PATTERNS OF BAR DEVELOPMENT AND SAND FLAT INITIATION IN THE SOUTH SASKATCHEWAN RIVER

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F. Malcolm Conly

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ABSTRACT

This is a study of the development of bars and the initiation of sand flats in a braided sand-bed river. The changes in morphology, flow direction and hydraulic character on the surface of bars are documented. This information is used to assess conditions on the surface of the bar as it migrates downstream and prior to the initiation of a sand flat. The relationship between channel topography and bar development is also considered.

Several bars were monitored in the sandy braided South Saskatchewan river from May to August, 1988. Measurements included flow direction, depth, velocity, bedload transport and topographic surveys of the channel reach. Diagrams illustrating channel topography, bar morphology, flow direction and hydraulic character of the surface are presented. These diagrams are used to identify changes in the spatial pattern of the variables as the bar features migrate downstream, and to identify changes in channel topography.

The data suggest that bar development and sand flat development are associated with the channel topography and morphology, particularly with the location and alignment of deep troughs such as the thalweg. The troughs tend to draw flow over the surface of the bars creating asymmetric hydraulic conditions, thus affecting the downstream migration of the bar. The flow and sediment are directed away from the downstream

edge of the bars resulting in some of them diminishing into the channel bed. In some cases, the asymmetric hydraulic conditions over the surface of the bars resulted in the feature changing from one descriptive bar type to another.

The exposure of sand flats was only monitored at one study site, however observations were made in other parts of the river. At the site which was monitored, flow directed toward a channel trough created a shallow sluice which locally lowered the water surface elevation, thus contributing to the exposure of the sand flat. The channel morphology was also a strong influence on the development of the sand flat at this site. In other parts of the river, shoaling of the channel thalweg and general aggradation of the channel preceeded the initiation of sand flats.

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1 INTRODUCTION

Although many braided channels have been described and the characteristics of their morphology and alluvium are well known, comparatively little is known of their sedimentary mechanics. The bed morphology of sand-bed braided rivers is dominated by large lobate bedforms called channel bars and by large exposed braid bars (Allen, 1968) or sand flats (Cant and Walker, 1978). Channel bars persist through most variations in flow conditions. When a portion of a channel bar becomes exposed it can act as a 'nucleus' for sand flat development by lateral accretion (Cant and Walker, 1978) and hence is a primary braiding mechanism. However, the mechanics of this process and the circumstances under which it occurs are not well known. There have also been few observations of the spatial patterns of velocity, shear stress and bedload transport on a bar surface, which are fundamental to explaining bar migration and the initiation of braiding.

1.1 Research Objectives

This thesis provides quantitative data which are used to obtain a better understanding of the processes involved in bar development and the initiation of sand flats. In light of the problems associated with the understanding of bar development and the processes involved, it is the purpose of this thesis to study both the hydraulic parameters, (i.e., velocity, shear and bedload transport) on the surface of submerged bars as they migrate downstream, and the development of bars as they move into topographically lower sections of the channel.

Specifically the objectives are:

1) to identify the factors influencing the spatial patterns of flow direction, flow depth, velocity, shear stress and bedload transport on the surface of actively developing bars.

2) to identify conditions necessary for the initiation of a sand flat.

3) to study the influence of channel topography on the development of bars and the initiation of sand flats.

The thesis is organized as follows. Chapter Two gives a brief review of channel pattern development and a discussion of the sand-bed braided system. Chapter Three describes the study area. Chapter Four outlines the methods used for the collection and presentation of data. Chapter Five describes the changes in channel topography, hydraulic conditions and bar morphology observed in this study. Chapter Six discusses the relationships between the channel topography, morphology and bar development. Chapter Seven presents the conclusions of the study.

2 LITERATURE REVIEW

2.1 River Channel Patterns

Channel pattern refers to the plan view or the form of the channel in the horizontal plane. Channel patterns are considered to be a reflection of the hydrodynamic nature of the flow, processes of sediment transfer, and energy dissipation within the river. The channel pattern is, therefore, influenced by both sedimentological and hydraulic factors.

Leopold and Wolman (1957) reduced the continuum of pattern types to three: straight, meandering and braided. This categorization of channel patterns is not completely satisfactory, since the terms are not mutually exclusive. A braided channel may be straight or meandering. Channel pattern may change with fluctuations in discharge. The distinction between the straight and meandering channel is often decided arbitrarily. Leopold and Wolman (1957), for example use a sinuosity value of 1.5 (i.e., channel length to valley length ratio) to distinguish between a straight and meandering channel.

A more logical and simplified two dimensional classification consists of single-thread and multi-thread channels, each having a range of sinuosities. Kellerhals et al. (1976) provide a classification for multi-thread channels based on the frequency of exposed alluvium within the channel and the development of channel bars. Since the plan form of a river is stage dependent, Kellerhals et al. (1976) suggest that descriptions of channel patterns be made near mean flow.

The channel pattern continuum which exists between the single and multi-thread channels is often reduced to empirical threshold equations between meandering and braiding. These equations, which define the channel pattern, can be based on either hydraulic or sedimentological variables. Some of the variables showing a functional relationship with channel pattern include channel slope, discharge, width-depth ratio, stream power, sediment supply, sediment size, bank erodibility, bedload competence and bedload capacity (Leopold et al., 1964; Richards, 1982; Knighton, 1984). Braiding is generally favoured in channels with steeper slopes, variable discharge, relatively high width-depth ratio, dominant bedload transport and noncohesive banks (Miall, 1977). It is also important to understand that these factors are interrelated and that relationships between slope, discharge and the calibre of sediment can also effect the braided pattern (Carson, 1984a).

2.2 Morphology of Sand-bed Braided Rivers

The majority of research on braided channels has centred around the origins of the sedimentary facies and the results of braiding (i.e., channel pattern thresholds and the functional relationships given above) rather than the mechanics of braiding. Although many braided channels have been described and the characteristics of their morphology and alluvium are well known, very little is known of their sedimentary mechanics as compared to meandering channels.

Furthermore, most investigations of braided rivers have occurred in gravel-bed rivers (Leopold and Wolman, 1957; Krigström, 1962; Church, 1972; Bluck, 1974; Smith, 1974; Hein and Walker, 1977; Ashmore 1982; Carson, 1984a, b, & c; and Rundle, 1985), consequently, little is known about braiding processes in sand-bed rivers. Brice (1964), Collinson (1970), Smith (1971), Cant (1976), Hunt (1979), Blodget and Stanley (1980) and Crowley (1983) have investigated the sedimentology and bedforms of sand-bed braided rivers but without quantitatively analyzing the sedimentary mechanics and the bifurcation processes associated with sand-bed braided rivers.

Sand-bed channels are common in low gradient rivers flowing across plains. Large rivers which originate in mountains and flow across the plains usually display a change in sedimentological characteristics along their length (Straub, 1935; Church and Kellerhalls, 1978; Shaw and Kellerhals, 1982). The channel bed material usually changes from boulders in the headwater reaches, through cobbles and gravel to sand in lower plains reaches. The type of material making up the channel bed is also dependent on the lithology of the immediate area and can determine whether a channel on the plains becomes dominated by silts and clays or remains a sand-bed channel.

Unlike a silt-clay channel, the banks of a sand-bed channel have little cohesive strength. Boulder and gravel-bed channels also have very little cohesive strength but a greater stream power is required to move particles than in sand-bed rivers. Therefore sand-bed rivers tend to transport sediment under a wide range of flow conditions.

Braided rivers consist of two or more channels separated by exposed areas of alluvium (i.e., braid bars/sand flats). The braided channel is usually wide and shallow with width-depth ratios in excess of 300 (Miall, 1977). Braiding is favoured in channels with a high stream power relative to the particle size of the bed material, large variable discharge, large bed load and non-cohesive banks (Church, 1972; Miall, 1977, Knighton, 1984). The braided river is often relatively straight with only individual channels meandering (Leopold and Wolman, 1957), however this is not a consistent characteristic (Carson, 1984). The channel morphology is closely related to a variety of bedforms occurring at several scales within the river.

2.3 Bedforms in Sand-bed Braided Rivers

Bedforms of a range of scales can be identified in sand-bed braided rivers. The smaller scale bedforms such as dunes and ripples are well understood from flume experiments but the larger bedforms (i.e., bars and sand flats) can only be studied in the field. The larger scale features constitute the major morphological features of the channel, their development is intrinsic to the occurrence of braiding.

Jackson (1975) proposed a multi-scale classification for bedform features. He identified ripples, bars and exposed bar features (sand flats) as individual classes of bedforms. Crowley (1983) agreed with this classification with some modifications. In general, the classification scheme designates ripples as microforms, dunes and submerged bars as mesoforms and exposed braid bars and sand flats as macroforms.

Ashley (1990) considered the storage of sediment in a river to consist of three fundamental types: bedforms, channel forms and unit bars; and an amalgamation of the three types into braid bar complexes (Table 2.1). The large scale bedforms are made up of two sub-categories, periodic forms and quasi-periodic or solitary forms.

Categories	Sediment storage bodies	Jackson (1975)
Ripples		
Periodic forms	ripples	Microform
Large-scale Bedforms		
Periodic forms	(1) bedforms	Mesoform
	(2) channel forms	Macroform
Quasi-periodic or Solitary forms	(3) unit bars	Mesoform
	(4) braid bar complexes	Macroform

Table 2.1: Sediment storage elements in fluvial systems (adapted from Ashley, 1990).

Bedforms are dynamic sediment storage bodies which are scaled to depth (Ashley, 1990). Bedforms were referred to as mesoforms by Jackson (1975). Ashley (1990) also considered channel forms as periodic features, but they are an order of magnitude larger than the bedforms. Channel forms are scaled to width and respond slowly to changes in the channel flow characteristics. Channel forms were referred to as macroforms by Jackson (1975). Unit bars are quasi-periodic or solitary features that are scaled to depth (Ashley, 1990). Ashley (1990) suggested that these features are controlled by "local" changes to the water depth and flow competence. Jackson (1975) also referred to these features as mesoforms. The braid bar complexes were referred to as macroforms by Jackson (1975). Ashley (1990) considered braid bar complexes as an amalgamation of the three fundamental types of sediment storage bodies, but did not provide any detail.

The classification provided by Jackson (1975) suggests that each feature forms within a defined set of hydraulic conditions. In Ashley's (1990) classification, ripples are an independent feature and the large bedform features can be broken up into those which scale with depth and those which scale with width. Therefore, little difference can be discerned between Ashley's (1990) and Jackson's (1975) classification.

The hydraulics of microforms are well known from numerous studies. Simons *et al*. (1961) described a sequence of small scale bedforms (microforms and mesoforms) which developed on a bed of fine sand size particles under a low flow regime. The sequence of bedforms, which are dependent on particle size (i.e., ripples will not develop with particle size >0.6 mm), develop as the flow strength increases. This sequence consisted of low regime plane bed with no sediment movement ripples ripples on dunes transition flat bed. The relationship between these bedforms, bed roughness and channel morphology are well documented by flume studies (Simons *et al*., 1961, 1965; Guy *et al*., 1966; Costello and

Southard, 1981) and by field investigations (Ore, 1964; Allen, 1968; Allen and Collinson, 1974; Jackson, 1975).

The meso-scale bedform features identified in sand-bed rivers are often referred to as 'bars' (Ore, 1964; Collinson, 1970; Smith, 1971; Cant, 1976). Mesoforms scale with the outer boundary layer (i.e., scaled to depth) unlike microforms, which scale with the inner zone (viscous sublayer). Crowley (1983) suggested meso-scale features form under high flow conditions and then become exposed remnant features when the flow declines. If these meso-scale features are regime bedforms formed during high flows, the question remains as to whether they are equivalent to dunes or are a geometrically and hydraulically distinct class.

2.3.1 Mesoforms

There are a variety of features identified in the literature which have the suffix 'bar'. Many of these are poorly classified or inadequately defined (Smith, 1978). A recent consensus among researchers has suggested that bedform features which scale to depth (i.e., mesoforms) should be considered as one feature (Ashley, 1990). Although there are differences in size and shape among the mesoforms, these researchers considered the formative processes to be sufficiently similar to assign a single name. The term "dune" was used because of the precedence for the term set by early researchers (Ashley, 1990). A classification scheme based on morphological characteristics with an underlying genetic rationale was recommended (Table 2.2).

First Order Descriptors (necessary)				
Size: Spacing =	small 0.6-5 m;	Medium 5-10 m;	large 10-100 m;	very large >100 m
Height* =	0.015-0.4 m;	0.4-0.75 m;	0.75-5 m;	>5 m
Shape: 2-Dimensional 3-dimensional				
Second Order Descriptors (important) - Superposition: simple or compound (sizes and relative orientation) - Sediment characteristics (size, sorting)				
Third Order Descriptors (useful) - Bedform Profile (stoss and lee slope lengths and angles) - Fullbeddedness (fraction of bed covered by bedforms) - Flow structure (time-velocity characteristics) - Relative strengths of opposing flows - Dune behaviour-migration history (vertical and horizontal accretion)				

*Height calculated using the equation $H = 0.0677L^{0.8098}$ (Flemming 1988).

Table 2.2: Classification scheme recommended by the SEPM Bedforms and Bedding Structures Research Symposium (Table 6 in Ashley, 1990).

Mesoforms (i.e., bars) have generally been classified on the basis of their form and function. Bars are often modified by erosion and this descriptive approach has led to a multiplicity of terminology. Miall (1977) attempted to eliminate some of the confusion, caused by the terminology, by suggesting four main groups for the large scale bedforms:

1) Longitudinal bars;
2) Linguoid and Transverse bars;
3) Point bars, Side bars, Lateral bars;
4) Other.

Many of these bar types can be identified in both sand and gravel bed channels. The following discussion applies primarily to the sand-bed environment.

Longitudinal bars are mid-channel depositional features which are bounded by active channels on both sides. The bars are lozenge-shaped and elongated parallel to the flow direction. Longitudinal bars rarely have a lee avalanche face and generally taper downstream. These bars are like those described by Leopold and Wolman (1957), Church (1972), Smith (1974) and Miall (1977). These bars are found primarily in gravel bed rivers however bars with a similar morphology have been identified in sand-bed rivers (Smith, 1970).

Transverse and linguoid bars are typically found in sandy braided rivers (Collinson, 1970; Smith, 1971; Cant, 1976). The linguoid bar is lobate in plan view and has a wedge shaped longitudinal profile. The typical height of the avalanche face ranges from 0.5 - 1.0 m but can be higher. Linguoid bars often occur in an out-of-phase series such that the upstream end of a bar progresses into the space between two upstream bars (Collinson, 1970). The transverse or cross-channel bars have a similar morphology to linguoid bars, except that they have a straighter crest line. Transverse bars usually extend between major topographic features such as sand flats, islands or the channel bank (Cant and Walker, 1978). It is possible that transverse bars represent a coalescing of linguoid bars (Miall, 1977).

Point bars, side bars and lateral bars are all similar features, deposited in low energy areas of a fluvial system, such as the inside of a meander bend. These bars, although considered typical of meandering rivers, have also been observed in braided rivers (Collinson, 1970; Cant, 1976). The formative processes and internal structure of these features can be different in braided rivers than in meandering rivers (Miall, 1977).

In some large rivers another class of mesoform, often referred to as sand waves (Coleman, 1969,) occurs. In the Brahmaputra River these features were 15 m high with wavelengths over 900 m (Coleman, 1969). This type of bedform feature falls into a category separate from those described previously and will not be considered further.

2.3.1.1 Hydraulic conditions for bar development in sand-bed rivers

It has been suggested that all large scale mesoforms are dunes and the differences that occur between features are due to modifying processes such as channelization, fluctuating water levels and unsteady flow conditions (Ashley, 1990). Since it is not possible to conduct flume experiments on the flow regime of the larger scale bedforms (mesoforms) there is still some disagreement about the hydraulic conditions required for their formation and their relationship to the wave-like bedforms (dunes and ripples).

Allen (1968, 1974) and Allen and Collinson (1974) did not distinguish between bars and dunes, and therefore regarded the hydrodynamic conditions to be the same for both. They suggested that rapid changes in discharge cause a disequilibrium between the flow and the bedforms. Dunes formed under high flow conditions are slow to adjust and therefore persist into periods of different hydraulic conditions. Allen and Collinson (1974) suggested bars are large dunes which, due to a lag between flow conditions and adjustment of bedforms, have been flattened and stretched out over the bed as the flow declined.

Cant (1976) and Jackson (1975) ignored the hydraulic considerations of bar development. They did not consider any direct connection between flow regime features (ripples and dunes) and bars. Cant (1976) considered the bed topography to be a principal control mechanism. He suggested that flow expansion causes sediment to be deposited as transverse bars, like a small delta. Flow expansion can occur when a channel deepens downstream, widens at the end of a sand flat or enters a bend in the river. This deposited material can build into an identifiable bar feature.

Smith (1971) and Hunt (1979) considered bars to be a distinct class separate from dunes and ripples, yet genetically similar. Smith (1971) suggested that complexes of dunes are responsible for bar development on the Platte River. Hunt (1979), through his observations of the William River, suggested that bars are able to develop under low flow regimes similar to that required for ripples to develop. Hunt (1979) did not observe the initiation of a bar but based his hypothesis on the fact that ripples were observed on the backs of recently formed transverse bars. This only indicates that the hydraulic conditions on the backs of these bars are suitable for the development of ripples.

The kinematic wave theory of sediment movement (Langbein and Leopold, 1968) has been related to the development of transverse bars in sand-bed rivers (Hunt, 1979). The bar is believed to develop from the interaction between the concentration of sediment and the sediment transport rate. This relationship results in a high concentration of sediments moving as a wave along the bed of the channel. The kinematic wave theory dictates that the merging of 'shock waves' causes a downstream migration of bedforms and attenuation of the wave accompanies bedform decay (Costello and Southard, 1981).

Hunt (1979) observed properties of kinematic wave behaviour on the transverse bars of the William River. He noticed a downstream attenuation due to the fading out of ripples and dunes, downstream extension of the bedforms due to their merging, and a reduction in sediment transport at the bar crest. Some of these behaviours have been noticed on other rivers (Culbertson and Scott, 1970; Jackson, 1975) but were not associated with the kinematic wave theory. Although this approach provides some insight into the random development and destruction of bedforms, it is only qualitative in nature and does not explain the mechanism of their formation.

Information on the development and evolution of bars in sand-bed rivers is sparse. Smith (1971), in his study of transverse bars in the Lower Platte River, considered several factors which can determine the outline or morphology of a bar. These factors include: the cross-sectional shape of the bar mouth, proximity to stable banks, strength and direction of adjacent currents flowing past the bar, steadiness of flow, and basin depth distribution (i.e., channel topography). Smith (1971) provided general descriptions of the flow over the bars due to these factors, but did not describe the subsequent evolution of the bars. Smith (1971) based his descriptions on symmetric bar forms yet stated that most of the active bars observed in the Lower Platte River were either simple irregular and asymmetric bars, or a complex of bars. Descriptions of bar development in other rivers have usually been based on generalized symmetric models (Collinson, 1970; Cant and Walker, 1978). The literature suggests that the majority of bar types in sand-bed rivers do not have regular and symmetric shapes.

2.3.2 Macroforms (Sand Flats)

A sand flat is a term used to distinguish emergent bedforms from submerged bedforms (Cant, 1976). Sand flats are similar to "braid bars" (Allen, 1968) and are often referred to as a geomorphic macro-form (Jackson, 1975; Crowley, 1983). The emergence of a bedform is considered a primary mechanism of braiding in sand-bed rivers such as the Loup River (Brice, 1964), the Tana River (Collinson, 1970), the Platte River (Smith, 1971), Wabash River (Jackson, 1976), South Saskatchewan River (Cant, 1976) and the William River (Hunt, 1979).

A newly emerged bar acts as a nucleus for sand flat development (Cant, 1976). This nucleus is subject to accretion of sediment and subsequent modification as the sand flat develops. The most common sequence of modification involves the creation of downstream extensions of the feature, referred to as horns (Cant and Walker, 1978). These horns point downstream on either side of the nucleus creating a back water area in the middle (figure 2.1). As the sand flat increases in size it may become attached to other sand flats combining to create large complexes. The large sand flat complexes are also subject to further development and destruction by lateral migration of the channel which can erode and remove all or portions of the feature (Cant and Walker, 1978; Crowley, 1983). Sand flats may be inundated during high discharge, which can result in all or part of them (e.g. minor channels atop the sand flats) being reactivated as a bedform feature. If the sand flat is large enough, and remains emergent long enough, a vegetation cover can be established and a semi-permanent island may result.

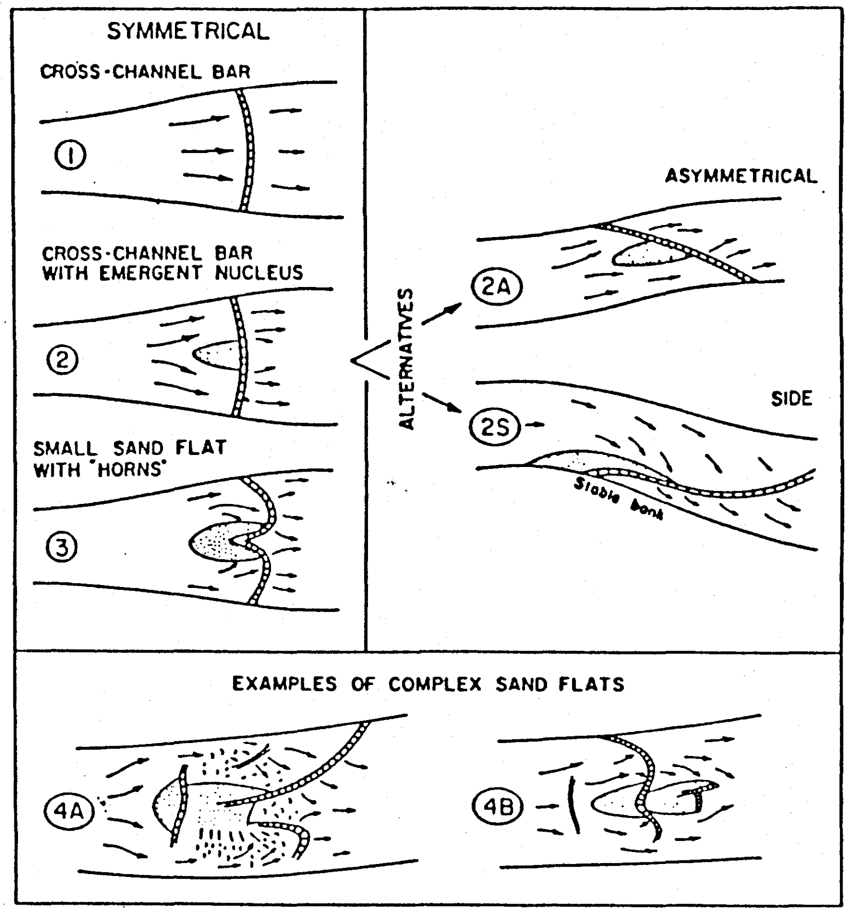


Figure 2.1: Development of sand flats. In stage 1 there is a submerged cross-channel bar (transverse bar) with a slip face. Stage 2 shows an emergent nucleus following a lowering in the river stage. If the original cross-channel bar is diagonal, the nucleus will be asymmetrical (2A) or adjacent to a stable bank (2S). Expanding flow downstream of the nucleus results in the development of 'horns' (stage 3). Complex sand flats are illustrated by 4A and 4B. (figure 9 from Cant and Walker, 1978).

2.4 Mechanics of Braiding and Bar Sedimentation

The causes of braiding are not well understood and they may differ between gravel-bed and sand-bed rivers. Mechanisms of braiding suggested in the literature include:

a) the deposition of coarse lag material which creates a medial bar thus dividing the channel (Leopold and Wolman, 1957);

b) by chute cutoff of alternating bars (Ashmore, 1982; Bridge, 1985);

c) by avulsion or rutting of the floodplain; (Carson, 1984);

d) by the reoccupation of old abandoned channels i.e., secondary anastomosis (Church, 1972) and;

e) creation of transverse and linguoid bars under bankfull flow which become exposed when the discharge decreases, resulting in division of the channel (Smith, 1971,1974; Cant, 1976).

Mid-channel deposition of a lag deposit of coarse material has been considered a primary mechanism of braiding in the geomorphic literature for three decades since it was first suggested by Leopold and Wolman (1957). Coarse material is deposited when the river becomes incompetent to transport the material because of a decrease in discharge or an increase in sediment supply. As accretion of material continues on the mid-channel deposit, the flow is diverted to the sides. The flow which is concentrated in the flanking channels causes the bed to be scoured and the banks to be eroded. This effectively lowers the water surface elevation, until the central bar emerges and the channel is divided. This process is unlikely in sand-bed channels because of the necessity for a loss of competence for the coarsest material (i.e., selective deposition of certain particle sizes).

The development of chute cutoffs of alternating side or lateral bars has been identified in several natural rivers (Krigström, 1962; Church, 1972; Carson, 1984a; Crowley, 1983) and in flume experiments (Ashmore, 1982). A chute cutoff occurs when a small channel dissects a side bar detaching it from the bank. The separated bar, if not already exposed, may emerge when increased flow in the chute scours out the bottom and causes the water level in this location to drop.

High flows spilling over the banks cutting new channels and reoccupying abandoned channels in the surrounding floodplain can be a primary process involved in the development of a braided pattern. This form of braiding is common in deltaic regions of the Mississippi River, Amazon River and Brahmaputra River (Coleman, 1969) as well as some glacial outwash areas (Church, 1972). The avulsion of the floodplain occurs during high return period floods. The flow moves across the floodplain scouring out a channel. If the avulsion has been significant, a permanent channel may be formed in the floodplain i.e., secondary anastomosis. If the avulsion is not severe the floodplain is left 'rutted' when the stage declines (Carson, 1984a). The rutted appearance of the floodplain may heal with sediment infilling and vegetation growth. During the next flood however, these rutted areas may be subject to reoccupation by the flow in the channel. These, as well as other channels which may have been abandoned when the river shifted, can be reoccupied and may remain as a dominant channel when the river's stage declines.

Probably the most important braiding mechanism in sand-bed channels involves the exposure of meso-scale bedform features such as transverse or linguoid bars. These features may be formed under high flow conditions and when the stage drops they become exposed (Allen, 1968; Jackson, 1975). Dissection of these remnant features has also been suggested as a factor contributing to the development of a braided pattern (Smith, 1971). The dissection of these bedforms creates a chute which concentrates the flow and can effectively lower the water surface elevation and create an exposed area on either side of the chute (Hunt, 1979). It has been suggested that dissection of the transverse bar is dependent on the relationship between bar surface area and the discharge over the bar (bar mouth discharge) (Smith, 1971).

The exact mechanism involved in this process of braiding and sand flat initiation is uncertain. One possible mechanism involves the falling stage exposure of bedforms formed under high discharge (Allen, 1968; Collinson, 1970; Smith, 1971; Jackson, 1975), which are then modified by subsequent flow events. The precise mechanism involved in this process requires some prior knowledge of the flow and sediment transport patterns associated with the submerged bars from which the sand flats develop.

In general, the process may operate as follows. A decrease in discharge results in a decrease in the velocity and the bed shear stress over the bedforms. The decrease in the velocity and shear stress results in a reduction in the sediment transport rate over the bar surface. In places, transport ceases and the accumulation of sediment at that point causes the flow to be diverted around it to one or both sides (Cant and Walker, 1978). This is analogous to the mechanism described by Leopold and Wolman, (1957) in shallow gravel-bed channels.

Smith (1971) observed that flow concentrated on either side of an inactive area transports sediment beyond the stationary portion of the bedform effectively dissecting the transverse bedform and developing new smaller bedforms on either side of the inactive area. Further decreases in discharge resulted in the stationary portions of the bedform becoming exposed forming a 'nucleus' of a sand flat (Cant and Walker, 1978). Observations made by Crowley (1983) agree with those made by Smith (1971), however, Crowley did not consider the dissection of the bedform features nor the hydraulic mechanics involved.

Similar processes were observed in the South Saskatchewan River by Cant and Walker (1978). They attributed sand flat initiation to falling stage dissection of bars. The deposition of sediment and the dissection by the flow did not include any widening of the river, which was considered an important factor in the development of braiding by Leopold and Wolman (1957). This may be attributed to the constant discharge used by Leopold and Wolman (1957) in flume studies, and to the lack of any vegetation, which reduces bank erosion. Also, in a sand-bed braided river, widening by bank resistance erosion may not occur but rather individual channels may be widened by the erosion of existing sand flats.

However, bar dissection of this kind has also been observed in situations where the discharge is apparently stable. In the William River Hunt (1979) observed that as the surface area of the transverse bars increased, sediment transport ceased at the crest. The convergence of the flow that occurred on either side of the stationary area is similar to that which was described by Smith (1971) on the Platte River and Cant and Walker (1978) on the South Saskatchewan River. The concentrated flow then began to scour the bed of the channel forming ridges on either side. The down-cutting lowered the water surface in the vicinity of the ridge allowing it and the inactive area to emerge. Hunt (1979) suggested that this same type of dissection would likely occur in a river which had a decreasing discharge such as described by Smith (1971), however, the degree of dissection would be dependent on the rate of change in discharge (Jones, 1977).

Smith's (1971) relationship between the bar top surface area and the "bar mouth discharge" provides some support for the formation of braiding at a constant discharge. The bar mouth discharge is defined as the flow at the upstream end of the bar, usually measured where the channel is confined between two well defined banks. Smith (1971) suggested that for a given bar surface area, there is a critical discharge at the bar mouth above which sediment transport occurs everywhere on the bar surface. Below this discharge, portions of the bar would have no sediment transport. Conversely at a given discharge there is a threshold in the bedform surface area below which sediment transport occurs ubiquitously and above which portions of the bar surface can become inactive. Smith (1971) observed that as a bar enlarges it also aggrades, which also contributes to decreasing flow depth. Flow velocity may also decrease and the combination of these flow conditions causes a decrease in competence and capacity over the bar surface. Smith (1971) did not state whether the increase in surface area was due to lateral expansion of the bar snout and/or forward expansion. Cant (1976) suggests that lateral expansion of the snout, as it enters a wider part of the channel, creates the flow expansion necessary to reduce velocity, bed shear stress and sediment movement over portions of the bar.

Dissection of side bars and lateral bars is also cited as a process which can establish a braided pattern. Side bars and lateral bars are attached to the bank of the channel and form in a manner similar to meander or point bars found in meandering channels (Miall, 1977). These bars are dissected from the bank by the formation of a minor channel across the surface of the bar. The dissection of these bars has been attributed to falling stage which accompanies a decrease in discharge (Collinson, 1971). This process has also been observed in gravel bed rivers (Hein and Walker, 1977) and in flume studies using sand size sediment to model a gravel bed river (Ashmore, 1982).

