society, v. 123, p. 160-202.

Leopold, L. B., and Wolman, M. G., 1957, River channel patterns: Braided, meandering and straight: Geological Survey Professional Paper 282 - B, p. 45 - 62.

Leopold, L. B., Wolman, M. G., and Miller, J. P., 1964, Fluvial processes in geomorphology: San Francisco, W.H. Freeman and Company, 522 p.

Locking, T., 1983, Hydrology and sediment transport in an anastomosing reach of the upper Columbia River, B.C. [M.Sc. thesis]: University of Calgary, 107 p.

Ludwig, W., and Probst, J. L., 1998, River sediment discharge to the oceans: Present-day controls and global budgets: American Journal of Science, v. 298, p. 265-295.

Mackin, J. H., 1956, Cause of braiding by a graded river: Geological Society of America Bulletin, v. 67, no. 12, Pt.2, p. 1717-1718.

McKeague, J. A., 1981, Manual on soil sampling and methods of analysis: Ottawa, Ontario, Canadian Society of Soil Science, 212 p.

Miall, A.D., 1977, A review of the braided-river depositional environment: Earth Science Reviews, v. 13 (1), p. 1-62.

Milliman, J. D., and Syvitski, J. P. M., 1992, Geomorphic/Tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers: The Journal of Geology, v. 100, p. 525-544.

Myers, T. J., and Swanson, S., 1992, Variation of stream stability with stream type and livestock bank damage in northern Nevada: Water Resources Bulletin, v. 28, no. 4, p. 743-754.

Nanson, G. C., and Knighton, A. D., 1996, Anabranching rivers: Their cause, character and classification: Earth Surface Processes and Landforms, v. 21, p. 217-239.

Nevins, T. H. F., 1969, River training - The single-thread channel: New Zealand Engineering, p. 367-373.

Osterkamp, W. R., 1979, Bed-and bank-material sampling procedures at channel-geometry sites, in National Conference on Quality of Environmental Measurements, Denver, Colorado, p. 86-89.

Osterkamp, W. R., and Hedman, E. R., 1982, Perennial-Streamflow characteristics related to channel geometry and sediment in Missouri River basin: Geological Survey Professional Paper 1242, p. 1-37.

Ouchi, S., 1985, Response of alluvial rivers to slow active tectonic movement: Geological Society of America Bulletin, v. 96 (4), p. 504-515.

Parker, G., 1976, On the cause and characteristic scales of meandering and braiding in rivers: Journal of Fluid Mechanics, v. 76, no. 3, p. 457-480.

Pettapiece, W. W., 1986, Physiographic subdivision of Alberta: Edmonton, AB, Agriculture Canada - Alberta Institute of Pedology.

Rains, R. B., Shaw, J., Skoye, R., Sjogren, D., and Kvill, D., 1993, Late Wisconsin subglacial megaflood paths in Alberta: Geology, v. 21, no. 4, p. 323-326.

Richards, K., 1982, Rivers; forms and process in alluvial channels: London, UK, Methuen, 369 p.

Rowntree, K. M., and Dollar., E.S., 1999, Vegetation controls on channel stability in the Bell River, Eastern Cape, South Africa: Earth Surface Processes and Landforms, v. 24, p. 127-134.

Rubey, W. W., 1952, Geology and mineral resources of the Hardin and Brussels quadrangles (in Illinois): U.S. Geological Survey Professional Paper. 1952., p. 179.

Schumm, S. A., 1960, The shape of alluvial channels in relation to sediment type: Geological Survey Professional Paper 352 - B, p. 17 - 30.

Schumm, S. A., 1973, Geomorphic thresholds and complex response of drainage systems, in Morisawa, M., ed., Fluvial Geomorphology: Fourth Annual Geomorphology Symposia Series: Binghampton, New York, State University at New York, p. 299 - 310.

Schumm, S. A., 1980, Some applications of the concept of geomorphic thresholds, in Coates, D. R., and Vitek, J. D., eds., Thresholds in Geomorphology: Ninth Annual Geomorphology Symposia Series: London, UK, George Allen & Unwin, p. 473 - 485.

Schumm, S. A., 1981, Evolution and response of the fluvial system, sedimentologic implications, in Ethridge, F. G., and Flores, R. M., eds., Recent and ancient nonmarine depositional environments; models for exploration: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists, p. 19-29.

Schumm, S. A., 1985, Patterns of alluvial rivers: Annual Review of Earth and Planetary Sciences, v. 13, p. 5-27.

Schumm, S. A., and Beathard, R. M., 1976, Geomorphic thresholds: An approach to river management, Rivers 76: 3rd Symposium Waterways, Harbors and Coastal Engineering Division, American Society of Civil Engineers, p. 707-724.

Schumm, S. A., and Khan, H. R., 1972, Experimental study of channel patterns: Geological Society of America Bulletin, v. 85, p. 1755 - 1770.

Schumm, S. A., and Lichty, R. W., 1963, Channel widening and flood-plain construction along Cimarron River in southwestern Kansas: Geological Survey Professional Paper 352-D, p. 71 - 88.

Schumm, S. A., and Lichty, R. W., 1965, Time, space, and causality in geomorphology: American Journal of Science, v. 263, p. 110-119.

Shaw, J., 1996, A meltwater model for Laurentide subglacial landscapes, in McCann, B., and Ford, D. C., eds., Geomorphology Sans Frontiers: Chichester, Wiley, p. 181-236.

Shaw, J., and Kellerhals, R., 1982, The composition of recent alluvial gravels in Alberta River Beds: Research Council of Alberta Bulletin 41, p. 151

Shoemaker, 1992, Subglacial floods and the origin of low-relief ice sheet lobes: Journal of Glaciology, v. 38, p. 105-112.

Smith, D. G., 1973, Aggradation of the Alexandra - North Saskatchewan River, Banff Park, Alberta, in Morisawa, M., ed., Fluvial Geomorphology: Fourth Annual Geomorphology Symposia Series: Binghampton, New York, State University of New York, p. 201 - 219.

Smith, D. G., 1976, Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river: Geological Society of America Bulletin, v. 87, p. 857-860.

Smith, D. G., 1983, Anastomosed fluvial deposits: modern examples from Western Canada, in Collinson, J. D. a. Lewin., J., ed., Modern and Ancient Fluvial Systems, Special Publication of the International Association of Sedimentologists, p. 155-168.

Smith, D. G., 1986, Anastomosing river deposits, sedimentation rates and basin subsidence, Magdalena River, northwestern Colombia, South America: Sedimentary Geology, v. 46, p. 177-196.

Smith, D. G., and Pearce, C. M., 1999, River ice and its role in limiting woodland evolvement on a sandy braid-plain, Milk River, Montana: Wetlands, p. in press.

Smith, N. D., 1970, The braided stream depositional environment: Comparison of the Platte River with some Silurian clastic rocks, North-Central Appalachians: Geological Society of America Bulletin, v. 81, p. 2993-3014.

Smith, N. D., 1971, Transverse bars and braiding in the Lower Platte River, Nebraska: Geological Society of America Bulletin, v. 82, p. 3407-3420.

Smith, N. D., 1974, Sedimentology and bar formation in the upper Kicking Horse River, a braided outwash stream: The Journal of Geology, v. 82, no. 2, p. 205-223.

Smith, N. D., and Smith, D. G., 1984, William River: An outstanding example of channel widening and braiding caused by bed-load addition: Geology, v. 12, p. 78-82.

Spitzer, M. O., 1988, Milk River sediment data: Calgary, Water Survey of Canada.

Stalker, A. MacS., 1961, Buried valleys in central and southern Alberta: Geological Survey of Canada Paper 60-32, p. 12.

Stalker, A. MacS., 1976, Quaternary stratigraphy of the southwestern Canadian prairies, in Mahaney, W. C., ed., Quaternary stratigraphy of North America: Stroudsburg, PA, Dowden, Hutchinson & Ross.

Straus, M. W., 1948, Milk River project, reclamation project data: Washington D.C., United States Department of the Interior, p. 189 - 196.

Trimble, S. W., 1994, Erosional effects of cattle on streambanks in Tennessee, U.S.A.: Earth Surface Processes and Landforms, v. 19, p. 451-464.

Trimble, S. W., 1997, Stream channel erosion and change resulting from riparian forests: Geology, v. 25, no. 5, p. 467-469.

Trimble, S. W., and Mendel, A. C., 1995, The cow as a geomorphic agent - A critical review: Geomorphology, v. 13, p. 233-253.

US Bureau of Reclamation, 1984, Fresno Reservoir - 1978 Sedimentation Survey: Billings, MT, Department of the Interior, 84 p.

Walder, J.S. 1982, Stability of sheet flow of water beneath temperate glaciers and implications for glacier surging: Journal of Glaciology, v. 28, p. 273-293.

Westgate, J. A., 1968, Surficial geology of the Foremost Cypress Hills area, Alberta: Research Council of Alberta Bulletin, v. 22, p. 122.

Williams, M. Y., and Dyer, W. S., 1930, Geology of southern Alberta and southwestern Saskatchewan: Geological Survey of Canada Memoir 163, p. 160.

Young, R. R., Burns, J. A., Smith, D. G., Arnold, L. D., and Rains, R. B., 1994, A single, late Wisconsin, Laurentide glaciation, Edmonton area and southwestern Alberta: Geology, v. 22, p. 683-686.

# Appendix 1

## Bed Material Sieving Datasheet

# Appendix 1



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0.5 | 2.26 | 0.5 | 1.73 | 0.5 | 6.55 | 0.5 | 6.80 |
| 1.0 | 1.17 | 1.0 | 1.97 | 1.0 | 5.36 | 1.0 | 5.85 |
| 1.5 | 6.04 | 1.5 | 13.82 | 1.5 | 18.89 | 1.5 | 27.14 |
| 2.0 | 50.63 | 2.0 | 119.46 | 2.0 | 95.60 | 2.0 | 131.35 |
| 2.5 | 106.84 | 2.5 | 101.36 | 2.5 | 91.64 | 2.5 | 86.99 |
| 3.0 | 63.73 | 3.0 | 41.57 | 3.0 | 50.17 | 3.0 | 30.92 |
| 3.5 | 48.41 | 3.5 | 14.13 | 3.5 | 20.15 | 3.5 | 7.45 |
| 4.0 | 13.48 | 4.0 | 2.92 | 4.0 | 5.01 | 4.0 | 1.34 |
| Pan | 5.18 | Pan | 1.99 | Pan | 3.77 | Pan | 1.16 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0.5 | 2.46 | 0.5 | 4.16 | 0.5 | 1.43 | 0.5 | 4.05 |
| 1.0 | 3.38 | 1.0 | 3.48 | 1.0 | 0.81 | 1.0 | 2.53 |
| 1.5 | 19.44 | 1.5 | 12.09 | 1.5 | 5.27 | 1.5 | 12.91 |
| 2.0 | 120.21 | 2.0 | 98.02 | 2.0 | 60.16 | 2.0 | 95.86 |
| 2.5 | 81.88 | 2.5 | 119.33 | 2.5 | 132.84 | 2.5 | 104.57 |
| 3.0 | 47.89 | 3.0 | 46.40 | 3.0 | 66.41 | 3.0 | 51.92 |
| 3.5 | 19.62 | 3.5 | 10.85 | 3.5 | 24.51 | 3.5 | 18.47 |
| 4.0 | 3.05 | 4.0 | 2.05 | 4.0 | 3.95 | 4.0 | 4.22 |
| Pan | 1.35 | Pan | 1.53 | Pan | 2.33 | Pan | 2.82 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0.5 | 3.95 | 0.5 | 0.70 | 0.5 | 0.54 | 0.5 | 0.73 |
| 1.0 | 3.86 | 1.0 | 0.85 | 1.0 | 0.66 | 1.0 | 0.85 |
| 1.5 | 24.64 | 1.5 | 6.71 | 1.5 | 17.86 | 1.5 | 7.86 |
| 2.0 | 130.88 | 2.0 | 64.82 | 2.0 | 32.41 | 2.0 | 42.41 |
| 2.5 | 83.67 | 2.5 | 125.58 | 2.5 | 86.13 | 2.5 | 86.13 |
| 3.0 | 39.19 | 3.0 | 75.92 | 3.0 | 55.25 | 3.0 | 54.25 |
| 3.5 | 9.56 | 3.5 | 20.81 | 3.5 | 44.68 | 3.5 | 30.68 |
| 4.0 | 1.23 | 4.0 | 3.10 | 4.0 | 25.42 | 4.0 | 32.82 |
| Pan | 0.67 | Pan | 1.33 | Pan | 34.12 | Pan | 44.12 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0.5 | 3.54 | 0.5 | 3.12 | 0.5 | 0.41 | 0.5 | 0.36 |
| 1.0 | 4.66 | 1.0 | 3.74 | 1.0 | 0.81 | 1.0 | 0.78 |
| 1.5 | 17.86 | 1.5 | 7.88 | 1.5 | 4.08 | 1.5 | 3.76 |
| 2.0 | 30.68 | 2.0 | 33.48 | 2.0 | 26.19 | 2.0 | 29.26 |
| 2.5 | 86.13 | 2.5 | 80.40 | 2.5 | 66.48 | 2.5 | 62.78 |
| 3.0 | 54.25 | 3.0 | 52.84 | 3.0 | 77.10 | 3.0 | 81.22 |
| 3.5 | 62.41 | 3.5 | 27.46 | 3.5 | 58.40 | 3.5 | 55.46 |
| 4.0 | 14.82 | 4.0 | 19.81 | 4.0 | 26.64 | 4.0 | 22.25 |
| Pan | 24.12 | Pan | 69.13 | Pan | 37.95 | Pan | 41.84 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0.5 | 0.51 | 0.5 | 0.75 | 0.5 | 0.98 | 0.5 | 2.65 |
| 1.0 | 0.99 | 1.0 | 0.87 | 1.0 | 0.75 | 1.0 | 1.33 |
| 1.5 | 4.22 | 1.5 | 3.47 | 1.5 | 2.72 | 1.5 | 2.60 |
| 2.0 | 33.32 | 2.0 | 32.00 | 2.0 | 30.67 | 2.0 | 52.54 |
| 2.5 | 89.54 | 2.5 | 99.68 | 2.5 | 109.81 | 2.5 | 150.48 |
| 3.0 | 58.92 | 3.0 | 67.32 | 3.0 | 75.71 | 3.0 | 66.17 |
| 3.5 | 33.87 | 3.5 | 37.51 | 3.5 | 41.15 | 3.5 | 19.07 |
| 4.0 | 26.82 | 4.0 | 21.21 | 4.0 | 15.60 | 4.0 | 2.56 |
| Pan | 50.55 | Pan | 36.05 | Pan | 21.54 | Pan | 1.45 |
| [illegible] | | | | | | | |

| | | | |
|---|---|---|---|
| 0.5 | 0.20 | 0.5 | 2.10 |
| 1.0 | 0.05 | 1.0 | 0.50 |
| 1.5 | 0.39 | 1.5 | 2.08 |
| 2.0 | 31.73 | 2.0 | 27.30 |
| 2.5 | 162.92 | 2.5 | 106.51 |
| 3.0 | 78.58 | 3.0 | 109.38 |
| 3.5 | 21.46 | 3.5 | 41.18 |
| 4.0 | 2.95 | 4.0 | 6.29 |
| Pan | 1.24 | Pan | 2.63 |
| [illegible] | | | |