Sand flat initiation and development is a key element of the sedimentary mechanics of braided sand-bed rivers. The process of sand flat development is understood at a descriptive level but the sedimentary mechanisms are not well known quantitatively. A necessary step towards this quantitative explanation is the simultaneous observations and measurement of flow and sediment transport over bar surfaces and the morphological changes of the bar.

3 STUDY SITE

3.1 Location and Setting

The study sites are located on the South Saskatchewan River, approximately 66 km and 86 km upstream of Saskatoon (figure 3.1). The South Saskatchewan River has its headwaters in the eastern slopes of the Rocky Mountains, and is formed by the confluence of the Oldman and Bow rivers in southern Alberta. It is the largest river flowing across the southern Canadian Prairies. It receives only one major tributary, the Red Deer River, before it joins the North Saskatchewan River approximately 200 km downstream of Saskatoon. The river changes from a relatively high gradient gravel bed channel in the mountains to a relatively low gradient sand bed channel on the prairies (Kellerhals et al., 1972).

The river between the Gardiner Dam and Saskatoon flows in a valley which is incised approximately 30 m into the surrounding plain. The river is straight to irregularly curving with an average slope of 0.0003. The valley width averages approximately 600 m from the Gardiner Dam to a point approximately 25 km upstream of Saskatoon where it widens to 12 km.

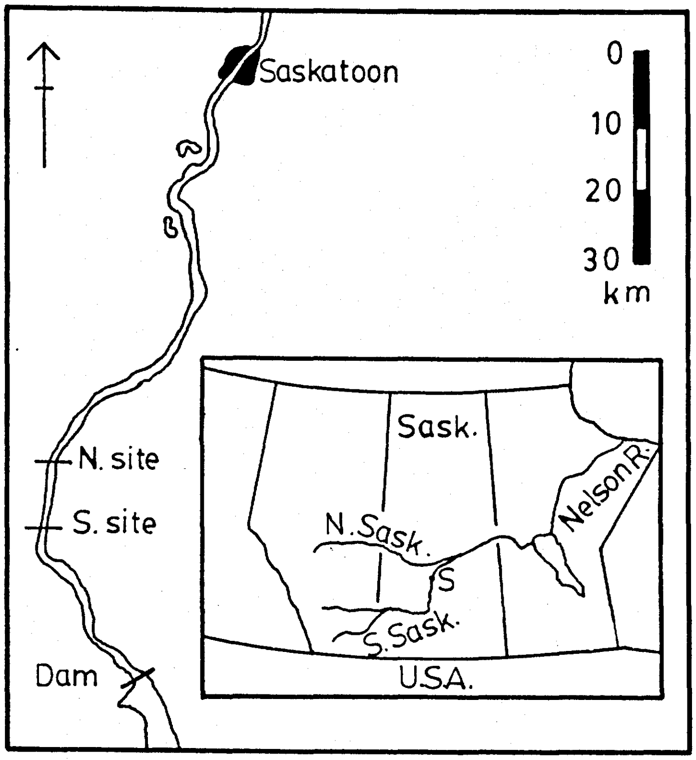


Figure 3.1: Location map of the South Saskatchewan River. N. site and S. Site indicate the approximate location of the North study site and the South study site respectively. The "S" on the inset map represents the location of Saskatoon, SK on the Saskatchewan River system.

3.2 Hydrology of the South Saskatchewan River

The long term average discharge of the South Saskatchewan River at Saskatoon is approximately 262 m^3s^{-1} (1911 - 1984). The maximum daily discharge during the period of record (1911-1984) is 3,940 m^3s^{-1} on June 15, 1953 and the minimum daily discharge is 14.2 m^3s^{-1} on December 12, 1936, measured at Saskatoon (Water Survey of Canada, 1984). Prior to flow regulation at the Gardiner dam the natural annual flow regime at Saskatoon had two peak flow periods, the first in April - May fed by snow melt in the foothills and the western prairies, and the second, usually larger, in June, resulting from snow melt in the Rocky Mountains and increased precipitation throughout the drainage basin. The lowest flows normally occurred during the winter.

The completion of the South Saskatchewan River Project in 1968, and the subsequent operation of the hydro-electric generating station at Gardiner Dam, has altered the river flow regime. Seasonal variations in flow have been greatly reduced as the operation at Gardiner Dam has lowered the summer flows and augmented the winter flows (figure 3.2). The total flow volume is 30% less than during the pre-reservoir period. The mean annual discharge measured at Saskatoon from 1946 to 1963 was 9,211,000 dam^3 and from 1968 to 1985 was 6,462,000 dam^3 with mean daily discharges of 292 m^3s^{-1} and 205 m^3s^{-1} respectively. The maximum peak discharge for the post-reservoir period is 1900 m^3s^{-1} on June 26, 1975 and the minimum is 28.1 m^3s^{-1} on May 3, 1968. The years from 1964 to 1967 are not included because the reservoir was filling. The reduction in flow volume can not be directly attributed to regulation. The drought experienced on the prairies during the late 1970s and 1980s is also reflected in the decrease in flow volume (Yuzyk, 1987).

3.3 Geology and Glacial History of the Area

The South Saskatchewan River valley is cut into the Bearpaw Formation down to the Outlook Member. The Upper Cretaceous Bearpaw Formation consists primarily of silty clay and some sandy members. The Bearpaw clays contain up to 80 % montmorillonite making them very soft

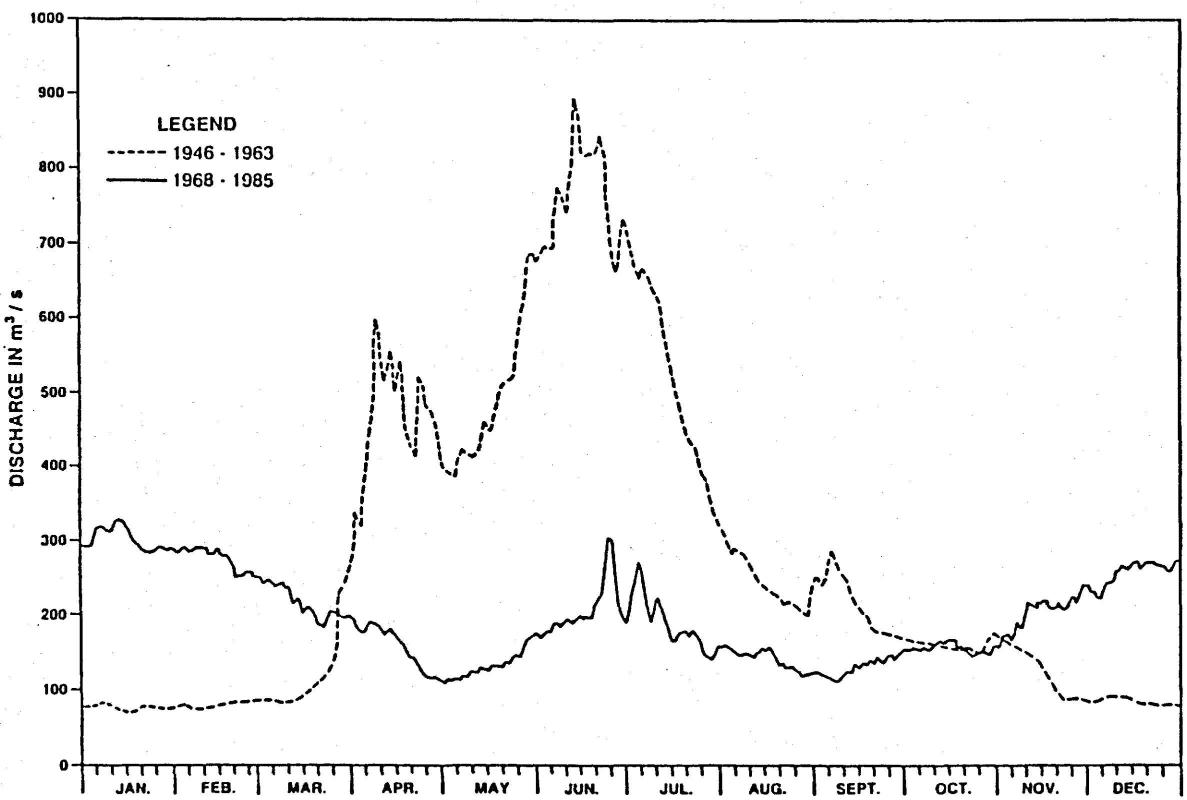


Figure 3.2: Changes in the mean annual daily discharges on the South Saskatchewan River at Saskatoon, SK., pre and post reservoir (Yuzyk, 1987).

and erodible (Pollock, 1962). The Outlook Member is a buff-weathering, fine grained, friable sandstone and provides some of the sediment to the river downstream of the Gardiner Dam (Scott, 1962).

Surficial deposits in the area surrounding the South Saskatchewan River valley consist of tills and moraines made up of sands and gravels, lacustrine silts, clays and fine sands, and aeolian deposits (Scott, 1962). These surficial deposits are a major sediment source for the river.

The South Saskatchewan River follows a pre-glacial drainage channel in western Saskatchewan. However, in the study area the valley is believed to be the result of erosion by glacial meltwater (Pollock, 1962). Initially as the ice retreated, meltwater flow to the north was blocked by the ice and the meltwater in this channel flowed southeastward through the Qu'Appelle valley system. When the ice had disappeared the meltwater could flow northward. This meltwater eroded the valley to a maximum of 60 m below the surrounding plain. The increased height and steepness of the valley wall caused a great deal of rotational slumping of the till and shale. Since the end of the Pleistocene approximately 30 m of alluvium has been deposited in the valley. Test boring into the alluvium of the valley indicates that it is mainly sand with some rich clay and gravel zones (Pollock, 1962).

3.4 Geomorphology and River Morphology

The river in the vicinity of the study sites has a sand-bed braided pattern. The main macro-scale geomorphic features characterizing the river in this area are: a) the vegetated floodplain; b) vegetated islands; c) channels and; d) sand flat complexes (photograph 3.1) (Cant and Walker, 1978).

The vegetated floodplains are poorly developed along the narrower portions of the valley. The floodplain is widest (i.e., approx. 12 km) in the section of the river approximately 25 km upstream of Saskatoon. Vegetated islands are irregularly spaced, and are elongated parallel to the river direction. Some islands result from the dissection of the floodplain (Cant, 1976). The islands and floodplains are vegetated by

Photograph 3.1: Macro scale geomorphic features of the South Saskatchewan River: a) vegetated floodplain; b) vegetated islands; c) channel and; d) sand flat complexes. Approximate scale 1:38000.

mixed prairie grasses, willows, bushes and in some places by large trees such as aspen and balsam poplar.

The river typically consists of one or two major channels and several minor channels. Major channels are less than 3 m deep and vary in width up to 200 m (Cant, 1976). The major channels periodically shift from one side of the river to the other but do not follow a consistent pattern. Meso and micro-scale features such as bars, sand waves, dunes and ripples are present in these channels. Minor channels are narrower and have a maximum depth approaching 1.5 m. Since these minor channels are smaller, and in topographically higher parts of the system, changes in the river stage are more noticeable. The minor channels have similar bedform features to the major channels but the transport of sediment is more intermittent.

Sand flats range in size from 50 m to 2 km in length. The shapes of the sand flats are highly variable but they are generally elongated parallel to the flow. The morphology of the sand flats is relatively insensitive to short term variations in stage, yet they are continually being modified by the flow in the river (Cant, 1976).

The change in flow regime and sediment transport caused by the creation of Lake Diefenbaker has resulted in changes to the channel morphology. Sediment is trapped by Lake Diefenbaker causing the water released from Gardiner Dam to be largely sediment free. This, coupled with the decreased flow volume, has caused the river to alter its cross-sectional geometry and gradient downstream of Gardiner Dam (Rasid, 1979; Galay et al., 1985; Yuzyk, 1987). Yuzyk (1987) found that the degradation of the channel extended 13 km downstream of the Gardiner Dam. The median particle size in the area of active degradation has increased since the completion of the dam. This increase in particle size suggests that the channel bed is beginning to armour as degradation progresses downstream.

The channel width has also changed downstream of the Gardiner Dam. Rasid (1979) compared the channel width of the river at constant discharge before and after the completion of the dam and found that the channel width had decreased significantly after completion of the reservoir. The magnitude of the width changes decreases progressively downstream (Rasid, 1974). Since the changes in channel width decreased progressively downstream it is assumed that the channel width at the study sites has decreased since 1966. Galay et al., (1985) maintain that the channel width has now stabilized.

The fluctuation in daily discharge is an important factor in establishing the pattern of the low-flow channel (Galay et al. 1985). These fluctuations affect the sediment movement in the river especially in the minor channels where changes in discharge result in pronounced changes in the stage. The decrease in the discharge reduces the velocity and lowers the stage, often retarding the movement of sediment in these channels. The sediment therefore moves more intermittently due to these fluctuations in the flow.

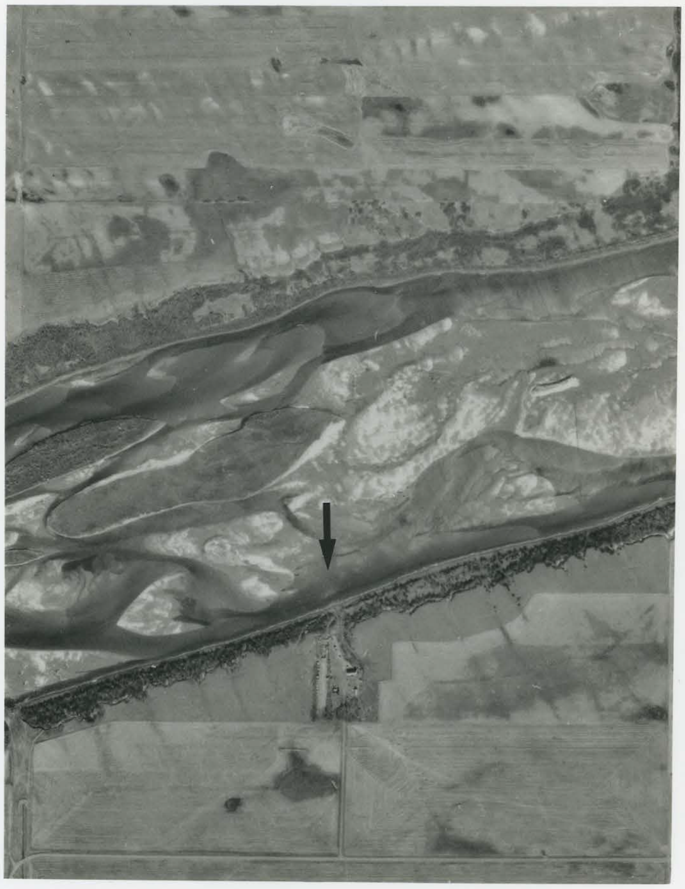
Although changes have occurred to the regime and morphology of the South Saskatchewan River, comparison of aerial photography before and after impoundment of Lake Diefenbaker indicates that the low-flow channel pattern has not been significantly altered in the area of the study sites. The type and scale of active bars and sand flats has not changed but sand flats do show an increase in vegetation cover. This is likely the result of the dampened flow regime which minimizes the number of peak flows which can flood the sand flats and reactivate them as a mobile bedform features.

3.5 Site Selection

Two sites were chosen following aerial and ground reconnaissance of the river. One is approximately 46 km upstream of Saskatoon and another 20 km further upstream (figure 3.1). Both sites had good access and a nearby elevated position from which the changing morphology of the study reaches could be observed and photographed. The south site (66 km upstream of Saskatoon) is adjacent to a high steep valley side and the north site (46 km upstream of Saskatoon) is adjacent to a raised island.

The river at the south site is located in a straight, constricted portion of the valley. The top width of the valley is approximately 900 metres. The river is approximately 700 metres wide with a 10-20 m floodplain. The river is divided into multiple channels by two islands and several sand flat complexes (photograph 3.2). The two islands have extensive vegetation cover, including large trees. Aerial photography of the reach suggests that the islands in this reach have been present since 1949 but have been modified by erosion and deposition. The sand flats also have some vegetation cover. The submerged bars selected for monitoring are along the right bank of the river in one of the two major channels which extend through the reach. The other major channel is situated along the left bank of the river. Minor channels are also present in between the islands and on the sand flat complexes.

At the North site the top width of the valley is approximately 1900 m. The river is approximately 650 metres wide, without including one large island which is separated from the floodplain by a small back channel. The floodplain on the right bank is up to 400 m wide but virtually no floodplain exists along the left bank. Aerial photography shows that the back channel was present prior to 1960. This back channel did not carry any of the river flow during the summer of 1988. The bars selected for monitoring are located in a minor channel which has dissected a sand flat complex since 1986. This anabranch flows out of the main channel, along the left bank, diagonally across the sand flat complex towards the right bank (photograph 3.3). The changes in stage associated with the fluctuations in discharge are amplified at this site, since this minor channel is in a topographically higher part of the reach.



Photograph 3.2: Aerial photograph of the South site on the South Saskatchewan River (1978). The arrow indicates the portion of the river under investigation. North is at the top of the photograph and the flow is from left to right. This photograph was reprinted from Energy, Mines and Resources, Government of Canada Aerial Photograph 78004-23-L05, number 224.

Scale = 1:18000

Photograph 3.3: Aerial photograph of the North site on the South Saskatchewan River. The arrow indicates the portion of the river under investigation. North is to the right of the photograph and the flow is from left to right. This photograph was reprinted from Energy, Mines and Resources, Government of Canada Aerial Photograph 78004-14-L7, number 122.

Scale = 1:30000

4 METHODOLOGY

The data were collected from May to August, 1988 and consist of measurements of channel topography, bar configuration, depth, velocity, current direction, bedload transport rate and bed material particle size in each of the reaches, combined with photographic monitoring of channel changes. Surveys of the channel topography were carried out four times at each site throughout the summer. The collection of all other data consisted of making measurements once a week on the surface of specific bars.

4.1 Data Collection Techniques

The bed topography and bar configuration were measured with an engineer's level which also measured horizontal angles (± 0.5°). A 210 metre base line was established at the South site and a 100 metre base line was established at the North site. The base line at the South site was extended to over 230 metres as the bars migrated downstream, with measurements made beyond the end of the grid. The base line at the North site was extended by 20 metres and had to be moved another 25 metres away from the original channel due to the rapid erosion of an adjacent cutbank on the sand flat. Elevations at both sites were measured from a control point which was given an arbitrary elevation of 100 m.

Depth and velocity were measured by standard techniques using a wading rod-mounted pygmy Price current meter. The velocities were measured at 0.6 of the depth to determine the average velocity and at 2 cm above the bed of the channel. Flow direction was measured at the 0.6 depth by taking a compass bearing on a piece of flagging tape attached to the current meter.

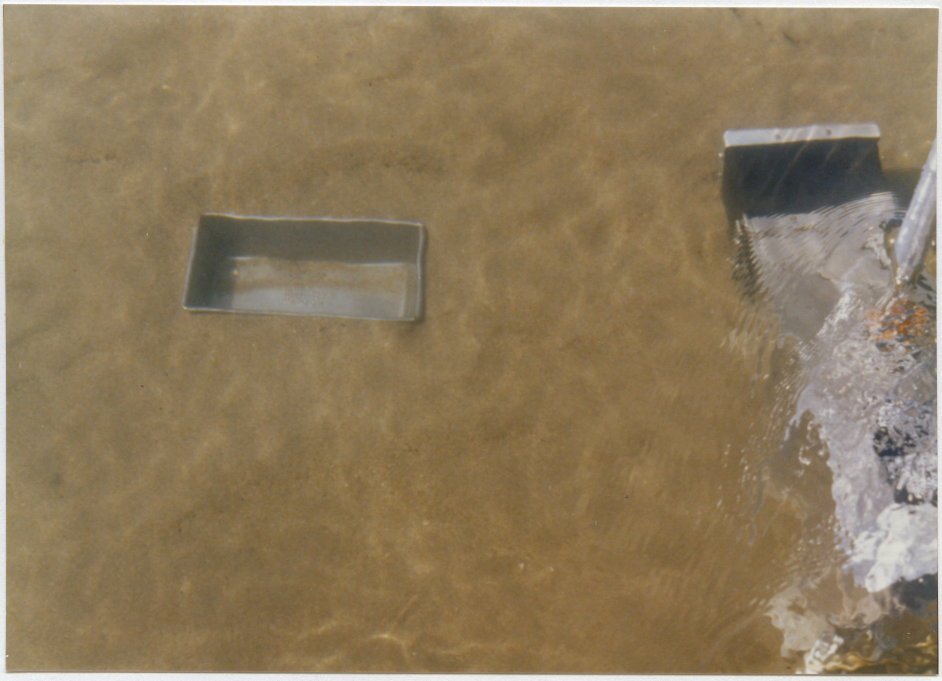
Bed load transport rates were determined with the use of a Bogardi bed load sampler in deeper water (photograph 4.0), and in shallow water by a pan placed into the bed (photograph 4.1). The pan was usually used where flow velocity and bedload transport were small.

The hydrologic data for the South Saskatchewan River during May - August 1988 were obtained from flow records at the Gardiner Dam (Saskatchewan Water Corporation, unpublished data) and at Saskatoon (Water Survey of Canada, unpublished data).

4.2 Data Mapping and Interpretation

The data collected on the channel topography of the study reach were mapped using the UNIMAP software system to create three dimensional diagrams and two dimensional contour maps. These maps are used to describe changes in the channel topography during the field season and to identify changes to the bar morphology related to the channel topography.

Photograph 4.0: Bogardi bedload sampler.



Photograph 4.1: Pan and Bogardi bedload sampler.

Irregularly spaced observations of surface elevations and hydraulic variables were interpolated to regular grids to permit the generation of contour images of the data. The interpolation was made using UNIMAP Method 1 as outlined in the following sections. Observations were interpolated to a 50 x 25 grid overlaid on the study site. Each grid cell represented a ground area of 7 m x 7 m. Each irregularly spaced observation was assigned to a grid cell on the basis of its X and Y coordinates. If more than one data point fell within a grid cell, an average value was calculated for that cell. Values for cells which had no observations assigned were estimated using a bi-linear interpolation. The program improves its estimate by computing gradients at the points and using quadratic interpolation. The final refining of the estimated values was done by a distance weighting factor.

The next procedure was to estimate values for each of the grid nodes. This involves the identification of data values around a grid node. The search radius around a grid node is the entire map area, unless otherwise specified by the user. The closest datum in each quadrant surrounding the grid node is selected. If the closest data point is at a distance of less than 50% of the grid size it is taken as the grid node value. If the values are at a distance greater than 50% of the grid size then a bi-linear interpolation is performed. If any one or more of the quadrants is empty other special treatments of the data are performed.

Once the bi-linear interpolation is completed, the quality of the surface fit is improved by quadratic interpolation. Slope components are calculated from the closest data points at each grid node. Quadratic interpolation is then performed on these slope components. This interpolation may produce local maxima or minima which can be outside the range of surrounding data point values. The final step in the interpolation of the values onto the grid network involves a smoothing operation which is performed at each grid node. If the distance between the grid node and the nearest data point is short no smoothing takes place. The further away the data point the more smoothing is performed at the grid node.

The contour lines which are drawn by the computer are based on the interpolated values. Interpolated values are calculated along the edges of each grid cell. Isolines are drawn between two equal values along the opposite or adjacent edges of a grid cell. The contour interval or class limits for the isolines are established by the user.

This method for interpolation and contouring used in UNIMAP has several advantages. It is a relatively rapid method since the main components used for the interpolation are linear. No erratic behaviour in the interpolated data was identified in areas where there were few measurements. This method of data interpolation and mapping also maintains the integrity of the original data.

5 RESULTS AND ANALYSIS

The presentation of results includes information on the hydrology of the river, changes in channel morphology and changes to channel topography within the section of the river under study, during the summer of 1988. Hydraulic data collected in the vicinity of the bars are presented in the form of maps, illustrating changes through time as the bar migrates downstream.

5.1 Hydrology

During the months of May - August, 1988 the total flow at Saskatoon was 516,000 dam^3 with an average flow rate of 48.5 m^3s^{-1}, measured at Saskatoon (Water Survey Canada, unpublished data). The total flow measured at the Coteau Creek power generating station at Gardiner Dam during this time was 497,000 dam^3 with an average discharge of 46.8 m^3s^{-1} (Saskatchewan Power Corporation, unpublished data). The mean daily discharge varied substantially during this period (Figure 5.1). Fluctuations in the instantaneous discharge at Saskatoon ranged from a minimum of 28.1 m^3s^{-1} on June 7, 1988 to a maximum of 73.0 m^3s^{-1} on August 20, 1988. The discharge from the power station ranged from 0 m^3s^{-1} to over 95 m^3s^{-1} during peak power demand (Figure 5.2).

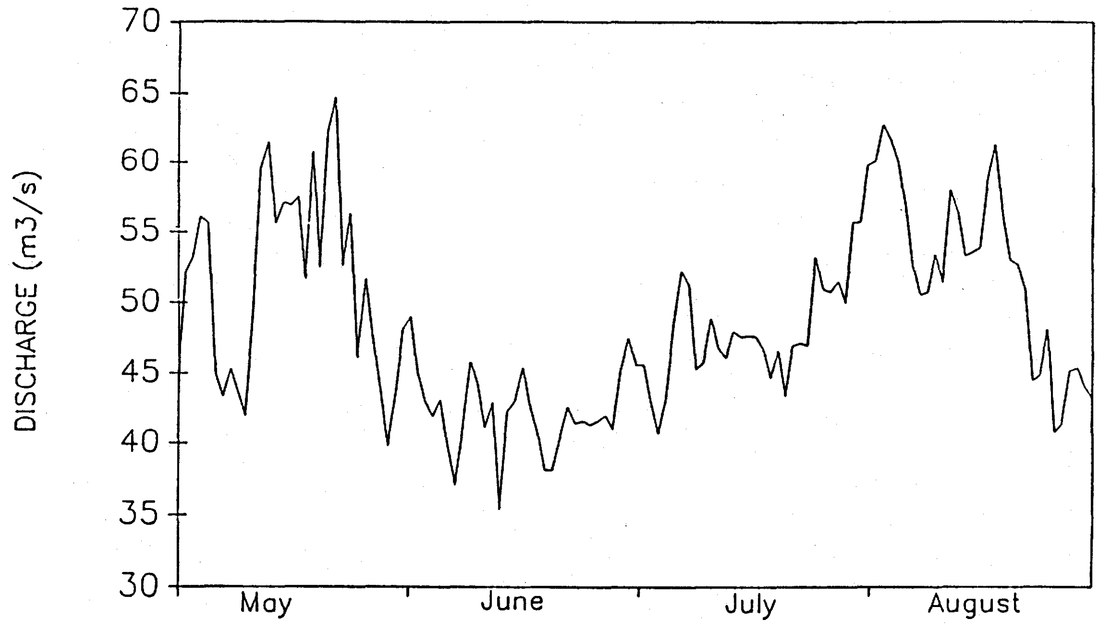


Figure 5.1: Mean daily discharge May - August, 1988, Saskatoon.

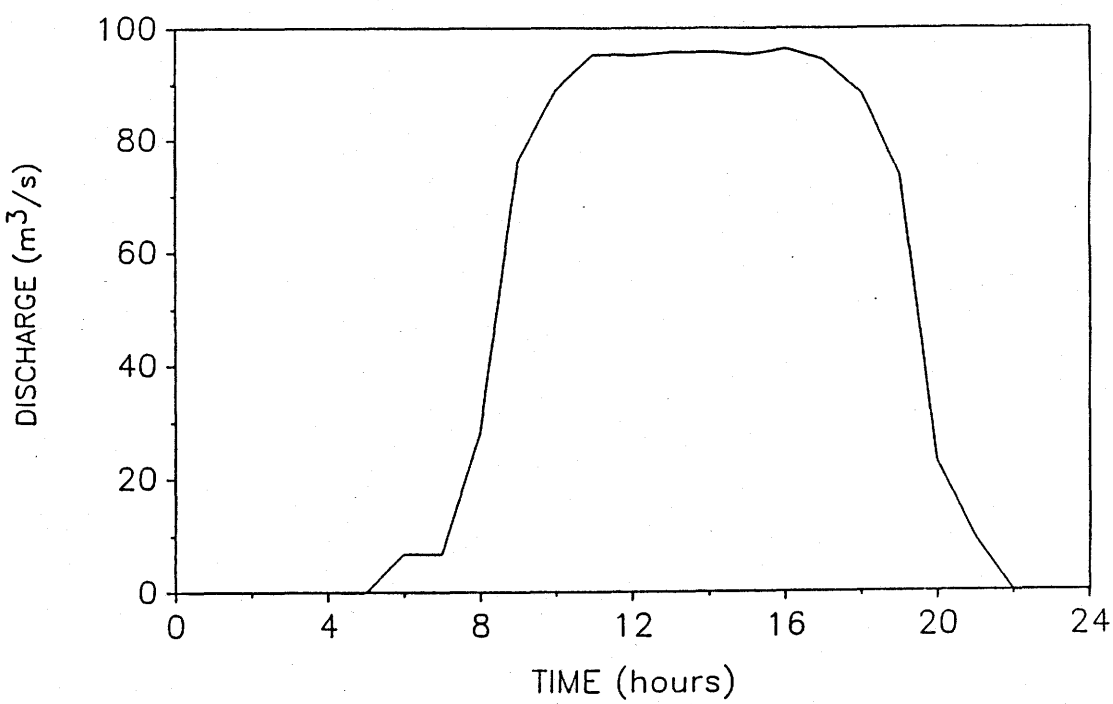


Figure 5.2: Mean hourly discharge from Gardiner Dam, June 13 to June 26, 1988.

There is a 2% discrepancy between the mean daily discharge measured at Saskatoon and that at the Coteau Creek power generating station. The differences in the discharge between these stations can be partly attributed to i) errors in the stage discharge relationship used to obtain discharges at Saskatoon; ii) the conversion of megawatt hours to a discharge used by the Saskatchewan Power Corporation; iii) input from the irrigation outfall located approximately 48 km downstream of the Gardiner Dam; iv) inputs from Beaver Creek and; v) contributions from groundwater.

Daily fluctuations in discharge resulted in noticeable changes in stage at each site. The peak flows at both the north site and south site usually occurred during mid to late afternoon. The lowest flows were observed during the early morning. As expected, the observations of the flow at the sites lag behind the water release records provided by Saskatchewan Water Corporation. Although the stage was not routinely measured at either study site, when measured periodically, daily variations in stage were between 2 and 4 cm.

The narrow secondary channel of the North site, showed a slightly greater range in stage. Some areas at the north site which were exposed in the early morning, were submerged by late afternoon. The relationship between the diurnal fluctuations and the sediment transport on re-submerged features were not considered in this study. It is, however, interesting to note that many of these features that were re-submerged were subsequently modified by the flow.

5.2 Channel Topography

Channel topography was surveyed four times at each site, to document the changes which occurred throughout the study period. Figures 5.3 to 5.10 illustrate the initial and final topography for both the South and North site as follows:

Location	Date	Figure
South site	May 27	5.3 a and b
	June 17	5.4 a and b
	July 11	5.5 a and b
	August 8	5.6 a and b
North site	May 25	5.7 a and b
	June 16	5.8 a and b
	July 05	5.9 a and b
	August 10	5.10 a and b

Surveys of channel topography were extended downstream because of bar migration. The average water surface elevation at the South site was 98.2 m. Photographs at the South site were taken from the right bank at an x-coordinate position of 150 m. The average water surface elevation at the North site was 99.2 m. Photographs at the North site were taken from the island at an x-coordinate position of 100 m.

The diagrams of the channel topography are insufficiently detailed to identify individual bars. They indicate, however, that the channel at both sites aggraded during the monitoring period. To get a better representation of the extent of channel shoaling a third illustration was derived by subtracting interpolated grid values of the initial survey from those of the final survey. This procedure creates a map showing locations of relative aggradation and degradation. For the area common to the

a)

b)

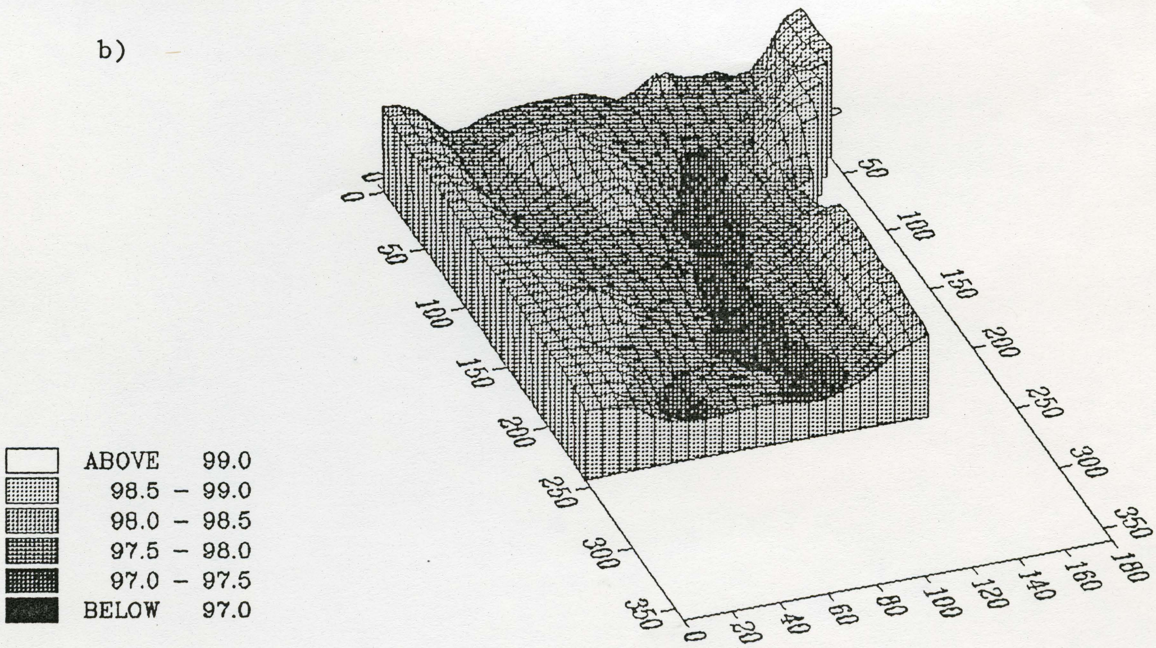


Figure 5.3: Channel topography at the South site, May 27, 1988 (upstream view): a) Photograph of site from the right bank; b) Three dimensional diagram of channel topography (all axes and elevations in metres).

a)

b)

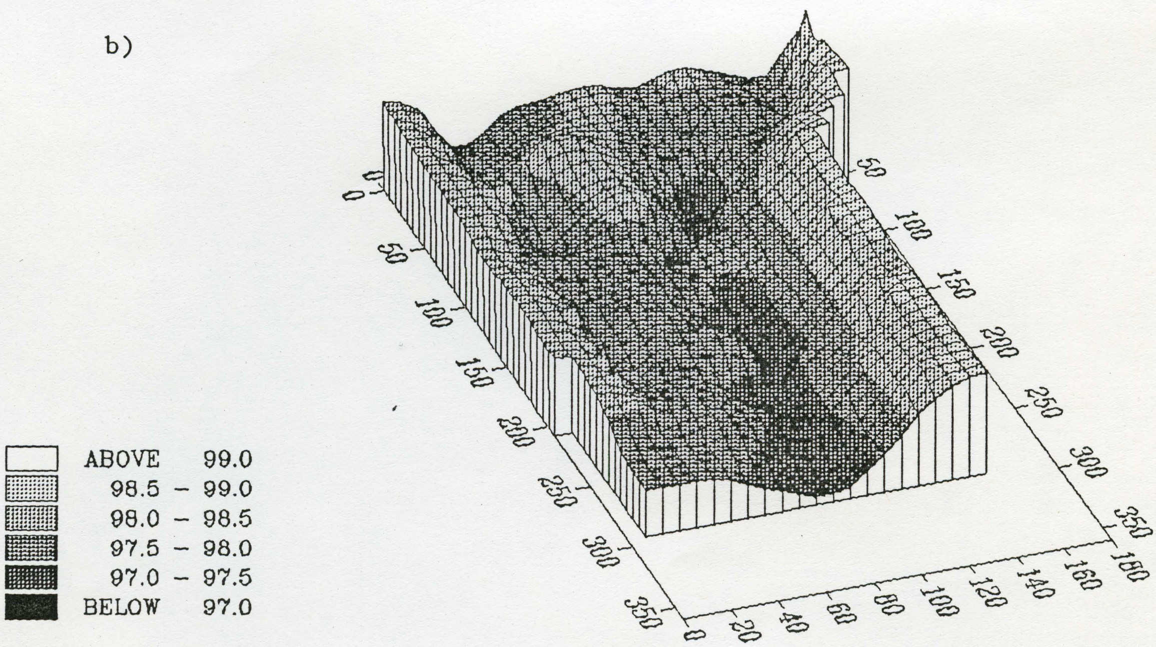


Figure 5.4: Channel topography at the South site, June 17, 1988 (upstream view): a) Photograph of site from the right bank; b) Three dimensional diagram of channel topography (all axes and elevations in metres).

a)

b)

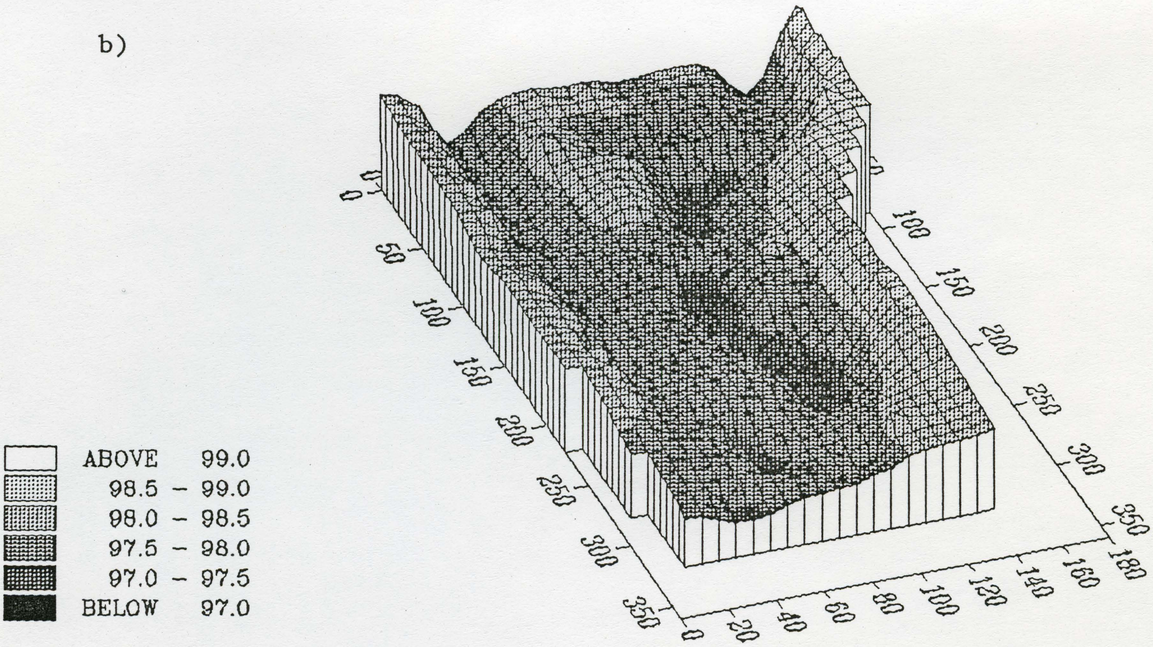


Figure 5.5: Channel topography at the South site, July 11, 1988 (upstream view): a) Photograph of site from the right bank; b) Three dimensional diagram of channel topography (all axes and elevations in metres).

a)

b)

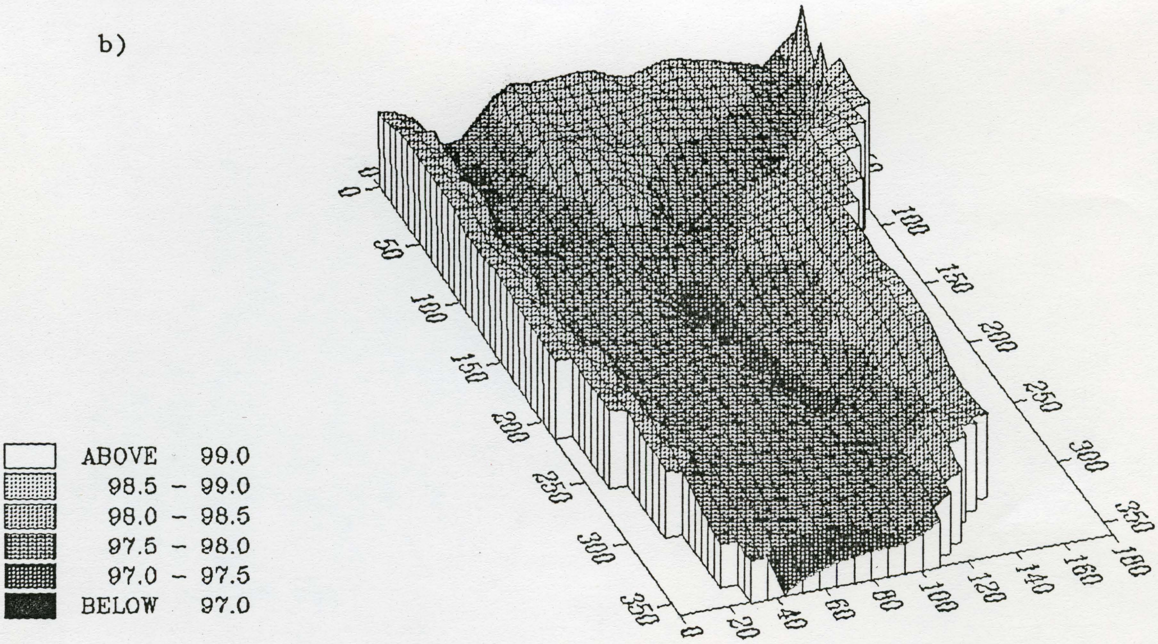


Figure 5.6: Channel topography at the South site, August 09, 1988 (upstream view): a) Photograph of site from the right bank; b) Three dimensional diagram of channel topography (all axes and elevations in metres).

a)

b)

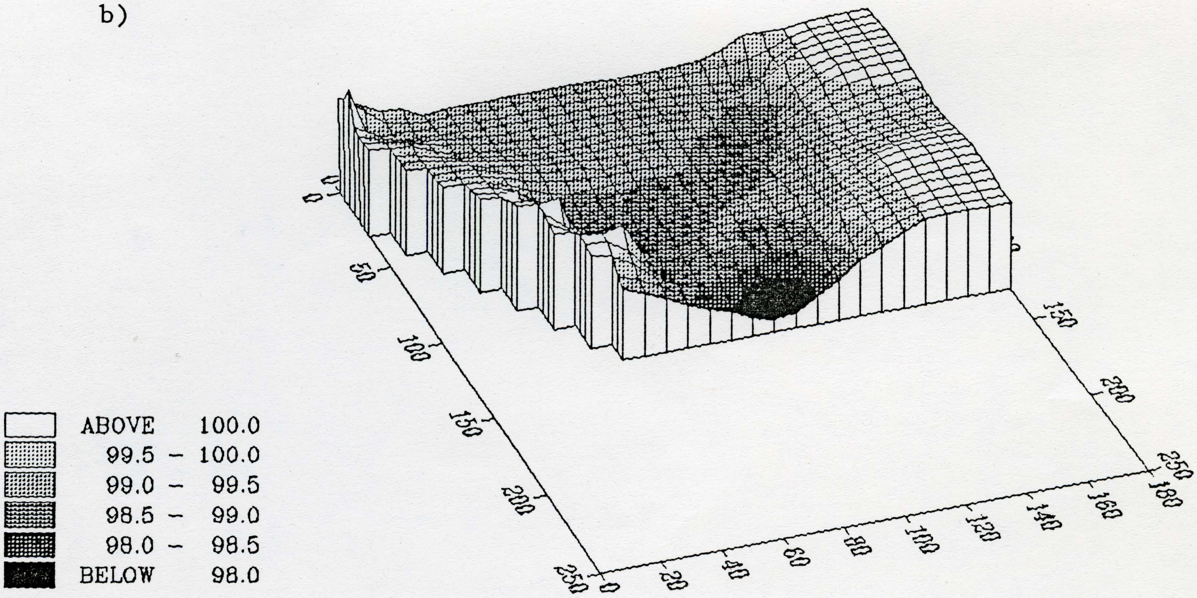


Figure 5.7: Channel topography at the North site, May 25, 1988 (upstream view): a) Photograph of site from the island; b) Three dimensional diagram of channel topography (all axes and elevations in metres).

a)

b)

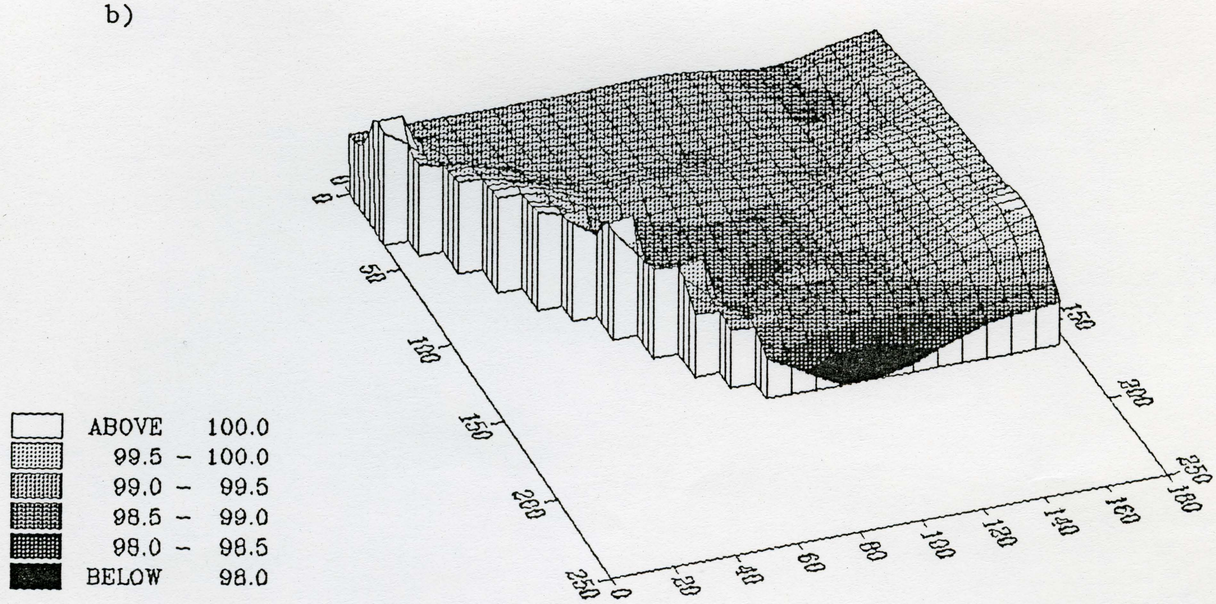


Figure 5.8: Channel topography at the North site, June 16, 1988 (upstream view): a) Photograph of site from the island; b) Three dimensional diagram of channel topography (all axes and elevations in metres).

a)

b)

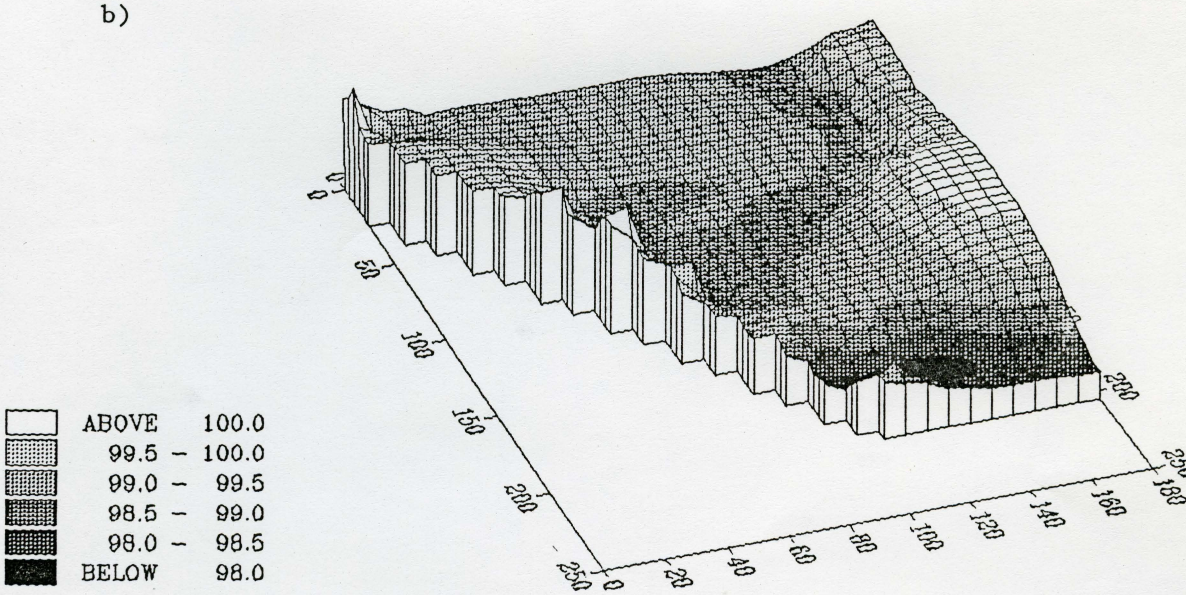


Figure 5.9: Channel topography at the North site, July 05, 1988 (upstream view): a) Photograph of site from the island; b) Three dimensional diagram of channel topography (all axes and elevations in metres).

a)

b)

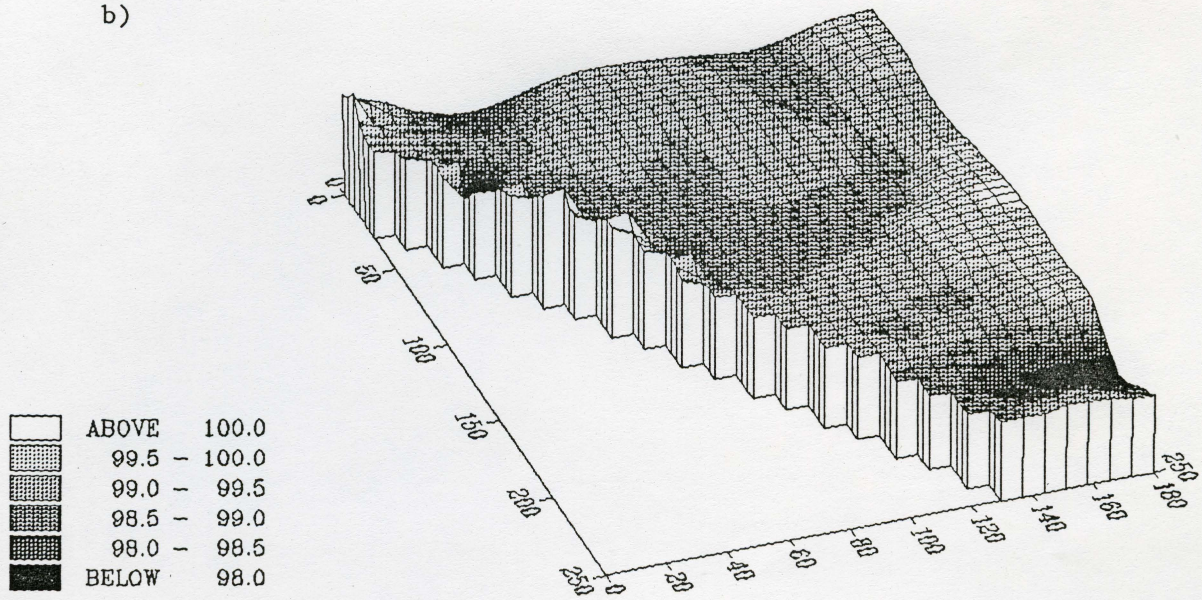


Figure 5.10: Channel topography at the North site, August 11, 1988 (upstream view): a) Photograph of site from the island; b) Three dimensional diagram of channel topography (all axes and elevations in metres).

initial and final surveys, the values at the grid nodes were subtracted to give topographic differences for the south and north site (Figures 5.11 and 5.12).

These diagrams verify that the channel at each site aggraded during the summer. The majority of channel infilling occurred along the trough at the South site. The trough at the North site was also subject to infilling by sediment. The diagrams of topographic differences suggest that the majority of sediment came from an upstream source, since there is very little channel scour indicated. Areas on the maps which indicate scour are on the tops of sand flats. Surveys on the tops of these exposed areas were not extensive, therefore, losses on these surfaces are likely exaggerated, and are assumed to be a result of aeolian deflation.

Cutbanks along the edge of sand flats also contributed sediment to the channel. Cutbanks formed at each site along the left upstream bank of the channel. The cutbanks formed in the sand flats from flow directed into the bank and then deflected, leaving a curved cutbank with the majority of the sediment deposited immediately downstream along the sand flat (Photographs 5.2 & 5.3). The topographic-difference maps under-represent the amount of erosion that occurred along the cutbank due to the continued aggradation of the channel along the cutbank.

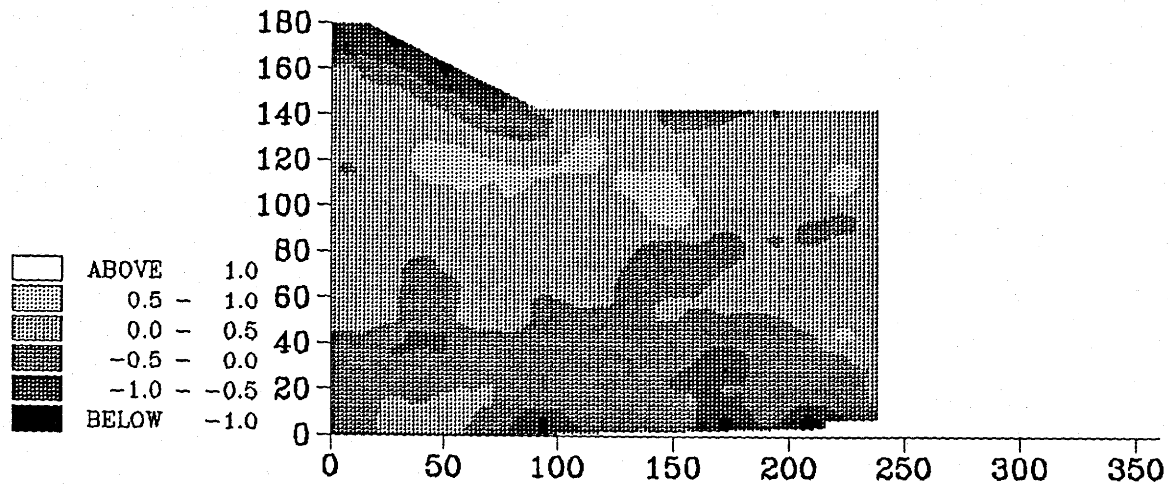


Figure 5.11: Topographic difference map at the South site between May 27 and August 9, 1988. All axes and elevations in metres.

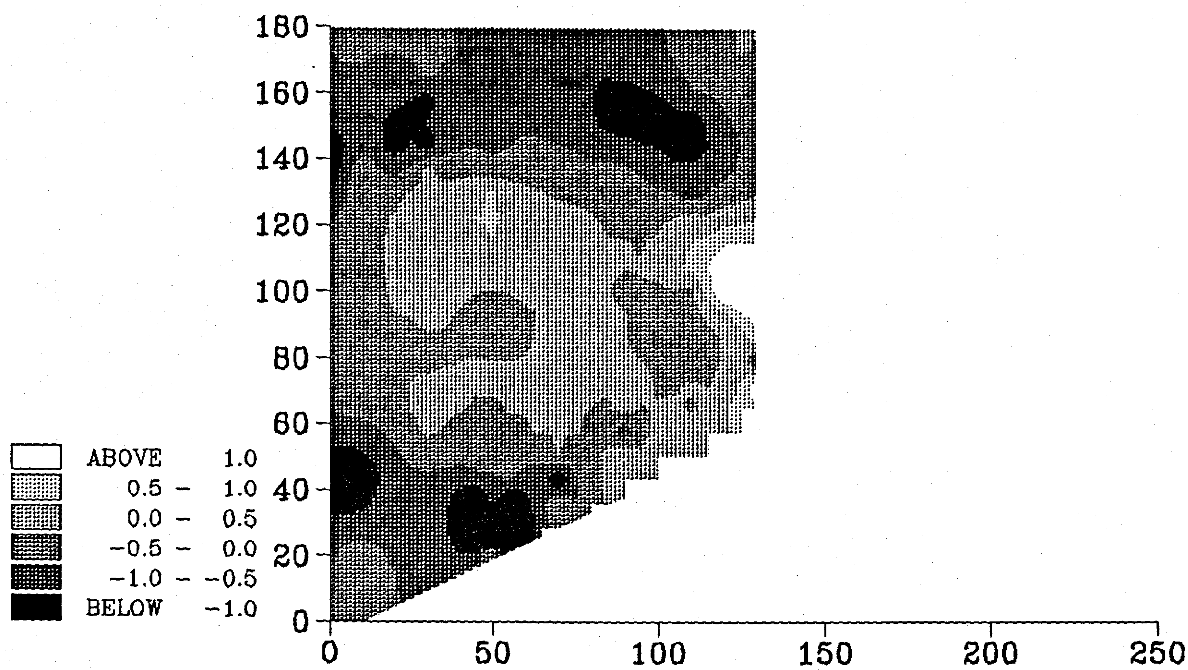


Figure 5.12: Topographic difference map at the North site between May 25 and August 11, 1988. All axes and elevations in metres.

a)

b)

Photograph 5.2: Cutbank formation at the South site: a) May 27, 1988; b) August 8, 1988.

a)

b)

Photograph 5.3: Cutbank formation at the North site: a) May 25, 1988; b) July 4, 1988.

5.3 Channel Bar Development

The character of bar development is presented by a series of diagrams illustrating changes of several parameters on the surface of the bar. These parameters include changes in morphology, flow depth, flow direction, near-bed velocity and bedload transport rate. For the purpose of presentation, four time periods corresponding to the dates of topographic surveys have been chosen for each location to illustrate the spatial changes in the hydrodynamic parameters as the bars migrate downstream. The diagrams are supplemented with observations made at the time of the bar survey, as well as other bar surveys not presented as diagrams. Using dates corresponding to the topographic surveys also allows the diagrams and photographs in Figures 5.3 - 5.10 to be used for reference. Tables of linear bar migrations are also included for each site. Linear bar migration was measured as the movement which occurred parallel to the direction of the main channel. The original raw data for each site are provided in the appendix.

Changes in the channel morphology can be determined from the bar outline on the diagrams. Surface elevations of the bars can be determined, in some cases, by inference from the channel topography and knowing the approximate elevation of the water surface (i.e., 98.2 m at the South site and 99.2 at the North site), but in most cases is provided in the site descriptions. Flow direction is indicated by the head of the arrows. Near-bed velocity (i.e., 2 cm above the bed) is indicated by the length of the arrow's shaft, which ranges from 0 to 0.5 m s^{-1}. The feathers of the arrow provide a reference for the bedload transport rate (i.e., more feathers indicates higher bedload transport rates). A legend for the diagrams is provided in Figure 5.13.

All axes in metres.

DESCRIPTION	SYMBOL
Exposed areas	— — — —
Contour	—— 98.0 ——
Slipface of bar	
Cutbanks/Avalanche face on exposed bars	
Flow direction (Arrow head*) Near-bed velocity (Shaft**) Bedload transport rate (Feathers***)	»——▸

* Indicates direction of flow.
** Length of shaft indicates a relative magnitude of the near-bed velocity ($m\ s^{-1}$).
*** Feathers indicate a relative magnitude of bedload transport rate ($kg\ s^{-1}\ m^{-1}$).

Figure 5.13: Legend for the channel bar diagrams.

5.3.1 South Site (downstream section)

The downstream section of the south site had two bars which were monitored (Figures 5.14 - 5.17). The first bar (i.e., bar I) under investigation was located along the right side of the channel. It was bordered by the channel bank on the right and by the channel thalweg on the left. The bar width remained relatively constant taking up approximately 30% of the channel width. A second bar (i.e., bar II) was developing upstream and to the left of bar I.

These bars migrated into a topographically lower (i.e., deeper) section of the channel. Bar I migrated approximately 120 m downstream during the study period. The rate of movement of bar I decreased throughout the study period (Table 5.1).

The development of bar II was more erratic than that of bar I. In general it extended into and along the main channel thalweg. The rate of movement of bar II was quite rapid once it began to move into the thalweg. As it entered deeper water its migration rate diminished (Table 5.2), and the terminus of the bar began to blend into the channel bed.