# Appendix 2

## Bank Material Hydrometer Datasheet

## Appendix 2

| | | | |
|---|---|---|---|
| 0.5 | 1033.0 | 28.5 | 71.25 |
| 1 | 1028.5 | 24.0 | 60.00 |
| 3 | 1021.0 | 16.5 | 41.25 |
| 10 | 1015.0 | 10.5 | 26.25 |
| 30 | 1013.0 | 8.5 | 21.25 |
| 90 | 1012.0 | 7.5 | 18.75 |
| 270 | 1010.5 | 6.0 | 15.00 |
| 1080 | 1009.5 | 5.0 | 12.50 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5

| | | | |
|---|---|---|---|
| 0.5 | 1027.5 | 23.0 | 57.50 |
| 1 | 1024.0 | 19.5 | 48.75 |
| 3 | 1016.5 | 12.0 | 30.00 |
| 10 | 1012.5 | 8.0 | 20.00 |
| 30 | 1010.5 | 6.0 | 15.00 |
| 90 | 1010.0 | 5.5 | 13.75 |
| 270 | 1009.5 | 5.0 | 12.50 |
| 1080 | 1009.0 | 4.5 | 11.25 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5

| | | | |
|---|---|---|---|
| 0.5 | 1030.0 | 25.5 | 63.75 |
| 1 | 1026.0 | 21.5 | 53.75 |
| 3 | 1017.0 | 12.5 | 31.25 |
| 10 | 1012.0 | 7.5 | 18.75 |
| 30 | 1011.0 | 6.5 | 16.25 |
| 90 | 1010.0 | 5.5 | 13.75 |
| 270 | 1009.0 | 4.5 | 11.25 |
| 1080 | 1008.0 | 3.5 | 8.75 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5

| | | | |
|---|---|---|---|
| 0.5 | 1031.5 | 27.0 | 67.50 |
| 1 | 1026.0 | 21.5 | 53.75 |
| 3 | 1018.5 | 14.0 | 35.00 |
| 10 | 1015.5 | 11.0 | 27.50 |
| 30 | 1014.5 | 10.0 | 25.00 |
| 90 | 1013.5 | 9.0 | 22.50 |
| 270 | 1012.0 | 7.5 | 18.75 |
| 1080 | 1011.0 | 6.5 | 16.25 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5

| | | | |
|---|---|---|---|
| 0.5 | 1031.5 | 27.0 | 67.50 |
| 1 | 1028.0 | 23.5 | 58.75 |
| 3 | 1021.0 | 16.5 | 41.25 |
| 10 | 1015.5 | 11.0 | 27.50 |
| 30 | 1013.0 | 8.5 | 21.25 |
| 90 | 1012.5 | 8.0 | 20.00 |
| 270 | 1011.0 | 6.5 | 16.25 |
| 1080 | 1010.0 | 5.5 | 13.75 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5

| | | | |
|---|---|---|---|
| 0.5 | 1023.0 | 18.5 | 46.25 |
| 1 | 1021.5 | 17.0 | 42.50 |
| 3 | 1017.0 | 12.5 | 31.25 |
| 10 | 1014.0 | 9.5 | 23.75 |
| 30 | 1012.5 | 8.0 | 20.00 |
| 90 | 1011.0 | 6.5 | 16.25 |
| 270 | 1010.5 | 6.0 | 15.00 |
| 1080 | 1009.5 | 5.0 | 12.50 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1026.5 | 22.0 | 55.00 |
| 1 | 1023.0 | 18.5 | 46.25 |
| 3 | 1015.0 | 10.5 | 26.25 |
| 10 | 1011.5 | 7.0 | 17.50 |
| 30 | 1011.5 | 7.0 | 17.50 |
| 90 | 1010.0 | 5.5 | 13.75 |
| 270 | 1009.5 | 5.0 | 12.50 |
| 1080 | 1008.0 | 3.5 | 8.75 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank** [redacted]
1004.5

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1029.5 | 25.0 | 62.50 |
| 1 | 1026.0 | 21.5 | 53.75 |
| 3 | 1019.5 | 15.0 | 37.50 |
| 10 | 1015.0 | 10.5 | 26.25 |
| 30 | 1013.0 | 8.5 | 21.25 |
| 90 | 1012.5 | 8.0 | 20.00 |
| 270 | 1011.0 | 6.5 | 16.25 |
| 1080 | 1010.0 | 5.5 | 13.75 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank** [redacted]
1004.5

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1033.5 | 29.0 | 72.50 |
| 1 | 1027.5 | 23.0 | 57.50 |
| 3 | 1016.5 | 12.0 | 30.00 |
| 10 | 1011.5 | 7.0 | 17.50 |
| 30 | 1010.5 | 6.0 | 15.00 |
| 90 | 1010.0 | 5.5 | 13.75 |
| 270 | 1009.0 | 4.5 | 11.25 |
| 1080 | 1009.0 | 4.5 | 11.25 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank** [redacted]
1004.5

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1023.5 | 19.0 | 47.50 |
| 1 | 1017.0 | 12.5 | 31.25 |
| 3 | 1011.0 | 6.5 | 16.25 |
| 10 | 1010.0 | 5.5 | 13.75 |
| 30 | 1010.0 | 5.5 | 13.75 |
| 90 | 1009.0 | 4.5 | 11.25 |
| 270 | 1008.0 | 3.5 | 8.75 |
| 1080 | 1008.0 | 3.5 | 8.75 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank** [redacted]
1004.5

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1037.0 | 32.5 | 81.25 |
| 1 | 1032.5 | 28.0 | 70.00 |
| 3 | 1021.5 | 17.0 | 42.50 |
| 10 | 1015.5 | 11.0 | 27.50 |
| 30 | 1013.5 | 9.0 | 22.50 |
| 90 | 1012.5 | 8.0 | 20.00 |
| 270 | 1011.5 | 7.0 | 17.50 |
| 1080 | 1009.5 | 5.0 | 12.50 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1034.5 | 30.0 | 75.00 |
| 1 | 1030.0 | 25.5 | 63.75 |
| 3 | 1019.5 | 15.0 | 37.50 |
| 10 | 1014.0 | 9.5 | 23.75 |
| 30 | 1012.5 | 8.0 | 20.00 |
| 90 | 1011.0 | 6.5 | 16.25 |
| 270 | 1010.0 | 5.5 | 13.75 |
| 1080 | 1009.0 | 4.5 | 11.25 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1037.0 | 32.5 | 81.25 |
| 1 | 1034.0 | 29.5 | 73.75 |
| 3 | 1024.5 | 20.0 | 50.00 |
| 10 | 1018.5 | 14.0 | 35.00 |
| 30 | 1015.5 | 11.0 | 27.50 |
| 90 | 1014.0 | 9.5 | 23.75 |
| 270 | 1012.0 | 7.5 | 18.75 |
| 1080 | 1010.5 | 6.0 | 15.00 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1025.5 | 21.0 | 52.50 |
| 1 | 1023.0 | 18.5 | 46.25 |
| 3 | 1017.0 | 12.5 | 31.25 |
| 10 | 1013.5 | 9.0 | 22.50 |
| 30 | 1011.0 | 6.5 | 16.25 |
| 90 | 1010.0 | 5.5 | 13.75 |
| 270 | 1009.5 | 5.0 | 12.50 |
| 1080 | 1008.0 | 3.5 | 8.75 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1022.5 | 18.0 | 45.00 |
| 1 | 1021.0 | 16.5 | 41.25 |
| 3 | 1016.5 | 12.0 | 30.00 |
| 10 | 1013.0 | 8.5 | 21.25 |
| 30 | 1010.5 | 6.0 | 15.00 |
| 90 | 1009.5 | 5.0 | 12.50 |
| 270 | 1009.0 | 4.5 | 11.25 |
| 1080 | 1008.0 | 3.5 | 8.75 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1034.5 | 30.0 | 75.00 |
| 1 | 1032.5 | 28.0 | 70.00 |
| 3 | 1024.5 | 20.0 | 50.00 |
| 10 | 1018.5 | 14.0 | 35.00 |
| 30 | 1014.5 | 10.0 | 25.00 |
| 90 | 1013.0 | 8.5 | 21.25 |
| 270 | 1012.0 | 7.5 | 18.75 |
| 1080 | 1010.5 | 6.0 | 15.00 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1034.0 | 29.5 | 73.75 |
| 1 | 1025.0 | 20.5 | 51.25 |
| 3 | 1017.5 | 13.0 | 32.50 |
| 10 | 1015.0 | 10.5 | 26.25 |
| 30 | 1014.0 | 9.5 | 23.75 |
| 90 | 1013.0 | 8.5 | 21.25 |
| 270 | 1012.0 | 7.5 | 18.75 |
| 1080 | 1011.0 | 6.5 | 16.25 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1036.0 | 31.5 | 78.75 |
| 1 | 1032.5 | 28.0 | 70.00 |
| 3 | 1023.0 | 18.5 | 46.25 |
| 10 | 1018.0 | 13.5 | 33.75 |
| 30 | 1014.0 | 9.5 | 23.75 |
| 90 | 1012.0 | 7.5 | 18.75 |
| 270 | 1012.0 | 7.5 | 18.75 |
| 1080 | 1010.5 | 6.0 | 15.00 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

| [redacted] | | | |
|---|---|---|---|
| 0.5 | 1016.5 | 12.0 | 30.00 |
| 1 | 1013.5 | 9.0 | 22.50 |
| 3 | 1010.5 | 6.0 | 15.00 |
| 10 | 1009.0 | 4.5 | 11.25 |
| 30 | 1008.5 | 4.0 | 10.00 |
| 90 | 1008.5 | 4.0 | 10.00 |
| 270 | 1008.0 | 3.5 | 8.75 |
| 1080 | 1008.0 | 3.5 | 8.75 |
| **W = Dry Sample Weight (g)** | | | |
| 40.0 | | | |
| **Rc = Blank** | | | |
| 1004.5 | | | [redacted] |

| [redacted] | | | |
|---|---|---|---|
| 0.5 | 1016.0 | 11.5 | 28.75 |
| 1 | 1012.0 | 7.5 | 18.75 |
| 3 | 1009.5 | 5.0 | 12.50 |
| 10 | 1009.5 | 5.0 | 12.50 |
| 30 | 1009.0 | 4.5 | 11.25 |
| 90 | 1008.5 | 4.0 | 10.00 |
| 270 | 1008.0 | 3.5 | 8.75 |
| 1080 | 1008.0 | 3.5 | 8.75 |
| **W = Dry Sample Weight (g)** | | | |
| 40.0 | | | |
| **Rc = Blank** | | | |
| 1004.5 | | | [redacted] |

| [redacted] | | | |
|---|---|---|---|
| 0.5 | 1009.0 | 4.5 | 11.25 |
| 1 | 1008.5 | 4.0 | 10.00 |
| 3 | 1008.0 | 3.5 | 8.75 |
| 10 | 1008.0 | 3.5 | 8.75 |
| 30 | 1008.0 | 3.5 | 8.75 |
| 90 | 1008.0 | 3.5 | 8.75 |
| 270 | 1007.5 | 3.0 | 7.50 |
| 1080 | 1007.5 | 3.0 | 7.50 |
| **W = Dry Sample Weight (g)** | | | |
| 40.0 | | | |
| **Rc = Blank** | | | |
| 1004.5 | | | [redacted] |

| [redacted] | | | |
|---|---|---|---|
| 0.5 | 1011.5 | 7.0 | 17.50 |
| 1 | 1010.0 | 5.5 | 13.75 |
| 3 | 1009.5 | 5.0 | 12.50 |
| 10 | 1009.5 | 5.0 | 12.50 |
| 30 | 1009.0 | 4.5 | 11.25 |
| 90 | 1008.0 | 3.5 | 8.75 |
| 270 | 1007.5 | 3.0 | 7.50 |
| 1080 | 1007.0 | 2.5 | 6.25 |
| **W = Dry Sample Weight (g)** | | | |
| 40.0 | | | |
| **Rc = Blank** | | | |
| 1004.5 | | | [redacted] |

| [redacted] | | | |
|---|---|---|---|
| 0.5 | 1011.0 | 6.5 | 16.25 |
| 1 | 1010.5 | 6.0 | 15.00 |
| 3 | 1010.0 | 5.5 | 13.75 |
| 10 | 1009.0 | 4.5 | 11.25 |
| 30 | 1009.0 | 4.5 | 11.25 |
| 90 | 1008.5 | 4.0 | 10.00 |
| 270 | 1008.5 | 4.0 | 10.00 |
| 1080 | 1008.0 | 3.5 | 8.75 |
| **W = Dry Sample Weight (g)** | | | |
| 40.0 | | | |
| **Rc = Blank** | | | |
| 1004.5 | | | [redacted] |

| [redacted] | | | |
|---|---|---|---|
| 0.5 | 1012.0 | 7.5 | 18.75 |
| 1 | 1011.5 | 7.0 | 17.50 |
| 3 | 1010.0 | 5.5 | 13.75 |
| 10 | 1009.5 | 5.0 | 12.50 |
| 30 | 1009.5 | 5.0 | 12.50 |
| 90 | 1008.5 | 4.0 | 10.00 |
| 270 | 1008.0 | 3.5 | 8.75 |
| 1080 | 1008.0 | 3.5 | 8.75 |
| **W = Dry Sample Weight (g)** | | | |
| 40.0 | | | |
| **Rc = Blank** | | | |
| 1004.5 | | | [redacted] |

| [redacted] | | | |
|---|---|---|---|
| 0.5 | 1008.0 | 3.5 | 8.75 |
| 1 | 1007.5 | 3.0 | 7.50 |
| 3 | 1007.5 | 3.0 | 7.50 |
| 10 | 1007.5 | 3.0 | 7.50 |
| 30 | 1007.5 | 3.0 | 7.50 |
| 90 | 1007.5 | 3.0 | 7.50 |
| 270 | 1007.5 | 3.0 | 7.50 |
| 1080 | 1007.5 | 3.0 | 7.50 |
| **W = Dry Sample Weight (g)** | | | |
| 40.0 | | | |
| **Rc = Blank** | | | |
| 1004.5 | | | [redacted] |

Missing 13 RB

Missing 14 LB

| [redacted] | | | |
|---|---|---|---|
| 0.5 | 1011.0 | 6.5 | 16.25 |
| 1 | 1010.0 | 5.5 | 13.75 |
| 3 | 1010.0 | 5.5 | 13.75 |
| 10 | 1009.5 | 5.0 | 12.50 |
| 30 | 1009.0 | 4.5 | 11.25 |
| 90 | 1008.5 | 4.0 | 10.00 |
| 270 | 1008.0 | 3.5 | 8.75 |
| 1080 | 1008.0 | 3.5 | 8.75 |
| **W = Dry Sample Weight (g)** | | | |
| 40.0 | | | |
| **Rc = Blank** | | | |
| 1004.5 | | | [redacted] |

| [redacted] | | | |
|---|---|---|---|
| 0.5 | 1009.0 | 4.5 | 11.25 |
| 1 | 1008.5 | 4.0 | 10.00 |
| 3 | 1008.0 | 3.5 | 8.75 |
| 10 | 1008.0 | 3.5 | 8.75 |
| 30 | 1008.0 | 3.5 | 8.75 |
| 90 | 1008.0 | 3.5 | 8.75 |
| 270 | 1008.0 | 3.5 | 8.75 |
| 1080 | 1008.0 | 3.5 | 8.75 |
| **W = Dry Sample Weight (g)** | | | |
| 40.0 | | | |
| **Rc = Blank** | | | |
| 1004.5 | | | [redacted] |

| [redacted] | | | |
|---|---|---|---|
| 0.5 | 1014.5 | 10.0 | 25.00 |
| 1 | 1012.0 | 7.5 | 18.75 |
| 3 | 1009.5 | 5.0 | 12.50 |
| 10 | 1009.5 | 5.0 | 12.50 |
| 30 | 1009.0 | 4.5 | 11.25 |
| 90 | 1008.5 | 4.0 | 10.00 |
| 270 | 1008.0 | 3.5 | 8.75 |
| 1080 | 1008.0 | 3.5 | 8.75 |
| **W = Dry Sample Weight (g)** | | | |
| 40.0 | | | |
| **Rc = Blank** | | | |
| 1004.5 | | | [redacted] |

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1012.5 | 8.0 | 20.00 |
| 1 | 1011.0 | 6.5 | 16.25 |
| 3 | 1010.5 | 6.0 | 15.00 |
| 10 | 1009.5 | 5.0 | 12.50 |
| 30 | 1009.0 | 4.5 | 11.25 |
| 90 | 1009.0 | 4.5 | 11.25 |
| 270 | 1008.5 | 4.0 | 10.00 |
| 1080 | 1008.0 | 3.5 | 8.75 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1014.0 | 9.5 | 23.75 |
| 1 | 1012.5 | 8.0 | 20.00 |
| 3 | 1010.0 | 5.5 | 13.75 |
| 10 | 1009.5 | 5.0 | 12.50 |
| 30 | 1009.0 | 4.5 | 11.25 |
| 90 | 1008.5 | 4.0 | 10.00 |
| 270 | 1008.0 | 3.5 | 8.75 |
| 1080 | 1008.0 | 3.5 | 8.75 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1016.0 | 11.5 | 28.75 |
| 1 | 1015.0 | 10.5 | 26.25 |
| 3 | 1011.0 | 6.5 | 16.25 |
| 10 | 1010.5 | 6.0 | 15.00 |
| 30 | 1010.0 | 5.5 | 13.75 |
| 90 | 1009.5 | 5.0 | 12.50 |
| 270 | 1009.5 | 5.0 | 12.50 |
| 1080 | 1009.0 | 4.5 | 11.25 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1019.0 | 14.5 | 36.25 |
| 1 | 1019.0 | 14.5 | 36.25 |
| 3 | 1014.0 | 9.5 | 23.75 |
| 10 | 1012.5 | 8.0 | 20.00 |
| 30 | 1011.5 | 7.0 | 17.50 |
| 90 | 1010.5 | 6.0 | 15.00 |
| 270 | 1009.5 | 5.0 | 12.50 |
| 1080 | 1009.0 | 4.5 | 11.25 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1011.0 | 6.5 | 16.25 |
| 1 | 1010.5 | 6.0 | 15.00 |
| 3 | 1009.5 | 5.0 | 12.50 |
| 10 | 1009.0 | 4.5 | 11.25 |
| 30 | 1008.5 | 4.0 | 10.00 |
| 90 | 1008.5 | 4.0 | 10.00 |
| 270 | 1008.0 | 3.5 | 8.75 |
| 1080 | 1008.0 | 3.5 | 8.75 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

[redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1012.0 | 7.5 | 18.75 |
| 1 | 1011.5 | 7.0 | 17.50 |
| 3 | 1010.0 | 5.5 | 13.75 |
| 10 | 1009.5 | 5.0 | 12.50 |
| 30 | 1009.0 | 4.5 | 11.25 |
| 90 | 1008.5 | 4.0 | 10.00 |
| 270 | 1008.0 | 3.5 | 8.75 |
| 1080 | 1008.0 | 3.5 | 8.75 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5 [redacted]

| | | | |
|---|---|---|---|
| 0.5 | 1010.5 | 6.0 | 15.00 |
| 1 | 1010.0 | 5.5 | 13.75 |
| 3 | 1009.0 | 4.5 | 11.25 |
| 10 | 1009.0 | 4.5 | 11.25 |
| 30 | 1008.5 | 4.0 | 10.00 |
| 90 | 1008.5 | 4.0 | 10.00 |
| 270 | 1008.0 | 3.5 | 8.75 |
| 1080 | 1008.0 | 3.5 | 8.75 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5

| | | | |
|---|---|---|---|
| 0.5 | 1013.0 | 8.5 | 21.25 |
| 1 | 1012.0 | 7.5 | 18.75 |
| 3 | 1010.0 | 5.5 | 13.75 |
| 10 | 1009.5 | 5.0 | 12.50 |
| 30 | 1009.0 | 4.5 | 11.25 |
| 90 | 1009.0 | 4.5 | 11.25 |
| 270 | 1008.0 | 3.5 | 8.75 |
| 1080 | 1008.0 | 3.5 | 8.75 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5

| | | | |
|---|---|---|---|
| 0.5 | 1041.0 | 36.5 | 91.25 |
| 1 | 1038.0 | 33.5 | 83.75 |
| 3 | 1033.0 | 28.5 | 71.25 |
| 10 | 1024.0 | 19.5 | 48.75 |
| 30 | 1020.0 | 15.5 | 38.75 |
| 90 | 1018.5 | 14.0 | 35.00 |
| 270 | 1016.5 | 12.0 | 30.00 |
| 1080 | 1014.5 | 10.0 | 25.00 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5

| | | | |
|---|---|---|---|
| 0.5 | 1032.0 | 27.5 | 68.75 |
| 1 | 1026.0 | 21.5 | 53.75 |
| 3 | 1016.0 | 11.5 | 28.75 |
| 10 | 1012.0 | 7.5 | 18.75 |
| 30 | 1011.0 | 6.5 | 16.25 |
| 90 | 1010.0 | 5.5 | 13.75 |
| 270 | 1010.0 | 5.5 | 13.75 |
| 1080 | 1009.0 | 4.5 | 11.25 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5

| | | | |
|---|---|---|---|
| 0.5 | 1040.0 | 35.5 | 88.75 |
| 1 | 1037.0 | 32.5 | 81.25 |
| 3 | 1030.5 | 26.0 | 65.00 |
| 10 | 1025.0 | 20.5 | 51.25 |
| 30 | 1021.5 | 17.0 | 42.50 |
| 90 | 1018.5 | 14.0 | 35.00 |
| 270 | 1017.0 | 12.5 | 31.25 |
| 1080 | 1015.0 | 10.5 | 26.25 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5

| | | | |
|---|---|---|---|
| 0.5 | 1036.0 | 31.5 | 78.75 |
| 1 | 1029.0 | 24.5 | 61.25 |
| 3 | 1018.0 | 13.5 | 33.75 |
| 10 | 1014.0 | 9.5 | 23.75 |
| 30 | 1011.5 | 7.0 | 17.50 |
| 90 | 1010.5 | 6.0 | 15.00 |
| 270 | 1009.5 | 5.0 | 12.50 |
| 1080 | 1009.0 | 4.5 | 11.25 |

**W = Dry Sample Weight (g)**
40.0
**Rc = Blank**
1004.5

| [redacted] | | | |
|---|---|---|---|
| 0.5 | 1043.0 | 38.5 | 96.25 |
| 1 | 1041.5 | 37.0 | 92.50 |
| 3 | 1036.0 | 31.5 | 78.75 |
| 10 | 1029.5 | 25.0 | 62.50 |
| 30 | 1025.0 | 20.5 | 51.25 |
| 90 | 1022.0 | 17.5 | 43.75 |
| 270 | 1020.0 | 15.5 | 38.75 |
| 1080 | 1016.5 | 12.0 | 30.00 |
| **W = Dry Sample Weight (g)** | | | |
| 40.0 | | | |
| **Rc = Blank** | | | |
| 1004.5 | | | [redacted] |

| [redacted] | | | |
|---|---|---|---|
| 0.5 | 1038.0 | 33.5 | 83.75 |
| 1 | 1035.0 | 30.5 | 76.25 |
| 3 | 1026.0 | 21.5 | 53.75 |
| 10 | 1020.5 | 16.0 | 40.00 |
| 30 | 1017.0 | 12.5 | 31.25 |
| 90 | 1015.0 | 10.5 | 26.25 |
| 270 | 1013.5 | 9.0 | 22.50 |
| 1080 | 1012.5 | 8.0 | 20.00 |
| **W = Dry Sample Weight (g)** | | | |
| 40.0 | | | |
| **Rc = Blank** | | | |
| 1004.5 | | | [redacted] |