Table 5.1: Rates of bar migration of bar I at the downstream section of the South site.

Dates	Rate (m/day)
June 1 - 7	2.7
June 7 - 13	3.3
June 13 - 21	1.5
June 21 - 27	1.8
June 27 - July 6	1.1
July 6 - July 19	1.2
July 19 - August 8	0.7

Table 5.2: Rates of bar migration of bar II at the downstream section of the South site. Rates of bar migration are for the dates when the bar was moving along the thalweg.

Dates	Rate (m/day)
June 21 - 27	8.3
June 27 - July 6	3.9

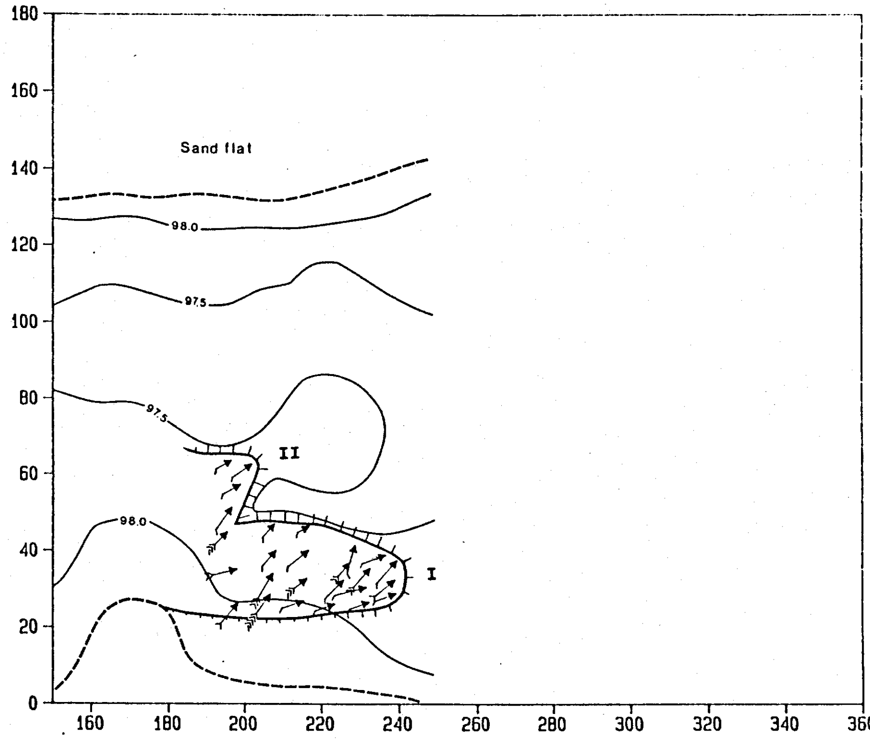


Figure 5.14: Bar development at the downstream section of the South site, June 1, 1988.

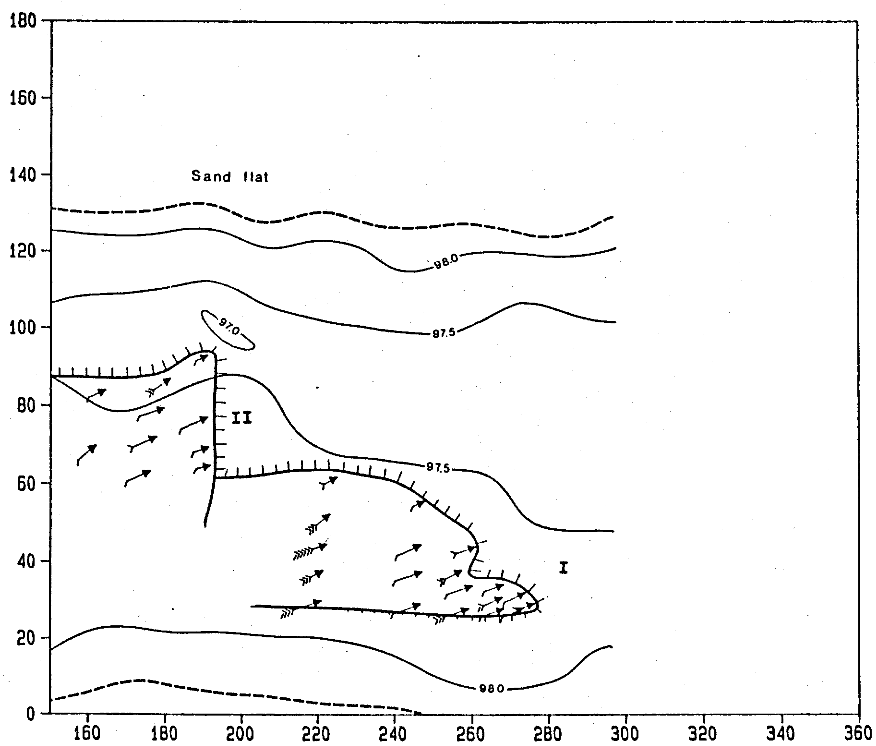


Figure 5.15: Bar development at the downstream section of the South site, June 13, 1988.

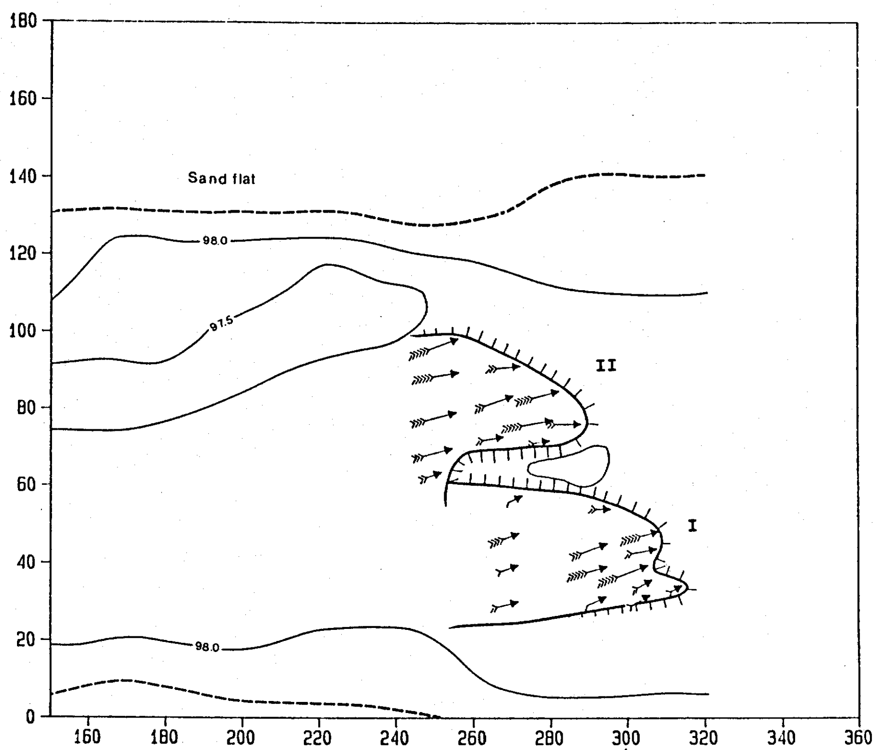


Figure 5.16: Bar development at the downstream section of the South site, July 6, 1988.

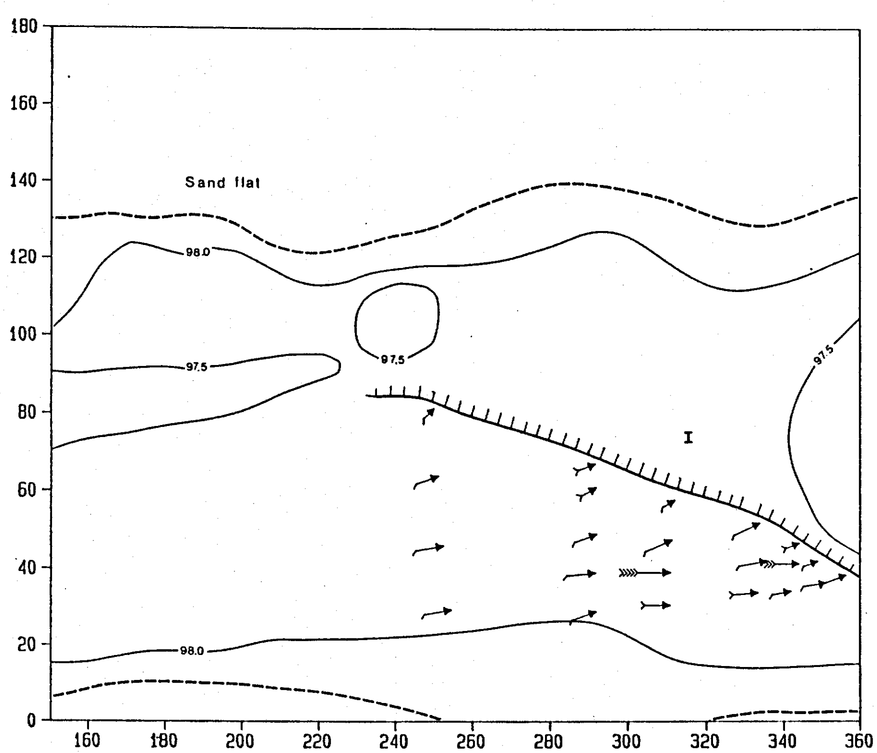


Figure 5.17: Bar development at the downstream section of the South site, August 8,1988.

5.3.1.1 Site descriptions

June 1, 1988

Bar I at the South Site was migrating into a topographically lower section of the channel. The bed of the channel downstream of the bar front consisted of silty sand, with several large rocks and boulders. The bed of the channel sloped gradually downstream. The bar had a blunt snout approximately 8.5 m wide (Figure 5.14). The poorly defined right edge of the bar extended upstream to a small gully outwash jutting approximately 10 m into the channel. A narrow, shallow trench having a pea gravel bed occupied the area between the bar and the right bank. The left edge of the bar had a well defined slip face which plunged into a deep section of the channel. The left edge of the bar extended upstream and intersected with bar II. The surface elevations of the bar graded down from the right to the left side. The flow over the bar surface was angled toward the left edge of the bar. The highest bed velocities and bedload transport rates occurred on upstream sections of the bar and then diminished over the surface of the bar.

Bar II was also migrating into a topographically lower section of the channel. Bar II appeared to be moving at an angle oblique to bar I and the channel. The bar surface elevation was raised slightly at the junction between the bar I and II. The terminus of the bar had lower surface elevations. Bed velocities and bedload transport rates where relatively uniform across the surface of the bar.

June 7, 1988

The snout of bar I had separated into two parts. The right side of the bar front had migrated a greater distance downstream than the left side. The right side was moving along a shallow ledge along the right bank whereas the left side was migrating into a deeper section of the channel. The upstream left edge migrated laterally, resulting in a bulged appearance. The flow was still moving laterally towards the left edge. The bar surface elevation was higher along the right and left edge and lower in the centre of the bar. The pattern of bed velocity and bedload transport was similar to that described for June 1. The left front edge of the bar however had relatively high bedload transport rates over its slip face compared to the right front edge.

Bar II had maintained a similar morphology as described on June 1. The bar,however, migrated downstream and laterally into the deeper channel. The bar was sloping gently towards the deeper channel but there was no evidence of the bar front tapering into the channel. The flow across the surface of the bar was directed laterally towards the deeper channel to the left of the bar. The highest bed velocities and bedload transport rates were observed at the intersection between bar I and II.

June 13, 1988

The morphology of bar I (Figure 5.15) was similar to that described for June 7. The bar had migrated further downstream, with the left and right side of the bar front taking on independent characteristics. The left side of the bar front was becoming lobate compared to the blunted appearance observed on June 7. The slip face of the bar was still distinct across the front and along the left edge. The right edge could still be identified, however the boundaries of the slip face (i.e., crest and base) were difficult to determine. Except for the extreme upstream left edge, the surface elevations were grading down towards the left. Flow was still directed toward the left edge of the bar. The bed velocity was highest along the right edge of the bar and lowest along the upstream left edge of the bar. The highest bedload transport rates were associated with relatively low bed velocities at the upstream end of the bar. Active dunes were observed in the area of high bedload transport. Surface flow and bedload were also observed being funnelled into the deep hollow between the left and right bar front.

The morphology of bar II was similar to earlier observations. The bar continued to migrate laterally into the deeper channel (Figure 5.15). The front of the bar was lower than the remainder of the bar surface, but a steep avalanche face was still evident. Bed velocity was high through the centre of the bar while the highest bedload transport rates were measured along the right edge of the bar. Bar II migrated onto the upstream left side of the bar I, making the junction between the two bars less distinct. No significant flow was funnelled into the intersection between the bars.

June 21, 1988

Bar I migrated further downstream but very few changes occurred to either the bar morphology or the hydrodynamic characteristics of the bar surface. Bar II, however, underwent several changes. Bar II became lobate, with a large portion of the flow being directed downstream rather than towards the deeper channel on the left. The downstream edge of the lobate bar was very steep, descending into a topographically lower section of the channel. The highest bed velocities and bedload transport rates were measured along the left edge and along the right edge downstream from the junction with bar I. A small ridge (extension ridge) was observed extending downstream from bar II, into deep water. The ridge appears to have formed from flow moving around either side of the bar and meeting in the middle.

June 27,1988

Bar I continued to migrate into deeper water and was beginning to lose some of its morphologic character. The right edge of the bar could no longer be defined. The right bar front had also tapered into the channel, however the outline of the snout could be determined by contrasting the sand of the bar with the silty sand of the bed. The surface elevation of the left bar front and the upstream left edge were higher than the remaining bar surface. A short section of the left edge just upstream from the bar front was slightly bevelled and at a lower elevation than the rest of the left edge, but still had a distinct slip face. Flow and bedload transport patterns were identical to those observed on June 13 and June 21.

Several morphologic and hydrodynamic changes had occurred to bar II. The bar was now actively migrating downstream parallel to bar I, with virtually no lateral movement, despite the flow being directed towards the deeper channel to the left of the bar. The bar appears to have moved over the top of the extension ridge described on June 21. The edge of the bar, although visible, was not very distinct. The bar's surface elevation mirrored the change in the channel topography, resulting in a bar elevation slightly lower than bar I, except for the upstream section. High bed velocities and bedload transport rates were observed on the upstream section of the bar and diminished downstream where flow depths were greater. Since this bar paralleled bar I, a trench was formed between the two bars. A funnelling of flow was observed at the junction between the two bars.

July 6, 1988

Bar I continued to migrate downstream with the ill-defined right bar front further downstream than the left bar front (Figure 5.16). The left downstream side of the bar was bevelled off making it difficult to identify the slip face. The left bar front had an elevated surface compared to the bar surface immediately upstream. The upstream left edge of the bar was elevated compared to the remainder of the bar surface. The flow, at the upstream end of the bar was directed towards the trench between bar I and II. The flow along the left central part of the bar seemed to be moving parallel to the trough, suggesting that this poorly defined portion of the bar was being influenced by the flow in the trough. The highest bed velocity and bedload transport rates were directed towards the left bar edge just upstream of the left bar front (i.e., where the left edge was bevelled off). It is interesting to note that the overall velocities and bedload rates have increased and moved downstream on the surface of the bar compared to June. The overall increase in velocities and bedload transport rates is likely due too the increased power demand (i.e., increased power for air conditioning) causing an increase in flow.

All the edges of bar II were bevelled, with poorly defined slip faces. The downstream portion of the bar was much lower than bar I, and the upstream section of the bar had a higher elevation than bar I. The flow over the downstream portion of the bar surface was directed downstream, whereas the upstream portion of the bar had flow directed towards the deep channel on the left. Bed velocities and bedload transport were relatively high on the bar surface compared to June 27. Ripples were observed over the entire surface of the bar. The intersection between the two bars was the location of the highest bar elevation for either bar. No funnelling of flow or bedload was observed at the junction.

July 19, 1988

Bar II did not migrate very far downstream between July 6 and July 19 but the elevation of the bar surface increased. The left edge of the bar immediately upstream from the left bar front was still bevelled off. The area between the left and right bar front was very deep (i.e., >1.5 m). The inside edges of the bar front were well defined, with steep avalanche faces. The right bar front and right edge of the bar could not be defined as having a slip face. The left upstream edge of the bar remained unchanged from July 6. The pattern of flow and bedload transport rates also remained the same as described on July 6, 1988.

Bar II had advanced as far downstream as the front of bar I. A slip face was absent at the snout, and along the right side. The surface elevation graded down from the left edge towards bar I. The flow over the surface of the bar was directed toward the left side of the bar. The bed velocities were highest near the upstream end of the bar and the bedload transport rates were highest towards the downstream end of the bar. Ripples were observed at the downstream end of the bar.

August 08, 1988

The right front of bar I had completely tapered into the channel bed (Figure 5.17). The left bar front was still evident with an elevated edge and a steep avalanche face. The bar edge upstream from the bar front was completely bevelled off. The upstream left edge of the bar still had the characteristics described on July 19. Although, the flow and bedload transport had decreased the general pattern was similar to that described for July 19. Flow was still moving towards the left side of the bar, with the highest velocities along the right side and the highest bedload transport rates occurring in the upstream sections of the bar. Bar II was no longer present.

5.3.2 South Site (upstream section)

The upstream section of the South Site had several bars which were monitored at different time periods (Figures 5.18 - 5.21). The first bar (i.e., bar I) was bounded by a small sand flat along the right side and a trough on the left. The second bar (i.e., bar II) was initially located further upstream and was flanked on its left side by a large sand flat complex. Bar II eventually became the dominant feature in this section of the channel. The two bars, situated between the small exposed sand flat and the major sand flat complex, occupied approximately 80%-90% of the channel width.

Unlike the downstream site, the migration of these bars was not directed downstream into topographically lower sections of the channel. The bar migration, however, was influenced by the channel trough which separated the two bars. The migration of bar I lasted until June 22. After this date the terminus of the bar could no longer be defined. The rates of movement for these bars are summarized in Table 5.3 and 5.4. The rates of movement for bar II are less variable than the rates indicated for bar I.

Table 5.3: Rates of bar migration of bar I at the upstream section of the South site.

Dates	Rate (m/day)
June 2 - 8	0.9
June 8 - 14	1.8
June 14 - 22	0.5
June 22 - 28	0

Table 5.4: Rates of bar migration of bar II at the upstream section of the South site.

Dates	Rate (m/day)
June 2 - 8	3.1
June 8 - 14	2.1
June 14 - 22	2.1
June 22 - 28	2.9
June 28 - July 7	2.8

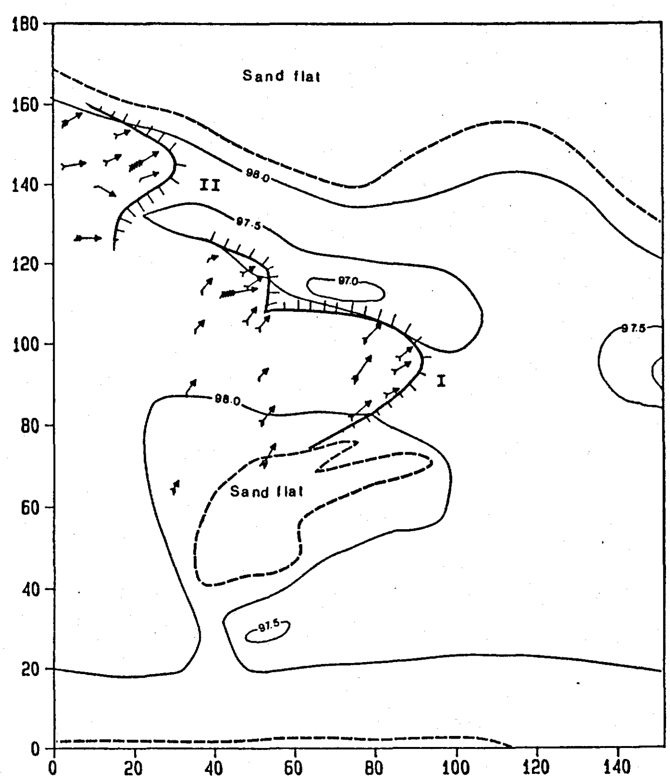


Figure 5.18: Bar development at the upstream section of the South site, June 2, 1988.

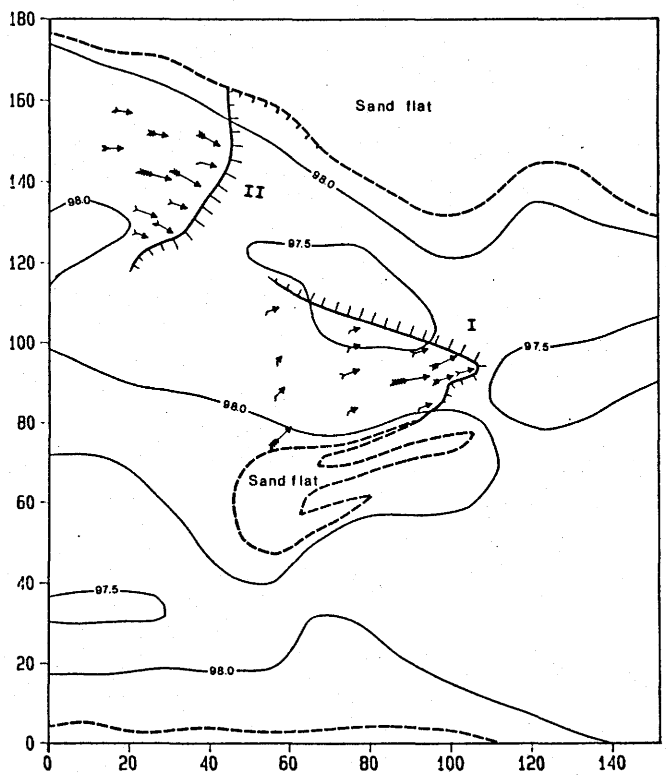


Figure 5.19: Bar development at the upstream section of the South site, June 14, 1988.

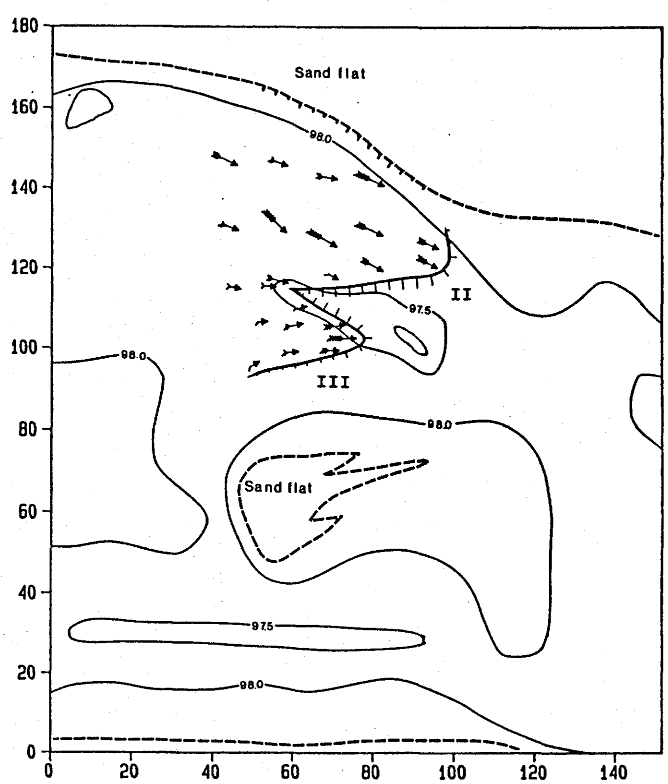


Figure 5.20: Bar development at the upstream section of the South site, July 7, 1988.

5.3.2.1 Site descriptions

June 2, 1988

The snout of bar I was migrating into the channel trough. Its right edge was attached to the small exposed sand flat on its right, whereas the left edge was the edge of the trough. All edges of the bar had well defined slip faces. The main flow direction over bar I was initially towards the channel trough (Figure 5.18). The upstream left section of the bar extended into the trough, reflecting the direction of the flow. The flow over the bar was shallower near the terminus and progressively deeper upstream. High bed velocities were observed in the centre of the bar and towards the left edge where the bar was extending into the trough. The highest bedload transport rates were measured along the right edge and in the vicinity of the extension into the trough. Anomalously low transport rates were measured in the centre of the bar where relatively high bed velocities were observed.

Bar II had a well-defined right edge, but the left edge, although visible, was poorly defined. The majority of the flow was directed towards the sand flat complex to the left of the bar. The edge of the bar adjacent to the channel trough had a raised surface compared to the remainder of the bar. The highest bed velocities were observed in the middle of the bar and extended towards the right side, where flow was observed funnelling into the trough. The highest bedload transport rates were observed along the left edge of the bar. Erosion of the cutbank along the sand flat complex to the left of the bar was occurring. The channel bed between the bar and the sand flat consisted of a plane bed which had relatively high bed velocities.

June 8, 1988

Bar I continued to migrate downstream, with the front of the bar directed into the channel trough. The small extension along the upstream left edge had moved further into the channel trough. The patterns of flow direction, bed velocity and bedload transport were similar to those observed on June 2.

Bar II had migrated downstream and the left edge of the bar had developed a distinct slip face. The left edge of the bar was relatively short, grading into the channel upstream, while the right edge of the bar extended further upstream. The flow direction had shifted to the right, with more of the flow directed downstream. Bed velocities and bedload transport rates were highest along the left edge and near the head of the trough.

June 14, 1988

The front of bar I had migrated far enough into the trough that the flow, bed velocity and bedload were directly influenced by the flow in the trough (Figure 5.19). The extension at the upstream left edge, observed on June 2 and 7 was no longer visible. The flow over the remainder of the bar surface continued to be directed towards the channel trough. The left edge of the bar was beginning to be bevelled and to lose its well-defined slip face.

Bar II had migrated downstream towards the channel trough. The left edge of the bar could no longer be defined and the leading edge of the bar terminated at the sand flat complex. The flow over the surface was no longer directed towards the sand flat complex. The cutbank on the sand flat was increasingly concave in plan form. The flow past the cutbank was deflected across bar II toward the trough. The surface of the bar had the lowest elevations closest to the sand flat complex and graded upwards towards the right edge of the bar. The right edge of the bar could be defined as being ridged, similar to the observations made on the upstream left edge of bar I at the downstream section of the South site. Bed velocities were relatively low along the edge of the sand flat complex, however high bedload transport rates were observed. Dunes and ripples were also observed next to the sand flat complex. High bed velocities coupled with relatively high bedload transport rates were measured in the centre of the bar and were directed towards the channel trough.

June 22, 1988

The slip face at the snout of bar I, although distinct, was elongating. The left edge of the bar was bevelled, except for the extreme upstream edge. The right edge of the bar was difficult to distinguish. A small bar (i.e., bar III) on the upstream left section of bar I was visible from the top of the bank, however, the outline was difficult to identify upon closer inspection. The patterns of flow and bedload transport were similar to the observation for June 14.

The snout and the right edge had the same morphologic characteristics as observed on June 14. The left edge of the bar was very short. The upstream left edge of the bar had tapered into the channel bed. The flow direction was still downstream toward the trough. The highest bed velocities and bedload transport rates were observed along the disintegrated left edge of the bar and at the intersection between bar I and II (which also was the head of the trough).

June 28, 1988

The snout and the right edge of bar I had begun to blend into the channel bed. The elevation of the bar surface graded down from the right to the left. The left edge of the bar was more rounded than previously observed. The flow over this disintegrating bar was still directed towards the channel trough. The bed velocity and bedload transport showed a significant decline as compared to earlier observations. A small bar (i.e bar III), however, had developed on the surface of bar I along the upstream left side, confirming its presence (it had previously been identified on June 22). The majority of flow on this bar was directed toward the channel trough. Bed velocities on bar III were low along the poorly defined right edge while getting progressively higher toward the left edge. Bedload transport rates were relatively high in the upstream left region while getting lower towards the left edge and the terminus.

Bar II had taken on a more significant role in terms of development compared to bar I. The erosion of the cutbank on the sand flat complex was also continuing but it was difficult to assess the relationship between the cutbank and the bar. It appeared as though the bar had progressed into the cutbank resulting in greater erosion but the flow deflected by the cutbank was moving across the surface of the bar towards the trough. The ridge at the right edge of the bar, along the channel trough, was getting higher. Bed velocities were high along the downstream section of the cutbank but the highest bed load transport rates were observed at the junction between bar I and II, where flow was funnelling into the trough.

July 7, 1988

No traces of bar I were visible (Figure 5.20). Bar III; which formed on its surface had progressed slowly downstream, primarily due to its association with the trough. The right edge of bar III was beginning to blend into the bed of the channel. The terminus, which had extended into the trough, was still very distinct. The bed velocity and bedload transport rates were highest near the terminus and along the left edge of the bar.

Bar II was also losing some of the morphologic features which characterized it as a bar. The downstream edge was very poorly defined, because of the downstream extension of the slip face into bed. The right edge of the bar which previously was ridged, with a steep avalanche face, was bevelled off. Flow was still directed toward the trough with bed velocity and bedload transport rates relatively high over the surface of the feature. Cutbank erosion on the sand flat complex was very active.

July 20, 1988

None of the features being monitored in the upstream section of the South site could be identified. Bar III, which had formed on the upstream section of bar I was now completely degraded. The disintegrated bars could be defined as plane beds with their boundaries defined by the trough and the sand flats. The head of the trough was still migrating downstream due to the material transported across the surface of the plane beds and being deposited in the trough.

5.3.3 North Site

The north site had two bars which originated in a shallow secondary channel and were migrating into a deeper secondary channel (Figures 2.21 - 2.24). The first bar (i.e., bar I) located in the downstream section of the study area was bordered by a sand flat complex on the left and an island on the right. A deep trough was present between bar I and the island. The second bar (i.e., bar II) located further upstream was bordered by the sand flat complex on the left and a small exposed sand flat on the right. The small sand flat on the right was an exposed section of bar II.

Bar I migrated round a bend in the channel at the end of the sand flat, during the period of observation. Bar I migrated a distance of approximately 110 m, (Table 5.5) and also expanded laterally. Once around the bend a ridge formed at the mouth of the trough and progressed downstream at a consistent rate (Table 5.6). Bar II migrated approximately 180 m before its terminus began to blend into the surface of bar I. The rate of movement of bar II varied, partly due to the lateral expansion toward the sand flat complex (Table 5.7).

Table 5.5: Rates of bar migration of bar I at the North site.

Dates	Rate (m/day)
June 3 - 9	0.6
June 9 - 15	2.5
June 15 - 23	1.1
June 23 - July 4	0.7

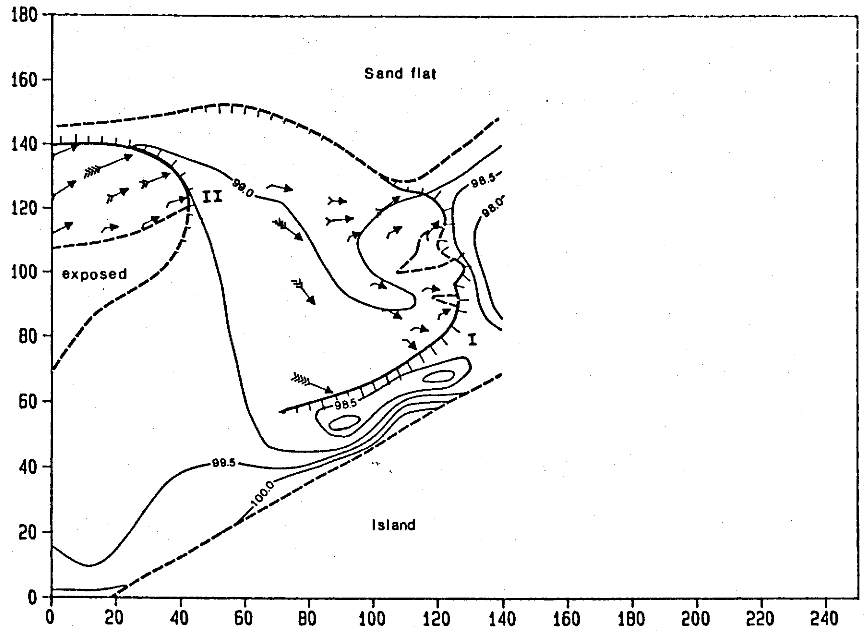


Figure 5.21: Bar development at the North site, June 3, 1988.

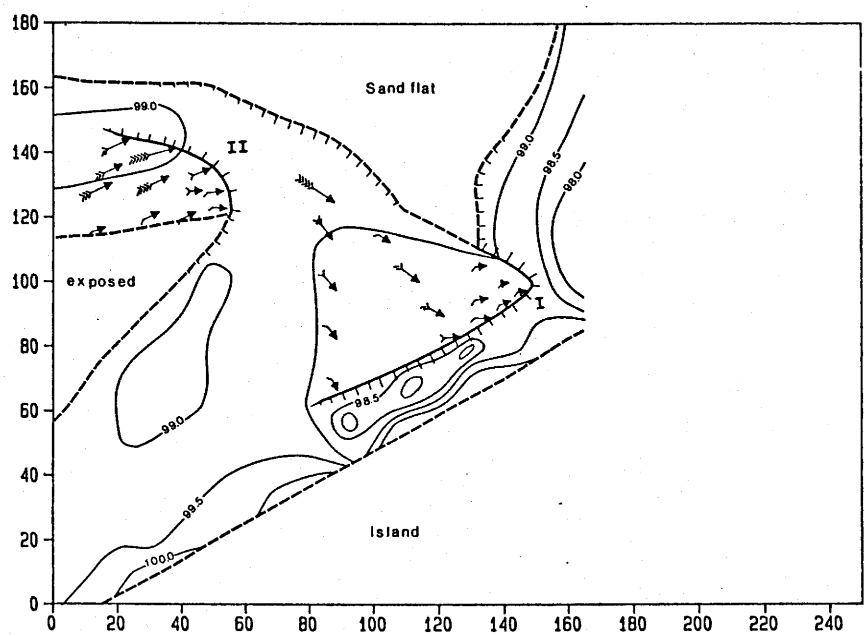


Figure 5.22: Bar development at the North site, June 15, 1988.

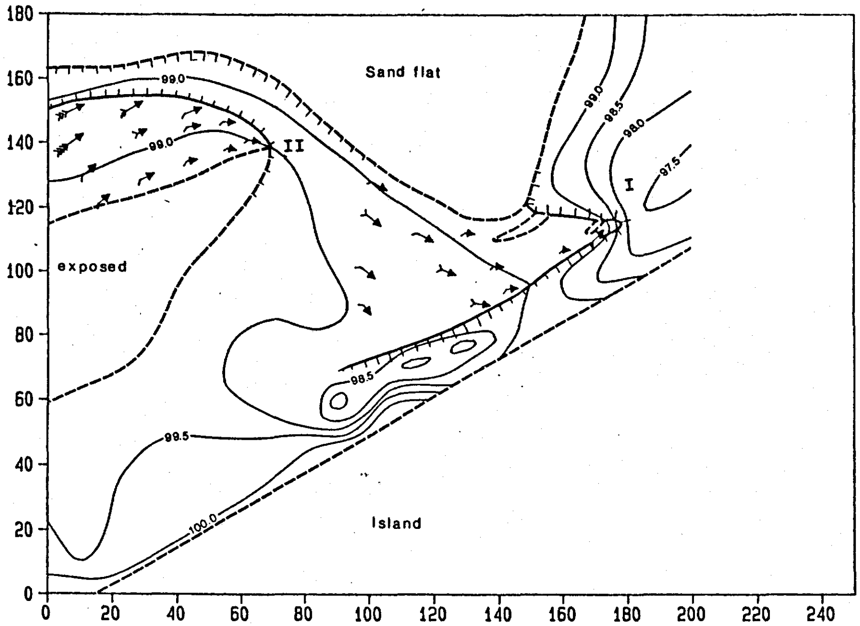


Figure 5.23: Bar development at the North site, July 04, 1988.

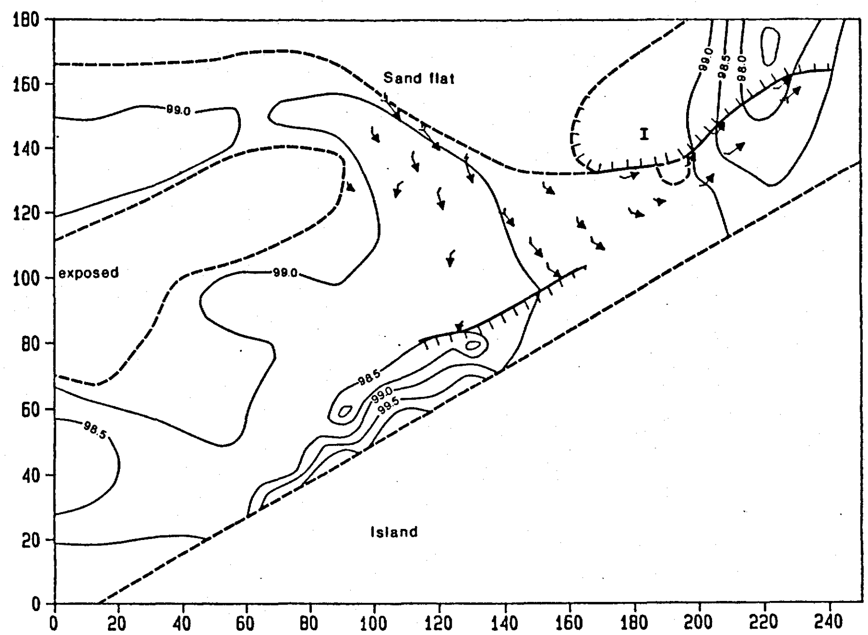


Figure 5.24: Bar development at the North site, August 10, 1988.

Table 5.6: Rates of migration of the extension ridge downstream from bar I at the North site.

Dates	Rate (m/day)
July 4 - 18	1.1
July 18 - August 3	1.9
August 3 - 10	2.1

Table 5.7: Rates of bar migration of bar II at the North site.

Dates	Rate (m/day)
June 3 - 9	1.7
June 9 - 15	0.8
June 15 - 23	0.6
June 23 - July 4	0.4
July 4 - 18	1.4

5.3.3.1 Site descriptions

June 3, 1988

Bar I had migrated past the end of sand flat and was progressing into the topographically lower channel (Figure 5.21). The snout of the bar was attached to the sand flat complex to the left and extended across the channel toward the island. The right edge of the bar extended upstream parallel to the island. Both the snout and the right edge had a steep avalanche face. Two small exposed sand flats had formed along the snout of the bar. The flow which originates from the shallow channel has the highest bed velocities and bedload transport rates. The flow direction over the bar was divided into two main directions. One flowing diagonally across the upstream end of the bar and the other flowing downstream along the edge of the sand flat complex. Higher velocities and bedload transport rates were observed in the flow moving across the bar surface to the trough between the island and the bar, than along the sand flat complex. Apart from the two areas described, the remainder of the bar front was relatively inactive, with lower bed velocities and bed load transport rates. The inactive area of the bar front had a ridge of material along the edge, similar to situations observed at the South site. The surface elevation of the bar showed a decrease from the upstream section of the bar to the bar edge where the two main flow paths described, drained off the bar.

Bar II was upstream in the shallow secondary channel. The right side of the bar consisted of a recently exposed sand flat. The bar edge and snout of the bar were well defined, with a distinct avalanche face. The surface elevation of the bar graded down from the exposed portion of the bar to the bar edge. Flow over the bar surface was directed laterally to the left, thus creating a more active slip face along the left side than at the snout. The highest bed velocities and bedload transport rates were measured at the upstream part of the bar. The channel between the bar and the large sand flat complex had relatively high velocities and bedload movement. The flow in this channel was directed into the cutbank on the sand flat complex causing it to erode.

June 9, 1988

The exposed areas observed on the front of bar I on June 3 had been reactivated and the bar migrated downstream. The left side of the bar front, from the sand flat to mid channel was now exposed. The main flow direction, which also had the highest bed velocities and bedload transport rates, were moving across the upstream end of the bar from the mouth of the shallow secondary channel toward the trough located between the island and the bar. A significant portion of the flow was also directed toward the right front edge of the bar. Two small submerged extension ridges were observed extending downstream from the right front edge of the bar.

Bar II had extended downstream a very short distance, but had migrated laterally a significant distance. The surface area of the submerged portion of the bar remained relatively unchanged but the exposed area of the bar increased. The left edge of the bar was starting to build up a small ridge. Flow was still directed laterally over the surface toward the left edge. The pattern of bed velocities and bedload transport rates was the same as those observed on June 3. Cutbank erosion on the sand flat complex was very active and was starting to form a concave bank similar to the cutbank described at the South site.

June 15, 1988

The right side of the bar front was beginning to extend downstream (Figure 5.22), moving over the extension ridges described on June 9. The extending snout was more tapered than lobate. A relatively large, newly-exposed sand flat was now established at the end of the sand flat complex where the shallow secondary channel entered deeper water. The newly formed sand flat extended across half the width of the deeper channel. The downstream side of the sand flat had a very steep slip face which extended into the deep part of the channel (i.e., >1.5 m). Flow was still exiting the mouth of the shallow secondary channel with relatively high near-bed velocities and bedload transport rates. The flow was moving laterally across the bar surface toward the trough. The high near-bed velocities and bedload transport observed along the trough on June 3 had diminished. The bed velocity and bedload transport rates were still diminishing across the surface of the bar with a small sluice across the bar surface carrying most of the flow. The surface elevation of the sluice was lower (i.e 0.06 to 0.20 m lower) than measured on June 3. The edge of the bar, where the sluice drained into the trough, was beginning to be bevelled off and the trough was beginning to aggrade.

Bar II continued to grow laterally with little progress downstream. The left edge of the bar remained slightly higher than the centre of the bar but was not as well defined as observed on June 9. The pattern of flow and bed velocity was similar to observations made at earlier times, but bedload transport rates were slightly higher. The lateral growth of the bar resulted in accelerated erosion of the cutbank on the main sand flat complex. The erosion of the cutbank appeared to be a significant contributor to the bedload at the mouth of the shallow secondary channel.

June 23, 1988

The morphologic and hydrodynamic characteristics of bar I were similar to those observed on June 15 with only a few notable exceptions. The shape of the bar remained relatively unchanged but the tapered terminus had migrated further downstream. The sluice running from the mouth of the shallow secondary channel to the trough was more pronounced. The edge of the bar where the sluice entered the trough had graded into the trough removing any trace of a slip face.

The morphology and the hydrodynamic character of bar II did not change from June 15, nor did the bar migrate substantially either downstream or laterally. The channel between the bar and sand flat cutbank was beginning to get wider due to the cutbank erosion along the sand flat and the stability of bar II. The erosion on the cut bank was progressing downstream along the sand flat.

July 4, 1988

The right bar front had moved further downstream, parallel to the island (Figure 5.23). The bar was moving over the surface of the extension ridge described on June 15. Two small exposed areas were observed along the extended bar front. Although these newly exposed areas had small channels on either side, the only measurable flow occurred on the right side of the small sand flat closest to the island. The entire right edge of the bar was bevelled allowing ripples to form on the disintegrating slip face. Although the bed velocity and bedload transport from the mouth of the shallow secondary channel were lower, the same pattern observed on June 23 was apparent. The sluice which had formed earlier was now aggrading but had become wider.

Bar II had changes occur to both its morphology and hydrodynamic character. The bar had extended downstream with more of its snout becoming exposed. This resulted in a more tapered appearance to the submerged bar. The left upstream edge of the bar was beginning to blend into the bed of the channel. The remainder of the bar's edge, although distinct, was lower than the remaining surface of the bar (i.e., it no longer had the ridge along the edge). The bed velocity and bed load transport rates were lower than previously measured, however, the spatial pattern of the flow distribution remained the same as observed on June 23. The erosion of the cut bank on the sand flat complex had progressed to the mouth of the shallow secondary channel. The channel between the sand flat complex and the bar was now wider, with shallower flow than observed on June 3.

July 18, 1988

The two small sand flats observed on the extended snout of the sand flat had been incorporated into the exposed sand flat extending from the sand flat complex across the front of bar I. The right bar front was continuing to migrate into deeper water. The right edge of this bar was poorly defined but the left edge was very distinct. The flow from the mouth of the secondary channel was still flowing across the surface of the bar towards the island. No bar edge could be defined where the flow entered the trough. The trough at this point had aggraded significantly but graded into deeper water both upstream and downstream. A similar pattern of high bed velocity and bedload transport rate was observed at the mouth of the minor secondary channel. The flow and sediment continued to expand over the surface of the bar, but was inhibited by the presence of the sluice. The sluice was drawing some of the flow and sediment from the surface of the bar.

Bar II was migrating downstream more than laterally. The edges of the bar were becoming less distinct, with the upstream left edge of the bar completely degraded. The pattern of flow direction, bed velocity and bedload movement were similar to those observed on July 4.

August 10, 1988

Neither bar I or II could be defined (Figure 5.24). The right edge of bar I had completely disappeared into the aggraded trough. The extension of the bar front had a well defined left edge which graded down towards the island. Erosion of the island was beginning parallel to the extended bar front. Bar II was no longer visible. The shallow secondary channel had become a wide plane bed. Cutbank erosion along the sand flat was observed but had diminished significantly. Flow from the mouth of the of the secondary channel was directed at the island and was deflected downstream along the extended bar front. The bed velocity and bed load transport rate still showed a similar pattern as observed on July 18.

5.4 Bedload - Near-bed Velocity Relationship

Bedload transport rates were plotted against near-bed velocity for each site (Figures 5.25 - 5.27). In evaluating the relationship illustrated in these plots, near-bed velocity was considered to be an index for shear stress at the bed of the channel. This is justified as follows.

Apparent shear stress can be determined using the Karman - Prandtl law of the wall, i.e.:

$$U* = ky(dU/dy)$$

where: $U*$ = shear velocity
= (τ/p)
τ = bed shear stress
p = water density
k = von Karman constant = 0.4
y = depth
U = velocity

The integrated version of this equation is:

$$\tau = \frac{p[k(U^1-U^0)]^2}{2.3 \log (z_1/z_0)} \quad \text{(Eq. 5.1)}$$

Velocities for U_1 and U_0 are measured at depth z_1 and z_0 respectively. This equation is considered to be most accurate when used in the lower 20-30% of the flow depth (Middleton and Southard, 1984). Yalin (1977) suggested that by keeping z_1/z_0 small when approaching the flow boundary (i.e., the flow bed) the apparent shear stress approaches the value of the boundary shear stress.

One approach to calculating the shear with a single velocity is to consider that z_0 is controlled by a representative coarser fraction of the moving or static bed surface (Dietrich and Whiting, 1989). Below this coarse fraction the velocity (U_0) would be equal to zero, therefore equation 4.1 becomes:

$$\tau = \frac{p[k(U_1)]^2}{2.3 \log (z_1/z_0)} \qquad \text{(Eq. 5.2)}$$

If z_1 and p are constant, and z_0 is assumed as a constant for a sand-bed river then:

$$\tau \ \alpha \ (U_1)^2$$

allowing the near-bed velocity (U_1) to be used as an index of the apparent shear stress.

The plots illustrate limits for which bedload transport occurs. Bedload transport could not be detected at bottom velocities less than 0.05 m s^{-1}. Intermittent bedload transport occurred at the North site and the upstream section of the South site for bottom velocities between 0.05 and 0.25 m s^{-1}, and at the downstream section of the South site between 0.05 and 0.45 m s-^{1}. These ranges of bottom velocities correspond with critical velocities required for the initiation of motion of sand size particles (Vanoni, 1975, pp 102). Bedload transport was observed in all situations when the bottom velocity was above the upper limits for the intermittent bedload transport. Correlation analysis suggests that bedload transport increases with an increase in near-bed velocity (Figures 5.25 - 5.27). The low correlation coefficients reflect the variation in the data, however, they are significant at a 99% confidence interval. Several possibilities can be presented to explain the scatter apparent in the data: non-linear relationship between variables, systematic differences due to sampling techniques, and the influence of grain size and bedforms.

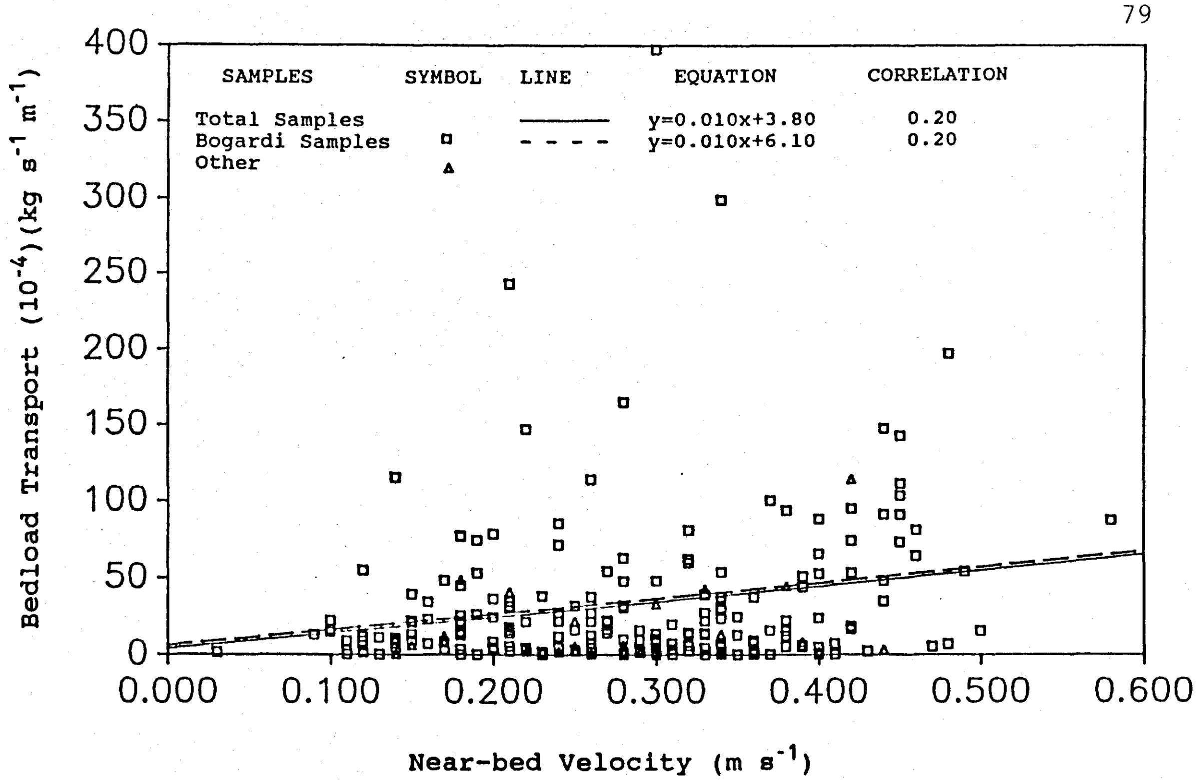


Figure 5.25: Bedload transport - near-bed velocity relationship, South site (downstream).

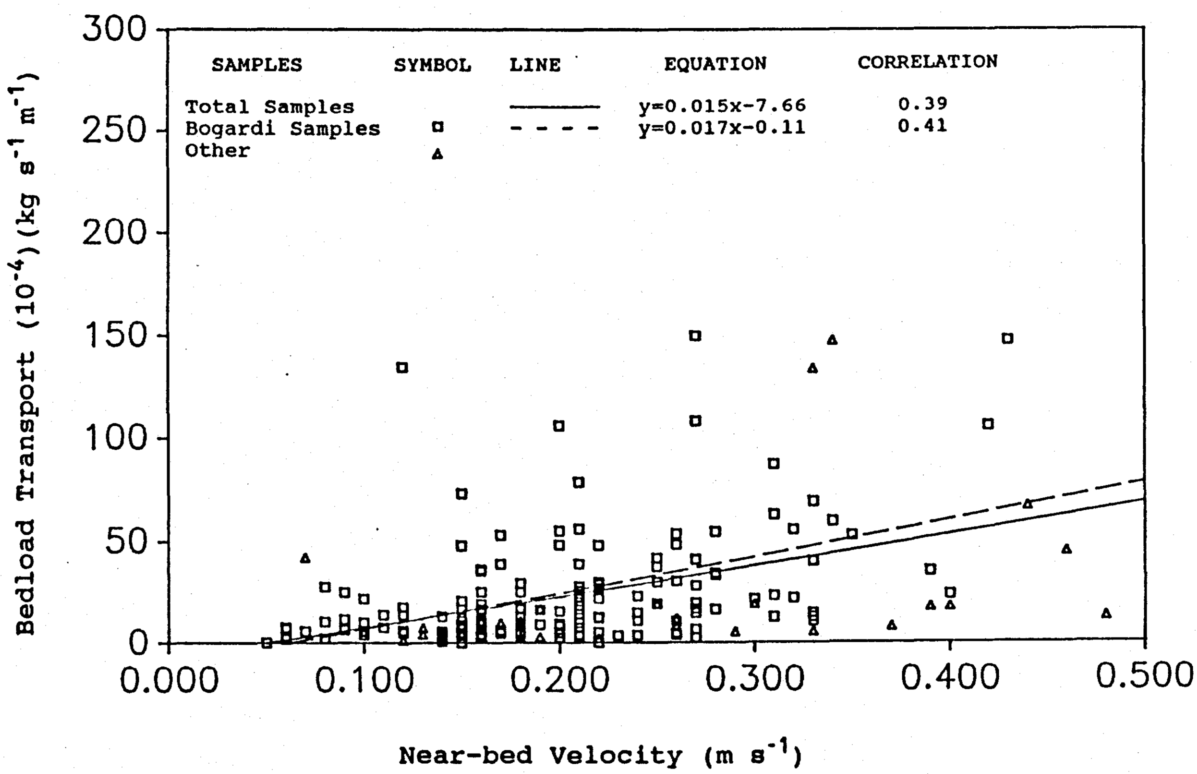


Figure 5.26: Bedload transport - near-bed velocity relationship, South site (upstream).

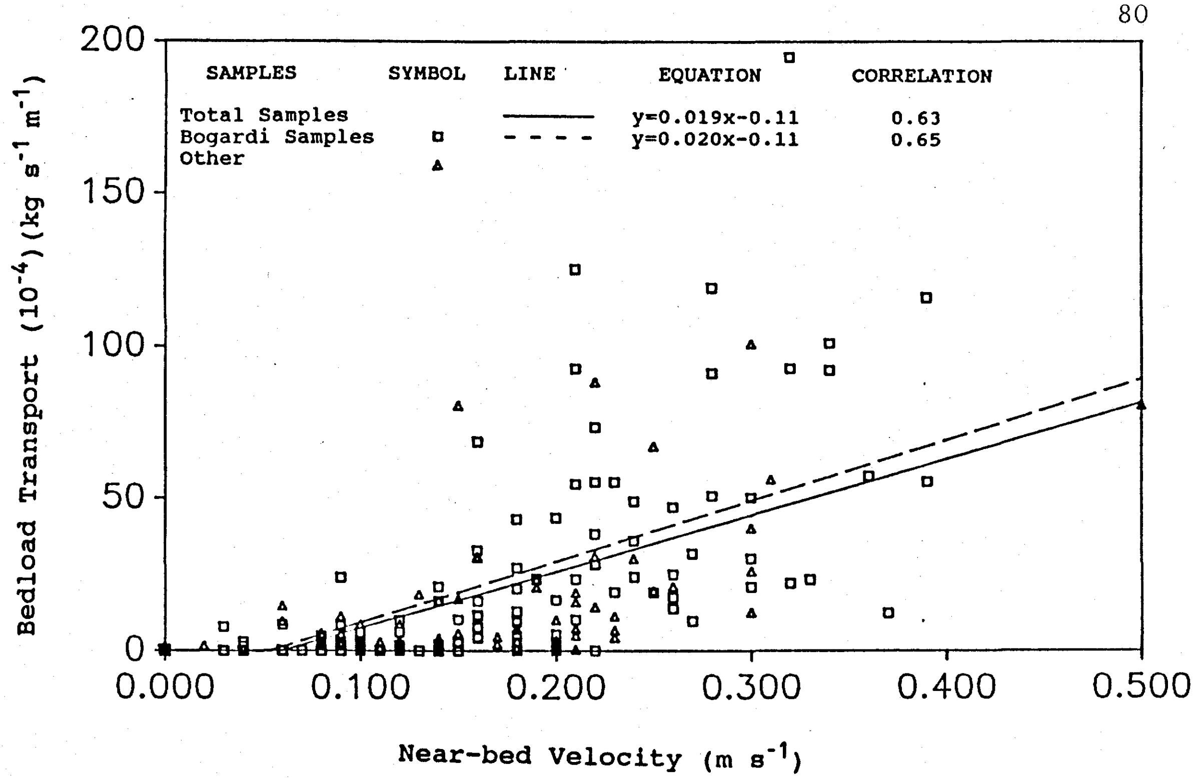


Figure 5.27: Bedload transport - near-bed velocity relationship, North site.

The data were plotted as log-log and semi-log to try and improve the correlation and obtain a better explanation of the variation. Fitting of a second order polynomial curve was also attempted. In some cases, the variation in the data did not appear as extreme, however, there was no case where the correlation coefficient was increased by a significant amount. In each case the same weak but significant trend of increasing bedload transport with increased bottom velocity occurred.

The difference in sampling techniques was also considered as a possible reason for the variation in the data. To evaluate this a regression line for all samples and a regression line for samples collected only with the Bogardi sampler was determined (Figures 5.25 - 5.27). The correlation coefficient calculated for the Bogardi samples compares favourably with the coefficient from all samples. A test between the slopes of the two regression lines suggest that they are not significantly different (at a 99 % confidence limit), therefore sampling techniques do not have a direct influence on the variation in data.

A plot comparing bedload transport rate measured with the pan and Bogardi is also presented (Figure 5.28). The plot compares transport rates which were sampled in shallow water conditions (i.e., conditions when the pan was utilized). The relationship between the pan and Bogardi is significant at a 99 % confidence interval. The regression equation suggests that the pan under-samples, compared to the Bogardi in low transport situations (which usually occurred when the pan was used). This, added to the fact that the pan was used infrequently, supports the conclusion that sampling techniques did not have a direct effect on the variation in the data.

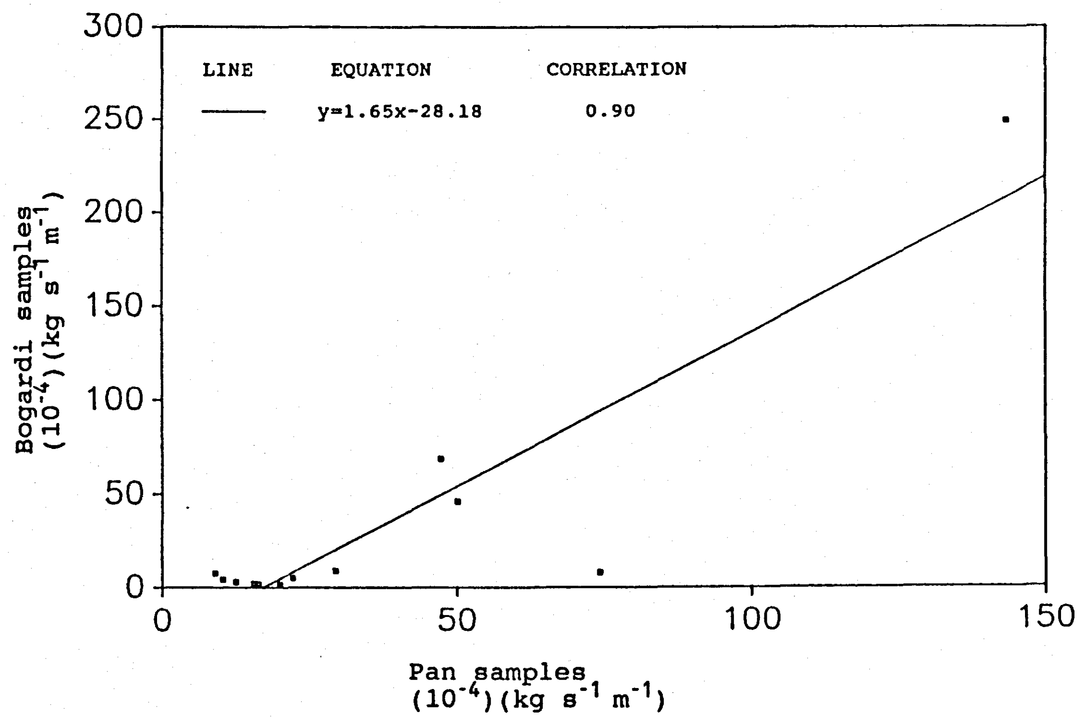


Figure 5.28: Plot of pan versus Bogardi bed load sampler.

The effect of grain size on the transport of bedload can only be dealt with superficially due to a lack of bed material samples. Grain size analysis was conducted on samples larger than 35 g collected when measuring bedload transport. Scatter plots of the bedload transport rate and near-bed velocity were plotted for each site using samples for which grain size data were available (Figures 5.29 - 5.31). The data were separated into various grain size classes based on d_{50}. The highest rates of bedload transport occurred for samples which had a d_{50} greater than 0.3 mm. This transport also occurred in the range of intermittent bedload transport. This may reflect the inefficiencies of the Bogardi sampler to collect larger size particles at lower flows.