# Appendix 3

## Channel Slope and Width Measurements

## Appendix 3

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) | | Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|---|---|---|---|---|
| 77850 | 3872.70 | 41.0 | 51.54 | | 74500 | 3699.90 | 39.0 | 46.00 |
| 77800 | 3872.30 | 49.0 | 50.86 | | 74400 | 3695.30 | 42.0 | 46.00 |
| 77700 | 3864.30 | 41.0 | 48.47 | | 74300 | 3690.70 | 36.0 | 50.60 |
| 77675 | 3861.00 | 26.0 | 49.16 | | 74200 | 3686.10 | 37.0 | 50.60 |
| 77650 | 3859.05 | 28.5 | 52.20 | | 74100 | 3681.50 | 69.0 | 50.60 |
| 77600 | 3857.10 | 31.0 | 51.80 | | 74000 | 3676.90 | 72.0 | 50.60 |
| 77550 | 3853.80 | 35.0 | 49.30 | | 73900 | 3672.30 | 52.0 | 50.60 |
| 77450 | 3851.80 | 40.0 | 46.80 | | 73800 | 3667.70 | 33.0 | 50.60 |
| 77400 | 3848.80 | 45.0 | 47.60 | | 73750 | 3663.10 | 25.0 | 55.20 |
| 77300 | 3844.10 | 43.0 | 49.80 | | 73700 | 3658.50 | 40.0 | 53.50 |
| 77250 | 3841.20 | 41.0 | 50.80 | | 73650 | 3656.20 | 45.5 | 53.50 |
| 77200 | 3839.20 | 20.0 | 52.10 | | 73600 | 3653.90 | 51.0 | 50.50 |
| [redacted] | | | | 1 | 73500 | 3649.30 | 45.0 | 50.70 |
| 77000 | 3831.50 | 33.0 | 50.90 | | 73400 | 3644.70 | 49.0 | 49.30 |
| 76900 | 3826.00 | 59.0 | 51.50 | | 73300 | 3640.10 | 32.0 | 47.90 |
| 76800 | 3820.50 | 30.0 | 53.40 | | 73250 | 3635.50 | 48.0 | 46.50 |
| 76700 | 3815.00 | 65.0 | 55.30 | | 73200 | 3632.60 | 59.0 | 41.90 |
| 76650 | 3812.25 | 71.5 | 53.40 | | 73150 | 3631.00 | 75.0 | 41.20 |
| 76600 | 3809.50 | 78.0 | 55.30 | | 73100 | 3629.40 | 91.0 | 40.50 |
| 76525 | 3804.00 | 32.0 | 54.00 | | 73000 | 3626.20 | 38.0 | 40.80 |
| 76500 | 3803.00 | 54.0 | 52.80 | | 72900 | 3623.00 | 44.0 | 41.00 |
| 76400 | 3796.70 | 32.0 | 51.60 | | 72800 | 3619.80 | 49.0 | 46.00 |
| 76350 | 3793.40 | 39.0 | 50.40 | | 72700 | 3616.60 | 56.0 | 43.30 |
| 76300 | 3793.20 | 43.0 | 49.80 | 3 | [redacted] | | | |
| 76225 | 3789.70 | 68.0 | 49.20 | | 72600 | 3613.40 | 51.0 | 44.90 |
| 76200 | 3785.80 | 77.0 | 48.00 | | 72500 | 3608.50 | 63.0 | 56.00 |
| 76100 | 3781.80 | 60.0 | 49.20 | | 72400 | 3603.70 | 62.0 | 56.00 |
| 76000 | 3777.50 | 43.0 | 47.00 | | 72350 | 3598.90 | 58.0 | 62.30 |
| 75900 | 3773.20 | 38.0 | 45.00 | | 72300 | 3594.10 | 42.0 | 71.80 |
| 75800 | 3768.90 | 46.0 | 46.00 | | 72200 | 3589.30 | 42.0 | 78.10 |
| 75700 | 3764.60 | 35.0 | 49.20 | | 72150 | 3586.90 | 38.0 | 84.40 |
| 75650 | 3762.45 | 38.5 | 54.90 | | 72100 | 3584.50 | 34.0 | 87.55 |
| 75600 | 3760.30 | 42.0 | 54.60 | | 72075 | 3579.70 | 30.0 | 90.70 |
| 75500 | 3756.00 | 48.0 | 54.90 | | 71975 | 3570.20 | 36.0 | 95.30 |
| 75400 | 3751.70 | 53.0 | 55.20 | | 71925 | 3560.70 | 24.0 | 94.90 |
| 75300 | 3747.40 | 43.0 | 55.50 | | 71875 | 3551.20 | 31.0 | 90.10 |
| [redacted] | | | | 2 | 71775 | 3541.70 | 34.0 | 89.90 |
| 75225 | 3737.60 | 55.0 | 55.80 | | 71675 | 3532.20 | 44.0 | 89.70 |
| 75200 | 3736.60 | 64.0 | 55.50 | | 71650 | 3527.45 | 39.5 | 87.30 |
| 75100 | 3726.90 | 44.0 | 56.40 | | 71575 | 3522.70 | 35.0 | 84.70 |
| 75000 | 3722.90 | 35.0 | 56.70 | | 71475 | 3513.20 | 37.0 | 84.40 |
| 74900 | 3718.30 | 32.0 | 56.40 | | 71375 | 3508.80 | 52.0 | 70.00 |
| 74800 | 3713.70 | 52.0 | 56.70 | | 71275 | 3504.20 | 55.0 | 67.50 |
| 74700 | 3709.10 | 30.0 | 45.40 | | 71175 | 3499.60 | 45.0 | 62.30 |
| 74650 | 3706.80 | 35.0 | 50.50 | | 71075 | 3495.00 | 75.0 | 58.45 |
| 74600 | 3704.50 | 40.0 | 45.40 | | 71025 | 3490.40 | 53.0 | 54.60 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) | | Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|---|---|---|---|---|
| 70975 | 3485.8 | 44 | 51.8 | | 67575 | 3346.80 | 44.0 | 31.40 |
| 70875 | 3481.2 | 32 | 52.4 | | 67525 | 3345.00 | 52.0 | 33.70 |
| 70810 | 3476.6 | 45 | 52.8 | | 67425 | 3340.80 | 82.0 | 36.00 |
| 70775 | 3474.2 | 58 | 53.2 | | 67325 | 3316.20 | 38.0 | 42.40 |
| 70675 | 3469.90 | 62.0 | 53.20 | | 67275 | 3332.60 | 30.0 | 38.30 |
| 70650 | 3469.00 | 63.0 | 53.20 | | 67175 | 3328.50 | 49.0 | 48.55 |
| 70575 | 3468.10 | 65.0 | 58.60 | | 67075 | 3324.40 | 32.0 | 50.60 |
| 70525 | 3466.70 | 85.0 | 59.00 | | 66975 | 3320.30 | 77.0 | 55.50 |
| 70425 | 3461.40 | 65.0 | 55.65 | | 66875 | 3316.20 | 38.0 | 58.60 |
| 70375 | 3456.40 | 45.0 | 54.80 | | 66775 | 3312.10 | 46.0 | 54.90 |
| 70275 | 3451.40 | 41.0 | 52.80 | | 66725 | 3308.00 | 56.0 | 54.90 |
| 70175 | 3446.40 | 45.0 | 52.80 | | 66710 | 3303.90 | 59.0 | 55.40 |
| 70125 | 3441.40 | 42.0 | 53.50 | | 66650 | 3300.05 | 60.5 | 55.40 |
| 70075 | 3436.40 | 41.0 | 55.10 | | 66575 | 3296.20 | 62.0 | 55.40 |
| 69975 | 3431.40 | 50.0 | 56.70 | | 66475 | 3289.50 | 64.0 | 54.20 |
| 69950 | 3430.15 | 49.0 | 57.65 | | 66375 | 3282.20 | 38.0 | 52.80 |
| 69925 | 3428.90 | 49.0 | 57.65 | | 66275 | 3277.70 | 55.0 | 54.30 |
| 69875 | 3426.40 | 48.0 | 55.30 | | 66175 | 3273.10 | 71.0 | 47.15 |
| 69775 | 3421.40 | 77.0 | 55.40 | | 66075 | 3269.00 | 74.0 | 46.10 |
| 69675 | 3416.40 | 78.0 | 60.60 | | 65975 | 3266.10 | 69.0 | 45.30 |
| 69650 | 3413.90 | 58.5 | 60.60 | | 65875 | 3263.40 | 118.0 | 46.10 |
| 69575 | 3411.40 | 39.0 | 55.70 | | 65775 | 3257.80 | 92.0 | 45.30 |
| 69475 | 3406.40 | 45.0 | 55.80 | | 65675 | 3252.90 | 75.0 | 41.50 |
| [redacted] | | | | 4 | 65650 | 3252.20 | 75.0 | 48.10 |
| 69375 | 3401.10 | 26.0 | 55.85 | | 65625 | 3251.50 | 75.0 | 48.10 |
| 69275 | 3396.00 | 53.0 | 55.90 | | 65575 | 3250.10 | 75.0 | 47.30 |
| 69225 | 3390.90 | 31.0 | 53.00 | | 65475 | 3244.20 | 45.0 | 47.40 |
| 69175 | 3385.80 | 28.0 | 49.80 | | 65375 | 3240.70 | 51.0 | 49.60 |
| 69075 | 3380.70 | 29.0 | 48.20 | | 65275 | 3235.20 | 63.0 | 49.90 |
| 68975 | 3375.60 | 50.0 | 46.60 | | 65225 | 3234.60 | 64.0 | 50.30 |
| 68950 | 3374.33 | 52.8 | 43.40 | | 65175 | 3225.00 | 59.0 | 52.00 |
| 68925 | 3373.05 | 55.5 | 39.90 | | 65075 | 3221.70 | 60.0 | 53.70 |
| 68875 | 3370.50 | 61.0 | 39.90 | | 64975 | 3218.70 | 68.0 | 51.80 |
| 68725 | 3368.40 | 78.0 | 36.60 | | 64875 | 3213.80 | 69.0 | 52.40 |
| 68675 | 3366.60 | 72.0 | 28.20 | | 64775 | 3207.90 | 55.0 | 52.70 |
| 68650 | 3365.70 | 78.5 | 28.20 | | 64675 | 3202.60 | 68.0 | 54.40 |
| 68575 | 3364.80 | 85.0 | 24.90 | | 64650 | 3200.20 | 71.5 | 48.20 |
| 68475 | 3363.00 | 64.0 | 21.60 | | 64625 | 3197.80 | 75.0 | 48.20 |
| 68375 | 3361.20 | 44.0 | 18.30 | | 64575 | 3196.40 | 79.0 | 54.00 |
| 68275 | 3359.40 | 39.0 | 18.00 | | 64475 | 3192.40 | 58.0 | 55.00 |
| 68175 | 3357.60 | 30.0 | 18.00 | | 64395 | 3188.30 | 73.0 | 55.00 |
| 68075 | 3355.80 | 46.0 | 18.00 | | 64275 | 3182.50 | 76.0 | 54.00 |
| 67975 | 3354.00 | 55.0 | 18.00 | | 64225 | 3180.20 | 66.0 | 53.60 |
| 67875 | 3352.20 | 52.0 | 20.40 | | 64175 | 3176.80 | 56.0 | 53.65 |
| 67775 | 3350.40 | 50.0 | 26.80 | | 64100 | 3174.50 | 64.0 | 53.70 |
| 67675 | 3348.60 | 64.0 | 29.10 | | 64050 | 3168.20 | 52.0 | 57.20 |
| 67650 | 3347.70 | 54.0 | 29.10 | | 63975 | 3163.70 | 57.0 | 58.10 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) | | Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|---|---|---|---|---|
| 63875 | 3158.80 | 56.0 | 58.90 | | 61000 | 2982.30 | 39.0 | 98.60 |
| 63775 | 3153.90 | 44.0 | 58.00 | | 60950 | 2976.50 | 46.0 | 94.50 |
| 63675 | 3149.00 | 34.0 | 57.20 | | 60900 | 2970.70 | 52.0 | 98.50 |
| 63650 | 3146.55 | 42.5 | 57.20 | | 60850 | 2966.40 | 59.0 | 96.50 |
| 63625 | 3144.10 | 51.0 | 57.20 | | 60800 | 2962.40 | 61.0 | 94.70 |
| 63575 | 3139.20 | 70.0 | 59.80 | | 60750 | 2958.40 | 61.0 | 92.90 |
| 63475 | 3134.30 | 65.0 | 53.90 | | 60700 | 2954.40 | 61.0 | 91.10 |
| 63375 | 3129.40 | 46.0 | 53.90 | | 60650 | 2950.40 | 65.0 | 89.30 |
| 63275 | 3124.50 | 48.0 | 53.90 | | 60600 | 2946.40 | 68.0 | 87.50 |
| 63175 | 3119.60 | 43.0 | 59.50 | | 60550 | 2942.40 | 72.0 | 85.70 |
| 63075 | 3114.70 | 45.0 | 57.05 | | 60500 | 2938.40 | 64.0 | 83.90 |
| 63025 | 3112.25 | 39.5 | 49.70 | | 60450 | 2934.40 | 59.0 | 82.10 |
| 62975 | 3109.80 | 34.0 | 53.10 | | 60400 | 2930.40 | 76.0 | 80.30 |
| 62875 | 3104.90 | 29.0 | 53.00 | | 60350 | 2926.40 | 36.0 | 80.00 |
| 62775 | 3100.00 | 62.0 | 52.90 | | 60300 | 2922.40 | 40.0 | 80.00 |
| 62700 | 3089.50 | 36.0 | 55.30 | | 60250 | 2918.40 | 51.0 | 80.00 |
| 62650 | 3089.50 | 40.0 | 52.80 | | 60200 | 2914.40 | 55.0 | 80.00 |
| 62575 | 3089.50 | 45.0 | 52.70 | | 60150 | 2910.40 | 39.0 | 80.00 |
| 62525 | [illegible] | [illegible] | [illegible] | 5 | 60100 | 2906.40 | 50.0 | 80.00 |
| 62475 | 3081.20 | 35.0 | 52.60 | | 60050 | 2902.40 | 39.0 | 80.00 |
| 62425 | 3078.80 | 31.0 | 55.00 | | 60000 | 2898.40 | 32.0 | 78.20 |
| 62375 | 3076.40 | 48.0 | 52.50 | | 59950 | 2894.40 | 33.0 | 75.90 |
| 62325 | 3074.00 | 58.0 | 50.00 | | 59900 | 2890.40 | 44.0 | 73.60 |
| 62275 | 3071.60 | 42.0 | 52.40 | | 59850 | 2886.40 | 68.0 | 71.90 |
| 62225 | 3069.20 | 30.0 | 44.30 | | 59800 | 2882.40 | 77.0 | 68.60 |
| 62175 | 3066.80 | 31.0 | 48.30 | | 59750 | 2878.40 | 73.0 | 67.00 |
| 62125 | 3064.40 | 40.0 | 52.40 | | 59700 | 2874.40 | 58.0 | 69.00 |
| 62075 | 3062.00 | 43.0 | 48.20 | | 59650 | 2870.40 | 56.0 | 66.90 |
| 62025 | 3059.60 | 37.0 | 47.10 | | 59600 | 2866.40 | 63.0 | 64.20 |
| 61975 | 3057.20 | 40.0 | 48.20 | | 59550 | 2862.40 | 67.0 | 61.10 |
| 61925 | 3054.80 | 38.0 | 49.90 | | 59500 | 2860.20 | 77.0 | 58.80 |
| 61875 | 3052.40 | 35.0 | 53.50 | | 59450 | 2858.50 | 38.0 | 60.80 |
| 61825 | [illegible] | [illegible] | [illegible] | 6 | 59400 | 2856.80 | 46.0 | 58.00 |
| 61775 | 3047.60 | 37.0 | 60.30 | | 59350 | 2854.50 | 58.0 | 55.20 |
| 61725 | 3045.20 | 40.0 | 57.90 | | 59300 | 2853.80 | 51.0 | 54.10 |
| 61650 | 3041.20 | 55.0 | 64.70 | | 59250 | 2851.40 | 56.0 | 51.50 |
| 61550 | 3037.10 | 23.0 | 71.50 | | 59200 | 2845.40 | 29.0 | 51.70 |
| 61450 | 3033.00 | 36.0 | 80.70 | | 59150 | 2843.50 | 26.0 | 50.00 |
| 61400 | 3028.90 | 36.0 | 84.10 | | 59100 | 2842.20 | 30.0 | 49.60 |
| 61350 | 3022.90 | 33.0 | 84.10 | | 59050 | 2841.30 | 35.0 | 46.00 |
| 61325 | 3020.00 | 34.5 | 83.60 | | 59000 | 2839.60 | 40.0 | 44.80 |
| 61300 | 3017.10 | 36.0 | 87.60 | | 58950 | 2833.60 | 28.0 | 46.80 |
| 61250 | 3011.30 | 24.0 | 89.20 | | 58900 | 2832.40 | 43.0 | 48.30 |
| 61200 | 3005.50 | 35.0 | 90.80 | | 58850 | 2831.20 | 53.0 | 47.20 |
| 61150 | 2999.70 | 38.0 | 90.80 | | 58800 | 2828.30 | 42.0 | 47.70 |
| 61100 | 2993.90 | 35.0 | 94.80 | | 58750 | 2826.90 | 44.0 | 48.40 |
| 61050 | 2988.10 | 35.0 | 94.70 | | 58700 | 2822.70 | 48.0 | 45.70 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) | |
|---|---|---|---|---|
| 58650 | 2820.40 | 55.0 | 47.60 | |
| 58600 | 2816.80 | 59.0 | 47.85 | |
| 58550 | 2816.40 | 58.0 | 48.50 | |
| 58500 | 2815.40 | 59.0 | 50.60 | |
| 58450 | 2811.70 | 60.0 | 46.80 | |
| 58400 | 2808.50 | 59.0 | 48.80 | |
| 58350 | 2807.30 | 58.0 | 51.60 | |
| 58300 | 2806.10 | 58.0 | 50.50 | |
| 58250 | 2803.00 | 61.0 | 52.20 | |
| 58200 | 2799.70 | 62.0 | 49.80 | |
| 58150 | 2795.90 | 68.0 | 51.80 | |
| 58100 | 2794.35 | 79.0 | 53.60 | |
| 58050 | 2792.80 | 90.0 | 54.90 | |
| 58000 | 2789.00 | 89.0 | 55.20 | |
| 57950 | 2786.80 | 85.0 | 53.40 | |
| 57900 | 2783.60 | 78.0 | 52.00 | |
| 57850 | 2779.60 | 79.0 | 54.30 | |
| 57800 | 2777.80 | 73.0 | 55.90 | |
| 57750 | 2774.70 | 72.0 | 55.70 | |
| 57700 | 2772.90 | 68.0 | 57.60 | |
| 57650 | 2768.60 | 68.0 | 54.00 | |
| 57600 | 2763.20 | 69.0 | 59.65 | |
| [redacted] | | | | 7 |
| 57500 | 2760.20 | 62.0 | 58.50 | |
| 57450 | 2758.30 | 72.0 | 58.90 | |
| 57400 | 2756.50 | 81.0 | 58.60 | |
| 57350 | 2753.00 | 76.0 | 56.50 | |
| 57300 | 2750.20 | 62.0 | 56.80 | |
| 57250 | 2747.30 | 77.0 | 56.50 | |
| 57200 | 2742.10 | 88.0 | 59.40 | |
| 57150 | 2741.90 | 99.0 | 60.70 | |
| 57100 | 2734.70 | 101.0 | 58.30 | |
| 57050 | 2732.80 | 78.0 | 59.00 | |
| 57000 | 2730.50 | 49.0 | 59.60 | |
| 56950 | 2727.90 | 56.0 | 61.40 | |
| 56900 | 2725.00 | 42.0 | 62.40 | |
| 56850 | 2723.10 | 47.0 | 61.50 | |
| 56800 | 2721.00 | 70.0 | 60.20 | |
| 56750 | 2718.20 | 73.0 | 58.70 | |
| 56700 | 2713.50 | 65.0 | 56.20 | |
| 56650 | 2707.90 | 55.0 | 58.90 | |
| 56600 | 2704.90 | 60.0 | 53.50 | |
| 56550 | 2702.50 | 91.0 | 53.40 | |
| 56500 | 2700.60 | 115.0 | 53.10 | |
| 56450 | 2696.90 | 128.0 | 53.30 | |
| 56400 | 2694.10 | 130.0 | 52.60 | |
| 56350 | 2691.50 | 116.0 | 51.30 | |

| | Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|---|
| | 56300 | 2690.00 | 116.0 | 51.60 |
| | 56250 | 2688.60 | 120.0 | 54.10 |
| | 56200 | 2685.90 | 122.0 | 53.40 |
| | 56150 | 2683.00 | 85.0 | 51.10 |
| | 56100 | 2681.20 | 75.0 | 50.30 |
| | 56050 | 2679.40 | 50.0 | 58.10 |
| | 56000 | 2677.40 | 45.0 | 62.70 |
| | 55950 | 2674.60 | 44.0 | 61.10 |
| | 55900 | 2672.40 | 45.0 | 60.00 |
| | 55850 | 2671.80 | 55.0 | 58.90 |
| | 55800 | 2669.40 | 34.0 | 61.50 |
| | 55750 | 2664.10 | 38.0 | 62.80 |
| | 55700 | 2660.10 | 68.0 | 62.80 |
| | 55650 | 2656.80 | 90.0 | 62.90 |
| | 55600 | 2654.60 | 129.0 | 62.30 |
| | 55550 | 2644.40 | 100.0 | 62.50 |
| | 55500 | 2637.90 | 37.0 | 62.20 |
| | 55450 | 2635.80 | 35.0 | 62.80 |
| | 55400 | 2634.10 | 45.0 | 63.90 |
| | 55350 | 2632.60 | 63.0 | 64.80 |
| | 55300 | 2628.50 | 74.0 | 64.20 |
| | 55250 | 2625.80 | 79.0 | 60.30 |
| | 55200 | 2623.10 | 73.0 | 57.00 |
| | 55150 | 2620.10 | 47.0 | 55.00 |
| | 55100 | 2618.90 | 27.0 | 57.50 |
| | 55050 | 2616.90 | 45.0 | 49.30 |
| | 55000 | 2615.20 | 48.0 | 45.00 |
| | 54950 | 2611.80 | 38.0 | 45.30 |
| | 54900 | 2608.50 | 32.0 | 46.20 |
| | 54850 | 2607.00 | 35.0 | 45.60 |
| | 54800 | 2605.20 | 37.0 | 44.90 |
| | 54750 | 2603.80 | 40.0 | 46.10 |
| | 54700 | 2603.10 | 48.0 | 45.70 |
| | 54650 | 2601.80 | 50.0 | 46.10 |
| | 54600 | 2597.10 | 49.0 | 46.50 |
| | 54550 | 2595.10 | 54.0 | 48.50 |
| | 54500 | 2592.90 | 47.0 | 51.00 |
| | 54450 | 2590.50 | 53.0 | 49.30 |
| | 54400 | 2587.90 | 53.0 | 47.10 |
| | 54350 | 2587.00 | 57.0 | 47.70 |
| | 54300 | 2583.60 | 64.0 | 50.20 |
| | 54250 | 2579.70 | 73.0 | 53.30 |
| | 54200 | 2577.40 | 74.0 | 54.80 |
| 8 | [redacted] | | | |
| | 54100 | 2572.40 | 88.0 | 54.40 |
| | 54050 | 2568.40 | 82.0 | 55.00 |
| | 54000 | 2564.20 | 78.0 | 56.40 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|
| 53950 | 2562.50 | 77.0 | 57.50 |
| 53900 | 2561.40 | 76.0 | 59.80 |
| 53850 | 2559.30 | 74.0 | 61.00 |
| 53800 | 2555.00 | 73.0 | 59.70 |
| 53750 | 2550.50 | 60.0 | 58.40 |
| 53700 | 2548.30 | 62.0 | 56.80 |
| 53650 | 2545.00 | 63.0 | 55.70 |
| 53600 | 2542.70 | 78.0 | 56.30 |
| 53550 | 2540.10 | 88.0 | 56.00 |
| 53500 | 2536.50 | 88.0 | 55.40 |
| 53450 | 2533.00 | 92.0 | 55.90 |
| 53400 | 2528.10 | 59.0 | 57.60 |
| 53350 | 2526.00 | 36.0 | 58.20 |
| 53300 | 2523.90 | 35.0 | 54.40 |
| 53250 | 2521.30 | 44.0 | 51.70 |
| 53200 | 2520.60 | 66.0 | 54.00 |
| 53150 | 2518.30 | 74.0 | 51.60 |
| 53100 | 2516.10 | 90.0 | 50.50 |
| 53050 | 2512.40 | 104.0 | 54.50 |
| 53000 | 2508.80 | 105.0 | 51.50 |
| 52950 | 2506.60 | 102.0 | 48.40 |
| 52900 | 2503.80 | 88.0 | 45.90 |
| 52850 | 2501.10 | 82.0 | 45.90 |
| 52800 | 2500.60 | 89.0 | 45.60 |
| 52750 | 2498.80 | 89.0 | 44.30 |
| 52700 | 2494.30 | 66.0 | 45.80 |
| 52650 | 2493.40 | 50.0 | 45.80 |
| 52600 | 2492.20 | 40.0 | 45.70 |
| 52550 | 2485.60 | 38.0 | 44.10 |
| 52500 | 2485.00 | 31.0 | 43.30 |
| 52450 | 2484.60 | 66.0 | 43.80 |
| 52400 | 2482.20 | 85.0 | 43.10 |
| 52350 | 2480.10 | 98.0 | 42.30 |
| 52300 | 2478.30 | 75.0 | 44.10 |
| 52250 | 2477.00 | 62.0 | 43.50 |
| 52200 | 2474.80 | 50.0 | 39.50 |
| 52150 | 2472.50 | 51.0 | 42.20 |
| 52100 | 2470.40 | 72.0 | 45.40 |
| 52050 | 2468.30 | 71.0 | 40.20 |
| 52000 | 2465.50 | 67.0 | 44.30 |
| 51950 | 2462.80 | 63.5 | 44.60 |
| 51900 | 2460.70 | 60.0 | 44.40 |
| 51850 | 2458.80 | 58.0 | 43.00 |
| 51800 | 2456.50 | 56.0 | 42.30 |
| 51750 | 2455.30 | 69.0 | 43.20 |
| 51700 | 2454.80 | 74.0 | 43.20 |
| 51650 | 2451.20 | 65.0 | 43.80 |

| | Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|---|
| | 51600 | 2446.80 | 46.0 | 44.50 |
| | 51550 | 2445.40 | 56.0 | 45.50 |
| | 51500 | 2440.70 | 49.0 | 45.60 |
| | 51450 | 2440.00 | 47.0 | 46.60 |
| | 51400 | 2437.80 | 30.0 | 51.30 |
| | 51350 | 2437.10 | 37.0 | 51.50 |
| | 51300 | 2436.00 | 39.0 | 51.70 |
| | 51250 | 2433.80 | 42.0 | 52.80 |
| | 51200 | 2431.60 | 46.0 | 54.70 |
| 9 | [redacted] | | | |
| | 51100 | 2425.90 | 65.0 | 55.00 |
| | 51050 | 2422.80 | 82.0 | 54.30 |
| | 51000 | 2419.90 | 77.0 | 52.10 |
| | 50950 | 2416.20 | 82.0 | 52.70 |
| | 50900 | 2409.40 | 39.0 | 51.30 |
| | 50850 | 2407.30 | 39.0 | 52.00 |
| | 50800 | 2404.80 | 63.0 | 54.00 |
| | 50750 | 2402.50 | 46.0 | 53.40 |
| | 50700 | 2400.10 | 42.0 | 53.80 |
| | 50650 | 2395.60 | 36.0 | 54.10 |
| | 50600 | 2391.80 | 38.0 | 53.50 |
| | 50550 | 2391.10 | 28.0 | 54.20 |
| | 50500 | 2388.60 | 42.0 | 52.40 |
| | 50450 | 2387.30 | 48.0 | 49.80 |
| | 50400 | 2386.50 | 50.0 | 45.10 |
| | 50350 | 2385.10 | 57.0 | 46.50 |
| | 50300 | 2382.00 | 53.0 | 45.80 |
| | 50250 | 2380.40 | 48.0 | 46.10 |
| | 50200 | 2377.80 | 52.0 | 46.00 |
| | 50150 | 2374.60 | 57.0 | 43.60 |
| | 50100 | 2372.40 | 68.0 | 41.60 |
| | 50050 | 2368.60 | 52.0 | 42.55 |
| | 50000 | 2367.50 | 55.0 | 41.70 |
| | 49950 | 2366.40 | 51.0 | 42.50 |
| | 49900 | 2364.30 | 57.0 | 44.90 |
| | 49850 | 2360.80 | 52.0 | 45.00 |
| | 49800 | 2359.00 | 54.0 | 43.10 |
| 10 | [redacted] | | | |
| | 49700 | 2354.10 | 50.0 | 42.90 |
| | 49650 | 2352.00 | 46.0 | 41.40 |
| | 49600 | 2350.20 | 26.0 | 42.00 |
| | 49550 | 2348.55 | 39.0 | 43.10 |
| | 49500 | 2346.90 | 55.0 | 44.30 |
| | 49450 | 2344.80 | 61.0 | 46.00 |
| | 49400 | 2341.60 | 57.0 | 46.20 |
| | 49350 | 2340.10 | 58.0 | 43.80 |
| | 49300 | 2338.90 | 50.0 | 43.10 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|
| 49250 | 2335.10 | 60.0 | 42.10 |
| 49200 | 2334.90 | 67.0 | 40.20 |
| 49150 | 2333.20 | 62.0 | 40.70 |
| 49100 | 2330.40 | 58.0 | 39.80 |
| 49050 | 2325.50 | 56.0 | 41.85 |
| 49000 | 2323.20 | 59.0 | 43.70 |
| 48950 | 2320.40 | 63.0 | 43.90 |
| 48900 | 2318.10 | 68.0 | 43.50 |
| 48850 | 2317.00 | 65.0 | 43.90 |
| 48800 | 2315.90 | 64.0 | 48.10 |
| 48750 | 2314.30 | 62.0 | 47.00 |
| 48700 | 2313.90 | 63.0 | 50.50 |
| 48650 | 2311.30 | 70.0 | 51.40 |
| 48600 | 2310.40 | 85.0 | 49.10 |
| 48550 | 2306.70 | 97.0 | 45.50 |
| 48500 | 2303.20 | 99.0 | 43.80 |
| 48450 | 2300.90 | 79.0 | 38.80 |
| 48400 | 2298.10 | 74.0 | 41.00 |
| 48350 | 2296.20 | 71.0 | 41.70 |
| 48300 | 2290.80 | 89.0 | 43.00 |
| 48250 | 2288.10 | 95.0 | 43.40 |
| 48200 | 2284.40 | 88.0 | 45.20 |
| 48150 | 2281.80 | 75.0 | 43.50 |
| 48100 | 2281.30 | 95.0 | 45.50 |
| 48050 | 2280.00 | 103.0 | 46.00 |
| 48000 | 2279.40 | 86.0 | 48.40 |
| 47950 | 2281.60 | 82.0 | 51.00 |
| 47900 | 2277.10 | 79.0 | 54.30 |
| 47850 | 2275.30 | 80.0 | 53.10 |
| 47800 | 2272.90 | 68.0 | 50.90 |
| 47750 | 2270.90 | 63.0 | 50.80 |
| 47700 | 2268.70 | 45.0 | 52.30 |
| 47650 | 2267.80 | 57.0 | 50.10 |
| 47600 | 2264.90 | 85.0 | 50.70 |
| 47550 | 2260.70 | 97.0 | 52.80 |
| 47500 | 2254.80 | 72.0 | 57.60 |
| 47450 | 2249.90 | 68.0 | 62.20 |
| 47400 | 2243.80 | 50.0 | 60.10 |
| 47350 | 2243.10 | 54.0 | 63.70 |
| 47300 | 2239.90 | 85.0 | 63.60 |
| 47250 | 2237.30 | 98.0 | 64.20 |
| 47200 | 2232.10 | 105.0 | 63.30 |
| 47150 | 2231.70 | 105.0 | 64.50 |
| 47100 | 2230.60 | 95.0 | 63.70 |
| 47050 | 2227.20 | 81.0 | 62.40 |
| 47000 | 2221.80 | 84.0 | 58.90 |
| 46950 | 2219.40 | 86.0 | 56.30 |

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|
| 46900 | 2217.00 | 67.0 | 54.70 |
| 46850 | 2211.60 | 34.0 | 55.70 |
| 46800 | 2209.30 | 35.0 | 56.30 |
| 46750 | 2206.70 | 41.0 | 54.70 |
| 46700 | 2205.40 | 52.0 | 51.20 |
| 46650 | 2203.30 | 62.0 | 53.60 |
| 46600 | 2201.20 | 64.0 | 54.70 |
| 46550 | 2198.30 | 67.0 | 55.10 |
| 46500 | 2195.90 | 68.0 | 52.90 |
| 46450 | 2193.60 | 75.0 | 53.40 |
| 46400 | 2189.10 | 89.0 | 53.50 |
| 46350 | 2187.40 | 87.0 | 49.60 |
| 46300 | 2183.60 | 86.0 | 49.30 |
| 46250 | 2182.60 | 84.0 | 47.80 |
| 46200 | 2180.90 | 96.0 | 47.80 |
| 46150 | 2178.10 | 97.0 | 48.90 |
| 46100 | 2175.90 | 105.0 | 51.00 |
| 46050 | 2172.10 | 120.0 | 51.00 |
| 46000 | 2168.90 | 122.0 | 51.20 |
| 45950 | 2166.00 | 121.0 | 50.70 |
| 45900 | 2163.50 | 120.0 | 47.50 |
| 45850 | 2162.00 | 135.0 | 47.00 |
| 45800 | 2160.00 | 140.0 | 45.50 |
| 45750 | 2158.90 | 148.0 | 47.70 |
| 45700 | 2157.60 | 125.0 | 48.80 |
| 45650 | 2154.40 | 92.0 | 48.20 |
| 45600 | 2150.20 | 75.0 | 48.30 |
| 45550 | 2147.30 | 75.0 | 46.00 |
| 45500 | 2144.70 | 88.0 | 45.70 |
| 45450 | 2142.90 | 88.0 | 46.10 |
| 45400 | 2141.60 | 84.0 | 45.60 |
| 45350 | 2140.40 | 90.0 | 49.20 |
| 45300 | 2138.10 | 96.0 | 50.40 |
| 45250 | 2134.90 | 94.0 | 51.80 |
| 45200 | 2132.10 | 92.0 | 51.10 |
| 45150 | 2129.90 | 80.0 | 51.00 |
| 45100 | 2127.60 | 78.0 | 48.90 |
| 45050 | 2126.10 | 75.0 | 48.60 |
| 45000 | 2123.20 | 65.0 | 48.10 |
| 44950 | 2119.90 | 60.0 | 50.50 |
| 44900 | 2117.90 | 67.0 | 53.10 |
| 44850 | 2112.80 | 76.0 | 55.80 |
| 44800 | 2109.60 | 81.0 | 55.60 |
| 44750 | 2107.10 | 98.0 | 55.50 |
| 11 | | | |
| 44650 | 2103.40 | 116.0 | 55.90 |
| 44600 | 2101.30 | 133.0 | 57.20 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|
| 44550 | 2098.70 | 112.0 | 60.00 |
| 44500 | 2096.60 | 95.0 | 60.70 |
| 44450 | 2092.40 | 101.0 | 58.80 |
| 44400 | 2088.50 | 101.0 | 59.70 |
| 44350 | 2084.60 | 122.0 | 59.40 |
| 44300 | 2082.50 | 135.0 | 60.10 |
| 44250 | 2079.40 | 135.0 | 60.80 |
| 44200 | 2077.20 | 100.0 | 62.90 |
| 44150 | 2074.00 | 86.0 | 63.10 |
| 44100 | 2070.40 | 90.0 | 63.50 |
| 44050 | 2066.10 | 114.0 | 62.30 |
| 44000 | 2062.50 | 136.0 | 63.70 |
| 43950 | 2061.10 | 135.0 | 60.30 |
| 43900 | 2058.20 | 126.0 | 59.10 |
| 43850 | 2053.40 | 105.0 | 57.30 |
| 43800 | 2049.50 | 77.0 | 57.40 |
| 43750 | 2046.30 | 71.0 | 55.10 |
| 43700 | 2043.60 | 50.0 | 55.60 |
| 43650 | 2040.30 | 92.0 | 53.70 |
| 43600 | 2037.80 | 102.0 | 54.40 |
| 43550 | 2036.40 | 110.0 | 52.50 |
| 43500 | 2032.90 | 125.0 | 51.70 |
| 43450 | 2032.10 | 140.0 | 51.20 |
| 43400 | 2029.40 | 138.0 | 51.00 |
| 43350 | 2027.30 | 145.0 | 48.80 |
| 43300 | 2025.10 | 144.0 | 46.60 |
| 43250 | 2024.30 | 142.0 | 46.50 |
| 43200 | 2021.60 | 140.0 | 46.90 |
| 43150 | 2020.30 | 139.0 | 46.90 |
| 43100 | 2016.00 | 120.0 | 48.50 |
| 43050 | 2013.60 | 87.0 | 49.70 |
| 43000 | 2010.80 | 82.0 | 49.50 |
| 42950 | 2009.90 | 78.0 | 50.20 |
| 42900 | 2007.20 | 75.0 | 52.60 |
| 42850 | 2004.60 | 81.0 | 51.10 |
| 42800 | 2002.90 | 83.0 | 51.30 |
| 42750 | 1999.80 | 70.0 | 51.70 |
| 42700 | 1996.70 | 75.0 | 51.30 |
| 42650 | 1993.40 | 79.0 | 53.60 |
| 42600 | 1989.30 | 120.0 | 50.90 |
| 42550 | 1986.70 | 128.0 | 51.40 |
| 42500 | 1983.40 | 136.5 | 50.40 |
| 42450 | 1981.90 | 126.0 | 52.10 |
| 42400 | 1976.80 | 111.0 | 52.50 |
| 42350 | 1976.20 | 88.0 | 53.20 |
| 42300 | 1973.80 | 71.0 | 53.20 |
| 42250 | 1972.60 | 55.0 | 52.00 |

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|
| 42200 | 1970.30 | 53.0 | 53.80 |
| 42150 | 1966.70 | 74.0 | 53.40 |
| 42100 | 1965.10 | 69.0 | 53.10 |
| 42050 | 1962.20 | 69.0 | 52.00 |
| 42000 | 1960.40 | 68.0 | 49.40 |
| 41950 | 1957.80 | 69.0 | 50.40 |
| 41900 | 1954.70 | 62.0 | 48.40 |
| 41850 | 1951.40 | 44.0 | 49.90 |
| 41800 | 1949.70 | 35.0 | 50.40 |
| 41750 | 1947.80 | 36.0 | 52.10 |
| 41700 | 1942.90 | 45.0 | 53.60 |
| 41650 | 1940.00 | 49.0 | 53.50 |
| 41600 | 1936.20 | 42.0 | 53.30 |
| 41550 | 1934.70 | 44.0 | 53.00 |
| 41500 | 1934.00 | 57.0 | 53.80 |
| 41450 | 1931.50 | 70.0 | 52.80 |
| 41400 | 1928.40 | 82.0 | 52.50 |
| 41350 | 1926.30 | 93.0 | 51.30 |
| 12 [illegible] | [illegible] | [illegible] | [illegible] |
| 41250 | 1920.50 | 115.0 | 52.80 |
| 41200 | 1916.70 | 144.0 | 50.00 |
| 41150 | 1913.20 | 177.0 | 49.30 |
| 41100 | 1911.80 | 182.0 | 50.40 |
| 41050 | 1909.20 | 174.0 | 49.00 |
| 41000 | 1906.60 | 168.0 | 50.60 |
| 40950 | 1905.00 | 161.0 | 53.60 |
| 40900 | 1902.20 | 155.0 | 53.30 |
| 40850 | 1900.10 | 108.0 | 53.20 |
| 40800 | 1896.30 | 66.0 | 54.40 |
| 40750 | 1895.00 | 65.0 | 54.90 |
| 40700 | 1892.90 | 67.0 | 53.20 |
| 40650 | 1890.70 | 55.0 | 55.40 |
| 40600 | 1885.80 | 56.0 | 57.60 |
| 40550 | 1885.70 | 74.0 | 57.00 |
| 40500 | 1883.40 | 141.0 | 58.10 |
| 40450 | 1877.90 | 146.0 | 60.00 |
| 40400 | 1875.10 | 127.0 | 64.50 |
| 40350 | 1873.10 | 106.0 | 64.30 |
| 40300 | 1869.00 | 90.0 | 61.70 |
| 40250 | 1865.60 | 95.0 | 62.50 |
| 40200 | 1863.50 | 116.0 | 61.50 |
| 40150 | 1857.80 | 130.0 | 62.00 |
| 40100 | 1854.20 | 120.0 | 59.00 |
| 40050 | 1852.20 | 106.0 | 61.70 |
| 40000 | 1848.50 | 66.0 | 61.30 |
| 39950 | 1845.00 | 72.0 | 61.20 |
| 39900 | 1837.70 | 74.0 | 61.10 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|
| 39850 | 1835.80 | 76.0 | 62.80 |
| 39800 | 1834.60 | 79.0 | 61.30 |
| 39750 | 1832.50 | 69.0 | 58.40 |
| 39700 | 1831.40 | 51.0 | 57.60 |
| 39650 | 1828.70 | 59.0 | 52.50 |
| 39600 | 1826.80 | 57.0 | 46.70 |
| 39550 | 1824.00 | 53.0 | 49.20 |
| 39500 | 1822.10 | 58.0 | 47.30 |
| 39450 | 1816.70 | 77.0 | 46.20 |
| 39400 | 1814.00 | 110.0 | 40.90 |
| 39350 | 1810.30 | 115.0 | 41.20 |
| 39300 | 1807.70 | 114.0 | 40.90 |
| 39250 | 1807.20 | 95.0 | 41.70 |
| 39200 | 1805.90 | 90.0 | 44.80 |
| 39150 | 1805.30 | 87.0 | 48.00 |
| 39100 | 1807.50 | 99.0 | 51.00 |
| 39050 | 1803.00 | 114.0 | 54.30 |
| 39000 | 1801.20 | 117.0 | 53.10 |
| 38950 | 1798.80 | 120.0 | 50.90 |
| 38900 | 1796.80 | 131.0 | 50.80 |
| 38850 | 1794.60 | 92.0 | 52.30 |
| 38800 | 1793.70 | 62.0 | 50.10 |
| 38750 | 1790.80 | 60.0 | 50.70 |
| 38700 | 1786.60 | 68.0 | 52.80 |
| 38650 | 1780.70 | 113.0 | 57.60 |
| 38600 | 1775.80 | 107.0 | 60.40 |
| 38550 | 1769.70 | 98.0 | 58.50 |
| 38500 | 1769.00 | 88.0 | 60.10 |
| 38450 | 1765.80 | 95.0 | 61.60 |
| 38400 | 1763.20 | 101.0 | 62.00 |
| 38350 | 1758.00 | 97.0 | 61.70 |
| 38300 | 1757.60 | 83.0 | 62.10 |
| 38250 | 1756.50 | 70.0 | 61.80 |
| 38200 | 1753.10 | 66.0 | 59.20 |
| 38150 | 1747.70 | 34.0 | 54.80 |
| 38100 | 1747.10 | 38.0 | 53.30 |
| 38050 | 1744.50 | 37.0 | 50.30 |
| 38000 | 1741.10 | 57.0 | 52.20 |
| 37950 | 1737.20 | 69.0 | 50.10 |
| 37900 | 1734.80 | 75.0 | 49.90 |
| 37850 | 1732.90 | 73.0 | 46.80 |
| 37800 | 1731.60 | 76.0 | 50.40 |
| 37750 | 1729.00 | 72.0 | 51.10 |
| 37700 | 1727.40 | 75.0 | 52.50 |
| 37650 | 1725.90 | 78.0 | 49.70 |
| 37600 | 1722.50 | 78.0 | 52.30 |
| 37550 | 1719.40 | 71.0 | 53.90 |