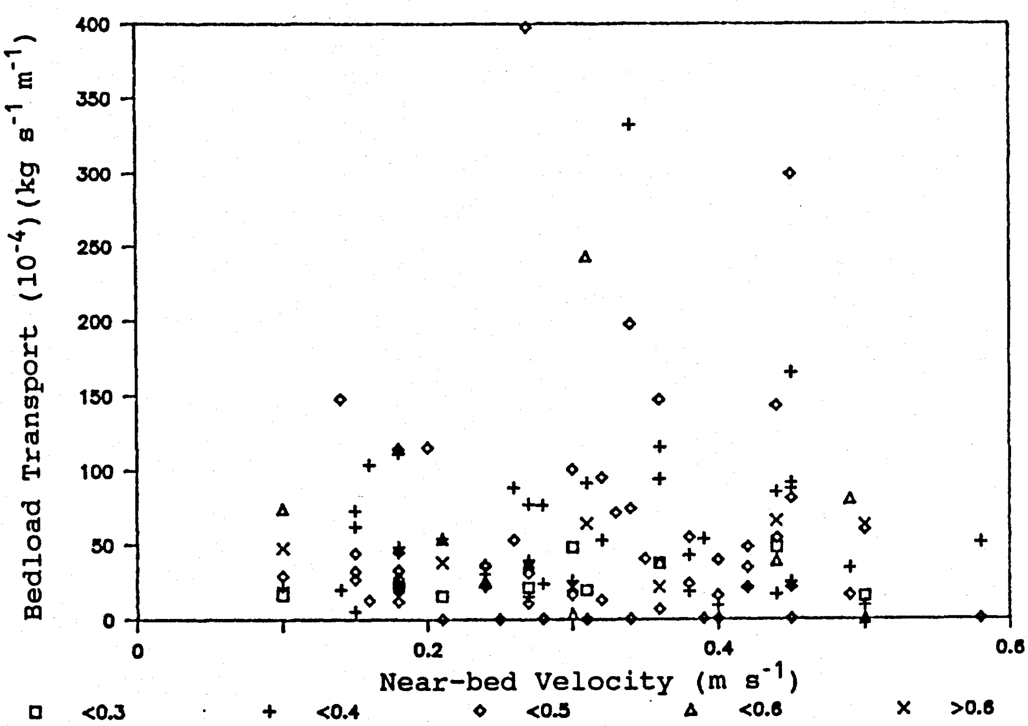


Figure 5.29: Scatter plot of bedload transport versus near-bed velocity with data separated into grain size classes. South site, downstream. Grain sizes in millimetres.

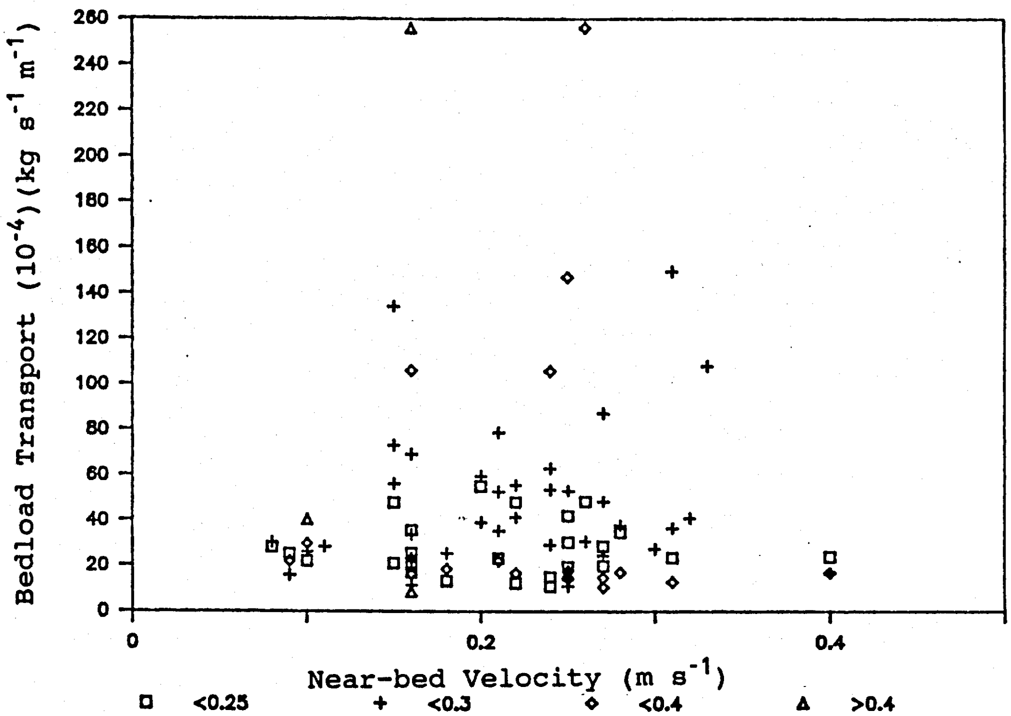


Figure 5.30: Scatter plot of bedload transport versus near-bed velocity with data separated into grain size classes. South site, upstream. Grain sizes in millimetres.

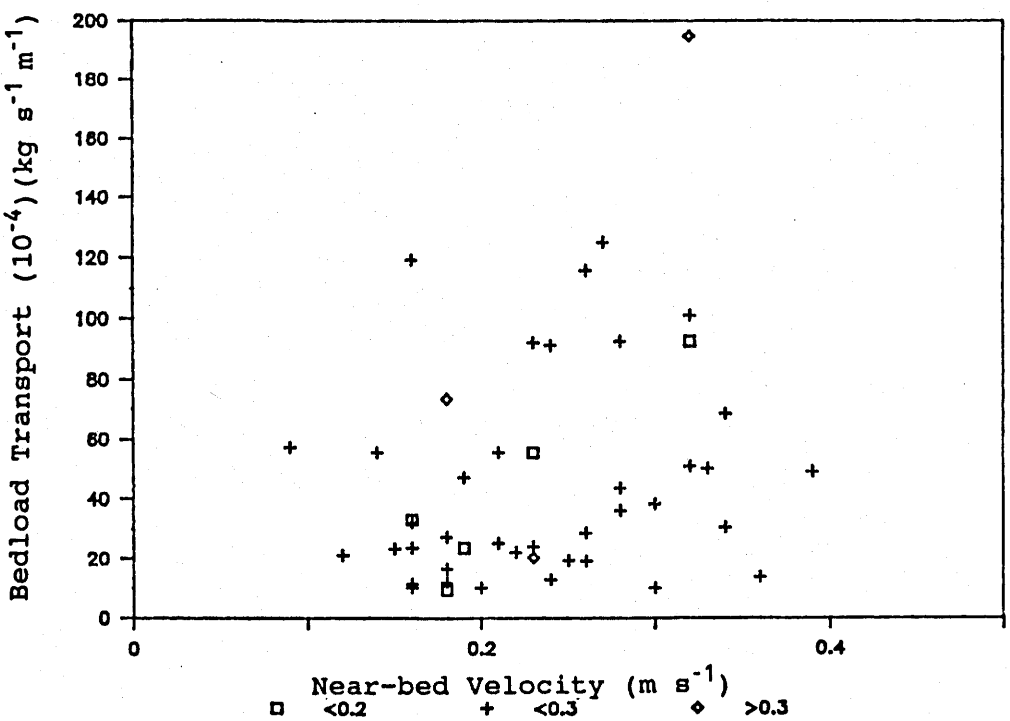


Figure 5.31: Scatter plot of Bedload transport versus near-bed velocity with data separated into grain size classes. North site. Grain sizes in millimetres.

The variation in the bedload transport - near-bed velocity data may be due to the movement of smaller bedforms such as ripples. Ripples were observed migrating on the surface of the bars at the time of bedload transport measurements. Depending on the placement of the sampler in relation to the small bedforms, variations in measured transport rates occur. If the mouth of the sampler is placed on the immediate lee side of an actively migrating bedform a large sample will be collected. If the sampler is placed on the crest of a bedform, a smaller sample will be collected. Depending on the wavelength between bedforms and rate of migration the time required to get a fully integrated bedload sample varies. Since consistent times were used at the sampling points, variations in the wavelengths in the bedforms could be a source of scatter in the data.

Vortices in the flow, which often create three-dimensional bedforms, can also affect the bedload transport. The random fluctuations in the flow results in a spatially non-uniform transport of bedload. If the fluctuations in the flow are completely random, the variation in bedload transport affected by these fluctuations should be normally distributed with a large data set. Since the data are not normally distributed, factors other than flow vortices are believed to be the source of the variation in the data.

6 DISCUSSION

Observations and data collected at each site have led to the identification of several general points about bar morphology, hydraulics, and factors contributing to the evolution of a bar. General points about the development of sand flats have also been synthesized. These generalizations regarding bar and sand flat development will be discussed and, where appropriate, will be examined relative to previous research related to sand-bed braided rivers.

6.1 Bar Morphology

The bars in the South Saskatchewan River have the morphology of classical "transverse bars" (Smith, 1971; Miall, 1977; Cant and Walker, 1978), although Ashley (1990) suggests they be included in the general category "dunes". Most of the bars were first observed with a symmetric morphology, however, the asymmetric hydrodynamic characteristics on the surface of the bars eventually changed their morphology.

The transverse bars identified in the South Saskatchewan River were solitary features which took up less than the full channel width. The bars developed in straight sections of the channel, such as those at the

South site, and at the mouth of secondary channels, such as bar I at the North site. The bars had a variety of shapes and sizes, but were generally lobate with one side extending toward a bank. The slip face of the bars varied in height (i.e., 1-2 cm to over 1 m) on individual bars, as well as between bars. The variability of the slip faces was partly due to the channel topography and the asymmetric flow patterns on the surface of the bars.

The morphology of the transverse bars was not static and modifications to the bars occurred throughout the study period. Morphologies identified include transverse bars (symmetric) with irregular snouts, features with the characteristics of side bars (asymmetric) and, in some cases, bars diminished creating a plane bed. The first bar (i.e., bar I) at both the downstream section of the South site and the North site evolved into features resembling side bars (Figures 5.17 and 5.24). Bar I at the downstream section of the South site also had an irregularly shaped snout during the mid-summer (Figures 5.15 and 5.16). All bars monitored at the upstream section of the South site eventually diminished into the channel bed. Bar II at the North site also evolved into a plane bed.

The extension and flattening out of the avalanche face of these bars resembles processes suggested by Allen and Collinson (1974). This implies that these features were large dunes formed at a higher discharge and when the discharge decreased the dunes began to lengthen to adjust to the changing flow conditions. Hydrologic records for the river from May to August, 1988 (Figure 5.1) do not indicate a high discharge period. The construction of Gardiner Dam has resulted in a flow which has been regulated in such a manner that the annual mean daily flows for May are among the lowest during the year (Figure 3.2). The fluctuations in discharge which occur each day (Figure 5.2) only result in stage fluctuations of a few centimetres. The data demonstrate that a high discharge and stage did not occur during the spring, therefore the development of these features can not be attributed to high flow conditions, nor can they be considered as diminishing dunes. The hydrologic data suggest that these features form during relatively uniform flow conditions and are then modified as they migrate downstream.

The hydrodynamic character of the surface of the bars strongly influenced the evolution of the bars. Although the flow direction, flow depth, near-bed velocity and bedload transport varied both spatially and temporally over the surface of the bars, some general patterns do emerge.

The flow on the surface of the bars was primarily oblique to the direction of the channel, causing sediment to be transported laterally over the surface of most of the bars. The highest near-bed velocities and sediment transport usually occurred toward the centre of the bar, but were not always associated with one another. In situations where there was a high bedload transport with a low near-bed velocity, bedform features such as ripples and dunes were present creating a boundary condition related to the height of the bedforms as well as the grain sizes. This is a situation where using the near-bed velocity as an index of the shear stress may not be representative, without incorporating bedform roughness heights.

No patterns related to the flow depth on the surface of the bar could be determined. At one time period the edges of the bars would be elevated above the remainder of the bar surface and at other times the bars edge would be bevelled and be lower then the remainder of the bar. It was observed, however, that relatively low near-bed velocities occurred along the edge of the bar when it was elevated, and higher near-bed velocities occurred when the edge of the bar was bevelled. The variability of the hydrodynamic character on the surface of the bar was influenced by factors within the channel.

6.2 Controls on Bar Morphology and Migration

Some of the factors affecting the development of the bars in the South Saskatchewan River are similar to those considered by Smith (1971) for the Lower Platte River. The most important factors influencing the development of the bars include channel troughs, channel topography and channel morphology. The spatial patterns of flow direction, flow depth, near-bed velocity and bedload transport on the surface of the bar, coupled with changes to the bar morphology, were used to identify how these external factors influence the development of the bar. Modification of the bars by combinations of these factors resulted in them changing from one descriptive bar type to another or disintegrating into a plane bed.

6.2.1 Channel troughs

A channel trough is a deeper section of the channel which is adjacent to a bar. The trough may be a thalweg adjacent to a bar, between two bars, or between a bar and a bank. Channel troughs draw the water from the surface of the bar, resulting in an asymmetric hydrodynamic character (Figures 5.16, 5.20 & 5.23). The magnitude of the interference by a trough on the spatial patterns of flow and sediment transport on the surface of the bar is a function of the size of the trough and its flow. Regardless of the trough size, the general effects on the hydrodynamic character of the bar surface are similar.

The effects of adjacent currents and the proximity to stable banks, both of which result from a channel trough, were discussed by Smith (1971). Smith (1971) suggests that the flow in the troughs associated with these factors removes the sediment passing over the edge of the bar resulting in a quasi-stable slip face. This suggests that the rate of sediment transport in the trough is greater than the sediment transport over the bar. Smith (1971) did not, however, discuss the effect these troughs have on the spatial pattern of flow and sediment transport on the surface of a bar, or the subsequent evolution of the bar as a result of this influence. The influence of the trough results in a decrease in the amount of flow and sediment transported to the downstream edge of the bar. With less flow and sediment at the downstream edge, a distinct avalanche face can no longer be maintained and it begins to taper into the channel bed. The flow directed towards the trough, across the downstream edge of the bar, also contributes to the demise of the slip face.

The flow over the bar relative to the flow in the trough also affects the elevation of the bar edge. Raised and bevelled bar edges were identified on several of the features monitored in the South Saskatchewan River. The raised edges developed because the flow over the bar was not strong enough to carry sediment beyond the crest. The bars edges were bevelled when the flow could carry sediment beyond the edge. Some of the bars developed raised edges which were later bevelled. In some situations, only sections of the bars edge would become bevelled, due to the concentration of flow on the bar surface. It has been suggested that the elevated edges of a bar lead to flow separation and the subsequent dissection of a bar surface (Smith, 1971,; Hunt, 1979).

Although measurements of the flow in the troughs were not made, observations indicate that in locations where the discharge per unit width over the edge of the bar adjacent to the trough was low relative to the flow in the trough, a raised bar edge developed. Conversely, where the discharge per unit width over the bar is higher, relative to the flow in the trough, the edge of the bar would become bevelled. When the flow in the trough is higher than the flow over the bar surface a shear layer is established along the edge of the bar which inhibits the flow and the movement of sediment into the trough, resulting in a raised edge. When the flow over the bar is higher or is concentrated in one location no shear layer exists and sediment is transported into the trough. If the flow over the bar's edge is capable of transporting more sediment it will remove from the crest of the slip face forming a bevelled morphology (Figure 6.1).

The concentration of the flow over the surface of a bar can scour a shallow sluice. The sluice acts as a small trough on the surface of the bar drawing water and sediment into it, reducing supplies to other areas of the bar. The sluice also lowers the local water surface elevation and may result in the exposure of the elevated edges of a bar. An example is that found on the surface of bar I at the North site June 15, 1988

a)

b)

c)

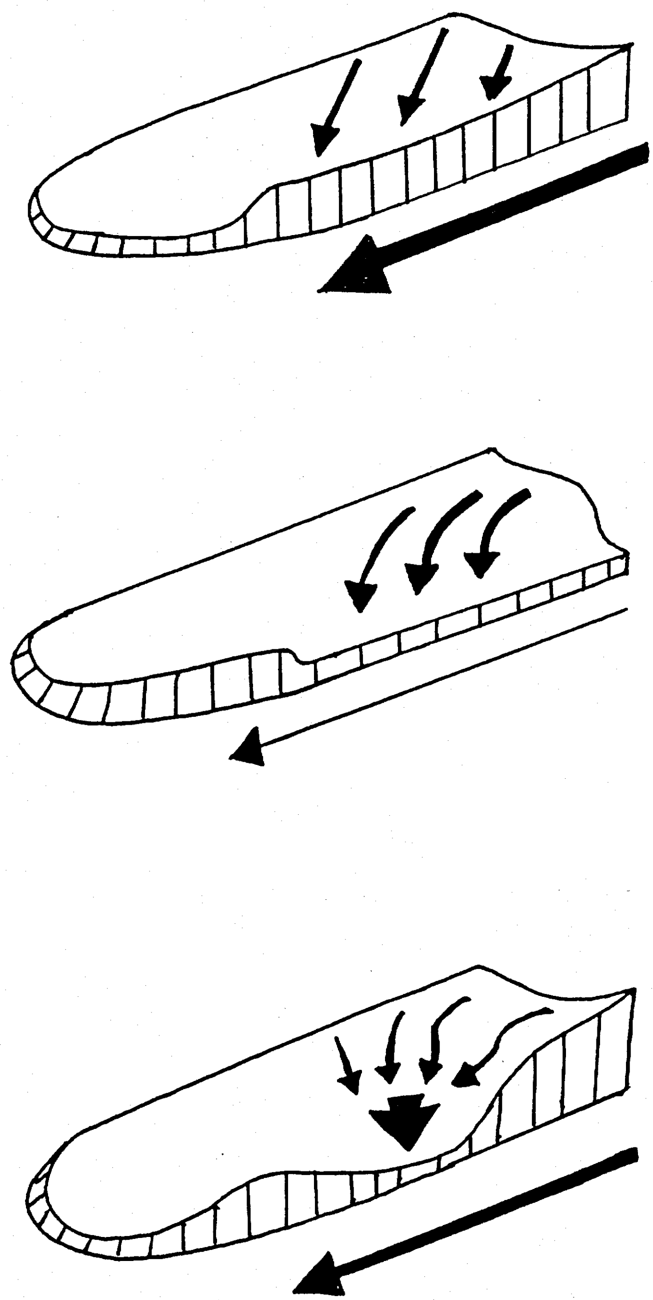


Figure 6.1: Diagrammatic simplification of bar edge development due to the influence of the flow in a channel trough. a) Elevated bar edge; b) Bevelled bar edge, and; c) Bevelled bar edge due to concentrated flow. Thickness of the arrow along the bar represents the flow conditions in the trough relative to the surface of the bar.

resulting in the exposure of the elevated downstream edge of the bar. Features similar to this were also identified in the William River (Hunt, 1979).

The flow in the channel troughs also influenced the development of extension ridges. Extension ridges are submerged features extending downstream from the edge of a bar. This feature was observed at two separate locations, one on bar II in the downstream section of the South site (June 21, 1988), the other on bar I at the North site (June 9, 1988). The development of these elevated ridges raised the bed topography allowing for rapid migration of the bar fronts at both the South site (Table 5.2) and the North site (Table 5.6). The extension ridge at the South site formed symmetrically whereas the ridge at the North site formed asymmetrically.

Symmetric extension ridges form due to the flow from troughs on both sides of a bar moving along the lee of the slip face until they meet. When the two flows meet the resultant flow vector is usually downstream into a deeper part of the channel. The flow expansion downstream of the slip face results in the deposition of the sediment carried by the flow (Figure 6.2a). Asymmetric extension ridges form by the flow and sediment load carried in a trough on one side of a the bar. Commonly the opposite flank of the bar is bounded by a bank. When the flow in the trough reaches the front of the bar it expands and/or separation eddies which may be present along the slip face of the bar die out, depositing the sediment carried by the flow. The deposited sediment forms into a submerged ridge which is attached to the downstream edge of the bar (Figure 6.2b).

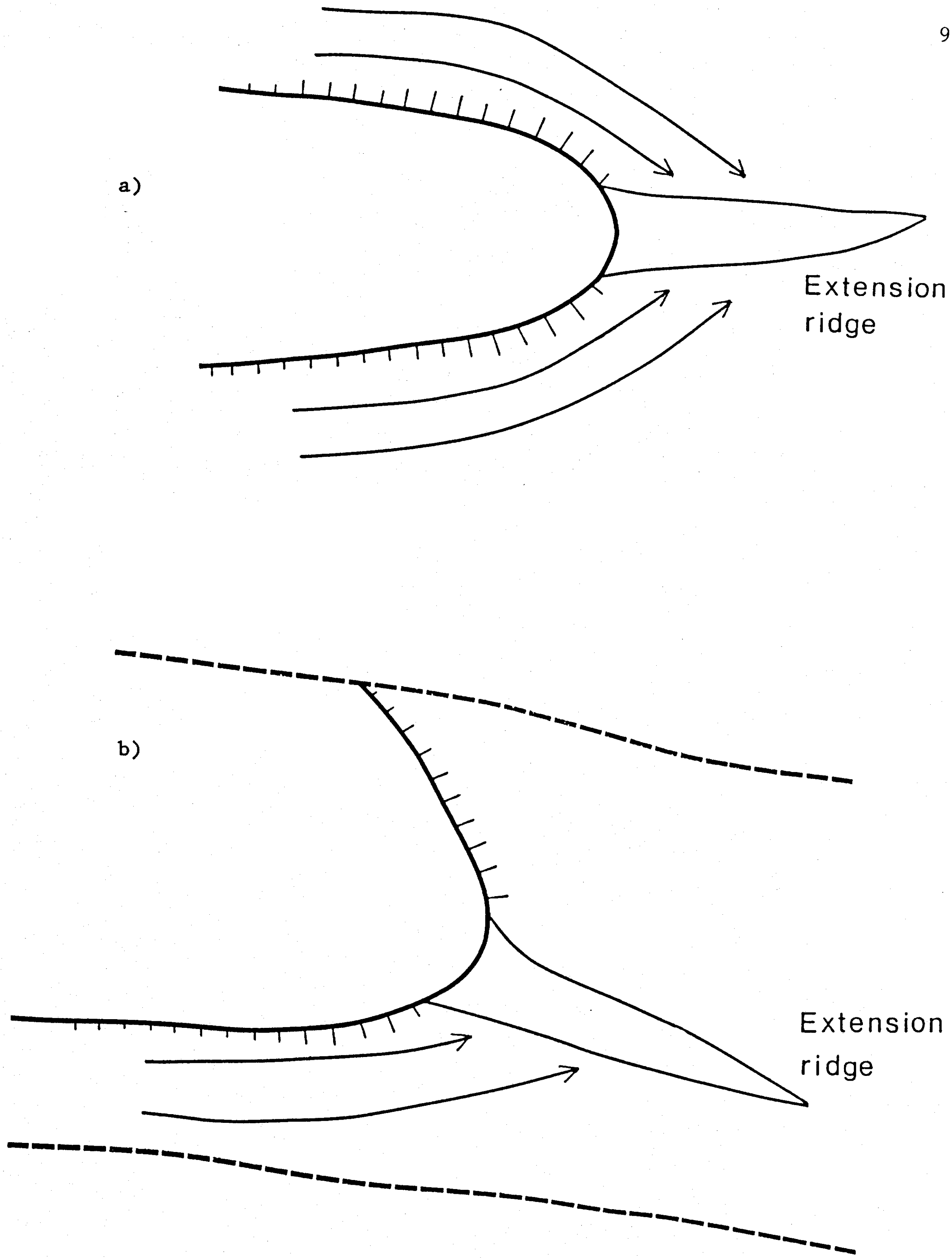


Figure 6.2: Diagrammatic simplification of the development of an extension ridge. a) Symmetric development of an extension ridge; b) Asymmetric development of an extension ridge.

6.2.2 Channel topography

Channel topography is an important factor in the development of the bars in the South Saskatchewan River. The channel topography influences the development of a bar in several ways. The first involves the cross-sectional basin depth distribution (Smith, 1971), a second involves abrupt changes in channel bed topography (Cant, 1978) and the third involves gradual changes in the longitudinal profile of the bed.

Bars commonly show more rapid migration of the margin closer to the bank. This is the result of the cross-sectional basin depth distribution in the channel. The sediment supplied to the outside edge of the bar (i.e., the bar edge closest to the thalweg) is used to shoal the channel bed and maintain the slip face, reducing the rate of migration along the edge. The inside margin of the bar (i.e., the bar edge closest to the bank) is in shallow water and does not require channel shoaling downstream of the slip face and can therefore migrate downstream at a rate higher than the outside edge. Variable migration rates caused by the basin depth distribution can result in changes to the symmetry of the bar morphology.

Modification of bar I at the downstream section of the South site resulted in it changing from a transverse bar to a side bar (Collinson, 1970; Miall, 1977) (Figure 5.19). Very little information is available on the development of side bars but Collinson (1970) considered the side bars in the Tana River to be made up of a complex of linguoid bars attached to the channel side. Features similar to side bars have also been identified in the South Saskatchewan River (Cant, 1976). The morphology of bar I at the North site also tended towards that of a side bar (Figure 5.24). The changes to the morphologies of the bars from one descriptive bar type to another, without major changes to the size or shape of the bar coincides with the concept of bedform continuums (Ashley, 1990). The development of bar I in the downstream section of the South site and, to a lesser extent, bar I at the North site, provides new insight into the evolution of large scale bedforms such as transverse and side bars.

A channel trough can modify the effects of the basin depth distribution by reducing the amount of sediment supplied to the downstream inside margin. Depending on the extent of the basin depth distribution and the sediment supply, the downstream inside edge may still progress downstream but at a rate comparable to that of the outside edge. This can produce a bar with a symmetric morphology yet an asymmetric hydrodynamic character. An example is that of bar I in the downstream section of the South site June 1, 1988 (Figure 5.14). If sediment supplied to the inside margin is not enough to maintain the slip face it may extend forward and blend into the channel bed.

Abrupt changes in the channel topography result in a vertical flow expansion depositing sediment in a delta-like manner (Cant, 1978). Flow and sediment from a secondary channel construct a delta-like bar into the main channel, similar to the tributary bar discussed by Krigstöm (1962). The initial development of bar I at the North site is an example of this process (Figures 5.7 and 5.21).

An increase in flow depth, which is due to a gradual decrease in the channel bed elevation results in the slip face of the bar extending forward and tapering into the channel bed. This was particularly evident for the downstream bars at the South site. It is difficult to separate the individual processes associated with the migration of a bar into a deeper part of the channel, due to the influence of the channel trough on bar development. Although the bars extend forward and blend into the channel bed, the net result is aggradation of the channel.

Decreases in flow depth due to increases in the bed elevation, such as those associated with extension ridges, also affect the development of the bars. The extension ridges extending downstream from the slip face of a bar, create an artificially raised bed. The localized increase in bed elevation allows for a more rapid migration of the bar. The increases in the rates of bar migration occurred at both locations where extension ridges were identified (Table 5.4 and 5.6).

6.2.3 Lateral flow expansion

Lateral flow expansion over the surface of an enlarging bar (Smith, 1971), and around the end of a sand flat (Cant, 1978) also affect bar morphology. An example is bar I at the North site. Flow from the mouth of the secondary channel spread out over the surface of the bar and reduced the rate of sediment transport over the bar (Figure 5.23). The reduced rate of sediment transport caused some of the sediment to be deposited upstream of the avalanche face. Flow expansion, therefore, encourages the deposition of sediment and the development of flow division over the surface of the bar. These processes of flow expansion are similar to processes described by Smith (1971) for the Lower Platte River.

Flow expansion also occurred as bar I at the North site moved around the end of the sand flat complex. The lateral flow expansion due to the bar extending around the end of the sand flat occurred for only a short period and was similar to the processes described by Cant (1978). Once established in the deeper channel, bar I began to migrate downstream.

6.2.4 Cutbank erosion/sediment supply

The development (i.e., disintegration) of the second bars (i.e., bar II) at the upstream section of the South site and the North site were associated with cutbank erosion. Initially the flow from the surface of the bars was directed toward the sand flat, initiating bank erosion. Cutbank erosion on the sand flats adjacent to the bars provided a source of sediment to downstream bedforms and locally increased the channel width. The continued development of cutbanks changed the channel morphology and affected the local flow conditions. These changes altered the spatial pattern of flow and sediment transport on the bar surface and therefore influenced the development of the bar.

Increases in the channel width have often been observed with bar development and have often been considered a result of bar development (Leopold and Wolman, 1957; Miall, 1977; Bridge, 1984). Carson (1984b), however, suggests that channel aggradation particularly the channel thalweg, causes the flow to locally spill onto the floodplain. Since the sand flats are often raised features, the lateral expansion of the flow results in active erosion of a cutbank. This, therefore, suggests that as long as the channel is aggrading, cutbank erosion and the subsequent widening of the channel can occur regardless of bar development.

The destruction as well as the construction of bars can be associated with cutbank erosion. At the South site the concave plan form of the cutbank resulted in some of the flow and the sediment load being deflected across the surface of the bar toward the thalweg (Figure 5.20). This reduced the sediment supply to the downstream edge of the bar. As the concave shape of the cutbank progressed downstream the flow was deflected across the diminished downstream edge of the bar completely removing any traces of a slip face. At the North site, once the cutbank developed an extreme concave plan form, flow in the channel was directed away from the bar. Since the channel was aggrading as cutbank erosion continued, bar II remained relatively stationary. Once the channel width had reached a maximum and the cutbank had progressed to the end of the sand flat complex, cutbank erosion decreased. Bar II began to migrate forward diminishing into the channel bed because the sediment supply was insufficient to maintain the slip face of the bar. Eventually a plane bed was established in the shallow secondary channel with only the newly exposed area of the bar as evidence of there being a bar (Figure 5.26).

The development of bars adjacent to active cutbanks will be affected as the cutbank progresses downstream. The shape of the cutbank will locally alter the flow in the channel, affecting the spatial patterns of flow and sediment transport on the surface of the bar. These changes will affect the morphology of the bar.

6.3 Modification of Sand Flats

Newly exposed sand flats occurred at both sites, but only the bars at the North site were monitored. The new sand flat developments resulted from a decrease in stage, as has been suggested by other researchers

(Allen, 1968; Collinson, 1970; Smith, 1971; Jackson, 1976; Cant and Walker, 1978). The change in stage affecting the exposure of a bar surface was a result of changes in the morphology of the channel and the bars, and possibly due to diurnal fluctuations in discharge. Maximum variations in the mean daily discharge ranged between 35 m^3s^{-1} and 65 m^3s^{-1}, causing small fluctuations in the stage (Figure 5.1).

Since sand flat exposure was monitored at only one site, generalizing the processes involved is difficult. Some observations, however, are comparable to processes described in the literature for sand flat exposure. A discussion of the observations and data collected, relative to the exposure of sand flats, are discussed for each site. Comparisons are made with processes previously identified in the literature.

6.3.1 North site

The development of bar I, which has already been described, was controlled by both lateral and vertical flow expansion. The migration of the bar into the larger channel allowed the surface area of the bar to expand. The flow and sediment load from the mouth of the shallow secondary channel spread out over the surface. As near-bed velocities diminished toward the edges of the bar sediment was deposited. As the bar continued to migrate around the end of the sand flat, a greater portion of the flow was directed toward the trough between the bar and the island, and became concentrated into a shallow sluice. This resulted in a local lowering of the water surface elevation, allowing the sediment, which was built up along the downstream edge of the bar adjacent to the sand flat, to become exposed. This process is similar to the bar dissection and channelization described by Smith (1971) and Hunt (1979).

The newly deposited portion of the sand flat extended out from the end of the major sand flat complex into the deeper secondary channel (Figure 5.24). Further development of this side flat occurred by the lateral accretion of sediment similar to point bar formation in meandering rivers (Jackson, 1976; Bridge and Jarvis, 1977). The morphology of this new sand flat was analogous to the side flat morphology described by Cant and Walker (1978). The side flat formation described by Cant and Walker (1978) occurred in a bend in a channel, whereas the formation of this side flat occurs both at a bend and at the mouth of a secondary channel. Although Cant and Walker (1978) describe the formative processes of a bar at the mouth of a secondary channel, no reference was made to the development of side flats.

Mid-bar front exposures were also observed on bar I (Figures 5.21 and 5.23). These features did not resemble the sand flat 'nuclei' described by Cant and Walker (1978), suggesting that the processes leading to their exposure differed from those described for a sand flat 'nucleus'. The exposure of the sand flat "nuclei" described by Cant and Walker (1978) is partly due to flow separation around an inactive area. There was no evidence suggesting that these mid-channel exposures were the result of flow separation. In fact, many of the small channels between the exposures had no measurable flow (Figure 5.23). These small exposed features were usually reactivated by small daily fluctuations in discharge. As the sluice across the surface of the bar continued to develop, the entire bar front, including the mid-channel exposures, became part of the sand flat complex (Figure 5.26). This suggests that their exposure was a function of the micro-relief along the inactive bar edge as the local water levels decreased. The diurnal fluctuations in discharge also caused some exposure of the bar surface in the morning and then inundation of the area by late afternoon. Jones (1977) has suggested that slow variations in discharge can have an effect on the morphology of bars. The extent to which these slow diurnal variations in flow affect the exposure of bars and the development of sand flats is unknown.

Sediment supply to bar I was also important to the exposure of the side flat. The increased sediment provided by cutbank erosion, which occurred in the shallow secondary channel, aided by flow expansion at the end of the sand flat, resulted in a rapid build up of material along the lee of the sand flat complex. When the cutbank erosion had extended to the end of the sand flat complex and stopped the rate of sand flat exposure decreased.

Part of bar II at the North site was also exposed. The exposure of this bar was not a function of flow expansion on the bar's surface (Smith, 1971), but rather to the lateral shift in the channel and the initial degradation of the channel bed. As the flow in the main channel moved toward the sand flat complex, the cutbank began to erode. The curved shape of the cutbank resembled the outside of a meander bend. When the erosion began, the channel along the cutbank was also being scoured in a manner similar to that observed in meander bends. The degradation and shifting of the channel caused the bar to migrate laterally. The local water surface elevation was also lowered, resulting in the exposure of the right side of the bar (Figure 5.24).

Further erosion of the cutbank resulted in a concave plan form which caused the flow to be directed away from the bar and into the cutbank. The channel began to widen and aggrade thus reducing the rate of development of the bar and the new sand flat. The widening and aggradation of the channel, coupled with a decrease in sediment supply over the surface of the bar, resulted in bar disintegration.

6.3.2 South site

It has been suggested that in some circumstances channel shoaling is a necessary precursor to braiding (Carson, 1984b). Carson (1984b) observed that shoaling of rivers in New Zealand resulted in the flow spreading out onto the floodplain and eventually creating a large plane bed. He further suggested that the large exposed bars in these rivers are merely exposed tracts of the flat bed. Flows are then concentrated on either side of these exposed areas resulting in a dissection of the channel bed.

General net aggradation of the channel topography occurred at both sites (Figures 5.3 - 5.10). The results indicate that the channel trough is the final portion of the channel to aggrade. Since channel shoaling of the trough was not complete before the end of the study period, the initiation of sand flats based on channel shoaling (Carson, 1984b) could not be monitored. Areas of the channel upstream of the South study site, which were completely shoaled, had exposed areas similar to those described by Carson (1984b & c) (Photograph 6.1). The increase in channel width associated with the shoaling of the thalweg was accomplished by erosion of cutbanks on the sand flat complexes. Photograph 6.2 shows an

Photograph 6.1: Sand flat formation in an aggraded channel.

Photograph 6.2: Cutbank erosion adjacent thalweg shoaling, South site (upstream).

example of thalweg shoaling which occurred in the upstream section of the South site. Progression of the cutbank downstream, at this site, coincided with the upstream shoaling of the trough.

The cutbank erosion generated sediment which was supplied to the channel thalweg and also created newly exposed sand flats at the end of the cutbank (Photographs 5.2, 6.1 and 6.2). The cutbank formed a concave shape as it progressed downstream along the sand flat complex. Once the cutbank reached a maximum, the flow at the end of the cutbank expanded into the channel, causing the sediment to be deposited. The deposition of the material results in the formation of a side flat extending out from the end of the cutbank.

6.3.3 Summary of sand flat modification

Based on information obtained in this study and from the literature a couple of factors influencing the exposure of new sand flats were identified. The first involves channelization (i.e., formation of a sluice) on the surface of the bar. This has the effect of locally lowering the water surface elevation, causing elevated areas of the bar surface to become exposed. The second factor involves channel widening, which appears to be associated with channel shoaling and cutbank erosion. The increase in the channel width reduces the flow depth resulting in the exposure of elevated sections of the bed.

7 CONCLUSIONS

Channel troughs, channel topography and channel morphology are important factors influencing the development of bars and sand flats in the sandy, braided, South Saskatchewan River. These factors influence the spatial patterns of flow direction, flow depth, near-bed velocity and bedload transport on the surface of the bars, resulting in either a change in the bar morphology, exposure of portions of the bar surface, or the development of a plane bed. Quantitative descriptions of these processes were synthesized from data collected on the channel topography, channel morphology, bar morphology and the hydrodynamic character of the bar surfaces.

The bars identified in this study were solitary features which usually extended part way across the channel from one bank. There were a variety of shapes and sizes, but the bars were generally lobate with a slip face which varied in height between 1cm and 1m. The variability of slip face height occurred between bars as well as on individual bars. The flow over the surface of the bars was primarily oblique to the direction of the channel, resulting in sediment being transported laterally over most of the bar surface. The highest near-bed velocities and bedload transport usually occurred toward the centre of the bar, but were not always associated with each other. The variability of the hydrodynamics on the surface of the bar was influenced by the topography and morphology within the channel.

The channel trough and its flow draws water from the surface of the bar creating an asymmetric spatial pattern of the hydraulic parameters on the surface of the bar. The asymmetric conditions cause a decrease in flow and sediment to the downstream edge of the bar, causing the morphology of the bar to change. The flow in the channel trough relative to the flow over the bar's surface can affect the development of the bar's edge. A conceptual model describing these processes has been provided. The flow in channel troughs is also instrumental in the development of extension ridges on the downstream edge of bars. Extension ridges can be formed either symmetrically or asymmetrically. These ridges locally alter the channel topography, and some cases resulted in accelerated bar migration. Small troughs on the surface of the bars (i.e., a sluice) form as a result of flow concentration. These sluices were instrumental in exposing portions of a bar's surface.

Cross-sectional basin depth distribution, abrupt changes in channel topography and gradual changes in the longitudinal channel topography affect the development of bars and sand flats. Observations and data collected confirmed previous research suggesting that the basin depth distribution (Smith, 1971) and abrupt changes in channel topography (Cant, 1978) affect bar development. The influence on bar development by gradual changes in the channel topography could not be considered independently due to the influence of other factors such as the channel trough.

The data collected suggest that the development of the bars would initiate changes to the channel morphology. Changes in the channel morphology cause the flow in the channel to adjust, resulting in a change in the spatial pattern of flow and sediment transport on bar surfaces. The aggradation of the channel troughs also causes the channel morphology to change by forcing the flow to spill onto the sand flats. Elevated sand flats had cutbanks form in response to the channel infilling and bar migration. Newly exposed sand flats were observed in locations where the channel had completely aggraded and the channel width increased. This provides evidence to support the suggestion that channel shoaling precedes exposure of braid bars (Carson, 1984b).

The results of this study have provided a better understanding of the braiding processes in a sand-bed river. This study provides quantitative descriptions of bar and sand flat development, and identifies some of the influential factors affecting their development. This thesis has determined that the channel morphology, channel topography, and especially the channel trough influence both bar and sand flat development, and are, therefore, instrumental in the development of a braided pattern in a sand-bed river.

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APPENDIX A

Downstream section at the South site

Downstream section at the South site

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/m/s) (*10^{-4})	D_{50} (mm)
June 1, 1988							
233.210	26.690	97.940	0.190	0.250	0.410	3.353	-99.990
240.080	28.840	97.870	0.270	0.280	0.670	2.313	-99.990
239.660	32.370	97.900	0.310	0.340	0.510	13.020	0.480
240.150	37.570	97.780	0.310	0.440	0.520	2.756	-99.990
239.980	39.490	97.790	0.340	0.330	0.490	0.007	0.480
232.390	30.470	97.840	0.260	0.470	0.580	5.154	-99.990
233.340	35.470	97.820	0.340	0.340	0.500	30.954	0.400
229.420	41.550	97.830	0.320	0.430	0.510	2.109	-99.990
228.130	36.880	97.770	0.400	0.210	0.530	34.593	0.430
226.570	32.290	97.840	0.350	0.360	0.620	7.503	-99.990
224.340	26.060	97.980	0.160	0.260	0.350	0.000	-99.990
216.340	26.840	98.000	0.160	0.290	0.420	1.435	-99.990
217.070	32.660	97.640	0.500	0.170	0.520	48.366	0.490
217.450	40.070	97.820	0.340	0.360	0.420	1.163	-99.990
217.610	46.340	97.760	0.380	0.110	0.300	2.565	-99.990
208.760	46.930	97.850	0.300	0.210	0.260	2.213	-99.990
209.120	39.890	97.880	0.240	0.260	0.400	1.675	-99.990
204.600	33.920	97.760	0.380	0.400	0.470	53.068	0.390
205.210	28.460	97.700	0.480	0.320	0.570	80.925	0.590
199.520	26.050	97.780	0.380	0.370	0.600	15.632	0.470
199.120	34.930	97.840	0.340	0.340	0.440	35.359	0.410
195.480	48.450	97.970	0.200	0.210	0.440	40.525	0.470
197.770	51.080	97.980	0.220	0.390	0.550	7.796	-99.990
199.890	57.040	97.940	0.220	0.240	0.410	1.486	-99.990
202.840	62.370	97.890	0.250	0.310	0.400	7.056	-99.990
197.590	63.260	97.840	0.300	0.200	0.340	2.811	-99.990
196.390	62.030	97.890	0.270	0.240	0.290	4.635	-99.990
June 7, 1988							
252.300	27.150	97.790	0.230	0.270	0.470	21.228	0.480
253.600	26.830	97.800	0.240	0.280	0.540	0.000	-99.990
253.300	31.400	97.840	0.180	0.250	0.410	2.234	-99.990
240.400	32.160	97.740	0.320	0.160	0.450	6.895	-99.990
248.000	32.060	97.840	0.240	0.190	0.390	0.039	0.520
246.130	26.690	97.780	0.280	0.290	0.430	3.640	-99.990
236.980	28.200	97.800	0.280	0.380	0.580	15.365	1.500
235.610	34.420	97.690	0.380	0.260	0.560	37.748	0.540
235.100	44.090	97.820	0.180	0.420	0.540	95.213	0.450
234.660	40.710	97.840	0.200	0.280	0.450	6.116	-99.990
216.670	59.980	97.880	0.240	0.170	0.290	3.378	0.520
216.590	42.990	97.800	0.370	0.190	0.310	74.375	0.510
216.360	30.220	97.660	0.450	0.330	0.700	39.200	0.540
196.220	26.600	97.780	0.370	0.440	0.620	35.110	0.800
196.150	36.020	97.660	0.470	0.200	0.560	78.619	-99.990
196.220	51.750	97.880	0.240	0.130	0.210	0.000	-99.990
197.120	66.220	97.930	0.160	0.170	0.230	11.976	0.430

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/m/s) ($*10^{-4}$)	D_{50} (mm)
181.190	79.540	97.870	0.260	0.310	0.510	19.591	0.290
182.510	74.160	98.040	0.080	0.240	0.270	2.264	-99.990
182.470	58.910	97.960	0.160	0.230	0.330	1.772	-99.990
190.810	42.400	97.940	0.180	0.220	0.380	1.919	-99.990
177.950	48.580	97.950	0.160	0.280	0.450	1.163	-99.990
177.820	50.960	97.910	0.130	0.300	0.410	32.925	0.400
171.750	70.190	97.940	0.200	0.330	0.490	42.816	0.390
172.280	84.520	97.830	0.280	0.310	0.530	0.066	0.430
150.520	87.990	97.840	0.290	0.190	0.350	26.463	0.550
151.260	76.620	97.800	0.350	0.280	0.500	32.314	0.440
152.300	57.390	97.900	0.260	0.350	0.500	24.815	0.390
153.920	42.850	97.940	0.240	0.270	0.460	16.551	0.320
June 13,	1988						
275.460	28.910	97.740	0.270	0.210	0.420	17.850	-99.990
273.070	31.630	97.820	0.200	0.290	0.460	1.569	-99.990
272.660	27.730	97.780	0.260	0.310	0.480	7.179	-99.990
267.540	27.500	97.800	0.230	0.300	0.500	0.000	-99.990
267.130	30.480	97.880	0.210	0.250	0.470	21.787	1.300
267.510	33.830	97.850	0.210	0.250	0.410	5.413	0.380
260.350	43.650	97.860	0.210	0.250	0.450	16.220	0.400
256.950	37.580	97.800	0.300	0.230	0.440	38.369	0.700
259.550	33.440	97.850	0.220	0.360	0.510	3.255	-99.990
258.660	27.450	97.850	0.240	0.340	0.510	53.983	0.520
246.380	28.600	97.870	0.210	0.410	0.500	7.088	-99.990
246.710	37.120	97.840	0.260	0.400	0.510	0.098	0.400
246.430	44.080	97.860	0.220	0.360	0.540	0.067	0.480
247.310	55.330	97.840	0.280	0.110	0.500	8.807	-99.990
224.590	61.410	97.860	0.260	0.140	0.270	10.786	0.430
220.940	47.300	97.840	0.280	0.190	0.370	53.251	0.430
222.050	44.120	97.750	0.400	0.140	0.560	115.264	0.470
214.950	25.890	97.620	0.540	0.120	0.590	54.815	0.400
220.610	29.420	97.770	0.390	0.400	0.660	65.977	1.500
191.220	91.890	97.850	0.290	0.110	0.510	0.091	0.430
191.200	76.260	97.910	0.250	0.410	0.630	0.086	0.470
191.520	68.620	98.000	0.170	0.170	0.480	7.536	-99.990
194.720	53.950	97.920	0.160	0.140	0.450	0.084	0.430
176.400	62.480	98.020	0.190	0.340	0.520	0.053	0.450
177.970	71.180	97.930	0.260	0.350	0.530	12.818	-99.990
179.960	78.540	97.860	0.330	0.350	0.580	0.060	0.490
181.560	86.010	97.770	0.420	0.250	0.560	32.188	0.430
164.920	82.990	97.760	0.380	0.210	0.390	5.308	-99.990
162.440	68.820	97.830	0.350	0.290	0.490	3.355	-99.990
June 21,	1988						
289.140	29.890	97.760	0.320	0.310	0.540	3.434	-99.990
281.630	34.410	97.890	0.200	0.210	0.450	31.697	-99.990
282.180	18.870	97.810	0.300	0.320	0.570	2.716	-99.990
275.560	28.500	97.820	0.290	0.290	0.560	15.942	-99.990
275.100	34.970	97.870	0.280	0.130	0.590	11.047	-99.990

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/m/s) (*10^{-4})	D_{50} (mm)
275.930	40.910	97.820	0.260	0.230	0.550	1.824	-99.990
276.630	46.380	97.860	0.230	0.170	0.520	8.125	-99.990
264.410	54.440	97.860	0.240	0.270	0.550	13.751	-99.990
261.010	45.400	97.850	0.290	0.260	0.520	7.576	-99.990
258.590	37.700	97.780	0.280	0.180	0.410	14.494	-99.990
255.980	28.990	97.860	0.240	0.390	0.570	44.345	0.400
234.480	27.490	97.820	0.310	0.230	0.400	0.000	-99.990
236.180	35.300	97.690	0.500	0.370	0.640	100.455	0.470
236.370	40.930	97.770	0.370	0.340	0.550	6.477	0.400
238.960	48.680	97.860	0.310	0.270	0.550	22.619	0.380
241.200	59.560	97.880	0.280	0.030	0.320	1.397	-99.990
209.030	82.460	97.880	0.260	0.180	0.390	76.852	0.380
209.710	76.920	97.880	0.280	0.490	0.660	54.302	0.300
208.590	69.960	97.900	0.290	0.180	0.490	0.059	0.400
205.560	63.990	98.000	0.200	0.180	0.480	48.541	0.310
191.670	63.480	97.960	0.280	0.320	0.490	62.235	0.370
195.110	72.470	97.800	0.370	0.180	0.580	25.685	0.300
199.380	79.640	97.860	0.300	0.500	0.610	15.325	0.260
202.850	88.410	97.760	0.440	0.280	0.650	30.616	0.340
186.690	87.510	97.720	0.540	0.140	0.720	115.421	0.320
180.290	73.280	97.780	0.390	0.290	0.520	9.576	-99.990
176.680	63.790	97.840	0.340	0.370	0.670	0.113	0.440
June 27,1988							
301.750	30.820	97.700	0.320	0.320	0.450	2.470	-99.990
294.120	34.570	97.820	0.220	0.320	0.510	13.147	-99.990
291.870	29.190	97.720	0.350	0.240	0.560	27.693	-99.990
287.090	29.840	97.740	0.360	0.340	0.560	5.220	-99.990
286.940	35.880	97.850	0.200	0.400	0.570	1.654	-99.990
286.700	41.050	97.880	0.170	0.480	0.600	6.860	-99.990
286.820	47.170	97.880	0.180	0.160	0.510	23.021	-99.990
273.490	55.530	97.820	0.260	0.100	0.420	14.622	-99.990
271.920	45.500	97.840	0.240	0.300	0.460	13.611	-99.990
269.830	37.380	97.860	0.270	0.280	0.500	63.066	0.780
270.240	28.940	98.480	0.240	0.200	0.510	3.277	-99.990
244.800	31.670	97.850	0.290	0.460	0.700	64.238	0.980
245.330	41.670	97.720	0.480	0.210	0.570	243.162	0.530
246.630	51.870	97.840	0.280	0.220	0.460	21.302	0.420
247.090	60.120	97.880	0.210	0.090	0.180	12.894	0.410
249.850	83.110	97.640	0.500	0.280	0.520	165.222	0.350
241.560	76.980	97.680	0.470	0.150	0.600	39.520	0.300
243.290	82.720	97.660	0.460	0.450	0.640	103.806	0.350
243.970	87.400	97.460	0.680	0.240	0.510	85.490	0.310
230.800	96.660	97.500	0.690	0.400	0.600	88.554	0.370
228.970	86.260	97.610	0.560	0.580	0.680	87.557	0.350
226.680	63.360	97.850	0.310	0.300	0.380	397.500	0.450
224.890	68.160	97.860	0.280	0.340	0.640	299.139	0.450
223.500	62.310	97.980	0.190	0.440	0.580	147.906	0.420

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/m/s) (*10^{-4})	D_{50} (mm)
202.450	61.840	97.910	0.260	0.240	0.460	71.669	0.480
203.480	70.920	97.860	0.330	0.420	0.640	18.576	0.320
205.230	82.490	97.620	0.590	0.200	0.520	36.593	0.400
206.260	93.000	97.650	0.640	0.460	0.660	81.041	0.430
207.300	102.000	97.580	0.640	0.440	0.630	91.587	0.310
July 6, 1988							
313.840	34.060	97.730	0.390	0.100	0.400	16.630	0.240
305.660	31.680	97.700	0.420	0.260	0.540	12.543	-99.990
306.240	35.700	97.740	0.390	0.180	0.440	20.221	0.350
305.220	39.370	97.780	0.320	0.480	0.680	197.544	0.460
307.540	43.640	97.760	0.280	0.340	0.520	23.721	0.380
308.070	48.140	97.680	0.460	0.220	0.440	147.170	0.400
295.800	53.880	97.620	0.460	0.150	0.500	22.125	0.330
294.790	45.070	97.820	0.320	0.390	0.580	51.231	0.380
294.690	39.090	97.790	0.360	0.260	0.600	114.170	0.450
294.440	31.380	97.780	0.380	0.260	0.570	4.554	-99.990
271.410	30.260	97.890	0.260	0.270	0.510	21.285	0.280
271.520	39.740	97.700	0.450	0.210	0.510	15.781	0.260
271.800	47.900	97.750	0.420	0.180	0.560	77.455	0.390
272.710	57.520	97.820	0.340	0.140	0.280	9.144	-99.990
288.290	75.840	97.800	0.410	0.360	0.660	37.490	0.290
282.570	84.540	97.760	0.470	0.380	0.620	94.058	0.310
280.810	76.910	97.740	0.440	0.450	0.570	143.137	0.400
280.040	71.710	97.680	0.580	0.180	0.520	22.006	0.290
268.180	72.770	97.740	0.500	0.260	0.540	21.547	0.340
270.680	83.400	97.760	0.480	0.440	0.660	48.326	0.290
272.500	91.020	97.660	0.570	0.300	0.540	48.304	0.280
256.740	98.200	97.600	0.580	0.450	0.570	111.703	0.320
256.660	89.500	97.700	0.530	0.340	0.480	332.115	0.390
255.960	79.130	97.600	0.620	0.450	0.680	73.141	0.320
254.960	69.840	97.830	0.430	0.420	0.580	53.532	0.390
252.130	63.740	97.720	0.470	0.160	0.740	34.427	0.320
250.490	56.490	98.020	0.230	0.360	0.480	-99.990	-99.990
252.330	45.550	97.800	0.440	0.090	0.480	-99.990	-99.990
July 19,1988							
331.290	33.580	97.840	0.320	0.340	0.500	29.243	0.400
325.040	38.850	97.860	0.340	0.280	0.560	48.064	0.630
325.390	32.510	97.940	0.260	0.280	0.600	9.848	-99.990
319.690	30.300	97.810	0.300	0.300	0.620	8.103	-99.990
320.440	36.580	97.890	0.240	0.420	0.600	16.494	0.400
317.180	42.300	97.750	0.390	0.420	0.540	74.306	0.490
321.170	47.040	97.820	0.300	0.380	0.480	22.422	0.400
306.890	53.720	97.750	0.380	0.180	0.520	45.089	0.400
306.450	43.770	97.800	0.310	0.270	0.540	14.267	-99.990
304.210	35.570	98.030	0.130	0.420	0.620	114.308	0.540
306.250	28.790	97.790	0.390	0.330	0.620	39.279	0.450
285.270	28.860	97.760	0.420	0.330	0.620	22.076	0.800

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/m/s) (*10⁻⁴)	D_{50} (mm)
285.960	40.180	97.860	0.360	0.400	0.580	24.115	0.460
286.340	56.720	97.830	0.360	0.140	0.330	7.245	-99.990
354.240	51.670	97.500	0.560	0.240	0.480	22.050	0.320
353.030	55.730	97.590	0.440	0.270	0.580	54.434	0.400
345.870	61.280	97.620	0.410	0.320	0.540	5.747	-99.990
343.800	56.610	97.540	0.520	0.330	0.510	12.938	-99.990
343.290	51.690	97.560	0.540	0.150	0.520	20.891	0.360
326.510	48.380	97.560	0.510	0.200	0.400	3.917	-99.990
328.060	54.640	97.440	0.620	0.200	0.570	24.588	0.390
330.430	62.260	97.560	0.540	0.120	0.600	5.791	-99.990
333.040	69.900	97.720	0.330	0.200	0.460	8.502	-99.990
312.170	84.000	97.630	0.460	0.200	0.500	4.817	-99.990
309.680	75.100	97.680	0.380	0.240	0.480	21.914	0.300
308.620	67.110	97.520	0.570	0.120	0.480	8.610	-99.990
July 27, 1988							
342.460	36.430	97.770	0.300	0.180	0.360	3.571	-99.990
337.340	38.930	97.700	0.280	0.220	0.380	4.179	-99.990
336.770	34.220	97.860	0.250	0.300	0.440	10.640	-99.990
329.410	32.780	97.840	0.240	0.380	0.540	12.381	-99.990
330.480	39.760	97.800	0.300	0.180	0.400	12.626	-99.990
331.270	44.680	97.770	0.340	0.100	0.500	22.387	0.400
320.440	52.180	97.870	0.240	0.260	0.450	27.020	0.450
318.460	43.980	97.860	0.260	0.240	0.450	11.874	-99.990
319.180	37.570	97.910	0.190	0.380	0.520	44.770	0.380
318.710	30.120	97.840	0.290	0.330	0.520	27.563	0.480
295.940	29.280	97.770	0.370	0.180	0.580	20.833	0.480
295.940	40.510	97.860	0.230	0.340	0.500	38.089	0.530
296.660	50.900	97.840	0.220	0.140	0.460	4.532	-99.990
297.140	57.890	97.860	0.260	0.120	0.450	11.603	-99.990
August 8, 1988							
356.360	38.230	97.810	0.310	0.330	0.480	4.331	-99.990
351.120	36.370	97.800	0.270	0.300	0.520	4.720	-99.990
348.960	41.930	97.730	0.400	0.150	0.480	8.995	-99.990
337.450	44.800	97.720	0.340	0.150	0.560	13.265	-99.990
344.010	41.160	97.780	0.320	0.320	0.630	59.938	0.400
341.860	34.190	97.740	0.340	0.220	0.460	3.260	-99.990
333.270	33.880	97.740	0.360	0.330	0.580	14.192	-99.990
335.600	41.990	97.800	0.260	0.390	0.570	4.916	-99.990
333.820	51.780	97.880	0.200	0.400	0.510	0.598	-99.990
312.260	57.640	97.880	0.200	0.120	0.240	1.487	-99.990
311.500	47.520	97.880	0.260	0.390	0.560	6.148	-99.990
311.040	39.060	97.820	0.340	0.450	0.580	91.372	0.380
310.990	30.590	97.750	0.360	0.320	0.520	14.472	-99.990
292.410	29.050	97.760	0.380	0.340	0.520	2.016	-99.990
292.250	38.940	97.740	0.400	0.400	0.690	4.929	-99.990
292.580	48.990	97.900	0.240	0.300	0.450	1.987	-99.990
292.540	60.950	97.870	0.280	0.180	0.510	15.300	0.360

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/m/s) (*10^{-4})	D_{50} (mm)
292.360	66.900	97.820	0.310	0.210	0.450	13.793	-99.990
251.010	81.240	97.950	0.200	0.150	0.360	5.911	-99.990
251.990	63.860	97.900	0.260	0.300	0.510	9.256	0.390
253.240	46.000	97.780	0.360	0.380	0.560	5.199	-99.990
255.240	29.500	97.750	0.480	0.360	0.540	9.156	0.300

APPENDIX B

Upstream section at the South site

Upstream section at the South site.