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|
| 37500 | 1716.80 | 60.0 | 55.30 |
| 37450 | 1715.70 | 89.0 | 56.90 |
| 37400 | 1713.30 | 96.0 | 56.40 |
| 37350 | 1711.20 | 99.0 | 55.10 |
| 37300 | 1707.20 | 104.0 | 54.20 |
| 37250 | 1705.40 | 112.0 | 51.80 |
| 37200 | 1700.60 | 107.0 | 50.90 |
| 37150 | 1698.00 | 87.0 | 52.10 |
| 37100 | 1694.80 | 85.0 | 54.90 |
| 37050 | 1690.60 | 102.0 | 53.60 |
| 37000 | 1685.80 | 108.0 | 53.40 |
| 36950 | 1680.30 | 111.0 | 54.10 |
| 36900 | 1678.40 | 101.0 | 56.20 |
| 36850 | 1677.80 | 90.0 | 55.80 |
| 36800 | 1677.40 | 79.0 | 53.70 |
| 36750 | 1677.20 | 65.0 | 54.10 |
| 36700 | 1676.50 | 51.0 | 52.00 |
| 36650 | 1673.80 | 44.0 | 52.00 |
| 36600 | 1667.60 | 32.0 | 52.20 |
| 36550 | 1665.80 | 41.0 | 50.20 |
| 36500 | 1663.40 | 55.0 | 48.40 |
| 36450 | 1661.60 | 61.0 | 45.00 |
| 36400 | 1657.10 | 67.0 | 43.50 |
| 36350 | 1655.40 | 66.0 | 46.00 |
| 36300 | 1653.50 | 70.0 | 46.70 |
| 36250 | 1651.30 | 81.0 | 50.10 |
| 36200 | 1648.60 | 86.0 | 51.20 |
| 36150 | 1646.00 | 85.0 | 52.80 |
| 36100 | 1642.60 | 83.0 | 48.30 |
| 36050 | 1640.40 | 84.0 | 49.00 |
| 36000 | 1637.40 | 85.0 | 48.80 |
| 35950 | 1635.30 | 55.0 | 48.30 |
| 35900 | 1634.90 | 32.0 | 46.40 |
| 35850 | 1631.80 | 40.0 | 47.80 |
| 35800 | 1630.70 | 42.0 | 46.50 |
| 35750 | 1627.10 | 57.0 | 45.30 |
| 35700 | 1625.30 | 72.0 | 44.10 |
| 35650 | 1621.00 | 120.0 | 42.50 |
| 35600 | 1619.30 | 130.0 | 42.50 |
| 35550 | 1616.80 | 142.0 | 43.40 |
| 35500 | 1614.60 | 151.0 | 41.70 |
| 35450 | 1613.30 | 145.0 | 41.40 |
| 35400 | 1610.70 | 150.0 | 43.70 |
| 35350 | 1607.60 | 156.0 | 44.40 |
| 35300 | 1607.00 | 165.0 | 46.20 |
| 35250 | 1606.00 | 140.0 | 45.90 |
| 35200 | 1604.50 | 125.0 | 48.10 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) | |
|---|---|---|---|---|
| 35150 | 1603.50 | 110.0 | 46.20 | |
| 35100 | 1600.10 | 80.0 | 50.20 | |
| 35050 | 1597.00 | 57.0 | 48.60 | |
| 35000 | 1595.70 | 50.0 | 52.90 | |
| 34950 | 1593.90 | 35.0 | 53.70 | |
| 34900 | 1591.20 | 67.0 | 52.60 | |
| 34850 | 1587.40 | 93.0 | 54.70 | |
| 34800 | 1584.50 | 108.0 | 57.30 | |
| 34750 | 1581.20 | 126.0 | 61.80 | |
| 34700 | 1577.20 | 145.0 | 60.70 | |
| 34650 | 1574.80 | 170.0 | 60.10 | |
| 34600 | 1569.10 | 178.0 | 58.80 | |
| 34550 | 1568.20 | 171.0 | 57.90 | |
| 34500 | 1561.70 | 130.0 | 60.40 | |
| 34450 | 1559.60 | 104.0 | 62.10 | |
| 34400 | 1558.10 | 97.0 | 61.70 | |
| 34350 | 1552.90 | 85.0 | 61.30 | |
| 34300 | 1549.70 | 84.0 | 59.60 | |
| 34250 | 1544.20 | 86.0 | 57.10 | |
| 34200 | 1543.80 | 91.0 | 53.60 | |
| 34150 | 1543.40 | 95.0 | 52.00 | |
| 34100 | 1541.30 | 78.0 | 47.00 | |
| 34050 | 1539.10 | 44.0 | 50.40 | |
| 34000 | 1535.30 | 38.0 | 47.00 | |
| 33950 | 1531.80 | 44.0 | 48.00 | |
| 33900 | 1529.50 | 53.0 | 48.40 | |
| 33850 | 1526.10 | 59.0 | 45.10 | |
| 33800 | 1524.90 | 59.0 | 44.50 | |
| 33750 | 1524.10 | 62.0 | 41.30 | |
| 33700 | 1523.60 | 66.0 | 43.80 | |
| 33650 | | | | 13 |
| 33600 | 1522.10 | 123.0 | 45.90 | |
| 33550 | 1517.80 | 143.0 | 47.20 | |
| 33500 | 1514.70 | 165.0 | 45.70 | |
| 33450 | 1511.60 | 140.0 | 43.60 | |
| 33400 | 1509.70 | 120.0 | 44.80 | |
| 33350 | 1507.80 | 117.0 | 47.30 | |
| 33300 | 1505.20 | 104.0 | 48.50 | |
| 33250 | 1502.90 | 84.0 | 49.80 | |
| 33200 | 1500.00 | 115.0 | 54.40 | |
| 33150 | 1498.60 | 135.0 | 55.70 | |
| 33100 | 1495.40 | 167.0 | 59.40 | |
| 33050 | 1491.90 | 185.0 | 57.80 | |
| 33000 | 1489.60 | 180.0 | 56.90 | |
| 32950 | 1488.20 | 185.0 | 55.60 | |
| 32900 | 1484.70 | 176.0 | 59.10 | |
| 32850 | 1478.80 | 100.0 | 58.70 | |

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|
| 32800 | 1476.40 | 97.0 | 60.60 |
| 32750 | 1474.30 | 98.0 | 62.20 |
| 32700 | 1469.20 | 91.0 | 61.70 |
| 32650 | 1467.10 | 87.0 | 62.90 |
| 32600 | 1462.70 | 94.0 | 63.40 |
| 32550 | 1460.00 | 100.0 | 62.70 |
| 32500 | 1457.80 | 115.0 | 63.70 |
| 32450 | 1456.00 | 125.0 | 63.50 |
| 32400 | 1450.60 | 127.0 | 62.80 |
| 32350 | 1449.10 | 121.0 | 61.20 |
| 32300 | 1444.60 | 133.0 | 65.30 |
| 32250 | 1440.70 | 145.0 | 67.10 |
| 32200 | 1438.30 | 140.0 | 65.50 |
| 32150 | 1435.70 | 132.0 | 65.20 |
| 32100 | 1432.00 | 130.0 | 62.10 |
| 32050 | 1429.20 | 128.0 | 59.80 |
| 32000 | 1425.90 | 120.0 | 59.60 |
| 31950 | 1424.70 | 133.0 | 61.00 |
| 31900 | 1421.90 | 135.0 | 58.70 |
| 31850 | 1417.60 | 132.0 | 60.40 |
| 31800 | 1411.10 | 133.0 | 57.20 |
| 31750 | 1407.20 | 144.0 | 54.80 |
| 31700 | 1403.70 | 133.0 | 58.00 |
| 31650 | 1401.90 | 102.0 | 57.40 |
| 31600 | 1400.60 | 97.0 | 57.50 |
| 31550 | 1400.20 | 84.0 | 56.20 |
| 31500 | 1398.20 | 75.0 | 54.60 |
| 31450 | 1395.00 | 85.0 | 55.30 |
| 31400 | 1391.90 | 90.0 | 55.30 |
| 31350 | 1388.70 | 110.0 | 53.60 |
| 31300 | 1387.40 | 118.0 | 49.60 |
| 31250 | 1385.90 | 116.0 | 48.65 |
| 31200 | 1380.30 | 108.0 | 48.10 |
| 31150 | 1378.30 | 102.0 | 51.10 |
| 31100 | 1374.50 | 126.0 | 51.90 |
| 31050 | 1373.00 | 111.0 | 54.80 |
| 31000 | 1371.30 | 96.0 | 56.40 |
| 30950 | 1369.40 | 80.0 | 56.60 |
| 30900 | 1366.60 | 68.0 | 57.60 |
| 30850 | 1364.00 | 75.0 | 56.70 |
| 30800 | 1361.50 | 94.0 | 56.40 |
| 30750 | 1358.55 | 116.0 | 58.10 |
| 30700 | 1355.60 | 136.0 | 55.60 |
| 30650 | 1350.80 | 138.0 | 56.30 |
| 30600 | 1348.70 | 126.0 | 56.00 |
| 30550 | 1345.40 | 68.0 | 54.80 |
| 30500 | 1341.80 | 74.0 | 57.90 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) | | Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|---|---|---|---|---|
| 30450 | 1338.40 | 85.0 | 57.40 | | 28100 | 1209.70 | 48.0 | 47.10 |
| 30400 | 1334.30 | 90.0 | 56.80 | | 28050 | 1207.90 | 57.0 | 46.20 |
| 30350 | 1332.00 | 90.0 | 56.00 | | 28000 | 1207.00 | 82.0 | 48.20 |
| [redacted] | | | | 14 | 27950 | 1204.50 | 103.0 | 49.10 |
| 30250 | 1327.80 | 148.0 | 55.95 | | 27900 | 1199.90 | 103.0 | 49.40 |
| 30200 | 1324.70 | 144.0 | 54.70 | | 27850 | 1196.40 | 99.0 | 46.60 |
| 30150 | 1322.00 | 145.0 | 51.80 | | 27800 | 1193.80 | 101.0 | 46.30 |
| 30100 | 1318.50 | 138.0 | 50.60 | | 27750 | 1193.10 | 100.0 | 46.50 |
| 30050 | 1318.20 | 143.0 | 51.70 | | 27700 | 1190.50 | 102.0 | 45.20 |
| 30000 | 1313.40 | 144.0 | 51.90 | | 27650 | 1189.80 | 127.0 | 44.60 |
| 29950 | 1312.00 | 140.0 | 51.20 | | 27600 | 1187.20 | 130.0 | 47.50 |
| 29900 | 1309.80 | 140.0 | 49.20 | | 27550 | 1183.70 | 129.0 | 47.90 |
| 29850 | 1308.00 | 104.0 | 51.70 | | 27500 | 1181.30 | 120.0 | 49.90 |
| 29800 | 1304.50 | 108.0 | 53.90 | | 27450 | 1178.60 | 105.0 | 48.20 |
| 29750 | 1302.60 | 82.0 | 54.20 | | 27400 | 1176.80 | 88.0 | 47.40 |
| 29700 | 1300.90 | 85.0 | 55.80 | | 27350 | 1175.70 | 124.0 | 46.50 |
| 29650 | 1299.00 | 85.0 | 56.90 | | 27300 | 1173.10 | 137.0 | 48.90 |
| 29600 | 1298.10 | 118.0 | 56.30 | | 27250 | 1170.30 | 135.0 | 51.00 |
| 29550 | 1293.70 | 134.0 | 59.90 | | 27200 | 1168.90 | 133.0 | 51.30 |
| 29500 | 1289.90 | 158.0 | 57.70 | | 27150 | 1166.80 | 106.0 | 55.30 |
| 29450 | 1287.20 | 159.0 | 58.40 | | 27100 | 1162.20 | 98.0 | 56.40 |
| 29400 | 1285.10 | 128.0 | 59.00 | | 27050 | 1160.00 | 102.0 | 54.20 |
| 29350 | 1280.30 | 132.0 | 60.40 | | 27000 | 1157.10 | 132.0 | 54.30 |
| 29300 | 1277.10 | 125.0 | 59.20 | | 26950 | 1156.30 | 160.0 | 53.90 |
| 29250 | 1273.60 | 147.0 | 58.80 | | 26900 | 1152.50 | 176.0 | 54.80 |
| 29200 | 1268.90 | 160.0 | 59.70 | | 26850 | 1149.90 | 181.0 | 56.80 |
| 29150 | 1265.10 | 176.0 | 62.50 | | 26800 | 1144.90 | 201.0 | 55.80 |
| 29100 | 1262.20 | 135.0 | 63.80 | | 26750 | 1142.10 | 194.0 | 56.90 |
| 29050 | 1258.30 | 130.0 | 63.80 | | 26700 | 1139.20 | 154.0 | 56.00 |
| 29000 | 1255.70 | 139.0 | 60.40 | | 26650 | 1134.50 | 126.0 | 56.00 |
| 28950 | 1253.60 | 139.0 | 59.50 | | 26600 | 1130.80 | 131.0 | 53.30 |
| 28900 | 1250.80 | 116.0 | 58.90 | | 26550 | 1129.50 | 133.0 | 53.80 |
| 28850 | 1247.60 | 90.0 | 58.00 | | 26500 | 1127.00 | 132.0 | 54.60 |
| 28800 | 1245.30 | 85.0 | 57.70 | | 26450 | 1124.70 | 125.0 | 54.90 |
| 28750 | 1243.80 | 79.0 | 56.80 | | 26400 | 1122.00 | 123.0 | 53.30 |
| 28700 | 1241.20 | 89.0 | 54.80 | | 26350 | 1118.90 | 139.0 | 55.10 |
| 28650 | 1236.50 | 110.0 | 53.70 | | 26300 | 1117.30 | 146.0 | 52.50 |
| 28600 | 1234.30 | 99.0 | 52.50 | | 26250 | 1113.40 | 140.0 | 52.80 |
| 28550 | 1229.90 | 85.0 | 50.40 | | 26200 | 1112.90 | 126.0 | 53.50 |
| 28500 | 1229.50 | 62.0 | 48.70 | | 26150 | 1110.80 | 123.0 | 51.30 |
| 28450 | 1227.70 | 54.0 | 49.10 | | 26100 | 1108.90 | 112.0 | 49.90 |
| 28400 | 1226.20 | 61.0 | 50.90 | | 26050 | 1106.20 | 94.0 | 50.80 |
| 28350 | 1222.30 | 66.0 | 51.20 | | 26000 | 1102.50 | 103.0 | 49.90 |
| 28300 | 1219.40 | 60.0 | 51.50 | | 25950 | 1101.40 | 90.0 | 52.00 |
| 28250 | 1216.80 | 62.0 | 50.70 | | 25900 | 1099.20 | 67.0 | 52.80 |
| 28200 | 1214.10 | 54.0 | 50.70 | | 25850 | 1094.80 | 62.0 | 52.10 |
| 28150 | 1211.40 | 36.0 | 46.70 | | 25800 | 1092.40 | 57.0 | 56.30 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) | |
|---|---|---|---|---|
| 25750 | 1089.30 | 40.0 | 57.70 | |
| 25700 | 1085.70 | 63.0 | 57.60 | |
| 25650 | 1083.20 | 86.0 | 56.90 | |
| 25600 | 1080.90 | 100.0 | 56.20 | |
| 25550 | 1078.70 | 102.0 | 54.90 | |
| 25500 | 1077.10 | 83.0 | 52.50 | |
| 25450 | 1072.70 | 56.0 | 51.90 | |
| 25400 | 1069.20 | 53.0 | 54.30 | |
| 25350 | 1066.80 | 47.0 | 50.50 | |
| 25300 | 1061.00 | 63.0 | 51.30 | |
| 25250 | 1055.70 | 62.0 | 50.15 | |
| 25200 | 1055.30 | 52.0 | 48.50 | |
| 25150 | 1053.90 | 50.0 | 48.00 | |
| 25100 | 1052.70 | 44.0 | 49.80 | |
| 25050 | 1051.30 | 63.0 | 48.30 | |
| 25000 | 1050.00 | 94.0 | 50.50 | |
| 24950 | 1049.50 | 110.0 | 48.80 | |
| 24900 | 1044.90 | 140.0 | 48.30 | |
| 24850 | 1044.30 | 161.0 | 48.70 | |
| 24800 | 1041.10 | 161.0 | 44.40 | |
| 24750 | 1039.15 | 125.0 | 40.50 | |
| 24700 | 1037.20 | 85.0 | 42.70 | |
| 24650 | 1035.20 | 65.0 | 45.20 | |
| 24600 | 1031.10 | 43.0 | 46.50 | |
| 24550 | 1030.40 | 48.0 | 49.10 | |
| 24500 | 1026.60 | 71.0 | 50.40 | |
| [redacted] | | | | 15 |
| 24400 | 1020.90 | 98.0 | 48.60 | |
| 24350 | 1018.10 | 97.0 | 48.40 | |
| 24300 | 1016.60 | 90.0 | 45.60 | |
| 24250 | 1015.20 | 92.0 | 44.35 | |
| 24200 | 1012.60 | 90.0 | 46.40 | |
| 24150 | 1008.70 | 109.0 | 45.90 | |
| 24100 | 1006.20 | 102.0 | 42.40 | |
| 24050 | 1002.20 | 120.0 | 42.90 | |
| 24000 | 999.60 | 117.0 | 41.40 | |
| 23950 | 997.90 | 116.0 | 41.70 | |
| 23900 | 996.30 | 148.0 | 39.60 | |
| 23850 | 995.90 | 140.0 | 39.00 | |
| 23800 | 995.50 | 122.0 | 42.90 | |
| 23750 | 994.80 | 88.0 | 43.80 | |
| 23700 | 990.80 | 73.0 | 42.30 | |
| 23650 | 989.30 | 63.0 | 39.60 | |
| 23600 | 988.70 | 53.0 | 39.50 | |
| 23550 | 987.50 | 49.0 | 38.00 | |
| 23500 | 985.20 | 50.0 | 36.50 | |
| 23450 | 982.20 | 44.0 | 36.20 | |

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|
| 23400 | 981.30 | 37.0 | 35.70 |
| 23350 | 979.10 | 44.0 | 37.40 |
| 23300 | 973.70 | 110.0 | 41.80 |
| 23250 | 971.40 | 50.0 | 44.80 |
| 23200 | 970.30 | 35.0 | 43.20 |
| 23150 | 969.10 | 45.0 | 43.60 |
| 23100 | 966.70 | 73.0 | 44.50 |
| 23050 | 964.20 | 106.0 | 46.90 |
| 23000 | 963.10 | 124.0 | 47.70 |
| 22950 | 961.70 | 116.0 | 47.60 |
| 22900 | 960.60 | 116.0 | 49.70 |
| 22850 | 958.50 | 127.0 | 50.80 |
| 22800 | 953.70 | 123.0 | 48.90 |
| 22750 | 950.00 | 113.0 | 48.30 |
| 22700 | 947.60 | 104.0 | 50.80 |
| 22650 | 945.70 | 102.0 | 51.50 |
| 22600 | 944.20 | 102.0 | 51.80 |
| 22550 | 940.60 | 80.0 | 53.00 |
| 22500 | 937.50 | 64.0 | 56.60 |
| 22450 | 934.60 | 65.0 | 57.40 |
| 22400 | 931.60 | 65.0 | 56.70 |
| 22350 | 928.30 | 72.0 | 55.70 |
| 22300 | 924.80 | 126.0 | 53.00 |
| 22250 | 923.10 | 147.0 | 51.10 |
| 22200 | 919.50 | 150.0 | 52.10 |
| 22150 | 917.60 | 151.0 | 50.40 |
| 22100 | 914.90 | 144.0 | 49.90 |
| 22050 | 911.20 | 107.0 | 47.50 |
| 22000 | 906.50 | 112.0 | 46.20 |
| 21950 | 904.30 | 110.0 | 43.70 |
| 21900 | 903.90 | 101.0 | 41.70 |
| 21850 | 902.80 | 86.0 | 41.10 |
| 21800 | 900.70 | 56.0 | 38.70 |
| 21750 | 898.90 | 41.0 | 37.70 |
| 21700 | 895.50 | 69.0 | 36.60 |
| 21650 | 895.30 | 105.0 | 36.10 |
| 21600 | 894.30 | 116.0 | 36.00 |
| 21550 | 893.10 | 176.0 | 33.80 |
| 21500 | 891.30 | 194.0 | 34.40 |
| 21450 | 890.90 | 197.0 | 36.90 |
| 21400 | 889.90 | 184.0 | 39.80 |
| 21350 | 887.20 | 156.0 | 40.80 |
| 21300 | 886.10 | 110.0 | 42.10 |
| 21250 | 885.40 | 73.0 | 43.70 |
| 21200 | 882.90 | 47.0 | 42.60 |
| 21150 | 881.50 | 47.0 | 43.20 |
| 21100 | 878.90 | 49.0 | 42.80 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|
| 21050 | 877.40 | 73.0 | 42.90 |
| 21000 | 872.10 | 115.0 | 42.50 |
| 20950 | 867.40 | 150.0 | 45.00 |
| 20900 | 864.10 | 170.0 | 46.40 |
| 20850 | 862.00 | 192.0 | 45.40 |
| 20800 | 858.60 | 180.0 | 47.00 |
| 20750 | 855.20 | 150.0 | 46.60 |
| 20700 | 852.90 | 130.0 | 48.70 |
| 20650 | 852.10 | 75.0 | 50.80 |
| 20600 | 851.50 | 48.0 | 50.70 |
| 20550 | 850.20 | 52.0 | 51.10 |
| 20500 | 848.80 | 63.0 | 47.10 |
| 20450 | 845.90 | 67.0 | 47.20 |
| 20400 | 843.50 | 72.0 | 47.80 |
| 20350 | 841.80 | 86.0 | 47.80 |
| 20300 | 839.10 | 110.0 | 45.50 |
| 20250 | 838.80 | 124.0 | 42.60 |
| 20200 | 834.20 | 158.0 | 41.10 |
| 20150 | 830.70 | 175.0 | 41.10 |
| 20100 | 828.20 | 174.0 | 41.30 |
| 20050 | 826.30 | 160.0 | 43.70 |
| 20000 | 825.00 | 166.0 | 45.80 |
| 19950 | 820.20 | 166.0 | 43.60 |
| 19900 | 816.30 | 187.0 | 43.30 |
| 19850 | 814.20 | 185.0 | 43.50 |
| 19800 | 813.10 | 190.0 | 43.20 |
| 19750 | 812.60 | 185.0 | 45.50 |
| 19700 | 811.80 | 180.0 | 43.10 |
| 19650 | 811.00 | 149.0 | 40.90 |
| 19600 | 810.20 | 109.0 | 41.10 |
| 19550 | 806.50 | 99.0 | 43.00 |
| 19500 | 803.00 | 110.0 | 42.50 |
| 19450 | 802.30 | 114.0 | 43.00 |
| 19400 | 800.20 | 106.0 | 40.60 |
| 19350 | 798.30 | 86.0 | 40.80 |
| 19300 | 795.90 | 60.0 | 43.90 |
| 19250 | 793.30 | 61.0 | 46.10 |
| 19200 | 791.10 | 60.0 | 49.70 |
| 19150 | 789.80 | 66.0 | 53.10 |
| 19100 | 787.10 | 77.0 | 57.30 |
| 19050 | 783.30 | 135.0 | 57.80 |
| 19000 | 782.50 | 137.0 | 60.20 |
| 18950 | 777.20 | 142.0 | 61.90 |
| 18900 | 775.70 | 138.0 | 60.70 |
| 18850 | 773.40 | 153.0 | 60.30 |
| 18800 | 769.20 | 167.0 | 58.50 |
| 18750 | 766.50 | 160.0 | 57.10 |

| | Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|---|
| | 18700 | 762.10 | 132.0 | 55.60 |
| | 18650 | 757.90 | 78.0 | 56.40 |
| | 18600 | 752.90 | 46.0 | 55.30 |
| | 18550 | 748.70 | 41.0 | 54.40 |
| | 18500 | 742.80 | 90.0 | 52.10 |
| | 18450 | 740.40 | 102.0 | 46.80 |
| | 18400 | 739.50 | 105.0 | 48.60 |
| | 18350 | 738.00 | 93.0 | 46.90 |
| | 18300 | 737.40 | 84.0 | 48.10 |
| | 18250 | 736.20 | 87.5 | 48.90 |
| | 18200 | 735.50 | 113.0 | 47.90 |
| | 18150 | 733.40 | 128.0 | 45.30 |
| | 18100 | 731.80 | 133.0 | 41.40 |
| | 18050 | 728.90 | 145.0 | 38.60 |
| | 18000 | 730.40 | 140.0 | 34.80 |
| | 17950 | 730.40 | 120.0 | 33.20 |
| | 17900 | 727.10 | 110.0 | 35.90 |
| | 17850 | 726.50 | 95.0 | 38.90 |
| | 17800 | 721.10 | 72.0 | 43.30 |
| | 17750 | 717.60 | 40.0 | 43.00 |
| | 17700 | 714.20 | 30.0 | 43.50 |
| | 17650 | 712.60 | 44.0 | 44.10 |
| | 17600 | 711.50 | 50.0 | 45.40 |
| | 17550 | 710.10 | 40.0 | 45.20 |
| | 17500 | 708.00 | 40.0 | 51.60 |
| | 17450 | 707.20 | 60.0 | 55.00 |
| | 17400 | 703.60 | 110.0 | 53.20 |
| | 17350 | 699.10 | 129.0 | 52.10 |
| | 17300 | 694.10 | 129.0 | 47.50 |
| | 17250 | 693.20 | 127.0 | 46.20 |
| | 17200 | 692.00 | 118.0 | 44.60 |
| | 17150 | 689.30 | 103.0 | 44.60 |
| | 17100 | 686.40 | 86.0 | 43.70 |
| 16 | [illegible] | [illegible] | [illegible] | [illegible] |
| | 17000 | 678.80 | 119.0 | 43.00 |
| | 16950 | 675.40 | 130.0 | 43.50 |
| | 16900 | 673.90 | 120.0 | 44.10 |
| | 16850 | 674.40 | 115.0 | 40.10 |
| | 16800 | 673.60 | 115.0 | 40.90 |
| | 16750 | 671.40 | 109.0 | 42.10 |
| | 16700 | 669.60 | 118.0 | 46.00 |
| | 16650 | 668.00 | 130.0 | 44.10 |
| | 16600 | 667.80 | 133.0 | 44.40 |
| | 16550 | 666.40 | 135.0 | 42.40 |
| | 16500 | 665.00 | 147.0 | 38.10 |
| | 16450 | 663.70 | 161.0 | 41.50 |
| | 16400 | 659.50 | 165.0 | 42.60 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|
| 16350 | 659.00 | 172.0 | 44.70 |
| 16300 | 653.20 | 172.0 | 45.50 |
| 16250 | 651.10 | 170.0 | 45.50 |
| 16200 | 646.00 | 160.0 | 48.70 |
| 16150 | 645.20 | 151.0 | 51.10 |
| 16100 | 642.00 | 120.0 | 54.20 |
| 16050 | 641.30 | 141.0 | 55.70 |
| 16000 | 640.70 | 179.0 | 54.90 |
| 15950 | 633.90 | 198.0 | 55.80 |
| 15900 | 631.30 | 212.0 | 52.70 |
| 15850 | 629.70 | 220.0 | 52.50 |
| 15800 | 628.10 | 199.0 | 47.10 |
| 15750 | 625.90 | 172.0 | 46.40 |
| 15700 | 620.90 | 152.0 | 43.30 |
| 15650 | 616.90 | 136.0 | 43.30 |
| 15600 | 613.60 | 126.0 | 40.10 |
| 15550 | 610.70 | 110.0 | 41.80 |
| 15500 | 610.10 | 82.0 | 42.60 |
| 15450 | 607.90 | 70.0 | 37.10 |
| 15400 | 606.80 | 64.0 | 36.60 |
| 15350 | 606.50 | 60.0 | 36.80 |
| 15300 | 606.10 | 61.0 | 37.20 |
| 15250 | 604.70 | 78.0 | 36.00 |
| 15200 | 602.70 | 95.0 | 31.20 |
| 15150 | 601.90 | 95.0 | 29.70 |
| 15100 | 601.90 | 94.0 | 29.50 |
| 15050 | 599.50 | 87.0 | 27.10 |
| 15000 | 598.10 | 78.0 | 29.70 |
| 14950 | 596.80 | 75.0 | 31.40 |
| 14900 | 594.70 | 60.0 | 34.10 |
| 14850 | 592.90 | 54.0 | 35.40 |
| 14800 | 590.90 | 64.0 | 36.70 |
| 14750 | 589.90 | 81.0 | 40.60 |
| 14700 | 589.70 | 125.0 | 40.70 |
| 14650 | 587.20 | 108.0 | 41.30 |
| 14600 | 584.10 | 96.0 | 41.80 |
| 14550 | 583.60 | 99.0 | 45.50 |
| 14500 | 580.40 | 103.0 | 47.60 |
| 14450 | 576.50 | 112.0 | 48.40 |
| 14400 | 572.70 | 120.0 | 48.80 |
| 14350 | 571.10 | 158.0 | 49.10 |
| 14300 | 569.40 | 171.0 | 49.20 |
| 14250 | 564.10 | 175.0 | 52.20 |
| 14200 | 562.00 | 197.0 | 55.90 |
| 14150 | 560.60 | 192.0 | 54.20 |
| 14100 | 560.10 | 170.0 | 54.90 |
| 14050 | 554.00 | 141.0 | 56.30 |

| | Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|---|
| | 14000 | 550.50 | 119.0 | 54.30 |
| | 13950 | 548.40 | 94.0 | 51.20 |
| | 13900 | 545.90 | 88.0 | 48.30 |
| | 13850 | 543.80 | 83.0 | 48.20 |
| | 13800 | 541.70 | 92.0 | 48.10 |
| | 13750 | 537.70 | 81.0 | 46.20 |
| | 13700 | 533.80 | 44.0 | 46.20 |
| | 13650 | 533.00 | 44.0 | 48.40 |
| | 13600 | 529.20 | 60.0 | 50.20 |
| | 13550 | 527.30 | 96.0 | 44.90 |
| | 13500 | 526.10 | 120.0 | 43.30 |
| | 13450 | 525.30 | 124.5 | 43.20 |
| | 13400 | 524.40 | 138.0 | 43.10 |
| | 13350 | 522.90 | 146.0 | 45.20 |
| | 13300 | 521.30 | 140.0 | 44.30 |
| | 13250 | 517.90 | 120.0 | 43.70 |
| | 13200 | 515.80 | 114.0 | 43.20 |
| | 13150 | 512.20 | 86.0 | 43.70 |
| | 13100 | 509.90 | 46.0 | 41.60 |
| | 13050 | 509.10 | 58.0 | 41.20 |
| | 13000 | 507.20 | 108.0 | 41.70 |
| 17 | | | | |
| | 12900 | 502.80 | 123.0 | 46.30 |
| | 12850 | 498.60 | 123.0 | 48.20 |
| | 12800 | 497.40 | 116.0 | 48.20 |
| | 12750 | 494.00 | 106.0 | 47.30 |
| | 12700 | 490.60 | 95.0 | 47.70 |
| | 12650 | 489.30 | 89.0 | 45.20 |
| | 12600 | 487.60 | 100.0 | 46.60 |
| | 12550 | 486.10 | 109.0 | 47.30 |
| | 12500 | 484.40 | 110.0 | 47.80 |
| | 12450 | 480.00 | 110.0 | 49.50 |
| | 12400 | 478.10 | 111.0 | 50.00 |
| | 12350 | 474.70 | 120.0 | 46.70 |
| | 12300 | 473.10 | 105.0 | 46.70 |
| | 12250 | 470.60 | 85.0 | 44.30 |
| | 12200 | 468.10 | 75.0 | 41.40 |
| | 12150 | 467.00 | 30.0 | 40.60 |
| | 12100 | 463.30 | 54.0 | 40.10 |
| | 12050 | 461.80 | 66.0 | 39.90 |
| | 12000 | 459.40 | 83.0 | 43.60 |
| | 11950 | 455.70 | 79.0 | 42.60 |
| | 11900 | 452.80 | 78.0 | 43.70 |
| | 11850 | 451.90 | 78.0 | 42.60 |
| | 11800 | 450.70 | 76.0 | 44.90 |
| | 11750 | 449.70 | 76.0 | 43.80 |
| | 11700 | 449.20 | 82.0 | 44.00 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) | Cross Section |
|---|---|---|---|---|
| 11650 | 448.70 | 105.0 | 43.10 | |
| 11600 | 447.50 | 130.0 | 40.00 | |
| 11550 | 446.20 | 150.0 | 40.50 | |
| 11500 | 440.80 | 158.0 | 40.00 | |
| 11450 | 437.40 | 162.0 | 40.30 | |
| 11400 | 434.40 | 162.0 | 37.70 | |
| 11350 | 432.10 | 136.0 | 37.40 | |
| 11300 | 428.20 | 126.0 | 37.60 | |
| 11250 | 426.80 | 124.0 | 38.90 | |
| 11200 | 424.10 | 125.0 | 40.00 | |
| 11150 | 423.90 | 111.0 | 43.90 | |
| 11100 | 423.30 | 111.0 | 44.90 | |
| 11050 | 421.30 | 106.0 | 46.30 | |
| 11000 | 419.40 | 110.0 | 41.30 | |
| 10950 | 415.40 | 109.0 | 39.80 | |
| 10900 | 415.10 | 114.0 | 38.40 | |
| 10850 | 414.50 | 115.0 | 38.00 | |
| 10800 | 413.10 | 112.0 | 35.50 | |
| 10750 | 410.80 | 80.0 | 35.00 | |
| 10700 | 409.20 | 67.0 | 37.30 | |
| 10650 | 404.80 | 70.0 | 37.30 | |
| 10600 | 402.60 | 81.0 | 38.90 | |
| 10550 | 399.90 | 89.0 | 39.80 | |
| 10500 | 399.50 | 90.0 | 39.10 | |
| 10450 | 397.60 | 97.0 | 36.50 | |
| 10400 | 396.00 | 112.0 | 38.60 | |
| 10350 | 394.10 | 120.0 | 41.80 | |
| 10300 | 392.70 | 126.0 | 43.70 | |
| [redacted] | | | | 18 |
| 10200 | 386.80 | 123.0 | 41.70 | |
| 10150 | 386.60 | 124.0 | 38.70 | |
| 10100 | 384.40 | 120.0 | 39.60 | |
| 10050 | 381.50 | 123.0 | 39.10 | |
| 10000 | 380.30 | 120.0 | 41.40 | |
| 9950 | 378.90 | 114.0 | 42.60 | |
| 9900 | 376.50 | 102.0 | 44.50 | |
| 9850 | 372.70 | 91.0 | 45.50 | |
| 9800 | 369.40 | 95.0 | 45.00 | |
| 9750 | 369.20 | 101.0 | 45.40 | |
| 9700 | 367.50 | 114.0 | 41.80 | |
| 9650 | 366.10 | 123.0 | 46.60 | |
| 9600 | 363.00 | 125.0 | 46.00 | |
| 9550 | 360.80 | 116.0 | 44.00 | |
| 9500 | 358.10 | 129.0 | 43.00 | |
| 9450 | 355.00 | 108.0 | 41.80 | |
| 9400 | 351.50 | 86.0 | 40.20 | |
| 9350 | 348.60 | 73.0 | 37.80 | |

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|
| 9300 | 347.70 | 69.0 | 35.60 |
| 9250 | 346.40 | 68.0 | 38.70 |
| 9200 | 345.00 | 72.0 | 38.20 |
| 9150 | 340.00 | 73.0 | 38.80 |
| 9100 | 338.40 | 72.0 | 41.90 |
| 9050 | 337.50 | 85.0 | 41.40 |
| 9000 | 337.30 | 110.0 | 40.10 |
| 8950 | 337.10 | 124.0 | 39.00 |
| 8900 | 336.30 | 133.0 | 37.60 |
| 8850 | 334.90 | 137.0 | 35.40 |
| 8800 | 333.80 | 137.0 | 35.00 |
| 8750 | 330.50 | 138.0 | 39.05 |
| 8700 | 329.30 | 161.0 | 43.00 |
| 8650 | 327.30 | 166.0 | 41.50 |
| 8600 | 321.10 | 165.0 | 40.40 |
| 8550 | 319.40 | 145.0 | 43.00 |
| 8500 | 318.00 | 125.0 | 45.60 |
| 8450 | 316.00 | 108.0 | 47.30 |
| 8400 | 313.90 | 102.0 | 47.50 |
| 8350 | 313.20 | 78.0 | 49.20 |
| 8300 | 312.70 | 58.0 | 50.30 |
| 8250 | 307.35 | 80.0 | 47.20 |
| 8200 | 302.00 | 115.0 | 46.20 |
| 8150 | 298.50 | 128.0 | 47.10 |
| 8100 | 298.00 | 107.0 | 44.40 |
| 8050 | 294.50 | 98.0 | 43.50 |
| 8000 | 291.70 | 88.0 | 43.50 |
| 7950 | 289.80 | 108.0 | 47.10 |
| 7900 | 288.80 | 131.0 | 48.90 |
| 7850 | 285.70 | 164.0 | 49.70 |
| 7800 | 283.50 | 168.0 | 48.80 |
| 7750 | 283.30 | 157.0 | 43.65 |
| 7700 | 283.10 | 150.0 | 41.50 |
| 7650 | 280.20 | 125.0 | 41.30 |
| 7600 | 276.70 | 97.0 | 43.60 |
| 7550 | 275.90 | 105.0 | 44.80 |
| 7500 | 274.50 | 104.0 | 44.60 |
| 7450 | 268.90 | 118.0 | 43.90 |
| 7400 | 265.00 | 129.0 | 44.00 |
| 7350 | 263.50 | 140.0 | 41.60 |
| 7300 | 263.90 | 127.0 | 39.70 |
| 7250 | 263.70 | 118.0 | 42.20 |
| 7200 | 260.50 | 115.0 | 42.70 |
| 7150 | 257.20 | 108.0 | 39.90 |
| 7100 | 254.40 | 100.0 | 38.40 |
| 7050 | 249.70 | 106.0 | 39.50 |
| 7000 | 247.10 | 114.0 | 38.20 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) | | Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|---|---|---|---|---|
| 6950 | 245.90 | 118.0 | 35.20 | | 4600 | 149.90 | 58.0 | 40.40 |
| 6900 | 244.80 | 84.0 | 33.60 | | 4550 | 147.80 | 35.0 | 42.30 |
| 6850 | 244.10 | 60.0 | 34.90 | | 4500 | 147.80 | 26.0 | 43.70 |
| 6800 | 243.80 | 65.0 | 37.30 | | 4450 | 148.80 | 36.0 | 43.60 |
| 6750 | 241.10 | 60.0 | 36.00 | | 4400 | 147.70 | 51.0 | 40.90 |
| 6700 | 240.40 | 54.0 | 34.90 | | 4350 | 145.20 | 63.0 | 43.50 |
| 6650 | 240.30 | 55.0 | 33.70 | | 4300 | 142.40 | 64.0 | 45.50 |
| 6600 | 238.30 | 61.0 | 33.10 | | 4250 | 138.40 | 62.0 | 45.90 |
| 6550 | 236.40 | 77.0 | 30.80 | | 4200 | 138.20 | 70.0 | 46.60 |
| 6500 | 236.30 | 84.0 | 29.70 | | 4150 | 137.10 | 82.0 | 42.80 |
| 6450 | 233.70 | 76.0 | 30.40 | | 4100 | 133.70 | 96.0 | 41.20 |
| 6400 | 231.40 | 63.0 | 34.10 | | 4050 | 130.80 | 87.0 | 40.10 |
| 6350 | 228.60 | 55.0 | 36.40 | | 4000 | 125.80 | 49.0 | 42.30 |
| 6300 | 226.60 | 61.0 | 40.30 | | 3950 | 123.70 | 45.0 | 47.00 |
| 6250 | 227.70 | 63.0 | 43.30 | | 3900 | 121.50 | 68.0 | 48.10 |
| 6200 | 225.60 | 59.0 | 44.40 | | 3850 | 118.70 | 50.0 | 47.90 |
| 6150 | 223.50 | 69.0 | 45.80 | | 3800 | 114.80 | 31.0 | 46.00 |
| 6100 | 221.30 | 84.0 | 44.40 | | 3750 | 113.90 | 40.0 | 40.70 |
| 6050 | 218.90 | 99.0 | 43.20 | | 3700 | 111.40 | 35.0 | 41.90 |
| [illegible] | [illegible] | [illegible] | [illegible] | 19 | 3650 | 110.50 | 43.0 | 39.10 |
| 5950 | 215.50 | 128.0 | 43.20 | | 3600 | 108.70 | 66.0 | 40.30 |
| 5900 | 210.70 | 120.0 | 45.40 | | 3550 | 107.70 | 90.0 | 39.70 |
| 5850 | 207.70 | 120.0 | 43.60 | | 3500 | 105.50 | 98.0 | 37.60 |
| 5800 | 203.50 | 120.0 | 44.20 | | 3450 | 101.80 | 83.0 | 36.60 |
| 5750 | 197.80 | 114.0 | 46.90 | | 3400 | 99.60 | 78.0 | 34.80 |
| 5700 | 196.00 | 100.0 | 46.30 | | 3350 | 97.30 | 76.0 | 32.30 |
| 5650 | 194.50 | 90.0 | 48.80 | | 3300 | 96.40 | 80.0 | 29.30 |
| 5600 | 193.90 | 92.0 | 47.20 | | 3250 | 97.70 | 83.0 | 31.50 |
| 5550 | 193.20 | 87.0 | 45.80 | | 3200 | 96.30 | 88.0 | 30.30 |
| 5500 | 192.10 | 87.0 | 47.90 | | 3150 | 98.00 | 92.0 | 30.60 |
| 5450 | 190.50 | 74.0 | 48.20 | | 3100 | 93.40 | 77.0 | 29.70 |
| 5400 | 186.00 | 59.5 | 48.30 | | 3050 | 91.10 | 29.0 | 29.10 |
| 5350 | 185.00 | 70.0 | 45.50 | | 3000 | 88.20 | 38.0 | 28.00 |
| 5300 | 182.40 | 72.0 | 43.20 | | 2950 | 87.10 | 39.0 | 25.70 |
| 5250 | 180.80 | 71.0 | 38.00 | | 2900 | 86.70 | 62.0 | 26.10 |
| 5200 | 179.30 | 71.0 | 38.00 | | 2850 | 86.40 | 67.0 | 22.80 |
| 5150 | 174.70 | 76.0 | 41.20 | | 2800 | 85.50 | 68.0 | 23.60 |
| 5100 | 174.10 | 78.0 | 44.00 | | 2750 | 82.40 | 61.0 | 25.80 |
| 5050 | 173.10 | 72.0 | 45.40 | | 2700 | 81.10 | 46.0 | 25.10 |
| 5000 | 169.50 | 62.0 | 44.30 | | 2650 | 79.90 | 35.0 | 28.00 |
| 4950 | 167.30 | 48.0 | 41.70 | | 2600 | 79.00 | 36.0 | 26.20 |
| 4900 | 162.40 | 40.0 | 38.30 | | 2550 | 78.60 | 50.0 | 25.90 |
| 4850 | 162.20 | 43.0 | 39.80 | | 2500 | 77.50 | 50.0 | 24.70 |
| 4800 | 160.30 | 47.0 | 40.00 | | 2450 | 76.10 | 48.0 | 24.20 |
| 4750 | 159.80 | 52.0 | 42.40 | | 2400 | 73.50 | 44.0 | 25.40 |
| 4700 | 158.00 | 62.0 | 41.10 | | 2350 | 74.50 | 50.0 | 26.90 |
| 4650 | 153.30 | 64.0 | 37.60 | | 2300 | 72.80 | 53.0 | 27.50 |

Highlighted position represents a channel cross section. Cross Section Number in centre column.

| Position (m) | Corrected Elevations (cm) | Width (m) | Slope (cm/km) |
|---|---|---|---|
| 2250 | 71.90 | 58.0 | 26.60 |
| 2200 | 71.20 | 58.0 | 26.60 |
| 2150 | 70.00 | 49.0 | 25.60 |
| 2100 | 67.20 | 50.0 | 28.90 |
| 2050 | 65.20 | 50.0 | 31.00 |
| 2000 | 63.50 | 42.0 | 33.40 |
| 1950 | 62.90 | 43.0 | 33.40 |
| 1900 | 61.30 | 43.0 | 31.80 |
| 1850 | 59.50 | 39.0 | 32.80 |
| 1800 | 58.00 | 42.0 | 36.30 |
| 1750 | 55.80 | 43.0 | 37.00 |
| 1700 | 54.50 | 38.0 | 39.70 |
| 1650 | 54.30 | 40.0 | 38.80 |
| 1600 | 50.10 | 38.0 | 37.70 |
| 1550 | 47.60 | 43.0 | 35.80 |
| 1500 | 44.10 | 50.0 | 37.00 |
| 1450 | 42.70 | 49.0 | 38.70 |
| 1400 | 41.70 | 51.0 | 37.30 |
| 1350 | 41.70 | 52.0 | 37.10 |
| 1300 | 36.50 | 54.0 | 37.10 |
| 1250 | 34.90 | 48.0 | 36.20 |
| 1200 | 31.50 | 39.0 | 35.60 |
| 1150 | 31.20 | 39.0 | 37.00 |
| 1100 | 29.50 | 34.0 | 35.90 |
| 1050 | 29.40 | 33.0 | 33.50 |
| 1000 | 26.50 | 34.0 | 31.90 |
| 950 | 24.20 | 40.0 | 31.00 |
| 900 | 24.00 | 43.0 | 31.60 |
| 850 | 22.40 | 35.0 | 33.20 |
| 800 | 20.90 | 35.0 | 29.80 |
| 750 | 19.60 | 40.0 | 28.90 |
| 700 | 18.90 | 38.0 | 26.20 |
| 650 | 17.30 | 35.0 | 26.50 |
| 600 | 14.20 | 24.0 | 25.90 |
| 550 | 14.10 | 38.0 | 27.60 |
| 500 | 12.20 | 50.0 | 26.50 |
| 450 | 11.70 | 48.0 | 25.47 |
| 400 | 10.10 | 37.0 | 26.67 |
| 350 | 8.50 | 26.0 | 26.35 |
| 300 | 6.70 | 34.0 | 26.12 |
| 250 | 6.00 | 45.0 | 26.13 |
| 200 | 5.30 | 53.0 | 27.00 |
| 150 | 4.70 | 58.0 | 26.62 |
| 100 | 3.60 | 52.0 | 23.67 |
| 50 | 1.80 | 34.0 | 25.64 |
| 0 | 0.00 | 30.0 | 24.40 |

**Meandering Reach**
77 850 - 49 650

**Braided Reach**
49 600 - 2 650

**Backwater Reach**
2 600 - 0

Highlighted position represents a channel cross section. Cross Section Number in centre column.