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/s/m) (*10^{-4})	D50 (mm)
June 2, 1988							
86.680	89.020	97.280	0.120	0.190	0.440	16.671	0.200
89.530	95.420	97.960	0.200	0.300	0.390	19.007	0.220
89.870	99.090	97.950	0.200	0.260	0.430	11.595	0.200
88.580	124.130	97.940	0.220	0.400	0.560	23.620	0.220
89.780	97.020	97.940	0.200	0.460	0.520	44.856	0.260
77.600	86.150	98.010	0.130	0.480	0.520	12.395	0.200
56.100	75.840	97.860	0.330	0.320	0.520	55.572	0.250
56.140	84.860	97.800	0.410	0.320	0.530	21.872	0.340
54.430	93.950	97.860	0.370	0.170	0.320	4.743	-99.990
54.890	106.940	97.890	0.280	0.260	0.330	10.390	0.330
51.790	109.000	97.650	0.550	0.280	0.540	16.296	0.320
52.100	113.500	97.640	0.630	0.420	0.570	105.730	0.340
53.360	116.480	97.730	0.480	0.310	0.520	12.417	-99.990
51.500	119.000	97.720	0.500	0.190	0.490	16.253	0.300
43.750	104.930	97.780	0.420	0.100	0.280	5.919	-99.990
40.980	115.980	97.640	0.480	0.270	0.520	2.321	-99.990
38.950	105.680	97.780	0.430	0.180	0.410	7.694	0.350
36.780	91.180	98.000	0.200	0.260	0.330	3.774	-99.990
32.510	66.920	97.940	0.320	0.080	0.460	27.877	0.240
28.140	142.460	98.070	0.160	0.330	0.430	5.330	-99.990
28.080	147.520	97.940	0.260	0.330	0.510	133.385	0.300
21.140	152.810	97.810	0.390	0.210	0.540	16.616	0.430
18.900	146.670	97.880	0.220	0.250	0.480	18.931	0.230
17.600	136.540	98.010	0.170	0.370	0.480	7.762	-99.990
12.870	128.880	96.990	0.220	0.330	0.510	40.351	0.430
1.280	144.840	97.980	0.200	0.400	0.480	17.522	0.220
17.870	127.270	97.790	0.380	0.270	0.550	40.894	0.280
June 8, 1988							
93.140	95.380	97.960	0.160	0.120	0.220	1.014	-99.990
91.630	100.320	97.880	0.230	0.180	0.400	13.009	0.230
90.030	90.780	98.020	0.110	0.160	0.280	10.297	0.250
90.310	85.620	98.020	0.100	0.180	0.280	2.640	-99.990
78.520	84.240	98.040	0.120	0.180	0.290	9.065	0.240
80.150	93.200	97.960	0.190	0.070	0.460	41.906	0.280
81.480	99.620	97.850	0.270	0.310	0.520	62.743	0.270
82.680	105.020	97.750	0.330	0.240	0.590	14.684	0.240
66.360	107.880	97.920	0.240	0.110	0.300	13.700	0.250
65.320	102.470	97.860	0.290	0.200	0.390	8.461	0.410
63.940	94.080	97.830	0.330	0.160	0.490	16.795	0.340
61.860	82.260	97.870	0.310	0.220	0.520	5.095	-99.990
56.730	109.860	97.520	0.700	0.260	0.550	4.662	-99.990
57.040	115.850	97.640	0.580	0.160	0.430	36.359	0.260
48.780	119.970	97.700	0.450	0.060	0.270	1.819	-99.990
46.980	113.400	97.710	0.480	0.170	0.430	6.424	-99.990

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/s/m) $(*10^{-4})$	D50 (mm)
44.910	104.270	97.820	0.400	0.210	0.470	14.414	0.310
42.370	94.510	98.020	0.200	0.130	0.350	6.999	-99.990
37.780	74.560	97.940	0.280	0.160	0.340	3.337	-99.990
32.460	142.640	98.000	0.180	0.150	0.360	4.155	-99.990
30.000	148.340	97.920	0.280	0.170	0.380	39.065	-99.990
27.440	137.750	97.980	0.240	0.250	0.440	30.091	0.230
16.950	128.140	97.980	0.240	0.330	0.450	10.574	-99.990
21.910	132.010	97.990	0.230	0.250	0.490	41.860	0.220
23.610	143.110	98.020	0.210	0.270	0.460	41.322	0.260
26.080	151.740	97.860	0.350	0.230	0.400	3.395	-99.990
15.090	146.030	97.950	0.280	0.330	0.560	14.568	-99.990
11.540	142.090	97.980	0.260	0.100	0.470	21.766	0.210
9.050	134.460	98.020	0.220	0.170	0.430	9.799	0.200
June 14,1988							
105.960	93.870	97.900	0.230	0.250	0.490	19.223	0.210
101.750	97.040	97.860	0.290	0.350	0.570	52.728	0.260
100.940	92.290	97.850	0.280	0.220	0.490	48.037	0.220
95.690	85.520	98.020	0.100	0.190	0.220	2.619	-99.990
95.160	92.110	97.850	0.270	0.430	0.580	147.250	0.320
94.900	98.980	97.790	0.360	0.220	0.520	12.196	0.220
78.510	104.200	97.800	0.380	0.110	0.420	7.542	-99.990
78.460	100.050	97.820	0.330	0.150	0.400	8.049	-99.990
78.210	93.850	97.740	0.400	0.270	0.570	14.568	-99.990
77.650	84.540	97.960	0.160	0.100	0.320	4.993	-99.990
61.310	79.810	97.860	0.270	0.310	0.550	87.016	0.260
59.860	89.560	97.900	0.280	0.190	0.370	8.956	-99.990
59.130	97.170	97.920	0.240	0.050	0.250	0.000	-99.990
58.440	109.260	97.720	0.440	0.170	0.450	5.565	-99.990
44.220	148.810	97.790	0.440	0.280	0.530	54.547	-99.990
43.400	143.750	97.980	0.250	0.290	0.510	5.074	-99.990
39.460	138.940	98.070	0.170	0.440	0.510	66.499	0.260
36.330	133.570	97.990	0.230	0.270	0.490	19.749	0.220
32.880	127.530	97.950	0.280	0.270	0.520	28.267	0.220
26.760	126.400	98.000	0.220	0.180	0.430	10.701	0.230
28.990	131.430	97.980	0.240	0.390	0.530	17.333	0.210
32.410	130.500	98.020	0.200	0.340	0.450	146.998	0.360
31.670	151.110	97.930	0.290	0.170	0.550	53.029	0.270
22.970	156.750	97.880	0.400	0.220	0.640	29.978	0.270
20.790	148.130	97.990	0.280	0.260	0.530	30.546	0.270
19.220	141.080	97.980	0.240	0.310	0.500	23.249	0.220
18.370	133.640	98.020	0.220	0.260	0.520	11.506	-99.990
16.380	121.600	98.060	0.140	0.130	0.280	3.876	-99.990
June 22, 1988							
110.690	86.220	97.720	0.500	0.160	0.390	4.207	-99.990
104.020	84.310	97.930	0.240	0.150	0.270	0.000	-99.990
104.390	88.910	97.600	0.570	0.180	0.510	16.564	0.260
94.650	94.070	97.610	0.570	0.210	0.440	22.756	0.300
95.300	87.470	97.900	0.300	0.160	0.390	2.565	-99.990

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/s/m) ($*10^{-4}$)	D50 (mm)
95.450	81.580	99.060	0.120	0.140	0.220	0.795	-99.990
75.020	80.160	98.080	0.120	0.140	0.260	1.480	-99.990
78.220	89.110	97.890	0.310	0.220	0.400	0.000	-99.990
80.140	94.790	97.680	0.540	0.090	0.450	11.506	-99.990
82.140	100.450	97.730	0.450	0.090	0.340	6.356	-99.990
72.320	105.250	97.860	0.360	0.080	0.330	10.487	-99.990
63.640	102.200	97.950	0.230	0.160	0.320	2.988	-99.990
64.710	108.120	97.860	0.330	0.060	0.390	6.843	-99.990
54.280	112.960	97.780	0.420	0.150	0.400	5.088	-99.990
55.070	104.430	97.820	0.360	0.210	0.450	18.301	0.350
56.030	96.380	97.970	0.220	0.100	0.320	3.896	-99.990
57.230	82.770	97.700	0.480	0.180	0.420	9.472	-99.990
63.350	136.950	97.830	0.390	0.210	0.440	10.010	-99.990
58.540	144.320	97.810	0.440	0.180	0.500	25.117	0.270
56.900	131.380	98.020	0.220	0.330	0.450	12.740	-99.990
43.360	121.700	97.920	0.290	0.210	0.420	24.426	0.250
46.450	134.900	97.990	0.240	0.160	0.450	16.603	0.210
49.160	143.980	97.940	0.290	0.210	0.480	25.918	0.250
50.680	150.000	97.780	0.420	0.210	0.520	27.991	0.280
29.250	161.880	97.720	0.570	0.180	0.540	29.519	0.310
29.050	151.730	97.890	0.360	0.300	0.560	21.416	0.250
28.660	139.500	97.960	0.280	0.260	0.450	48.326	0.230
28.120	130.250	97.980	0.240	0.210	0.380	22.885	0.220
27.830	119.470	98.020	0.210	0.120	0.300	6.082	-99.990
June 28,	1988						
106.090	84.680	97.880	0.300	0.140	0.300	2.097	-99.990
99.460	91.420	97.690	0.480	0.150	0.450	16.451	0.330
98.130	82.260	97.980	0.190	0.140	0.200	0.458	-99.990
82.610	78.790	98.090	0.100	0.140	0.180	0.581	-99.990
84.670	89.890	97.870	0.310	0.200	0.360	15.569	0.250
86.270	98.410	97.610	0.590	0.070	0.340	5.714	-99.990
70.220	94.450	97.990	0.240	0.160	0.340	6.894	-99.990
65.700	108.980	97.840	0.400	0.210	0.420	7.479	-99.990
65.170	101.480	97.950	0.250	0.060	0.330	7.576	-99.990
56.210	99.880	97.920	0.260	0.090	0.300	25.045	0.220
56.940	108.350	97.780	0.420	0.220	0.460	12.589	0.320
57.270	114.340	97.650	0.580	0.150	0.440	7.285	-99.990
71.880	131.810	97.920	0.310	0.210	0.500	4.025	-99.990
66.230	137.650	97.930	0.340	0.280	0.500	33.478	0.270
63.220	126.410	98.020	0.220	0.270	0.460	6.449	-99.990
52.310	121.500	97.950	0.300	0.210	0.450	78.558	0.280
53.920	128.980	98.020	0.240	0.120	0.440	134.216	0.280
56.040	139.920	97.970	0.300	0.210	0.420	39.060	0.280
57.600	147.860	97.810	0.450	0.390	0.560	35.175	0.280
37.780	153.340	97.830	0.470	0.200	0.500	48.339	0.290
37.650	141.770	97.930	0.350	0.160	0.540	25.286	0.240
37.000	128.110	98.010	0.260	0.160	0.330	35.509	0.200
36.620	116.970	97.980	0.280	0.150	0.330	8.932	-99.990

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/s/m) ($*10^{-4}$)	D50 (mm)
22.740	112.540	98.000	0.230	0.180	0.330	4.476	-99.990
21.860	128.860	97.980	0.280	0.160	0.330	6.438	-99.990
22.600	145.960	97.900	0.360	0.200	0.510	9.556	-99.990
July 7, 1988							
76.220	102.240	97.940	0.270	0.200	0.380	106.010	0.310
73.540	105.490	97.910	0.340	0.200	0.360	55.120	0.230
72.000	101.220	97.920	0.290	0.150	0.330	47.911	0.230
61.890	98.890	97.940	0.280	0.150	0.340	20.733	0.230
63.120	105.800	97.820	0.420	0.220	0.360	28.924	0.260
64.250	110.190	97.670	0.530	0.160	0.420	9.279	-99.990
56.450	114.880	97.700	0.540	0.160	0.340	19.223	0.200
54.360	106.460	97.780	0.450	0.100	0.360	9.966	-99.990
52.300	96.500	97.980	0.240	0.140	0.280	5.560	-99.990
95.700	119.410	97.820	0.420	0.150	0.480	72.940	0.270
96.060	124.110	97.740	0.470	0.210	0.280	56.035	0.270
83.040	139.720	97.780	0.440	0.270	0.570	149.652	0.290
82.670	127.430	97.880	0.320	0.330	0.520	68.958	0.250
82.650	118.620	98.010	0.220	0.260	0.480	53.427	0.270
71.740	116.600	98.100	0.200	0.150	0.320	8.637	-99.990
71.400	124.790	97.980	0.240	0.300	0.480	256.108	0.380
71.540	141.480	97.880	0.380	0.250	0.540	37.630	0.260
59.350	144.770	97.900	0.340	0.220	0.560	27.160	0.270
59.080	128.260	97.960	0.260	0.270	0.460	108.075	0.280
59.510	115.700	97.820	0.380	0.280	0.460	34.523	0.230
47.700	114.430	97.940	0.320	0.140	0.380	12.958	-99.990
47.280	128.920	97.940	0.280	0.240	0.340	23.113	0.250
46.980	144.920	97.920	0.300	0.340	0.520	59.434	0.270
July 20, 1988							
84.770	98.980	97.800	0.400	0.240	0.460	10.844	0.230
78.410	101.630	97.750	0.480	0.200	0.420	2.352	-99.990
78.000	97.580	97.870	0.350	0.220	0.360	0.000	-99.990
66.590	94.160	97.960	0.270	0.150	0.280	3.413	-99.990
67.700	100.050	97.820	0.400	0.060	0.320	3.416	-99.990
69.180	105.380	97.740	0.520	0.120	0.460	13.829	0.310
57.900	109.800	97.690	0.540	0.140	0.400	4.546	-99.990
57.350	101.310	97.900	0.370	0.080	0.200	2.265	-99.990
56.710	91.330	97.990	0.230	0.150	0.280	8.043	-99.990
84.070	112.970	98.040	0.220	0.210	0.360	3.142	-99.990
85.330	120.430	98.000	0.260	0.200	0.390	5.003	-99.990
75.200	121.510	98.030	0.220	0.220	0.440	1.972	-99.990
74.290	113.520	98.020	0.230	0.240	0.440	3.575	-99.990
67.100	113.320	97.940	0.310	0.160	0.390	6.885	-99.990
67.860	123.320	98.000	0.270	0.220	0.400	21.830	0.310
58.560	124.280	98.000	0.260	0.200	0.450	4.856	-99.990
58.570	120.270	98.000	0.260	0.200	0.340	2.617	-99.990

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/s/m) ($*10^{-4}$)	D50 (mm)
July 27, 1988							
87.270	98.550	97.640	0.640	0.160	0.500	11.111	0.290
82.920	101.240	97.620	0.680	0.270	0.510	16.679	0.340
82.330	97.210	97.780	0.480	0.150	0.360	10.823	0.250
77.610	96.130	97.800	0.460	0.150	0.320	4.883	-99.990
77.360	100.370	97.640	0.600	0.150	0.340	4.494	-99.990
77.250	106.110	97.540	0.710	0.120	0.240	17.522	0.350
71.300	103.420	97.660	0.640	0.140	0.360	3.297	-99.990
71.520	96.720	97.880	0.360	0.120	0.270	4.819	-99.990

APPENDIX C

North site

North site

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/s/m) ($*10^{-4}$)	D50 (mm)
June 3, 1988							
121.650	116.360	99.040	0.060	0.220	0.210	0.000	-99.990
127.260	101.300	99.070	0.000	0.000	0.000	0.000	-99.990
125.240	89.090	99.030	0.050	0.100	0.120	0.846	-99.990
118.020	82.450	98.980	0.090	0.110	0.150	0.697	-99.990
121.750	85.060	98.550	0.070	0.110	0.160	2.769	-99.990
109.900	134.500	99.050	0.060	0.130	0.140	0.000	-99.990
109.370	124.180	98.930	0.170	0.300	0.570	26.113	0.200
92.370	122.450	98.450	0.120	0.130	0.300	18.475	0.220
94.510	117.260	98.960	0.040	0.300	0.340	12.538	0.200
96.740	112.750	99.060	0.060	0.080	0.170	0.000	-99.990
105.020	95.550	99.010	0.100	0.100	0.270	2.962	-99.990
109.670	86.100	98.980	0.110	0.170	0.300	4.493	-99.990
114.320	76.670	98.950	0.140	0.100	0.200	2.363	-99.990
103.590	84.050	99.090	0.000	0.000	0.000	0.000	-99.990
119.050	113.110	99.240	0.000	0.000	0.000	0.000	-99.990
87.740	63.710	98.650	0.460	0.320	0.570	92.693	0.180
82.120	90.630	98.920	0.220	0.260	0.460	47.152	0.200
78.420	110.280	98.880	0.280	0.250	0.500	67.112	0.240
75.380	125.990	98.870	0.320	0.270	0.510	9.674	-99.990
42.170	123.540	99.140	0.080	0.210	0.250	4.904	-99.990
33.310	117.450	99.160	0.060	0.180	0.160	0.000	-99.990
36.830	130.900	99.060	0.140	0.300	0.460	39.992	0.220
25.190	136.440	98.980	0.200	0.500	0.520	80.491	0.240
23.760	126.150	99.080	0.140	0.190	0.420	20.755	0.210
20.620	114.290	99.160	0.080	0.110	0.220	0.000	-99.990
6.340	115.350	99.120	0.120	0.280	0.320	119.271	0.210
7.400	128.430	99.040	0.250	0.340	0.580	101.154	0.230
8.430	139.460	98.960	0.240	0.360	0.550	57.344	0.230
June 9, 1988							
125.690	126.620	99.020	0.000	0.000	0.000	0.000	-99.990
128.720	119.720	99.040	0.000	0.000	0.000	0.000	-99.990
131.500	103.340	99.020	0.140	0.180	0.270	0.653	-99.990
131.000	89.000	98.950	98.940	0.200	0.250	0.425	267.460
130.980	95.070	98.920	0.200	0.370	0.530	12.294	-99.990
128.130	92.300	99.080	0.080	0.100	0.150	0.000	-99.990
123.820	104.220	99.020	0.140	0.210	0.330	7.083	0.220
103.540	115.260	99.080	0.100	0.120	0.200	0.000	-99.990
112.520	103.870	98.930	0.240	0.250	0.450	19.194	0.210
120.250	94.040	99.040	0.100	0.210	0.310	19.037	0.190
126.930	85.940	98.960	0.180	0.250	0.460	19.767	0.230
111.550	76.860	98.960	0.160	0.230	0.380	4.197	-99.990
105.130	87.040	98.960	0.200	0.230	0.440	6.560	-99.990
95.940	102.010	98.900	0.270	0.190	0.460	23.612	0.190
80.760	125.390	98.890	0.300	0.230	0.550	55.519	0.180
72.690	108.710	98.880	0.300	0.300	0.470	30.306	0.210

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/s/m) ($*10^{-4}$)	D50 (mm)
74.440	87.530	98.980	0.200	0.180	0.340	6.681	0.220
75.820	70.980	98.920	0.200	0.110	0.350	0.000	-99.990
49.900	125.140	99.120	0.100	0.140	0.160	0.000	-99.990
40.740	124.870	99.130	0.140	0.100	0.340	8.479	0.230
44.910	133.570	99.050	0.070	0.230	0.270	11.225	0.230
34.010	138.720	99.020	0.120	0.150	0.330	80.466	0.280
31.290	132.050	99.060	0.160	0.300	0.430	100.932	0.360
28.830	124.900	99.140	0.180	0.190	0.500	23.238	0.250
15.600	124.220	99.070	0.200	0.310	0.540	56.109	0.260
16.730	134.730	98.980	0.200	0.220	0.530	14.332	0.460
18.130	141.910	99.000	0.160	0.240	0.420	24.286	-99.990
June 15, 1988							
148.800	100.160	98.900	0.280	0.040	0.150	0.000	-99.990
143.900	96.910	98.870	0.280	0.100	0.180	0.000	-99.990
143.120	102.520	99.000	0.140	0.000	0.050	0.000	-99.990
136.210	107.480	99.120	0.060	0.070	0.100	0.000	-99.990
136.750	97.650	98.980	0.200	0.110	0.200	0.000	-99.990
138.010	91.570	98.690	0.450	0.180	0.380	9.274	0.140
128.370	85.840	98.770	0.420	0.160	0.380	11.881	0.200
123.210	91.960	98.820	0.320	0.180	0.510	27.221	0.200
115.290	102.280	99.000	0.190	0.260	0.450	21.111	0.220
106.230	114.290	99.000	0.180	0.120	0.450	3.201	-99.990
88.530	126.500	98.890	0.330	0.340	0.550	92.138	0.200
97.250	93.790	98.880	0.340	0.220	0.540	38.303	0.210
89.530	99.330	98.920	0.290	0.230	0.460	19.271	0.210
89.710	84.710	99.020	0.160	0.140	0.290	1.874	-99.990
90.160	68.830	98.980	0.200	0.090	0.210	0.000	-99.990
54.790	124.040	99.150	0.060	0.140	0.150	0.000	-99.990
53.610	129.280	99.110	0.120	0.170	0.280	2.164	-99.990
49.360	136.080	99.080	0.160	0.210	0.440	16.002	0.240
46.840	129.430	99.120	0.130	0.090	0.330	11.161	0.230
44.780	122.680	99.190	0.060	0.180	0.200	2.948	-99.990
33.300	122.530	99.180	0.100	0.200	0.220	1.388	-99.990
36.260	133.510	99.090	0.190	0.220	0.440	88.163	0.280
38.480	142.240	99.040	0.200	0.390	0.580	116.095	0.230
23.620	144.720	99.040	0.220	0.330	0.520	23.301	0.220
21.290	136.790	99.020	0.250	0.240	0.510	49.071	0.230
18.200	131.210	99.080	0.200	0.300	0.460	50.094	0.230
16.240	117.590	99.150	0.120	0.150	0.340	5.593	0.230
June 23, 1988							
154.860	104.010	99.110	0.000	0.000	0.000	0.000	-99.990
151.300	101.190	99.010	0.100	0.020	0.020	1.486	-99.990
144.900	108.800	99.020	0.100	0.000	0.000	0.000	-99.990
158.620	103.490	99.870	0.260	0.000	0.000	0.000	-99.990
136.820	114.770	99.120	0.000	0.000	0.000	0.000	-99.990
129.340	109.140	99.100	0.080	0.030	0.140	0.000	-99.990
137.130	99.660	99.020	0.100	0.140	0.180	0.000	-99.990
142.040	93.840	98.870	0.270	0.200	0.300	5.347	-99.990

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/s/m) ($*10^{-4}$)	D50 (mm)
128.830	81.040	98.790	0.370	0.160	0.420	11.422	0.200
118.380	93.820	98.870	0.300	0.240	0.510	36.104	0.220
109.940	103.720	98.850	0.320	0.160	0.510	68.654	0.240
92.840	122.780	98.800	0.370	0.160	0.450	32.980	0.190
91.930	104.560	98.920	0.240	0.260	0.360	13.808	0.240
90.980	93.480	98.980	0.160	0.090	0.240	1.957	-99.990
89.870	81.530	99.020	0.140	0.120	0.220	8.751	0.220
60.650	128.610	99.130	0.060	0.120	0.160	1.258	-99.990
53.790	127.990	99.160	0.000	0.000	0.000	0.000	-99.990
56.000	136.750	99.120	0.100	0.080	0.180	2.213	-99.990
44.530	144.620	99.060	0.140	0.120	0.220	2.106	-99.990
40.730	136.730	99.120	0.120	0.140	0.240	4.043	-99.990
38.640	125.580	99.160	0.040	0.080	0.080	2.313	-99.990
22.930	122.850	99.160	0.080	0.150	0.210	16.998	0.250
24.320	135.920	99.050	0.180	0.220	0.380	30.961	0.260
25.000	148.270	99.010	0.200	0.210	0.480	92.619	0.280
4.840	144.680	99.040	0.200	0.270	0.450	31.938	0.250
5.220	134.320	98.980	0.220	0.320	0.500	194.876	0.320
6.930	120.280	99.070	0.190	0.160	0.380	30.863	0.250
July 4,	1988						
174.690	115.430	98.700	0.380	0.160	0.320	4.685	-99.990
167.180	115.760	99.040	0.060	0.000	0.000	0.000	-99.990
164.240	108.980	99.060	0.040	0.000	0.000	0.000	-99.990
156.710	117.310	99.080	0.010	0.000	0.000	0.000	-99.990
149.290	119.890	99.090	0.020	0.000	0.000	0.000	-99.990
133.910	113.820	99.040	0.100	0.040	0.040	0.000	-99.990
143.020	103.850	99.000	0.120	0.040	0.140	0.000	-99.990
147.770	97.330	98.840	0.280	0.080	0.220	2.128	-99.990
138.950	91.740	98.800	0.330	0.150	0.460	10.222	0.210
143.960	83.610	98.920	0.220	0.140	0.420	16.385	0.210
121.020	111.390	98.920	0.220	0.200	0.440	3.321	-99.990
106.560	127.470	98.880	0.260	0.180	0.280	4.911	-99.990
104.540	116.260	98.750	0.370	0.210	0.400	10.148	0.210
102.820	99.970	98.950	0.160	0.210	0.240	0.299	-99.990
101.470	88.780	99.000	0.120	0.080	0.180	1.745	-99.990
99.630	76.660	99.060	0.050	0.150	0.150	0.000	-99.990
66.090	141.700	99.080	0.080	0.090	0.120	0.000	-99.990
58.580	139.060	99.100	0.040	0.030	0.030	0.000	-99.990
58.200	147.580	99.090	0.120	0.090	0.210	0.000	-99.990
47.340	152.020	99.000	0.160	0.200	0.300	0.000	-99.990
47.060	146.620	99.020	0.140	0.120	0.260	0.810	-99.990
46.130	136.070	99.100	0.060	0.060	0.060	0.000	-99.990
32.570	131.830	99.070	0.100	0.150	0.160	0.000	-99.990
30.100	145.110	98.980	0.200	0.060	0.400	14.546	0.280
28.640	153.730	98.940	0.240	0.220	0.450	28.436	0.250
10.550	152.510	98.800	0.380	0.220	0.520	55.519	0.270
10.320	143.420	98.900	0.300	0.220	0.480	73.471	0.300

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/s/m) ($*10^{-4}$)	D50 (mm)
14.420	134.230	98.990	0.220	0.200	0.460	9.991	0.230
18.670	125.310	99.060	0.140	0.140	0.270	3.125	-99.990
July 18, 1988							
190.290	128.110	98.780	0.380	0.140	0.300	2.147	-99.990
174.280	130.330	99.070	0.110	0.000	0.000	0.000	-99.990
184.440	122.650	98.920	0.260	0.040	0.200	1.468	-99.990
170.510	112.630	98.840	0.360	0.060	0.300	9.495	-99.990
166.630	117.650	99.140	0.060	0.030	0.030	0.000	-99.990
146.830	119.970	99.100	0.100	0.100	0.220	1.063	-99.990
155.040	110.230	98.880	0.340	0.060	0.360	8.481	-99.990
160.170	103.890	98.680	0.500	0.140	0.500	16.435	-99.990
146.770	95.730	98.740	0.450	0.030	0.330	7.755	-99.990
140.930	103.940	98.800	0.400	0.200	0.400	16.700	-99.990
133.080	113.720	98.840	0.390	0.180	0.440	43.045	-99.990
121.570	129.760	98.780	0.390	0.210	0.550	54.793	-99.990
117.610	112.010	98.780	0.380	0.090	0.380	8.051	-99.990
113.630	101.280	98.920	0.240	0.080	0.200	0.000	-99.990
109.850	86.110	99.000	0.180	0.060	0.120	0.000	-99.990
106.010	73.420	99.000	0.170	0.060	0.080	0.000	-99.990
90.700	137.250	99.000	0.140	0.100	0.200	2.986	-99.990
88.050	133.370	99.120	0.040	0.060	0.060	0.000	-99.990
81.770	134.500	99.140	0.020	0.000	0.000	0.000	-99.990
84.710	140.660	99.010	0.160	0.090	0.260	5.546	-99.990
87.560	144.060	98.920	0.270	0.180	0.300	2.756	-99.990
78.130	151.640	98.840	0.380	0.180	0.510	9.928	-99.990
74.820	144.830	98.960	0.220	0.240	0.330	30.193	-99.990
71.680	136.530	99.130	0.040	0.060	0.060	0.000	-99.990
50.900	138.150	99.060	0.160	0.120	0.270	1.767	-99.990
52.790	148.950	98.940	0.280	0.300	0.460	21.035	-99.990
54.660	159.620	98.780	0.410	0.260	0.420	17.611	-99.990
August 3, 1988							
211.990	150.600	98.620	0.560	0.160	0.380	4.166	-99.990
216.760	146.660	98.460	0.710	0.150	0.460	2.418	-99.990
206.630	137.790	98.460	0.700	0.120	0.390	1.441	-99.990
202.740	142.270	98.860	0.290	0.100	0.300	1.948	-99.990
194.910	132.880	99.120	0.020	0.000	0.000	0.000	-99.990
183.900	128.490	98.980	0.180	0.120	0.240	0.343	-99.990
187.170	123.690	98.940	0.220	0.100	0.300	5.946	-99.990
179.260	117.250	98.780	0.390	0.090	0.330	1.840	-99.990
157.330	132.320	98.990	0.180	0.040	0.150	0.455	-99.990
170.530	128.410	99.070	0.140	0.080	0.100	0.000	-99.990
160.970	136.120	99.160	0.010	0.000	0.000	0.000	-99.990
157.730	136.320	99.140	0.040	0.000	0.000	0.000	-99.990
152.450	126.110	99.020	0.150	0.140	0.200	0.363	-99.990
162.780	114.630	98.820	0.340	0.200	0.510	43.588	0.210
169.100	108.000	98.680	0.500	0.140	0.360	21.102	0.250
156.030	100.700	98.840	0.280	0.090	0.270	1.756	-99.990

X (m)	Y (m)	ELEV (m)	DEPTH (m)	B-VEL (m/s)	VEL (m/s)	BEDLOAD (kg/s/m) ($*10^{-4}$)	D50 (mm)
148.980	109.300	98.790	0.360	0.120	0.390	10.078	0.230
141.030	118.430	98.790	0.380	0.090	0.510	24.093	0.220
131.730	129.110	98.760	0.440	0.280	0.580	50.881	0.200
120.600	133.090	98.750	0.470	0.280	0.600	91.209	0.250
114.290	125.790	98.900	0.260	0.210	0.340	23.609	0.240
106.120	127.770	99.040	0.120	0.120	0.300	2.439	-99.990
110.400	132.970	98.860	0.320	0.180	0.420	12.948	0.220
114.770	137.840	98.740	0.480	0.210	0.570	125.134	0.280
102.140	146.390	98.750	0.460	0.390	0.570	55.563	0.260
97.480	138.220	98.960	0.200	0.160	0.380	30.369	0.260
91.940	129.020	99.140	0.040	0.080	0.080	5.563	0.210
August 10, 1988							
229.470	161.830	98.280	0.830	0.160	0.360	7.757	-99.990
232.660	159.070	98.350	0.720	0.180	0.440	20.388	0.380
215.110	142.020	98.220	0.860	0.200	0.360	1.722	-99.990
208.960	148.430	98.800	0.320	0.100	0.270	2.039	-99.990
199.790	139.370	99.000	0.100	0.100	0.120	0.797	-99.990
205.420	132.530	98.130	0.940	0.120	0.360	1.869	-99.990
190.280	124.420	99.050	0.100	0.000	0.030	0.000	-99.990
182.120	133.180	99.040	0.100	0.140	0.140	0.291	-99.990
174.670	133.580	99.090	0.020	0.000	0.000	0.000	-99.990
183.670	120.070	98.920	0.200	0.090	0.150	0.000	-99.990
171.580	109.750	98.700	0.430	0.120	0.280	6.122	-99.990
165.710	116.250	98.880	0.250	0.040	0.280	2.896	-99.990
155.950	126.950	98.970	0.140	0.080	0.150	0.000	-99.990
130.320	130.540	98.720	0.390	0.260	0.480	25.144	0.220
143.200	117.120	98.810	0.300	0.160	0.340	16.463	0.230
152.220	107.680	98.800	0.280	0.200	0.320	2.580	-99.990
158.190	101.600	98.800	0.290	0.150	0.270	3.140	-99.990
125.860	85.240	98.940	0.180	0.000	0.100	0.000	-99.990
123.270	104.990	98.870	0.240	0.080	0.150	4.803	-99.990
121.100	122.400	98.890	0.220	0.180	0.360	7.080	-99.990
120.240	140.350	98.730	0.390	0.320	0.580	22.132	0.220
113.560	133.800	98.860	0.260	0.160	0.390	7.525	-99.990
106.420	126.160	99.060	0.060	0.100	0.100	1.170	-99.990
93.400	128.020	99.090	0.020	0.000	0.000	0.000	-99.990
101.390	143.020	98.880	0.260	0.090	0.380	2.693	-99.990